SIMULATION OF LARGE WIND FARMS USING COHERENCY APPROACH

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Abstract

The penetration of wind turbines (WT) connected to the power system has increased enormously in recent years. As a result, they can no longer be neglected during power system planning and analysis. However, with over 18500 units in Germany alone, considering all of the individual wind turbines during the preparation of a power system model is not possible [1]. It could lead to an enormous burden of the simulators on the one hand and cause problems with the numeric stability of the simulation on the other hand. Therefore, an alternative method for aggregated representation of large wind farms for power system analysis is needed that would retain their dynamic characteristics. Such an approach is especially conceivable for the off-shore wind farms, which usually consist of a high number of wind turbines placed in similar distance to each other that are concentrated in one location. The aggregation method presented in this paper is based on the coherency analysis of the input wind speeds for individual wind turbines in a wind farm. The input wind speeds for individual wind turbines results from the farm's incoming wind profile and the mutual interactions between wind turbines; the so-called wake effect. In general, the intensity of the wake effect depends on the type of wind turbine, farm structure, wind direction and wind speed. Modern wind turbines vary their angular speed in order to find an optimal operation point according to the present wind conditions. Since wind turbines represent non-linear systems, their dynamic reaction for system faults depends strongly on the point of operation, and this should be considered in the aggregated simulation of wind farms.

Keywords: Power System, Wind Energy, Wind Park Simulation, Model Reduction.

Presenting Author's biography

Krzysztof Rudion studied electrical engineering at the Wroclaw University of Technology, Poland and the Rostock University of Technology, Germany. He graduated in 2003 from the Wroclaw University of Technology with a Dipl.-Ing. degree. He then joined the Chair of Electric Power Networks and Renewable Energy Sources at the Otto-von-Guericke-University Magdeburg, Germany as a research engineer. His primary field of interest is dispersed generation with a focus on wind energy.

1 Introduction

Since the influence of wind energy on the system operation can no longer be neglected, an appropriate representation approach of complex wind farms in the numeric simulations should be applied in order to reduce the calculation effort. There are different kinds of system studies concerning wind farm behavior. Generally, they can be divided into two categories. On one side there are the studies of short-time behavior, such as fault calculation, frequency control and protection coordination, and on the other side there are the long-time applications like control actions (active power limitation or voltage control and reactive power compensation as well as network security management actions). Moreover, an important task for power system operation and also for designing energy markets is the forecasting of wind power generation.

Consideration of all of the individual wind turbines (WT) in the aforementioned studies is not efficient. Therefore, an aggregated representation of wind farms has to be applied.

In this paper the aggregation approach of wind farms based on the coherency matrix will be presented. This matrix includes all information needed to create the equivalent wind turbine models within the wind farm.

In Section 2 the modeling of wind farms considering all WTs will be discussed. In Section 3 the aggregation approach based on the coherency matrix will be presented, and in section 4 the applications for the introduced aggregation approach will be discussed. In section 5 the chosen case studies will be introduced and analyzed.

2 Wind farm modeling

2.1 Wind turbine classification

In general, there are many different varieties of wind turbines depending on the type of generator and propeller, kind of operation, and kind of network coupling. A complex survey of the wind turbine types can be found in [2].

Currently, the two most commonly installed wind turbine types are:

- variable speed wind turbines with a doubly fed induction generator (DFIG),
- variable speed wind turbines with a converter facilitated synchronous generator (SG).

Both concepts use the pitch control system for limiting the angular speed and amount of produced power. The possibility of angular speed variation is used for optimization of the wind turbine operation and enhancement of the energy yield as well as for limiting the harmful torque fluctuations.

The behavior of both wind turbine concepts and their influence on the network operation is quite different, since WTs with DFIG have only the rotor of the machine decoupled from the electrical grid through the frequency converter, and the WTs with SG are completely decoupled with power electronics. Therefore, in the case of WTs with converter facilitated SG the behavior depends first and foremost on the structure and parameterization of the control system as well as the protection system. Thus, for analysis of the system operation adequate models of wind farms are needed.

2.2 Detailed simulation of wind farms

One possibility to simulate the operation of wind farms is the preparation of the model using individual representation of each wind turbine. In this approach the simulated wind turbines consist of the propeller model, generator model, drive train model, power electronics model as well as the model of the control and protection system. The general structure of the WT with DFIG and converter facilitated SG is presented in Fig. 1 and Fig. 2, respectively. Modeling the aforementioned wind turbines was often discussed in literature, e.g. [3] - [9], and will not be presented in this paper. Such detailed representation, on the one hand, makes it possible to obtain satisfactory results from the simulations. On the other hand, detailed representation means that fast simulations of several wind farms interconnected to the power system is not possible because of the high model complexity.

To solve this problem an alternative modeling approach will be presented in the next section, where the detailed simulations serve as the reference for comparison.

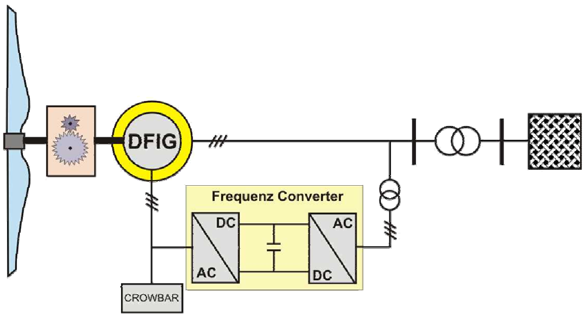

Fig. 1 Structure of the WT with DFIG

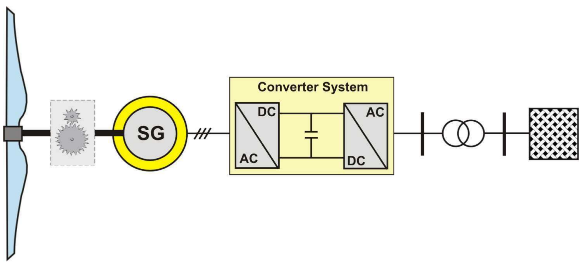

Fig. 2 Structure of the WT with converter facilitated SG

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3 Aggregation approach for wind farm simulation

3.1 General information

As already discussed in the first section there are two main kinds of studies that should be performed for wind farms. In the first category of studies the emphasis is placed on the satisfactory representation of the active and reactive power production by the wind farm and the simulated system has a quasi-stationary character. In the second category of studies the transient behavior of wind farms is the focus. In both cases the behavior of a wind farm depends on the current point of operation of each wind turbine. This point is defined by the electrical and mechanical parameters of WTs, like angular speed, active and reactive power level, and pitch angle. The value of these parameters is directly influenced by the speed of the incoming wind. In the wind farm the wind speeds at the individual wind turbines can have different values since there are strong interactions between WTs that are evoked by the wake effect.

Due to the fact that the controllers of each WT try either to find the optimal point of operation for each wind speed within the partial load operation or to limit the produced power and angular speed to the acceptable value within the full load operation, identifying wind turbines that are in the same or similar operation point can be performed based on the incoming wind speed of each WT. Thus, to find the points of operation of individual WT the wake effect has to be considered.

3.2 Wake effect model

The wake effect describes the mutual interactions between wind turbines within a wind farm. Because of these interactions the wind speed incoming to the wind farm is disturbed when passing through the rotor plane of the WTs. Therefore, the input wind speed of the individual wind turbines that are located in front of the wind farm, with respect to the direction of the incoming wind speed, is higher than the input wind speed of the wind turbines in the middle and in the back of the wind farm. The units located in the front induce the “wind shadow” for the following units as shown in Fig. 3.

Fig. 3 Visualization of the wake effect in a wind farm

This shadow is cone-shaped and its parameters are dependent on the wind turbine type as well the type of natural surrounding. In general, the wake effect has a three dimensional character, but such representation is too complex to be included in the power system analysis. Therefore, a simplified representation of the wake effect that can be considered within the one-dimensional profile of wind speed has to be used. In this paper the wake model according to Jensen was employed [10], [11]. This approach uses the entrainment constant for calculating the development of the wake. The value of this parameter is found by comparing the simulation results with the measurements. Moreover, the near-field effects just behind the rotor plane of the WT are neglected here and the wake distribution has a linear character, which results in the wind speed having a uniform profile at each distance downstream, so called “top hat”. The structure of the wake is presented in Fig. 4. The wake radius $R_W(x)$ at any distance from the rotor plane of the upwind WT can be calculated with Eq. (1).

$$R_W(x) = k \cdot x + R_R \tag{1}$$

The entrainment constant k describes the wake expansion and is defined with Eq. (2).

$$k = \tan(\alpha) \tag{2}$$

Its value is defined empirically and depends on the kind of surroundings – offshore, onshore.

The wind speed in the wake at any distance x can be calculated with Eq. (3).

$$v_W(x) = v_0\left[1-\left(\frac{R_R}{k \cdot x + R_R}\right)^2\left(1-\sqrt{1-c_T}\right)\right] \tag{3}$$

Where:

v_0 – the incoming wind speed [m/s],

R_R – the radius of the wind turbine rotor [m],

k – the entrainment constant [-],

C_T – the thrust coefficient [-], see Fig. 5.

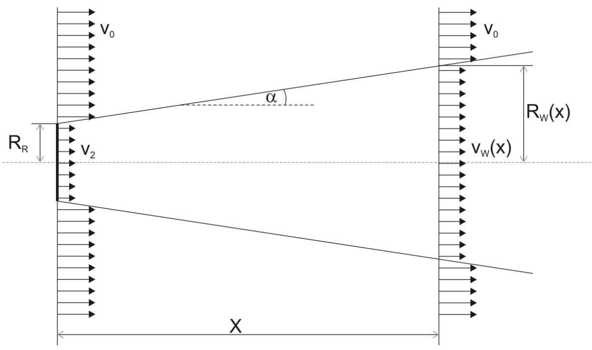

Fig. 4 Structure of the wake model by Jensen

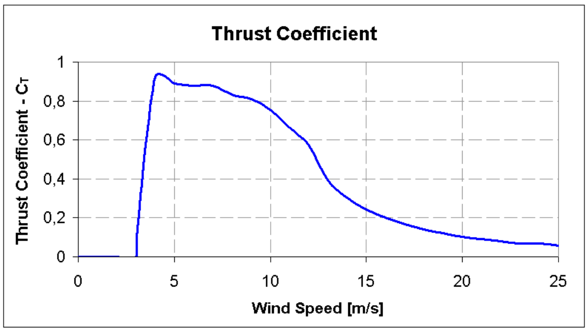

Fig. 5 Exemplary thrust characteristic of the wind turbine [12]

The influence of the k – parameter on the wake distribution is presented in [13]. It can be seen there that for lower values of k the wake cone is narrower and the higher wind speed deficit is observable far from the rotor plane-, when k has a higher value the opposite occurs.

As input for the calculation, the following parameters have to be defined:

- location of each wind turbine in the wind farm (x, y – coordinates),
- height and radius of each wind turbine,
- time series of the incoming wind profile to the wind farm (wind speed and wind direction),
- thrust characteristic of the wind turbines,
- k – entrainment coefficient.

The value of the k – parameter for onshore sites is usually set to k=0.075 and for offshore applications it should be set to k=0.04 [14].

It can happen in the farm that the wake acting on a downwind turbine is evoked by more than one upwind turbine or that the downwind turbine is only partially shadowed by the upwind unit. In this situation an additional coefficient that results from the intersection area of wakes of the individual upwind turbines with the rotor area of the downwind turbine has to be introduced [10].

The effect of the chosen wake model on the input wind speed of each wind turbine was tested in the exemplary wind farm shown in Fig. 6.

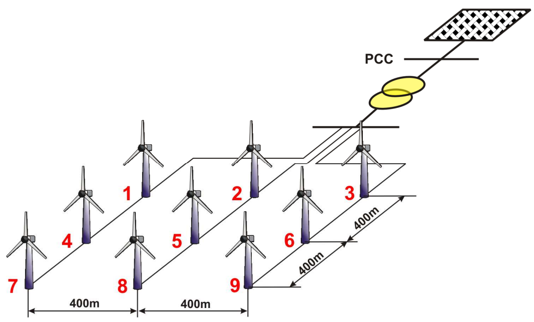

Fig. 6 Structure of the test wind farm

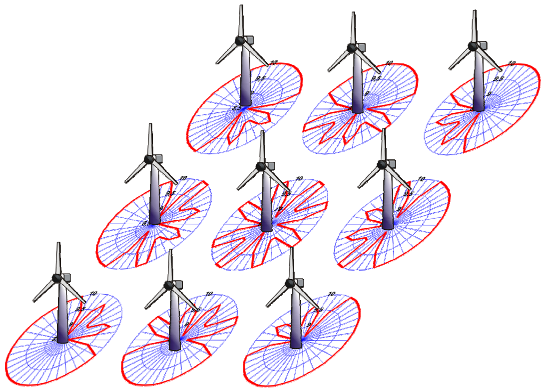

Fig. 7 Wake wind roses for individual WTs and constant input wind speed (10m/s; 0°-360°)

This wind farm consists of 9 WTs with a rated power of 1.5 MW and rotor radius of 35 m. The individual WTs are symmetrically placed within the farm and the distance between any two neighboring units in each row and column is 400 m. For the test calculation of the wake it was assumed that the incoming wind speed of the wind farm is constant and equal to 10 m/s and the wind direction is changed in a range from 0° to 360° with a step of 10°. The simulation results are given in Fig. 7 as wake wind roses. It can be seen that depending on the wind direction the resulting input wind speed of different units can vary significantly.

3.3 Determination of coherent WTs within the wind farm

The wake effect calculation provides information about the input wind speed for individual wind turbines within a wind farm depending on the wind direction and incoming wind speed. Based on these wind speeds the coherency analysis can be performed. The goal of this analysis is to find the units in the farm that obtain similar wind speed as input and therefore have a similar point of operation. All WTs with the same input wind speed are then replaced with a single equivalent unit. The parameters of the equivalent unit have to be adjusted in order to retain the same behavior at the point of common coupling (PCC).

Thus, for each wind farm its characteristics with regard to the influence of the wake effect on the creation of equivalent units can be described with the coherency matrix presented in Fig. 8. This matrix is a 3-D object that includes all information necessary to perform a wind farm simulation using its aggregated representation. The rows of this matrix correspond to the wind direction and their number depends on the chosen step of the wind direction. For the standard step of 10° the coherency matrix has 36 rows. The columns of the matrix correspond to the number of wind turbines in the wind farm. In the presented example there were 9 WTs. The third axis of the coherency matrix corresponds to the incoming wind speed profile of the wind farm that was used in the identification process.

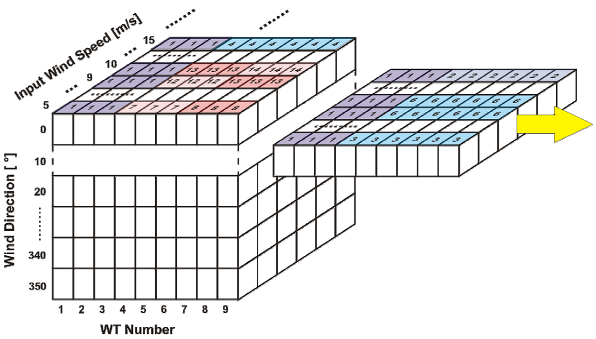

Fig. 8 Structure of the coherency matrix for the test wind farm

Its dimension depends on the chosen step of the wind speed and chosen wind speed range for the scanning process. Therefore, in order to describe the whole operation space of the wind farm an appropriate profile of the incoming wind that considers the relevant ranges has to be characterized. Thus, as input for the wake model the wind profile as step function was defined. It means that the wind speed is changed with the defined step within the range 4 – 25 m/s. The lower limit is defined by the cut-in wind speed of the wind turbine and the upper by the cut-off wind speed. For each step of the wind speed the direction is also changed from 0° to 360° with the defined step, see Fig. 9. In this paper the chosen step for wind speed profile was equal to 1 m/s and for wind direction to 10°. As a result of the wake calculation the input wind profiles for individual wind turbines within the farm are obtained. On the basis of these wind speeds the groups of coherent units can be evaluated. Furthermore, for each step of wind speed the wind roses which graphically present the influence of the wake effect on each wind turbine can be generated, see Fig. 7. To show the influence of the wind direction and the wind speed on the formation of groups of coherent wind turbines the box-diagram given in Fig. 10 was prepared. This diagram depicts with the different colours the decrease of the input wind speed for individual wind turbines in the test wind farms. The values of decreases were calculated according to Eq. (4).

$$v_{DECj} = \frac{v_{INF} - v_{WTj}}{v_{INF}} 100\% \quad (4)$$

Where: v_{INF} – wind speed incoming to the farm [m/s], v_{WTj} – input wind speed for individual wind turbine [m/s]. Thereby, the boxes with the same colour show the turbines that belong to the same equivalent group. The cells of the coherency matrix are filled with specific integers – so called coherency indexes CI – that are obtained from the identification process that is applied to the data derived from the wake model. Each coherency index includes information about the group to which the WT belongs. In this way the groups of equivalent wind turbines, depending on wind direction and speed, can be quickly obtained for the discussed wind farm.

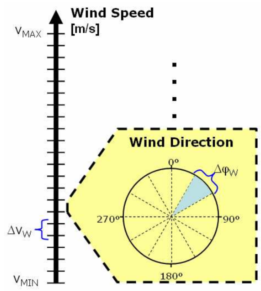

Fig. 9 Definition of the input wind profile for coherency analysis

Additionally, each coherency index in the coherency matrix includes information about the resulting wind speed for each equivalent WT that can be calculated with Eq. (5).

$$\begin{aligned} v_{G\_i} &= v_{INF} - \Delta v_W \cdot CI_i \\ &+ \frac{\Delta v_W}{2} \cdot sign(CI_i - 1) \\ &+ NOT\{sign(CI_i - 1)\} \cdot \Delta v_W \end{aligned} \quad (5)$$

Where: v_{G_i} – wind speed for group i [m/s], v_{INF} – wind speed incoming to the farm [m/s], Δv_W – assumed step size of the wind speed, CI_i – coherency index of group i. The number of different coherency indexes for the given speed and direction of the incoming wind provides information about the number of groups with similar wind conditions and about the number of equivalent wind turbine models for the simulation. The algorithm of the identification procedure is shown in Fig. 11. Before the identification process can be started the width of the identification step – V_{STP} has to be set. This parameter has to be carefully chosen because it is responsible for the resulting number of groups with coherent wind turbines. If its value is too high it can happen that all wind turbines within the farm get assigned to the one single group.

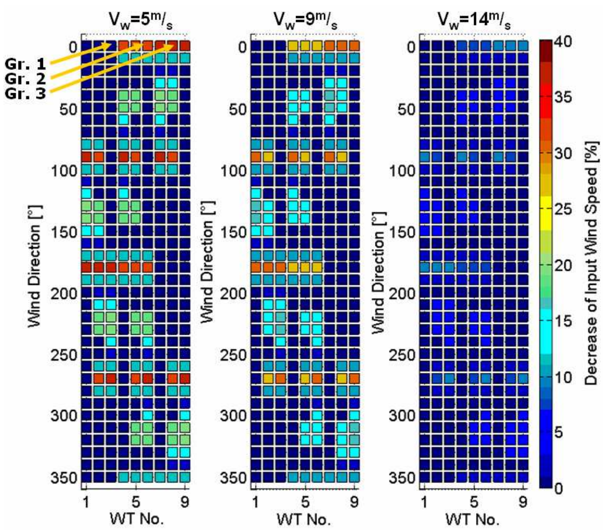

Fig. 10 Representation of the coherent wind turbines depending on the wind direction and wind speed

If the chosen value is too low the number of equivalent groups will be high. In this paper the value of this parameter was set to V_{STP}=0.1. In each recurrence of the identification process the upper and the lower limit of the wind speed interval - U_{LIM} and L_{LIM} - are evaluated for the current value of the incoming wind speed and its direction according to Eq. (6).

$$\begin{aligned} U_{LIM} &= v_{INF} - i \cdot V_{STP} \\ L_{LIM} &= v_{INF} - (i+1) \cdot V_{STP} \end{aligned} \tag{6}$$

Where: v_{INF} – wind speed incoming to the farm [m/s], V_{STP} – width of identification step, i – iteration index.

Then, the wind speeds incoming to the individual wind turbines are checked to see if any of them belong to the current wind speed interval – (L_{LIM}; U_{LIM}). If it is true, than this turbine obtains the appropriate coherency index, which is saved in the coherency matrix. If membership of all units to the current wind speed interval is checked, the new interval limits – L_{LIM} and U_{LIM} have to be calculated.

The identification process runs until all wind turbines obtain the coherency index and the coherency matrix is completely filled out for all wind speed and wind direction steps.

4 Applications for the coherency matrix

4.1 General information

The introduced coherency matrix includes complete information about wind farm characteristics that can be used for various simulations with high precision and with the additional advantage resulting from the reduced model complexity. Originally this approach was developed for the dynamic analysis of power system operation with a high penetration of wind energy, and this is the most important application. It results from the fact that dynamic simulations require detailed models of the system components and small time steps for the calculation. Other forms of analysis, for example energy yield analysis, use a very simplified representation of the wind turbines. Consideration of all single wind turbines in the simulation leads to a complex model of the power system and results in a solution that is very time consuming and, in extreme cases, not possible. In order to improve this situation wind farms can be represented in simulation by the equivalent models obtained from the coherency matrix.

Furthermore, models obtained on the basis of the coherency matrix can also be used for the quasi-stationary time-domain load flow and energy yield analysis as well as analysis of actions of network security management systems. The application of the coherency matrix in the aforementioned cases delivers the required information about the structure of the equivalent wind farm model.

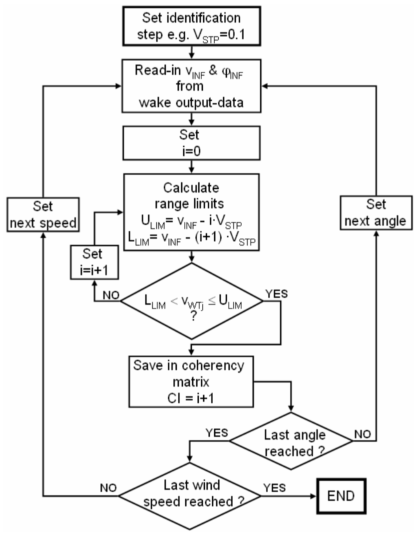

Fig. 11 Identification algorithm for construction of a coherency matrix

However, the information then has to be implemented in power system simulation software, like PSS™NETOMAC [15]. The information obtained from the coherency matrix includes:

- the number of equivalent wind turbines that represent the considered farm,
- the number of single wind turbines integrated into each equivalent unit,
- the input wind speed for each equivalent wind turbine.

Using this information the dynamic models, which are implemented in the power system simulator, can be appropriately configured and the analysis using a reduced system model can be carried out.

Apart from the dynamic simulations, where the coherency matrix is used for delivering necessary information about system modeling, the coherency matrix can be used also for the estimation of energy yield or in the dispatching process.

4.2 Dynamic simulations

In order to perform the dynamic simulation of the power system considering wind generation, the following procedure has to be executed. At the beginning it should be noted that it was assumed here that the coherency matrix for the considered wind farm is already known. Further, the values of the wind speed and wind direction incoming to the farm have to be defined. These two signals are used as input for the coherency matrix in order to find the structure of the reduced wind farm. The wind direction defines the appropriate row of the coherency matrix and the wind speed is responsible for the position on the third axis. In this way only the right cells containing the coherency indexes are localized and then used to form the reduced model. The number of the equivalent wind turbines that represents the entire wind farm under is equal to the number of different coherency indexes in the defined cells of the coherency matrix. Each equivalent wind turbine can integrate one or more single units. The number of single units that were replaced by the equivalent model is determined by the number of coherency indexes that have the same value. The equivalent model of the wind farm for the power system simulator is prepared using a model of the single unit by rescaling its parameters. The rated power of the equivalent wind turbine is assumed to be equal to the sum of the rated power of single units integrated into the considered equivalent unit. Since all other parameters of the model are specified using per unit notation, it was assumed that their values are not changed during the reduction process. This results from the fact that all per unit quantities are referred to the rated voltage and rated apparent power of the wind turbine. In the case of the equivalent model the value of the rated voltage is not changed and the rated apparent power results from the summation of the power of individual units. Each equivalent wind turbine obtains an appropriate input wind speed that is calculated on the basis of coherency indexes according to Eq. (5).

4.3 Energy yield calculation

Although the analysis of the energy yield has only a stationary character, it is also significant in some cases, like wind farm planning. An inappropriate calculation approach can lead to considerable overestimations. Generally, such calculations are performed using the wind profile, which was measured for the considered site, and the static power curve of the installed wind turbines. Both of these curves are combined together and the time curve of the produced power can be obtained. The area under this curve gives the energy yield of a single wind turbine in the simulated time period. For this calculation it is often assumed that all wind turbines in the farm obtain the same wind profile as input and that the resulting power of the whole wind farm is equal to the sum of the powers of all individual units. But, as already discussed, the mutual interactions between the wind turbines can cause significant differences in the input wind speeds for individual units. Therefore, the power produced by each unit can also be different and consequently the energy yield of the wind farm will deviate considerably from the energy yield approximated using the simplified approach. Due to this fact the wake effect has to be also considered during the calculation of energy yield. It is especially significant when the wind farm is in the planning phase and the investment analysis is carried out. Since the coherency matrix includes all significant information about wind farm characteristics, it can also be directly used for the calculation of energy yield. For this purpose the wind profile incoming to the wind farm in the form of the time series is used as input for the coherency matrix. Each row of the wind profile includes information about the current value of the wind speed and direction. Based on this information the parameters of the reduced wind farm model are obtained from the coherency matrix, in a similar way as discussed in the previous section. The values of the obtained wind speed for the equivalent wind turbines are further used to estimate the power produced by the wind farm. For this purpose the power curve of the wind turbine in the form of the lookup table is used. The energy yield of the wind farm can then be calculated with Eq. (7).

$$E_{CM} = \sum_{j=1}^{t_{end}} \sum_{i=1}^{n_G} \left(P_{Ti} \cdot \Delta t \cdot n_{Ti}\right) \tag{7}$$

Where: E_{CM} – energy yield of the farm obtained with coherency matrix [kWh]; P_{Ti} – power obtained from the power curve of the wind turbine for given i^{th} wind speed [kW], Δt – time step in wind profile time series [h]; n_{Ti} – number of turbines integrated into one equivalent unit; n_G – number of equivalent units for given wind speed and direction; j – index describing the rows of the wind profile time series, t_{end} – last row of the wind profile time series.

5 Case study

In this section some exemplary simulations of the power system with a wind farm using the introduced reduction method will be presented.

5.1 Energy yield calculation

At first the energy yield for the test wind farm, which consists of 9 WT and is characterized in section 3.2, will be calculated. To compare both approaches for energy yield calculation, which were discussed in section 4.3, the test simulation was performed. For this purpose the annual wind profile, which was measured on the chosen site, was used as input. Moreover, it was assumed that all nine wind turbines installed in the test wind farm are of the same type and have the same power curve that is given in Fig. 12. With these assumptions the energy yield was calculated using the simplified method and then the coherency matrix – based method. The results are given in Tab. 1. It can be seen that the annual energy yield obtained with the simplified approach is over 3.3 GWh higher than the energy yield obtained using the coherency matrix approach.

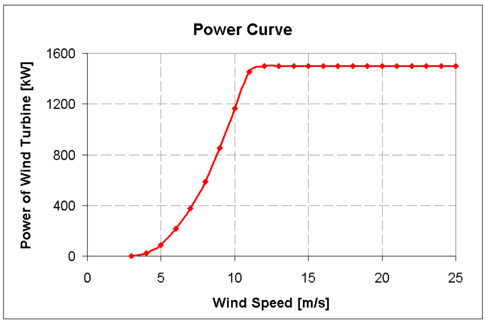

Fig. 12 Power curve of the variable speed WT

This corresponds to 244 hours full load operation per year and, with the assumption that the remuneration for wind energy is equal to 7 cent/kWh, results in an overestimation of the annual profit of more than 230000 Euro.

5.2 Dynamic simulation

In order to check the performance of the coherency matrix based reduction method the dynamic simulation of the short circuit in the discussed test system was carried out. For this purpose the detailed wind farm model consisting of all nine units was implemented using NETDRAW [16] – the graphical editor for PSS^{TM}NETOMAC. The structure of this system is presented in Fig. 13 whereby the distances and turbine types are the same as discussed in section 3.2. At node 3 of the system the three-phase short circuit was simulated. The duration of the fault was set to 100 ms while the residual voltage was equal to ca. 0.5 pu. The input wind speed to the wind farm was equal to 9 m/s and wind direction was set to 0°. According to the wake effect model each individual unit obtained adequate input wind speed as given in Tab. 2. Further, for the discussed test wind farm the equivalent model using the coherency matrix was created. For chosen wind speed and wind direction the reduced farm model consists of three equivalent units. Each unit integrates three single wind turbines. The parameters of the reduced system can be found in appendix. Moreover, the test wind farm was also represented as a single unit model that integrates all of the individual units. The simulation results for the three discussed wind farm representations in the point of common coupling – PCC are presented in Fig. 14 - Fig. 17. It can be seen that the reduced model obtained by the coherency approach agrees quite well with the detailed model for all observed parameters. The single-unit equivalent model shows significant deviations in the case of active and reactive power as well as current. The values provided by this model are considerably higher than those obtained with the detailed wind farm model, what leads to overestimations by the analysis.

Tab. 1 Results of energy yield calculation for the test wind farm

Parameter	Energy Yield [GWh]	Full Load Operation [h]
Energy yield using simplified approach	30.8	2279
Energy yield using coherency matrix	27.5	2035

Tab. 2 Input wind speeds for individual wind turbines

Unit No.	Wind Speed [m/s]
Input to the farm	9
WT1, WT2, WT3	9
WT4, WT5, WT6	6.6
WT7, WT8, WT9	6.2

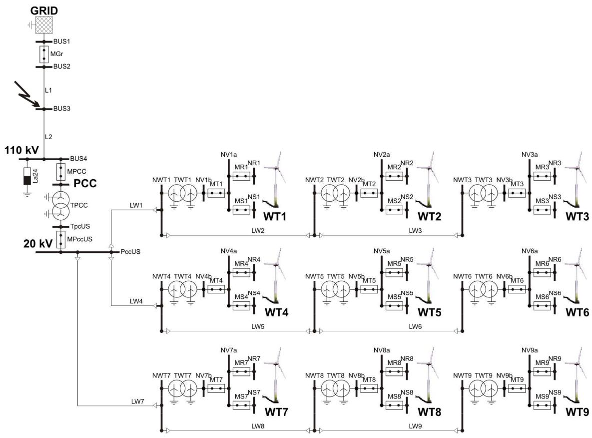

Fig. 13 Structure of the test system for dynamic simulation

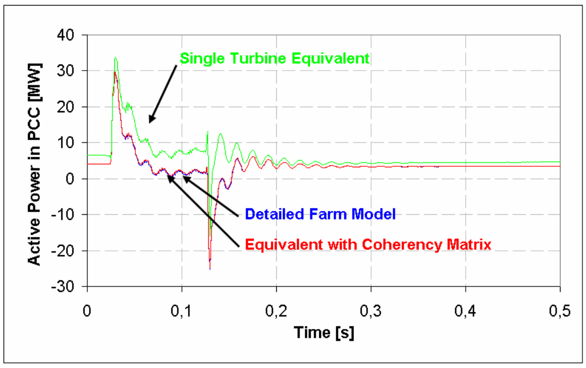

Fig. 14 Active power in point of common coupling

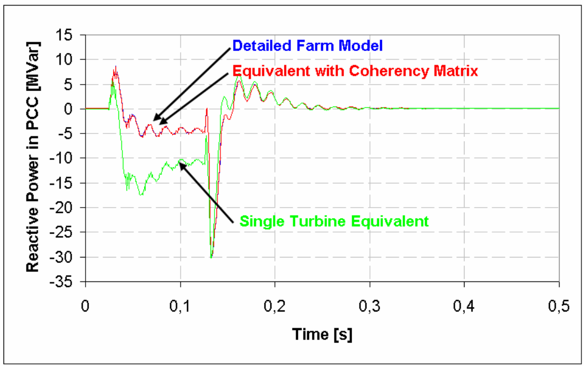

Fig. 15 Reactive power in point of common coupling

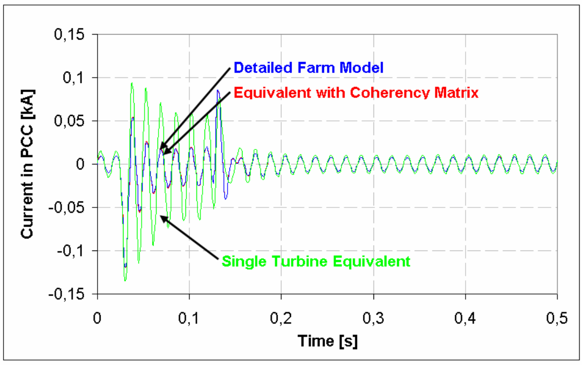

Fig. 16 Current in point of common coupling

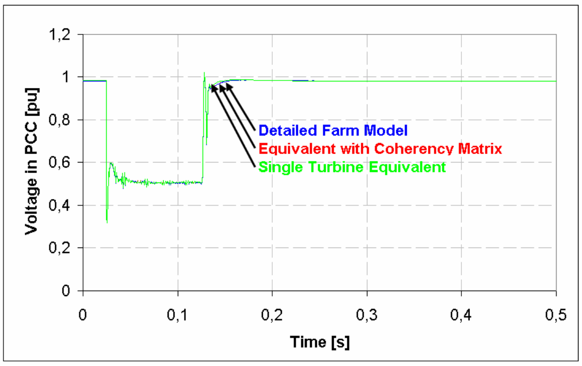

Fig. 17 Voltage in point of common coupling

6 Conclusion

In this paper the reduction method for wind farms was introduced and characterized. The coherency based approach allows for dynamic simulations of complex wind farms using simplified models that achieve a high level of accuracy. The significant advantage of this method is that the coherency matrix has to be created and saved only once for the given wind farm. Then it can be used to obtain information about the structure of the reduced model for the dynamic simulation in the power system simulators. The inputs for the coherency matrix are wind speed and wind direction. A comparison of the simulation results shows that this method is very much in agreement with the original system.

7 References

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8 Appendix

8.1 Parameters of the detailed wind farm model

Tab. 3 Parameters of the wind farm grid

Parameter	Value
L	0.45 km
R’	0.1 Ω/km
X’	0.175 Ω/km
C’	300 nF/km

*) all cables in the farm were assumed to be the same

Tab. 4 Parameters of the step-up transformers

Parameter	Value
U_{USn}	20 kV
U_{LSn}	0.69 kV
Sn	5 MVA
Group	Yy00
u_R	0.1 %
u_K	6 %

*) all transformers in the farm were assumed to be the same

Tab. 5 Parameters of the wind turbine

Parameter	Value
Un	0.69 kV
Sn	1.667 MVA
Pn	1.5 MW
R_T	35 m
ρ	1.225 kg/m3
n_{Tmax}	19 rpm
n_{Tmin}	10.6 rpm
n_{Tsyn}	15.8 rpm
c_{Pmax}	0.434
λ_{OPT}	9
H	0.5 s
Rs	0.008 pu
Xsσ	0.08 pu
Rr	0.008 pu
Xrσ	0.08 pu
Iμ/In	0.3274 pu

*) all turbines in the farm were assumed to be the same

8.2 Parameters of the reduced wind farm model - using the coherency matrix

Tab. 6 Parameters of the grid in the reduced farm with three equivalent units

Parameter	Value
L_{EQ1}	1 km
R'_{EQ1}	0.07 Ω/km
X'_{EQ1}	0.1225 Ω/km
C'_{EQ1}	405 nF/km

*) cable parameters of connecting equivalent units no. 2 and 3 were assumed to be the same

Tab. 7 Input wind speeds for equivalent turbines

Unit No.	Wind Speed [m/s]
Input to the farm	9
WT_{EQ1}	9
WT_{EQ2}	6.65
WT_{EQ3}	6.25

The parameters of each wind turbine are the same as in Tab. 5 apart from the rated apparent power, which in this case has to be multiplied by three – according to the number of single wind turbines integrated into each equivalent unit.

8.3 Parameters of the reduced wind farm model – single unit representation

Tab. 8 Parameters of the grid in the reduced farm with single unit representation

Parameter	Value
L_{EQ}	1 km
R'_{EQ}	0.0233 Ω/km
X'_{EQ}	0.0408 Ω/km
C'_{EQ}	1215 nF/km

The input wind speed for the single equivalent unit was equal to Vw= 9 m/s. This value does not consider the influence of the wake effect.

