EQUIVALENT TRANSFER FUNCTION FOR A VARIABLE SPEED WIND TURBINE IN POWER SYSTEM DYNAMIC SIMULATIONS

Joris Soens, Johan Driesen and Ronnie Belmans
K.U.Leuven, Electrotechnical Department ESAT-ELECTA
Kasteelpark Arenberg 10, B-3001 Heverlee
Tel: +32 16 32 10 31   Fax: +32 16 32 19 85
http://www.esat.kuleuven.ac.be/electa
joris.soens@esat.kuleuven.ac.be

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ABSTRACT

This paper presents a generic dynamic model for simulating variable speed wind turbines in power systems. The model is derived from a more detailed turbine model that is described in literature.

The wind turbine model presented here is basically an equivalent transfer function of the first or second order. The input is the wind speed, and the output is active and reactive power. This alleviates very much the computational efforts for power system simulations, and decreases the risk for numerical instabilities, compaired to the existing detailed wind turbine models described in literature. Also, the basic model blocks that are used in the model are available in practically all power system simulation packages.

The model structure is not directly linked to a certain turbine and generator technology, such as doubly fed or synchronous generator. However, the model parameters and time constants of the various model blocks are technology dependent. They summarize the complicated turbine behaviour in a very dense way that is directly usable for grid operators or project developers.

The model is intended for estimating the amount of wind power that can be absorbed in a given grid connection point, rather than to make accurate predictions of the impact of a specific farm with given turbine type. It may be used by system operators to quantify the general connection requirements on a certain grid connection point, taking into account the inherent characteristics of wind power and an accepted decrease of grid power quality.

1 INTRODUCTION

During the last decade, the installed wind power capacity has grown explosively in various regions in Europe and elsewhere. This wind power expansion is evolving at two levels: on the one hand, the number of large-scale (offshore) wind farms that are installed, or actually under development, is steadily increasing. These wind farms inject their power directly into the high-voltage transmission grid, e.g. at the 150 kV level. On the other hand, stand-alone wind turbines or small wind turbine clusters are more frequently installed in distribution grids.

The dynamic modelling of wind power generators, in order to estimate their impact on the power system dynamic behaviour, is a matter of high interest for grid operators. The development of these models has been the subject of many discussions: it requires a compromise between making substantial simplifications to reduce computational efforts on the one hand, and maintaining the necessary adequacy to be able to predict the wind power's influence on the electrical power system's dynamic behaviour on the other hand.

By investigating the dynamic behaviour of wind power generators, more insight is obtained concerning the ability of a wind farm to provide 'grid support'. 'Grid support', also known as 'ancillary services', represents a number of services that the power system operator requires from power generators, in order to secure a safe, reliable, stable and economically manageable grid operation. The reliable supply of ancillary services can be an additional source of revenue for electricity generators. 'Ancillary services' include support for [1]:

- frequency control, strongly related with active power control;
- voltage control, strongly related with reactive power control;
- black start capability;
- economic dispatch and financial trade reinforcements.

The relation between wind farms and grid support has been extensively discussed over the past years, especially in Denmark and Germany, where the relative amount of wind power in the grid is the highest of the world. Specific grid connection requirements for wind turbines were first issued by the Danish and German grid operators, and are used as a reference by most other grid operators who have to take a large amount of wind power in their power system into account. An overview of national grid connection requirements, specific for wind energy converters, is given in [2] and [3]. Typically, these connection requirements give thresholds for:

- (fast) active and reactive power controllability, in case of normal and disturbed grid operation;

- ride-through capability, i.e. the capability to continue normal operation and power production in case of a grid disturbance nearby.

Thus, the actual existing grid connection requirements are mainly focussed on the first two mentioned ancillary services. With advanced technology for wind turbine generators, their performance can be considered as high as with conventional generators, with respect to voltage control and control of active power input (mainly the fast and controlled reduction of active power in case of a grid disturbance).

On the other hand, even the most advanced turbine technology hardly improves the capability of wind power to facilitate the economic dispatch of the power market and financial trade reinforcements. These issues cannot be enforced by technical grid connection requirements, but must be part of the financial risk that a wind farm operator or a subsidizing party is willing to take. The criterion for success in these issues is mainly the accuracy of wind speed predictions on a mid- to long term, rather than the turbine technology.

This paper focuses on the grid impact items that can be optimized using advanced technology, i.e. active and reactive power controllability on a short term. A simplified equivalent model for both the active and reactive power behaviour of a typical modern wind turbine is elaborated. The model structure is independent of a specific turbine technology, such as doubly-fed induction or synchronous generators; although it is assumed that the turbine generators can operate at variable speed. In contrast to the structure of the model, the various parameters and time constants in the model blocks are dependent of the turbine technology.

The main purpose of this model is to provide a tool to estimate the amount of wind power that a certain grid point can absorb. This depends on the grid operation parameters defined by the user. The grid connection requirements, imposed by the grid operator, are an important parameter in this respect.

The model can be implemented in most power system simulation software packages, such as PSS/E, EUROSTAG, DigSilent, ETAP…

2 ACTIVE POWER MODEL

2.1 Detailed turbine models

Detailed models for wind turbines for power system simulations are described, amongst others, in references [4]-[12]: two recent PhD-theses are almost entirely focused on the subject ([4],[5]); [6] focuses on turbines with squirrel-cage induction generators, while [7]-[11] treat doubly fed induction generators and [12] synchronous generators.

Wind turbine models generally consist of the following elements, which can all be worked out to a high or low level of detail:

- *Wind speed model:* mostly a time series of measured or well-chosen wind speed values. However, wind speeds can also be generated as stochastic signals, based on a power spectral density function. Also methods based on Markov chains or wavelet decomposition are used to generate wind speed time series of various time resolutions [13].
- *Aerodynamic model of the turbine*: mostly an approximate formula for the coefficient of performance C_p, as a function of wind speed, turbine speed and turbine design. For more detailed models, the Blade Element Method (BEM) can be used.
- *Model for the shaft coupling and gearbox*: mostly modelled as a torsional spring between two rotating masses (turbine and generator). The equivalent spring stiffness is relatively low [4]. This may result in large torsional vibrations between turbine and generator, considerably affecting the electrical and mechanical behaviour.
- *Generator model*, containing the voltage differential equations and flux equations, mostly in a rotor- or stator-flux oriented (d,q) reference frame, as well as the torque and motion equation.
- Models for the *power electronic circuits*, if any, for instance the inverters of a direct-drive machine or the rotor-coupled converter of a doubly-fed machine.
- *Controller models*: pitch control, speed control, generator active and reactive power and current control, maximum power tracker.
- *Protective relays*: for switching off the turbine after a given duration of a given over- or undervoltage or –frequency.
- *Grid model*: for assessment of the wind turbine behaviour alone, it is sufficient to model the grid as a voltage source with given short-circuit power. When the impact of the turbine on the grid is to be investigated as well, the existing power lines need to be represented in the grid model, using dedicated power system simulation tools. This is the case in this paper, where the focus lies on the study of the interaction between wind farm and grid.

The wind turbine model that is used in this paper, as a starting point towards an equivalent active power model, is that of a GE3.6 turbine, i.e. a variable speed turbine, equipped with a doubly fed induction generator with a rated power of 3.6 MW . Its rated wind speed is 16 m/s. The turbine's power curve is shown in Figure 2.1. The model is taken from [11], its layout is shown in Figure 2.2.

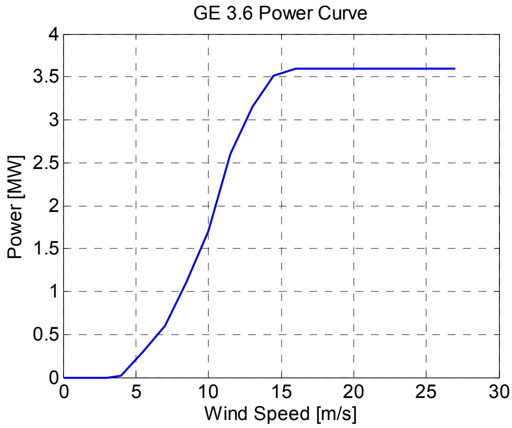

Figure 2.1. Power curve of a GE3.6 turbine

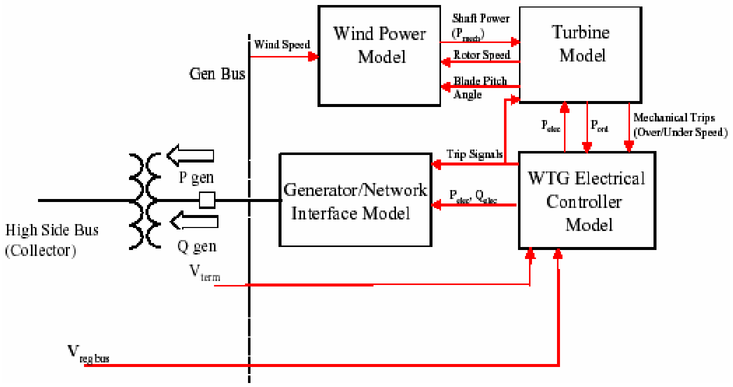

Figure 2.2. Model layout of a GE3.6 turbine [11]

The *'Wind Power Model'* contains the following basic formula to calculate the turbine mechanical power P_{mech}:

$$P_{mech} = C_p \cdot \frac{1}{2} \cdot \underbrace{\pi R_{turb}^{\ 2}}_{A_{turb}} \cdot \rho_{air} v_{wind}^{\ 3} \qquad (1)$$

The performance coefficient, C_p, is calculated by a numerically approximated formula, which is function of tip-speed ratio and pitch angle. The *'Turbine Model'* and *'Electrical Controller Model'* contains a relatively detailed description of pitch control and speed control (*'Turbine'*), and reactive power control and tripping signals (*'Electrical Controller'*). The model parameters and the settings of the various control loops, used by the manufacturer, are given in [11]. The *'Generator Model'* is a simplified model in this case, as the time constants of the generator are much smaller than those of the mechanical controllers.

2.2 Frequency characteristic of *Active Power Model*

Simulations were performed in Simulink with the blocks *'Wind Power Model'* and *'Turbine Model'*, to characterize the frequency response of P_{ord}, i.e. the available mechanical power, as output of the Turbine Model in Figure 2.2.

Wind speed signals were generated in SIMULINK as a superposition of a sine wave (with amplitude 1 m/s and varying frequency) on an average value. With these wind speed signals as input, the turbine active power consists also of a sine wave of the same frequency as the input signal, superposed on a constant value. This suggests that, for a fixed value of average wind speed, the entire system can be assumed to be linear, and can be approximated by a simple transfer function. The amplitude of the power oscillations depends on the mean value of the wind speed signal and on the frequency of its fluctuations.

Figure 2.3 shows examples from wind speed signals with an average value of 8 m/s (= 0.5•$v_{wind,rated}$) (figures a, b and c), and 19 m/s (= 1.2•$v_{wind,rated}$) (figures d, e and f). The corresponding mechanical powers are shown in the same figures.

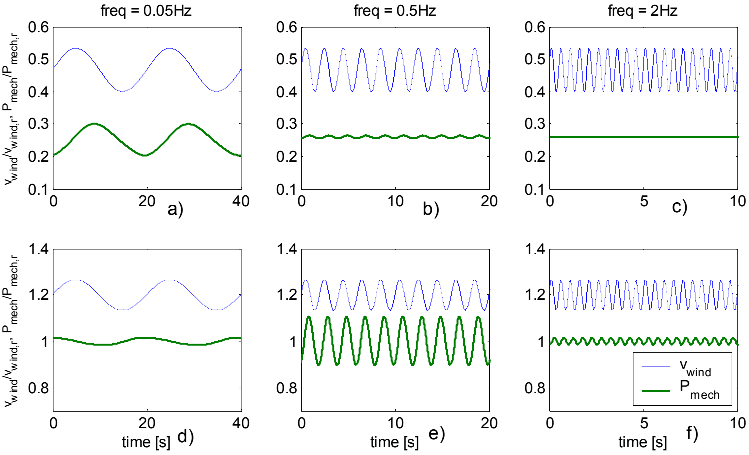

Figure 2.3. Wind speed and mechanical power for two values of average wind speed and three different wind speed fluctuation frequencies

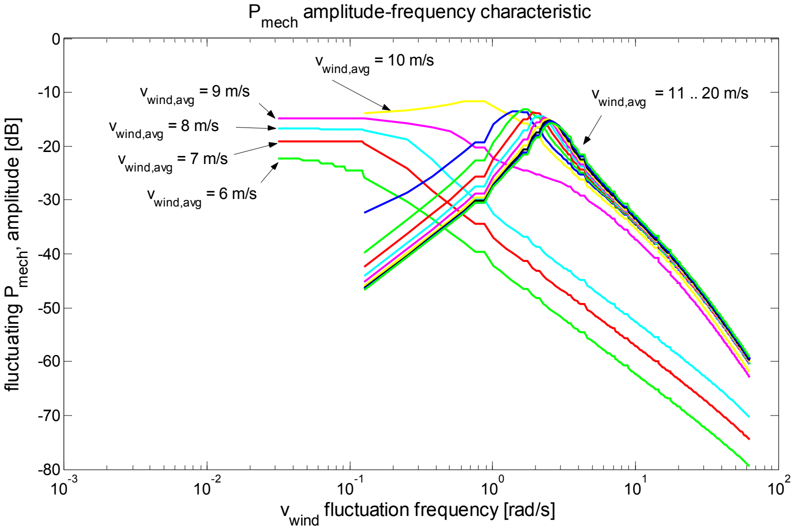

Figure 2.4. Frequency Characteristic of Power Fluctuation Amplitude

All simulation results, for a large range of frequencies and average wind speeds, are summarized in Figure 2.4. The 10-logarithm of the amplitude of the turbine power oscillations is plotted against the frequency of the wind speed oscillations. This plot can be interpreted as a Bode diagram, and it allows estimating equivalent transfer functions for the variable speed pitch-controlled turbine system.

In the Bode plot of Figure 2.4, two sets of curves can be distinguished:

1) Low average wind speed (below rated wind speed)

The curves for low average wind speeds show the behaviour of a low-pass filter: the amplitude of the output power oscillation remains constant as a function of the frequency, for low fluctuation frequencies. For higher fluctuation frequencies, the amplitude of the power oscillations decreases with a constant slope. This is explained in the following.

At low average wind speeds, the pitch angle remains at zero degrees to maximize C_p, and only the turbine speed control is active.

For slow wind speed fluctuations, the turbine speed is adjusted to obtain the maximum C_p-value, and the optimal turbine speed can be achieved at every moment. The output power is always equal to the maximum from the wind extractable power, as given by the power curve. Although the amplitude of the wind fluctuations was kept constant for all frequencies during the simulations, the amplitude of the power output oscillations depends on the average wind speed. This is explained by the non-linearity of the power curve in the low wind speed region.

For fast wind speed fluctuations, the turbine operates almost as a flywheel. It accelerates and decelerates to dampen the fluctuations in the output power. The system transfer function has the characteristic of a low-pass first order filter. The time constant of the filter depends on the average wind speed value but its range is between 1 s and 10 s.

2) High average wind speed (above rated wind speed)

For high average wind speeds, the frequency characteristic is influenced by the action of both the pitch and the speed controllers. The turbine speed is at its maximal rated value, but a small margin for speed variation above and below this speed is still allowed, to dampen the power oscillations.

If the wind speed goes above the rated value, the pitch control limits the output power. However, the pitch control action is rather slow. Only for very low frequencies of wind speed fluctuation, the pitch control is able to maintain the output power at 1 p.u. at every moment. The amplitude of the power fluctuation is then very low (Figure 2.3d).

For very high frequencies of wind speed fluctuation, the slow pitch control is not able to follow the fluctuations, but the power output fluctuations are then damped by (small) variations of turbine speed (the right side of the curves for high wind speed in Figure 2.4). This is again the behaviour of a low-pass filter, and the output power remains approximately constant at 1 p.u (Figure 2.3f).

Between the region of power control by means of pitch angle adjustment on the one hand, and fluctuation damping through speed variation on the other hand, there is a frequency zone, around 2 Hz, for which fluctuations of wind speed result in relatively high fluctuations of output power, as can be seen in Figure 2.3e and Figure 2.4.

The transition between low wind speed regime (only speed control) and high wind speed regime (speed and pitch control) would be expected to occur around the turbine rated wind speed. However, the turbine control is designed in such a way that the pitch control is already in operation during wind speed fluctuations at (slightly) lower averages, to assist the output power control and damping in case of wind speed fluctuations. For the turbine simulated here, the transition between the two distinguished frequency behaviour patterns occurs at a wind speed of around 12 m/s. For wind speeds close to this value, the system behaves strongly non-linear.

2.3 Equivalent transfer function for *Active Power Model*

From the plots in Figure 2.4, it can be concluded that an equivalent transfer function must be a first order low-pass filter for low wind speeds, and a higher order transfer function for high wind speeds. This is shown in Figure 2.5. The function input is the available wind speed. The output is the mechanical turbine power that is available to produce electricity.

In the upper part of Figure 2.5, the wind speed is low-pass filtered and converted into active power using the turbine power curve. The time constant of the low-pass filter corresponds to the frequency at which the slope of the first group of bode plots in Figure 2.5 evolves from 0 dB/decade to 20 dB/decade. This time constant depends on the average wind speed, but is assumed constant for this simplified model.

The power curve has an upper limit for the output power, which is equal to the rated power, being 1 p.u. The upper input of the summator in Figure 2.5 will remain constant at 1 p.u. for high wind speeds. The impact of wind speed fluctuations at rated power operation is taken into account by a second transfer function (in the lower part of Figure 2.5) that matches the second group of curves in Figure 2.4.

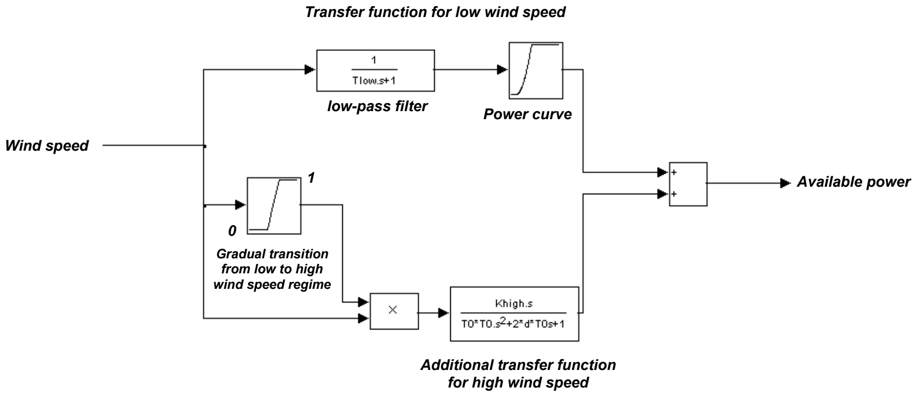

Figure 2.5. Equivalent Transfer Function for Active Power

The simplified model contains a gradual transition between the low wind speed and high wind speed region. For wind speeds below 90% of rated wind speed, the transfer function for high wind speeds is not taken into account (factor 0). For wind speeds above 100% of rated wind speed, the transfer function for high wind speeds is fully taken into account (factor 1). A linear interpolation is used for the intermediate wind speeds.

The parameters that result in an optimal match between the equivalent transfer function and the plots from Figure 2.4 were found to be (in per-unit scale):

T_{low} = 7 s
d = 0.3
T_0 = 0.5 s
K_{high} = 0.06

The output of the equivalent transfer function was compared with the output of the detailed model for the wind speed signal shown in Figure 2.6. The wind speed is first below the rated speed (16 m/s), and rises then to a value above 16 m/s. The resulting power outputs for the detailed model and the equivalent transfer function are also shown in Figure 2.6 and show a very good correspondence. The wind speed variations are clearly more damped in the low wind speed region, both with the detailed model and the equivalent transfer function.

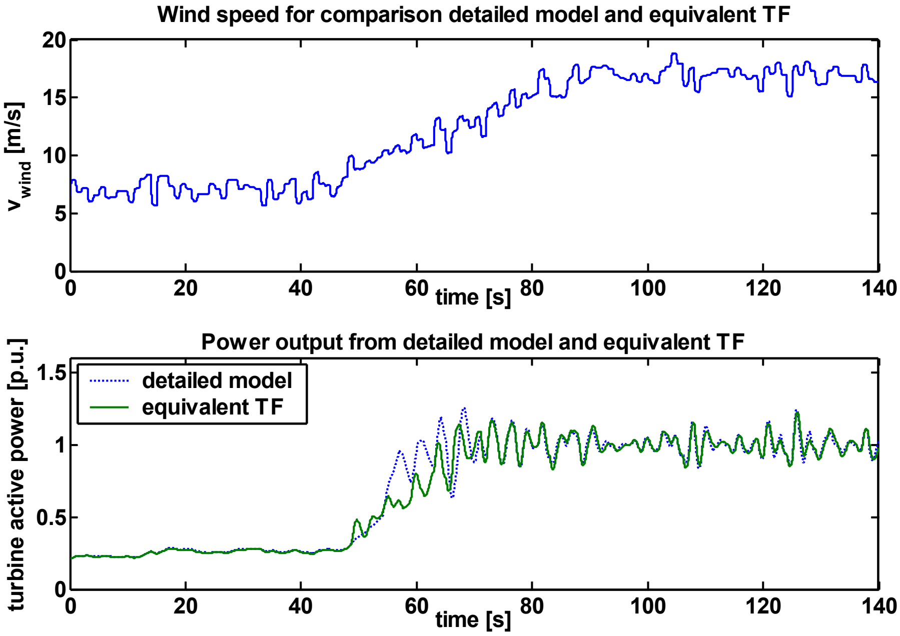

Figure 2.6. Wind speed signal (above) and corresponding power output (below) from the detailed model and the equivalent transfer function

2.4 Control modes for active power

In some circumstances, it may be necessary the limit the active power output and to control it at a predefined value. This may occur at the following cases:

- The available margin for electrical current of the equipment is needed for the supply of reactive power, when immediate assistance from the turbine is required to mitigate a voltage disturbance. Active power has to be decreased then, in order not to exceed the system's rated current.
- The power lines in the immediate vicinity of the turbines are overloaded. Existing power grids are seldomly designed to transport a large amount of wind energy. Basic grid reinforcements are not always sufficient to avoid line overloading at every energy generation and (local) load pattern scenario.
- The grid operator requires that a part of the available wind energy is kept as 'spinning reserve'. Alternatively, the wind turbine operator may take this decision by himself, to sell spinning reserves on the market for

ancillary services. The turbine blades are then partially pitched out of the wind and less electricity is produced.

Three control modes for a turbine are proposed here: ‘Full’, ‘Limited’ and ‘Balancing’. The choice of these control modes is based on (but not the same as) the control modes for the Horns Rev wind farm [14]. The three operation modes are shown graphically in Figure 2.7. The upper line in each graph is the available power from the wind speed. The lower, bold line in the figures ‘Balancing’ and ‘Limited’ represents the actually delivered power for these operation modes (assuming ideal control).

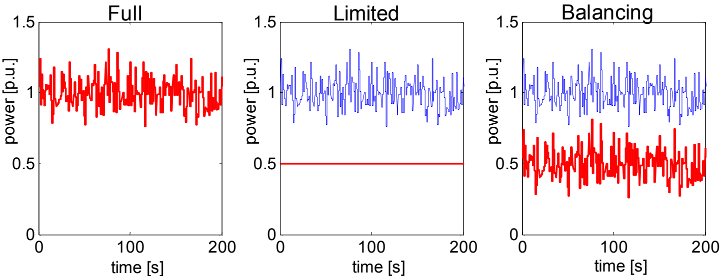

Figure 2.7. Three modes for active power operation

In the ‘Full Power’ mode, the wind farm converts all available mechanical power to electricity and injects it in the grid. In the ‘Limited’ mode, the electricity production does not exceed a maximal value, by permanently controlling the pitch angle of the turbine blades. This can be requested e.g. to prevent overloading of a power line. In the ‘Balancing’ mode, the turbine blades are partially pitched out of the wind, to maintain a fixed fraction of available wind energy as balancing power. This last service may have a high economic value for the farm operator, but is only very rarely applied because of the limited accuracy of actual wind speed predictions.

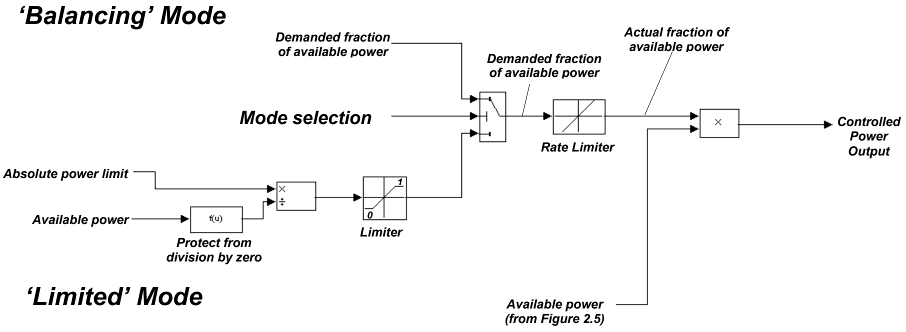

Figure 2.8. Model for transition between active power operation modes

The applicable operation mode is maintained by controlling the pitch angles of the turbines. The transition speed between two operation modes is determined by the pitch variation rate. The dynamic model for the transition between the operation modes is shown in Figure 2.8.

The switch in Figure 2.8 is controlled by the ‘Mode selection’. This determines whether the upper or lower input of the switch must be passed through as output. The switch output is the fraction (between 0 and 1) of the available active power that must be delivered to the grid. The upper switch input represents the ‘Balancing’ mode, in which a fraction of available active power can be chosen to be actually produced. The lower switch input represents the ‘Limited’ mode. Starting from a given maximal value for the output power, the fraction of the available power that must be produced is calculated and is passed through the switch. The most common operation mode (‘Full’) can be reached either by setting the absolute power limit to infinite or by setting the demanded fraction in ‘Balancing Mode’ to ‘1’.

The transition between the operation modes is modelled as a change of demanded fraction from the available power, through a rate limiter. The maximum rate depends on the pitch variation rate, and is set in this model at 20% per second. The value for the maximum rate may be given by the grid connection requirements. For example, the power output at the 160 MW offshore wind farm at Horns Rev must be able to be reduced from 100% to below 20% within 5 seconds [15].

The command for the ‘Mode selection’ and reference power may be set by the grid or turbine operator, but may also be set automatically by the overcurrent protection, when a large current is required to supply reactive power in case of a voltage disturbance.

2.5 Conclusions for the *Active Power Model*

In the previous sections, a detailed turbine model was replaced with an equivalent transfer function, to calculate the available active power with satisfying accuracy for simulations of continuous operation of a turbine. Much information about the turbine is lost (e.g. turbine speed, pitch angle) when the equivalent transfer function is used. On the other hand, the integration of this simplified turbine model in a power system model does not considerably increase the computational efforts for power system simulations, and a good assessment of undispatched fluctuating generated power caused by wind turbines can be made. Three operation modes were modelled, as well as the dynamic transition between these modes.

The model parameters, such as the time constants of the equivalent transfer functions, reflect the turbine behaviour only approximately. In general, these parameters are not given by manufacturers. However, they are strongly linked to the fundamental turbine performance characteristics. They summarize the complicated turbine behaviour in a very dense way that is directly usable for grid operators, project developers or anyone who is involved in the assessment of wind energy potential in a given grid point. The model can be used for power system simulations in order to calculate:

- specifications for the governor dynamics of conventional generators nearby a wind farm in order to maintain the angular stability of the power system;
- specifications for a turbine's active power control speed, starting from a given grid model;
- specifications for the allowed overloading of any lines, transformers or power electronic devices connected to the wind farm.

The *Active Power Model* assumes variable speed operation of the turbines, but does not prescribe a certain generator type such as doubly-fed induction generator or synchronous generator. It has already been stated in literature that, for transient power system simulations, the differences between the generator types used in variable speed wind turbines are not be seen in their interaction with the grid, because they are compensated by the controllers [16]. The model developed here is not applicable for fixed-speed turbines with squirrel cage induction generators.

3 REACTIVE POWER MODEL

Most grid operators require that wind turbines are able to control their reactive power output during both normal and disturbed grid conditions.

The modelling of the reactive power generation is shown in Figure 3.1. It does not start from a predefined detailed model from literature, as due to the used technology, it is generally possible for modern wind turbines to control their reactive power output.

Two control modes for the reactive power generation are suggested here:

- operating at a constant power factor, e.g. unity (upper part of Figure 3.1);
- controlling the reactive power output instantaneously to maintain the voltage at a given node at its reference value, or to provide voltage support in case of a grid disturbance (lower part of Figure 3.1).

As reactive power is the product of grid voltage and reactive current, controlling the reactive power is equivalent to controlling the reactive current. Because the turbine will be modelled as a current injector in the end, it is more appropriate to immediately act on the reactive current instead of power.

The reference reactive current for the first operation mode is calculated from the required power factor and the supplied active power, obtained from the *Active Power Model*. For the second operation mode, the required reactive current is calculated by a droop controller (a proportional controller), or optionally a more advanced controller. The reference current is then obtained after an equivalent delay T_{ictrl} that represents the current control loop of the generator. The implementation of a proportional controller is supported by most power system simulation software packages, and does not contain any particularities in its use for this model.

The structure of the *Reactive Power Model* does not depend on the generator technology, however the parameters do. The speed of reactive power control and the maximum amount of reactive power that can be supported may depend on the generator and power electronics type or additional equipment. The control speed is modelled as an equivalent time constant T_{ictrl}. The value of this T_{ictrl} must be assessed for each category of generator types. Suggested values are:

- T_{ictrl} = 20 ms for a synchronous generator, connected to the grid through a PWM-converter, rated for the entire power, in full control of the current;
- T_{ictrl} = 100 ms for a doubly-fed induction generator. In this generator type, the power exchange is split over the stator and the rotor, with the major part supplied by the stator. This stator current is controlled through the magnetic interaction with the rotor current, which is on its turn controlled by a PWM-converter, with a rating of ca. 30% of the turbine rated power. Because of this magnetic interaction, the current control speed is lower, and thus T_{ictrl} is higher.

From the reference reactive current, the maximum allowable active current and power is calculated to feed back to the active power controller, in order to never exceed the machine rated current in normal conditions. This way of modelling implies that priority is given to the reactive power control, and the active power must be tuned down to achieve the reference reactive power. Practically, the circumstances at which the active power must be limited because of reactive power requirements are only during grid disturbances, when full reactive power support is required.

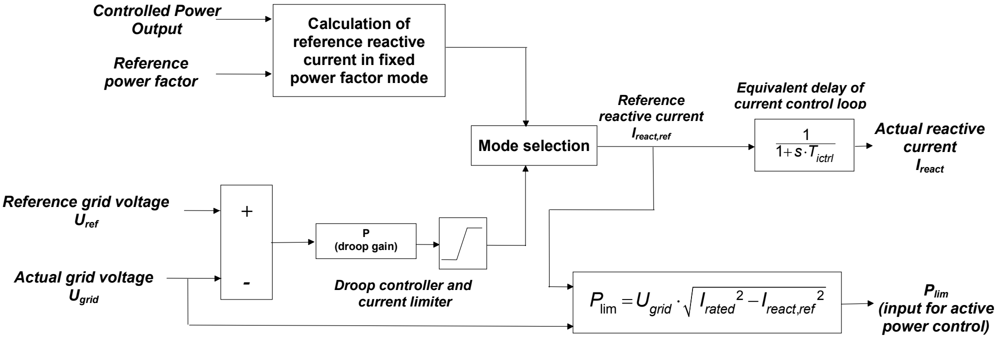

Figure 3.1. Dynamic model for reactive current control

4 TURBINE TRIPPING

At extreme grid conditions, the wind farm is allowed to be disconnected from the grid in order to protect itself from overcurrents etc. The cases at which a farm is allowed or demanded to disconnect are mostly given by the grid operator.

Tripping requirements are characterized by threshold values for voltage or frequency deviations and their duration. An example for voltage tripping requirements is graphically represented in Figure 4.1.

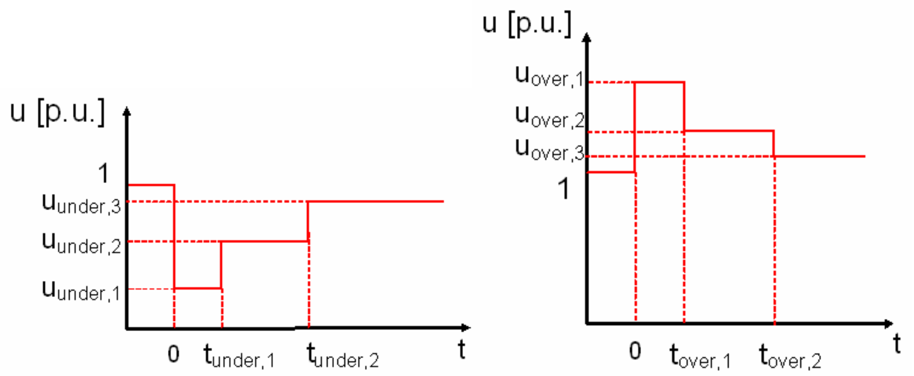

Figure 4.1. Voltage thresholds for tripping actions

Example threshold values are:

$u_{under,1}$ = 0.3 p.u. $u_{under,2}$ = 0.5 p.u. $u_{under,3}$ = 0.8 p.u.
$u_{over,1}$ = 1.8 p.u. $u_{over,2}$ = 1.3 p.u. $u_{over,3}$ = 1.1 p.u.
$t_{under,1}$ = 0.02 s $t_{under,2}$ = 0.15 s
$t_{over,1}$ = 0.02 s $t_{over,2}$ = 3 s

Most power system simulation software packages support the implementation of tripping relays included in a dynamic model. The associated threshold values are mostly given by the grid connection requirements and can be easily adapted in the model. Thus, the impact of more severe ride-through demands from the grid operator can be investigated using the model.

5 INTERFACE BETWEEN MACHINE MODEL AND GRID MODEL

Most power system simulation software packages allow dynamic modelling of machines as current injectors, power injectors, or controlled impedances. Modelling a machine as a current injector is a closer approach to the real nature of a machine, and leads also less to numerical problems during short-circuit simulations.

The exact outlook of the interface between the machine model and a grid model is dependent on the used software. The authors developed this model in EUROSTAG. In this software, care must be taken that the active and reactive current for the machine are correctly transformed towards the two-axis current reference system that is common for all machines in the grid model. This requires a rotational transformation of the current vector. This is further worked out in [17].

6 SIMULATION EXAMPLE

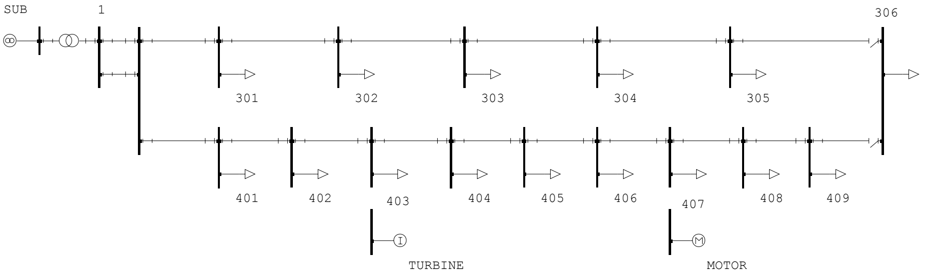

Figure 6.1. Model of simulated distribution grid

As a simulation example, a small distribution grid (10 kV) is modelled as shown in Figure 6.1. The distribution post (70 kV) is modelled as an infinite node with low short circuit power. The total load in the network is around 5 MW. A 1 MW – asynchronous motor is connected at bus 407, and a 4 MW-wind turbine is connected at bus 403.

The simulated wind speed is shown in Figure 6.2 (a-c). The wind speed is given as a fraction of the turbine rated wind speed (i.e. the lowest wind speed at which the turbine produces its rated power). The wind speed jumps from 50% to 90% of rated wind speed on t = 200 s, and further to 120% on t = 800 s. The turbine output power is shown in Figure 6.2 (d-f). The first wind speed change results in a first-order filtered output power, according to the set of curves in Figure 2.4 for low wind speeds. The second wind speed change follows the behaviour of the second set of curves: the output power stays at 1 p.u. after a small overshoot, representing the slowness of the pitch controllers.

At t = 1000 s, a command is given to switch to 'Limited' operation mode: the maximum power is set at 0.5 p.u, which is achieved in a few seconds (this is given by the maximum power variation rate from Figure 2.8).

The corresponding turbine voltage is shown in Figure 6.2 (g-i). Two control modes for the reactive power were simulated: fixed power factor cos $\phi = 1$, and reactive power control by a droop controller to maintain the turbine voltage at 1.1 p.u. The difference in the voltage impact of a wind speed change is clearly seen in Figure

6.2 (g-i). It is likely that, without voltage control, the turbine will be tripped by the overvoltage relays.

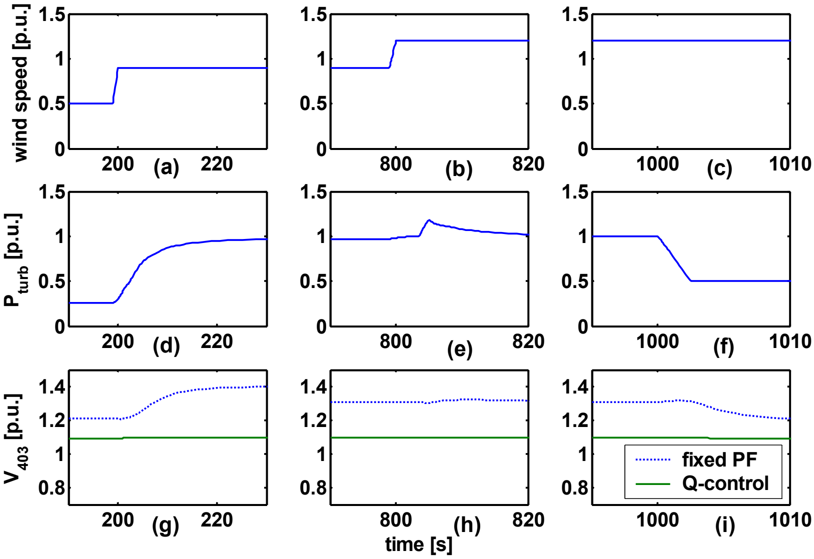

Figure 6.2. Simulated wind speed (a,b,c), turbine power (d,e,f) and turbine voltage (g,h,i)

At t = 400 s, the 1 MW-motor is started up, with a load torque of 0.4 p.u. During the starting up, a large amount of active and reactive power is consumed by the motor. This is seen on Figure 6.3a. The reactive power of the turbine remains zero in the case with fixed power factor, and is controlled to supply support in the other case (Figure 6.3b). The speed at which the turbine reactive current is controlled depends on the time constant of the current control loop, T_{ictrl}, as shown in Figure 3.1. It is set at 0.05 s for this example. The resulting voltage at the turbine node is shown in Figure 6.3c. With dynamic reactive power control, the wind turbine is able to support the voltage considerably, which can also prevent the turbine from being tripped. The voltage support capabilities of a turbine are most visible in weak grids (island grids or distribution grids with a very low short circuit power at the HV-substation)

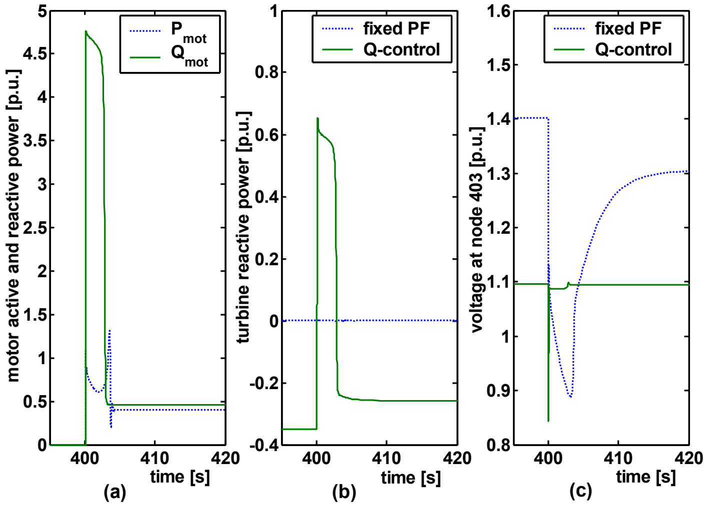

Figure 6.3. Motor active and reactive power (a),turbine reactive power (b) and turbine voltage (c) during motor start-up

7 CONCLUSION

A generic wind turbine model for power system simulations is built, consisting of a model for the active power generation, the reactive power generation, the tripping behaviour and the interface between the farm and the grid model.

The model is suited to simulate the impact of wind speed changes on the grid behaviour, and the grid support capabilities of a wind farm during normal operation and in case of grid disturbances. It is not intended for simulation of a fault or switching action at the turbine itself.

It must be noted that many parts of the model are not specific for wind turbines, but generally applicable for various kinds of distributed generators and loads that are grid connected through a controlled power electronic interface. Also the strategy for developing the *Active Power Model* can be applied if detailed models of other generating units are available and if model linearization does not result in excessive approximation errors.

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