AGGREGATED MODELLING OF WIND PARKS WITH VARIABLE SPEED WIND TURBINES IN POWER SYSTEM DYNAMICS SIMULATIONS

J.G. Slootweg[1], S.W.H. de Haan[2], H. Polinder[2], W.L. Kling[1]

[1] Electrical Power Systems Lab, [2] Electrical Power Processing Lab, Faculty of Information Technology and Systems
Delft University of Technology, P.O. Box 5031, 2600 GA Delft, The Netherlands
Phone: +31 15 278 6219, Fax: +31 15 278 1182, e-mail: j.g.slootweg@its.tudelft.nl

Abstract - More and more wind turbines are made part of electrical power systems, in order to reduce the adverse environmental impact of conventional electrical power generation. A tendency to erect these turbines in wind parks, that are connected to the high voltage transmission grid can be observed.

To facilitate the investigation of the impact of a wind park on the dynamics of the power system to which it is connected, an adequate model is required. In order to avoid the necessity of developing a detailed model of a wind park with tens or hundreds of wind turbines and their interconnections, aggregated wind park models are needed. A further advantage of aggregated models is a substantial reduction of computation time. In this paper, an aggregated model for a wind park equipped with variable speed wind turbines is developed and it is shown that the results yielded by the aggregated model and a detailed model show a high degree of correspondence.

Keywords: variable speed wind turbine, aggregated wind park model, power system dynamics, modelling, simulation, wind power

1. INTRODUCTION

As a result of increasing environmental concern, the impact of conventional electricity generation on the environment is being minimized and efforts are made to generate electricity from renewable sources. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the in principle infinite availability of the prime mover that is converted into electricity. One way of generating electricity from renewable sources is to use wind turbines that convert the energy contained in flowing air into electricity. Up to this moment, the amount of wind power integrated into large scale electrical power systems only covers a small part of the total power system load. The rest of the load is for the largest part covered by conventional thermal, nuclear and hydro power plants.

Wind turbines hardly ever take part in voltage and frequency control and if a disturbance occurs, the wind turbines are disconnected and reconnected when normal operation has been resumed. Thus, notwithstanding the presence of wind turbines, frequency and voltage are maintained by controlling the large power plants as would have been the case without any wind turbines present. This is possible, as long as wind power penetration is still low. However, a tendency to increase the amount of electricity generated from wind can be observed. Therefore, the penetration of wind turbines in electrical power systems will increase and they may begin to influence overall power system behaviour. In that case, it will no longer be possible to run a power system by only controlling large scale power plants. It is therefore important to study the behaviour of wind turbines in an electrical power system and their interaction with other generation equipment and with loads.

Further, a tendency to concentrate the turbines in wind parks can be observed in order to use regions with a good wind resource efficiently and to concentrate the visual impact of modern wind turbines, that can easily reach heights of more than a 100 m, at certain locations. These wind parks are connected to the high voltage transmission grid and therefore directly influence the dynamic behaviour of an electrical power system. This increases the need for adequate models.

In this paper, an aggregated model of a wind park with variable speed wind turbines is presented, similar to that proposed for fault studies of wind parks with constant speed wind turbines in [1]. The advantage of an aggregated model is that it eliminates the need to develop a detailed model of the wind park with tens or hundreds of wind turbines and their interconnections and that it reduces the computation time substantially. As will be shown, the response of the aggregated model and the detailed model is very similar.

This paper is organized as follows. In section 2, the two most widely used variable speed wind turbine concepts are introduced and models of the subsystems of which they consist are described. In section 3, it is discussed how the individual wind turbines are aggregated in a park model and the investigated wind park layouts are given. In section 4, simulation results of the detailed wind park model and the aggregated wind park model are compared for each of the studied layouts.

2. MODELLING VARIABLE SPEED WIND TURBINE CONCEPTS

2.1 Variable speed wind turbine concepts

Currently, two different kinds of variable speed wind turbines are widely used. The first is based on the doubly fed (wound rotor) induction generator. The rotor winding of the doubly fed induction generator is fed using a back-to-back voltage source converter with current control loops. The generator active and reactive power can easily be controlled by the quadrature and direct component of the rotor current respectively. The wind turbine rotor is coupled to the generator through a gearbox because of the different operating speed ranges of the wind turbine rotor and the generator. In high wind speeds, the power extracted from the wind can be limited by pitching the rotor blades.

The second concept is based on a direct drive synchronous generator. The synchronous generator may have a wound rotor or may be excited using permanent magnets. It is grid coupled through a back-to-back voltage source converter or a diode rectifier and voltage source converter. The synchronous generator is a low speed multi pole ring generator with a large diameter, therefore no gearbox is needed. Like in the other concept, the power extracted from the wind is limited by pitching the rotor blades in high wind speeds. Both concepts are depicted in figure 1.

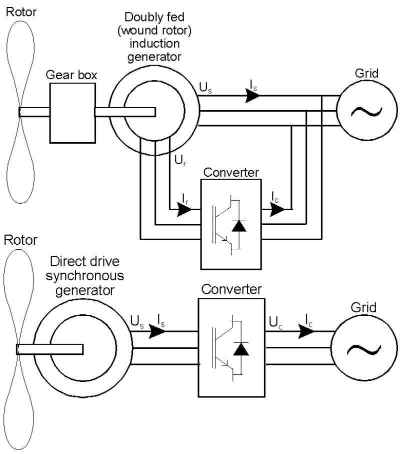

Figure 1: Actual variable speed wind turbine concepts: doubly fed (wound rotor) induction generator and direct drive synchronous generator.

2.2 Variable speed wind turbines in dynamics simulations

Detailed models of both of the above mentioned wind turbine concepts, including full models of the power electronic converters and their controllers, can be found in the literature [2,3]. However, these models can not be used in commercially available power system dynamics simulation software, in which a number of simplifying assumptions are made in order to increase the computation speed.

In such software, only the fundamental harmonic component of voltage and current is taken into account and higher harmonics are neglected. This approach enables the representation of the network by a constant impedance or admittance matrix, like in load flow calculations. Further, it reduces the number of differential equations, because no differential equations are associated with the network and fewer with generating equipment and it enables the use of a larger simulation time step, because short time constants are eliminated [4].

In order to keep the advantages of this approach, the detailed models of variable speed wind turbines must be adapted in the following ways [5]:

- the $d\psi/dt$ terms in the stator and the rotor voltage equations are neglected
- the power electronic converters are modeled as controlled fundamental harmonic current sources

Models of both variable speed wind turbine concepts in which these simplifications have been carried out can be found in [6,7].

As a result, it is possible to represent both kinds of variable speed wind turbine with one and the same model because of the following considerations:

- The differences in behaviour of the two generator types are cancelled by the power electronic converters and the controllers and the result is a great similarity with respect to grid interaction for both kinds of variable speed wind turbines [5]. The latter is the main point of interest in power system dynamics simulations.
- The dynamic behaviour of the wind turbines is mainly determined by the rotor inertia, which depends on the rotor diameter. The rotor diameter is dependent on the nominal power and not on the wind turbine concept. Therefore, the moment of inertia is similar for wind turbines of equal nominal power.

The resulting general variable speed wind turbine model comes down to a model of a controllable source of active and reactive power. Its active power output is based on the actual value of the rotor speed and its reactive power on the terminal voltage. In figure 2, this general variable speed wind turbine model is depicted.

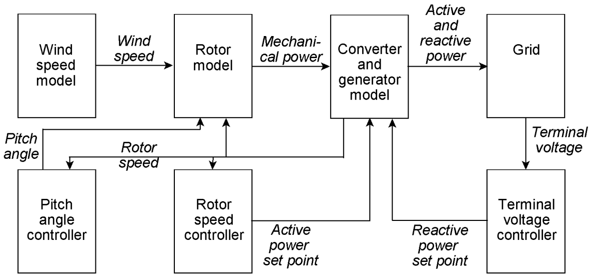

Figure 2: Structure of the general variable speed wind turbine model.

In figure 2, no shaft model is depicted. It has been argued in the literature that the incorporation of a shaft representation in a wind turbine model is very important [8]. However, this only applies to constant speed wind turbines and not to variable speed wind turbines, because in these systems the mechanical and electrical part are decoupled by the power electronic converter and the shaft properties hardly are hardly reflected at the grid connection [9].

2.3 Subsystem models

In this paragraph, models of the subsystems of which the general variable speed wind turbine model of figure 2 consists are described. The values of the various quantities apply to a 2 MW wind turbine that is used here as an example and whose characteristics are given in table 1. Some of the quantities must be given other values when a wind turbine of different nominal power is investigated. A model of a variable speed wind turbine consists of the following subsystems, which are described below:

- a wind speed model
- a rotor model
- a generator/converter model
- a rotor speed controller
- a pitch angle controller
- a terminal voltage controller

WT Characteristic	Value
Rotor diameter	75 m
Area covered by rotor	4418 m2
Rotor speed	9-21 rpm
Nominal power	2 MW
Nominal wind speed	12 m/s

Table 1: Characteristics of example wind turbine.

The wind speed model generates a time series of wind speed values. Each wind speed value is assumed to consist of the sum of the average wind speed, a ramp component, a gust component and a stochastic component [10]. The power spectral density of the stochastic component is given in [11] and a time series of stochastic values is generated using the method presented in [12].

The rotor is modelled using the following equation

$$P_w = \frac{\rho}{2} A_r c_p(\lambda,\theta) v_w^3 \tag{1}$$

in which

P_w is the mechanical power extracted from the wind [W]

A_r is the area swept by the rotor [m^2]

v_w is the wind speed [m/s]

λ is the tip speed ratio, which equals the rotor tip speed v_t [m/s] divided by v_w

θ is the blade pitch angle

and $c_p(\lambda,\theta)$ is the performance coefficient. The dependence of the performance coefficient c_p on λ and θ is depicted in figure 3.

The generator/converter combination is modelled using a first order model representing a rotating mass, combined with a controllable source of electrical torque. Given the frequency range of the phenomena that are investigated using dynamics simulations, 1 to 10 Hz, this representation is adequate. The dψ/dt terms in the voltage equations are compensated for by the power electronics converter with which both variable speed wind turbine concepts are equipped. Therefore, a new torque set point can assumed to be reached within one simulation time step and a quasistatic representation of the power electronics is allowed [5].

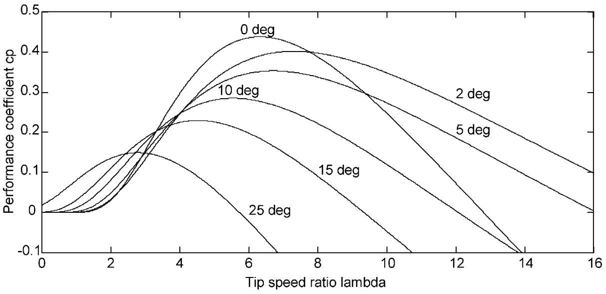

Figure 3: Performance coefficient c_p as a function of the tip speed ratio λ and the pitch angle θ [deg].

The rotor speed controller is a digital controller that generates an active power set point based on the actual rotor speed with a frequency of 20 Hz. The power set point is derived from the rotor speed versus power characteristic, which is depicted in figure 4 for the 2 MW example wind turbine used here.

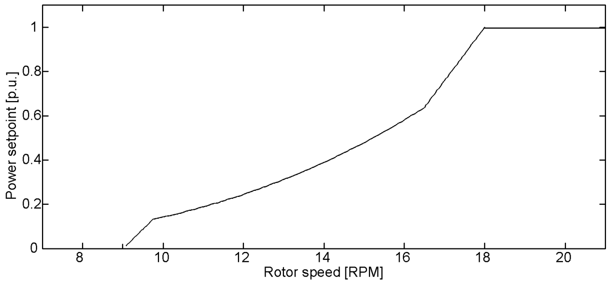

Figure 4: Rotor speed versus power control characteristic.

In figure 5, the pitch angle controller is depicted. T_s is the sample time of the pitch angle controller, which can be rather low because the blades can not be turned very rapidly, due to their size and the desire to keep cost low.

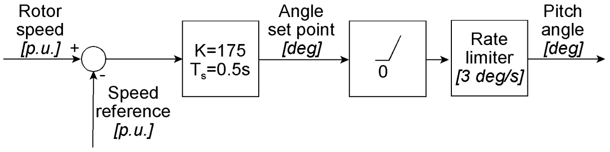

Figure 5: Pitch angle controller.

Although nowadays most wind turbines do not take part actively in grid voltage control, this might change in the future, when more wind turbines are connected to the electrical power system. It is therefore considered important to incorporate a terminal voltage controller in a model of a variable speed wind turbine and in the aggregated wind park model being developed here, which is meant for studying the impact of large amounts of wind turbines on an electrical power system. The voltage controller is depicted in figure 6. By making K_v equal to 0, the wind turbine is operated at unity power factor as common up to now.

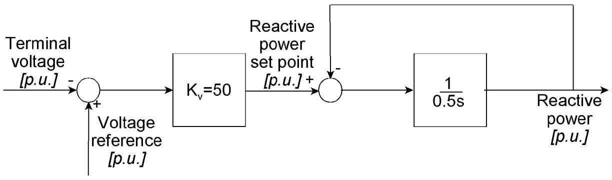

Figure 6: Terminal voltage controller.

3. WIND PARK MODEL AGGREGATION

3.1 Wind turbine aggregation

In this section, the development of an aggregated wind park model will be discussed. The aggregated wind park model is based on the following assumptions:

- Those subsystems of the detailed wind turbine model presented in section 2.3 that have only a minor impact on grid interaction, which is the main point of interest in power system dynamics studies, are neglected to make the model more user-friendly and to reduce the computation time.
- The impedances within the wind park are neglected, because they are normally small relative to the impedance of the grid connection.
- The aggregated park model is equipped with one single terminal voltage controller as depicted in figure 5, instead of having a terminal voltage controller at each single wind turbine. By adding the output power of the simplified models, the aggregated output power of the wind park results. This can be used to calculate the terminal voltage which is an input to the voltage controller.

The aggregated model should fulfill the following requirements:

- It must be possible to specify the wind park layout in a user-friendly way.
- Instead of specifying a wind speed signal at each individual turbine, it must be possible to specify a single wind speed signal for the whole park.

3.2 Wind speed modelling

As already said above, the wind speed model used to represent the wind speed at the hub height of the wind turbine consists of four parts:

- an average value
- a ramp component, characterized by start time, stop time and height
- a gust component, characterized by start time, stop time and amplitude
- turbulence, characterized by a power spectral density and a frequency band

When only one wind turbine is modelled, it is relatively easy to calculate a wind speed time series when the characteristics of each of the above mentioned components are given. However, when a wind park is modelled, this becomes quite complicated. The average value can be assumed to be the same throughout the park. The gust and ramp component, however, travel through the park and the time at which they arrive at the individual turbines depends on the wind speed, the angle of attack and the wind park layout. The turbulence is assumed to be stochastic and needs to be calculated for each wind turbine at each time step, forming a substantial computational burden.

These problems can be solved by calculating a wind speed value at each individual wind turbine from one general wind speed signal that is applied to an aggregated model of the whole wind park. The calculation of the aggregated wind speed model is based on the following considerations :

- Turbulence is neglected. In a wind park, the effect of turbulence on the aggregated output power is reduced due to the smoothing effect of a larger number of wind turbines, as can be seen from measurements presented in [13]. Further, in case of variable speed wind turbines, turbulence is hardly reflected in the output power, due to the large rotor inertia.
- Not only the average value of the wind speed is specified, but also the wind direction. When simulating only one wind turbine, the wind is assumed to be perpendicular to the rotor and the wind speed direction need not to be specified. However, when a wind park is simulated, the wind direction becomes important because it determines the aggregated output power pattern for a large part.
- Start and stop times of the gust and the ramp are given relative to the centre of the wind park. From these values, the start and stop times of the gust and the ramp at each individual wind turbine can be calculated from the average wind speed and the wind direction.

In this way, the user of the aggregated wind park model can specify one single wind speed signal for the whole park, from which the wind speed at the individual turbines is derived, instead of having to specify the wind speed time series at each turbine.

3.3 Simplified wind turbine representation

As can be concluded from section 2.3, a quite complex model is needed to represent a variable speed wind turbine in detail. It is, however, possible to develop a simplified wind turbine model, based on the following considerations:

- When it is assumed that $c_p(\lambda\theta)$ always equals the maximum value of c_p, the complicated $c_p(\lambda\theta)$ characteristic depicted in figure 3 can be omitted from the model and be replaced by a constant equal to the maximum value of c_p. Only a minor error results from this simplification, because the rotor speed versus power control characteristic is such, that c_p is kept at its maximum as much as possible.
- The rotor speed versus control characteristic is replaced by a first order approximation, as depicted in figure 7.
- When the integrator in which the rotor speed is stored is limited to a value of 1.1 p.u., the pitch angle

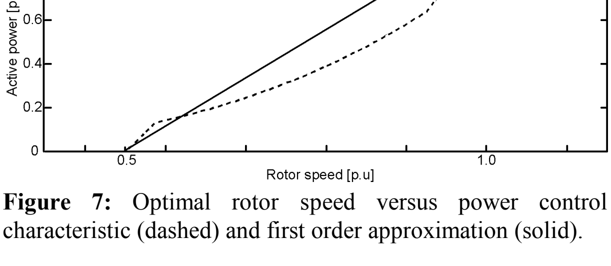

Figure 7: Optimal rotor speed versus power control characteristic (dashed) and first order approximation (solid).

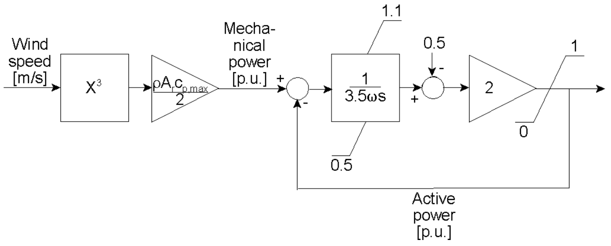

Figure 8: Simplified wind turbine model.

controller can be omitted from the model, because it is no longer needed for limiting the rotor speed.

The simplified wind turbine model that results from the above, with which each of the turbines in the aggregated park model is represented, is depicted in figure 8.

3.4 Specification of wind park layout

Above, the derivation of a wind speed time series at the individual turbines in a wind park has been described and a simplified representation of variable speed wind turbines was introduced. The last step to arrive at an aggregated wind park model, is the specification of the layout of the park. The wind park layout is specified by giving the x and y coordinates of the individual wind turbines. By combining these values and the wind speed signal that is specified relative to the park's centre, the wind speed value at each individual wind turbine can be calculated. This value can then be used as the input to the simplified wind turbine model depicted in figure 8.

4. SIMULATION RESULTS

4.1 Simulation setup

Two wind park layouts have been investigated, namely a string and a star connected wind park, consisting of ten wind turbines each. The wind parks are depicted in figure 9. With each wind park, two simulation runs with different wind speed signals are made. The characteristics of the applied wind speed signals are summarized in table 2. In this table, an angle of 0° corresponds to the wind coming from above and 90° to the wind coming from the left. Notice that the start time of the wind speed components is given with reference to the wind park's centre. Therefore, they can reach the outer turbines earlier than at the instant given in table 2, depending on the wind direction and park layout.

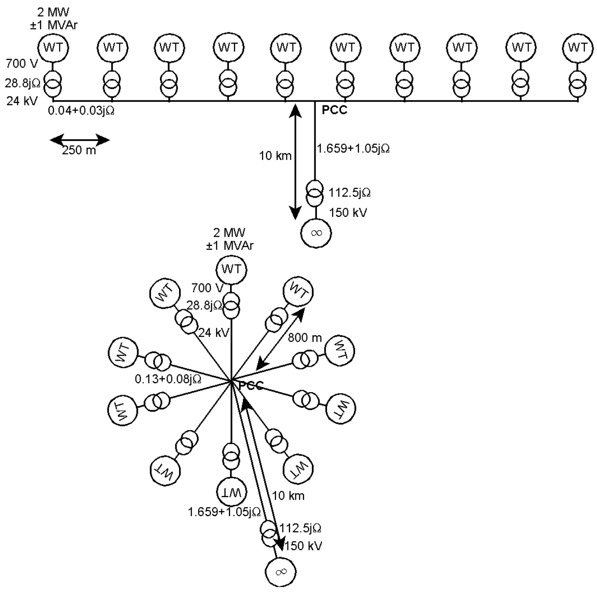

Figure 9: Investigated wind park layouts: string (upper) and star (lower).

The accuracy of the aggregated model has been investigated by comparing its results to a detailed model of each of the wind park layouts. In the detailed model, each of the wind turbines is represented by the model described in section 2.3 and the impedances within the park have been taken into account. For the simulations of the aggregated park model, Matlab was used and the detailed model was simulated using the widely used PSS/E power system dynamics simulation package. In both cases, the simulation time step was 10 ms.

Parameter	**String**		**Star**	
Run number	1	2	3	4
Initial wind speed [m/s]	10.4	10.4	10.4	10.4
Wind direction [deg]	0	90	0	90
Gust start time [s]	20	110	85	85
Gust stop time [s]	30	120	95	95
Gust amplitude [m/s]	-3	-3	-3	-3
Ramp start time [s]	30	120	95	95
Ramp stop time [s]	60	150	125	125
Ramp amplitude [m/s]	4	4	4	4

Table 2: Wind speed signals applied to each of the wind park layouts.

4.2 Simulation results

In figure 10, the simulation results are given. The active and reactive power flowing from the point of common coupling (PCC), which is indicated in figure 9, to the swing bus and the node voltage at the PCC are depicted for each of the simulation runs from table 2. In each graph, the solid line corresponds to the detailed full model and the dashed line to the aggregated model.

4.3 Evaluation of simulation results

It can be concluded from figure 10 that the responses of the detailed and aggregated wind park model match closely. The differences in the responses are caused by the simplifications made in the aggregated model and can be explained in the following way:

- Because the impedances within the wind park are neglected, the losses in these impedances are neglected as well, explaining why in steady state the output power of the aggregated model is slightly

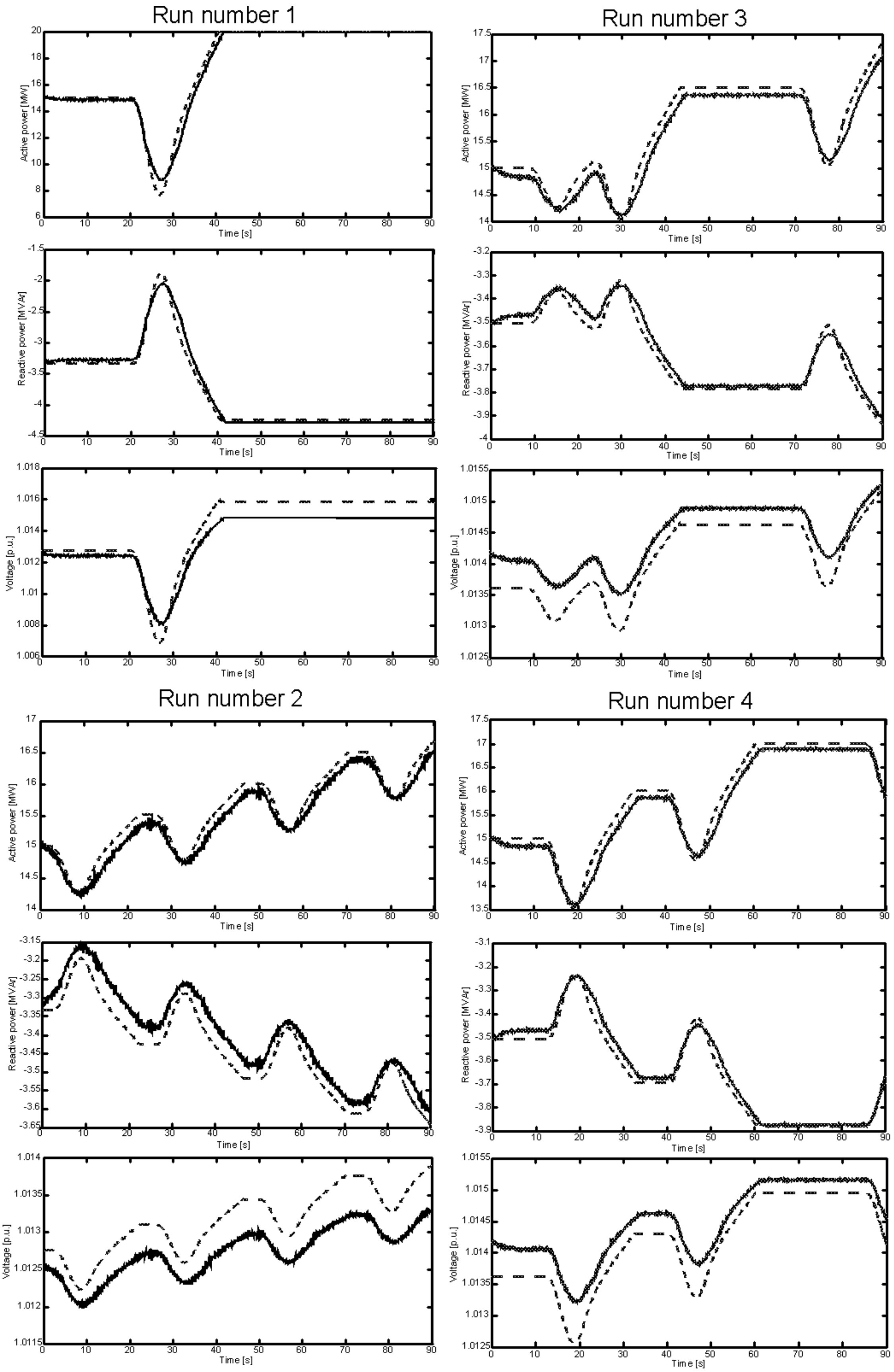

Figure 9: Simulation results for each of the simulation runs in table 2. Starting from above the active and reactive power and the node voltage at the point of common coupling are depicted. The solid lines correspond to the detailed model and the dashed lines to the aggregated model.

higher than that of the detailed model.

- The differences in the reactive power and node voltage at the point of common coupling are also caused by the neglect of the impedances within the park in the aggregated model.
- The differences in dynamic behaviour, that can particularly be observed during the gust, are caused by the discrepancies between the simplified wind turbine model used in the aggregated park model and the full wind turbine model used in the detailed park model.

The latter can be seen as follows. The initial operating point of the wind turbines is at an active power output of 0.75 p.u. From figure 7, it can be concluded that when the rotor speed decreases due to a decrease in wind speed, the active power decreases more quickly in the detailed model than in the aggregated model. Therefore, the rotor speed will drop less quickly in the detailed model than in the aggregated model. As a result, the active power decrease in case of the detailed model is slower and less deep than in the aggregated model. This can particularly be seen in the active power output in simulation run number 1, after approximately 27 s.

5. CONCLUSIONS

In this paper, an aggregated model of a wind park with variable speed wind turbines for use in power system dynamics simulations is presented and verified, using simulations of a detailed wind park model. The use of the aggregated model reduces the modelling effort for the user and the amount of data to be entered, because no longer a detailed model of the wind park infrastructure and of the individual turbines is required. Further, it eliminates the need to specify the wind speed at each individual wind turbine within the park and it reduces the computation time.

In the aggregated model, some simplifications were made:

- turbulence is neglected
- the impedances within the wind park are neglected
- a simplified model is used to represent the variable speed wind turbines

From the simulation results, it could be concluded that notwithstanding these simplifications, the agreement between the responses of the aggregated and detailed wind park models is very close, although some differences remain. These are caused by the neglect of the impedances within the park and by the simplified representation of the wind turbines in the aggregated park model.

The final decision whether to use an aggregated or a detailed model should be taken carefully considering the purpose of the task at hand. For dynamics simulations, the achieved accuracy is sufficient, but for calculation of the wind park energy production, the error in the losses is too large. For studying the behaviour of the individual turbines, a detailed model of the wind park with its individual turbines is of course necessary.

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