REDUCTION OF WIND FARM MODELS USING THE COHERENCY APPROACH

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Abstract – This paper deals with the issue of aggregated modelling and simulation of large wind farms. Since the impact of wind generation on power system behaviour will significantly increase when the new offshore installations are commissioned, large wind farms have to be considered during the analysis of power system operation. However, consideration of each individual wind turbine of a large farm consisting of more than one hundred units does not seem to be an effective solution, especially if several wind farms have to be considered in the analysis simultaneous with large synchronous generators. Therefore, new method for aggregated representation of wind farms is needed.

The approach presented in this paper allows for the development of such an aggregated model for dynamic simulations that, on the one hand, minimize the duration of the simulation and, on the other hand, provides accurate results. This approach is based on the detection of coherent wind turbines within a farm through the analysis of the individual input wind speeds. The coherent wind turbines are then replaced by an equivalent unit. Moreover, the method for creation of the equivalent grid within the aggregated farm is introduced in this paper. The advantages of the develop aggregation method will be presented by some simulation results.

Keywords: Aggregation, coherency, dynamic simulation, power system, wind farm

1 INTRODUCTION

According to the European Wind Energy Association there are now about 50 GW wind generation in Europe and will be additionally 70 GW [1] offshore wind farms (WF) by the year 2020. These wind farms have already a significant influence on the power system operation and, therefore, must be considered during the analysis of their operation. However, consideration of each individual wind turbine (WT) during the simulation of the interconnected power system, like UCTE [2], is not possible due to the high complexity of the resulting model and, therefore, some alternative approaches, which allow for reduced representation of the wind farms, are needed. The issue of aggregated representation of the power systems has been investigated by many authors in the past, e.g. [3]-[8]. The goal of such aggregated representation is, on the one hand, minimization of the computation effort for large interconnected systems and encoding of the confidential network data for information exchange between competitive companies, on the other hand. A lower number of equivalent generators and an equivalent grid structure represent the resulting aggregated model of the considered system part. The main challenge of the aggregation process is to retain the same dynamic behaviour of the original system model in the resulting model.

This paper discusses a novel approach for aggregation of large wind farms for dynamic system analysis. The presented method is based on the coherency analysis of individual wind turbines within a farm and includes the influence of the wake effect on the farm operation. In the second section the background of the aggregation issue for conventional and wind turbine systems is discussed. In the third section the developed aggregation approach is introduced. In section 4 the test systems are characterised, and in section 5 simulation results are presented and discussed.

2 BACKGROUND OF THE AGGREGATION ISSUE

2.1 Conventional Power Systems

The investigations that have been done on the field of aggregation so far are devoted to the conventional power systems that consist only of large synchronous generators. Such systems are characterised by the direct dependency between angular speed of the generators and the grid frequency, since the synchronous generator are directly connected to the grid. This means that changes of frequency in an interconnected system result from changes of the angular speed of generators, which in turn, result from unbalance between the mechanical and electromagnetic torque in the event of fault, for example. This fact has been used in some reduction approaches that rely on the analysis of swing behaviour of individual synchronous generators initialised by the change of grid voltage – as in the case of fault [3]. Due to the spatial distribution of generators within the grid they can show different swing behaviour that is characterised by a different magnitude, frequency and phase. Thus, in order to obtain an appropriate aggregated model only the group of generators that has similar swing behaviour can be replaced by an equivalent unit. The first step in the aggregation process is the identification of units with similar dynamic behaviour; which means units that are coherent. Next, the parameters of equivalent generators have to be determined and then the structure of the passive grid has to be reduced. The aggregated model obtained in this way has to guarantee the same values of the load flows at the coupling points to the other parts of the considered system model, and in case of dynamic analysis, like fault simulation, it has to deliver similar dynamic behaviour. Typical for the discussed aggregation approach is that the whole system has to be modelled first and then its behaviour has to be analysed in order to create the aggregated model. This method can be followed only if the conventional power system, like UCTE without wind generation, is considered. The exemplary model of this system consists of 610 generators, 4400 nodes, 12000 grid branches and 1050 controllers [9]. The detailed consideration of wind generation in Germany alone would require additional implementation of over 20000 WT into the model. Therefore, the optimal solution would be the possibility for the creation of an equivalent farm model without detailed modelling of the whole farm in advance.

2.2 *Wind Farms*

Most of the wind turbines installed in the last few years are units that operate at variable angular speed [10]. These turbines are usually equipped with doubly fed induction generators (DFIG) or converter driven synchronous generators (SG). In order to allow operation with variable speed the generators are decupled from the grid, which operates at constant frequency in normal state. Therefore, both WT concepts use the power electronic frequency conversion systems with DC-link as a grid interface. Since the frequency converter for the WT with SG has to be dimensioned for the full generator power, the rated power of the frequency converter for the WT with DFIG is only a fraction of the rated generator power, which makes this concept more profitable regarding the network interface.

Due to the different characteristic of WT and conventional power plants the aggregation methods developed for the latter become less meaningful in the new applications including wind generation [11]. The issue of wind farm aggregation has been already investigated in some publications, e.g. [11]-[13]. However, these approaches are usually either not comprehensive, e.g. there is no information about the equivalence of the internal farm grid, or they lead to an equivalent “black-box” model, which does not correspond to the physical structure of the considered farm and is difficult to implement into the professional power system simulator systems.

3 COHERENCY APPROACH FOR WIND FARM AGGREGATION

3.1 *General Information*

The dynamic behaviour of a wind farm depends strongly 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. This can lead to a situation where some of the wind turbines within a farm are still in partial load operation while the others are already in full load operation. Such turbines have different behaviour during a system fault since in the partial load operation the controllers of each WT track the optimal point of operation regarding the produced power, while in the full load operation the main goal for the control system is to keep the produced power and angular speed within the acceptable range. Due to the fact that the operating point of each wind turbine results from the present wind speed value, this variable can be used in order to identify the coherent units. As coherent units one understands those units that have the same or similar input wind speed and therefore, as already discussed, have the same operating points. Thus, to find the points of operation of an individual WT the wake effect has to be considered. 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, because the units located in the front induce the “wind shadow” for the following units. 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, e.g. according to Jensen model [14], that can be considered within the one-dimensional profile of wind speed has to be used, like discussed in [15].

3.2 *Identification of Coherent Wind Turbines*

In this paper the introduced coherency approach is based on search for units with similar behaviour on the basis of the wind profile. The turbines with a similar wind profile are coherent and belong to one group that is replaced with an equivalent unit. Due to the wake effects within the wind farm the input wind speeds for individual wind turbines are not equal. These wind profiles depend on the direction of the incoming wind to the farm and also on the structure of the farm. In Figure 1 the groups of turbines obtaining the same input wind speed for two different wind directions are marked. It can be seen that for the first direction (from the left) the turbines belonging to the same column of the farm obtain similar wind profile as input. Analogously, for the second wind direction (from the bottom) the turbines belonging to each row of the farm have similar wind profiles. Hence, for these two cases the groups of the coherent wind turbines can easily be found and correspond to each row, or respectively to each column of the wind farm, as stated in [16]. More complicated situations occur if the wind has a direction different than the basic one (N, S, W, E) – as presented in Figure 1.

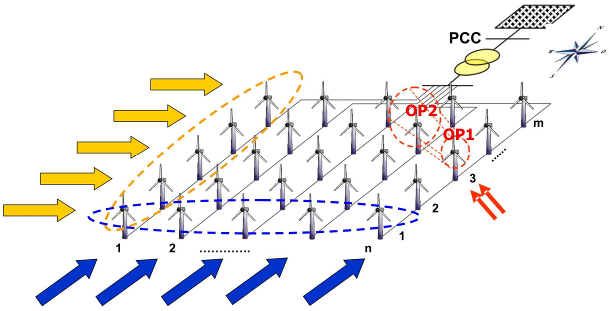

Figure 1: Influence of wind direction on coherency of WT.

In this case the turbines located in the middle of the farm can experience the influence of more than one wake, and therefore the detailed analysis of shadowing effects is necessary in order to find the groups of coherent wind turbines. In the example presented in Figure 1 the different points of operation are marked with OP1 and OP2, respectively. Assuming that the incoming wind speed is lower than the rated one the power produced by the considered wind turbines results from the power curve given in Figure 2. Additionally, the angular speed of both units can vary according to the curve given in Figure 3. This results from the fact that the angular speed of the aerodynamic turbine is adjusted by the MPPT – controller in the partial load operation in order to optimize the produced power.

In order to find groups of coherent wind turbines for a given wind farm an appropriate algorithm has been introduced and discussed in [15]. The method uses the wake model for calculating the input wind speeds of the individual wind turbines within the farm. Thus, at the beginning the structure of the farm has to be given, and the coordinates of all units and their parameters like rotor radius and hub height have to be defined. Additionally, an appropriate profile of the incoming wind has to be characterized. Since the wake characteristics in the farm depend on wind direction and wind speed the whole possible spectrum for the operation range has to be considered. For wind direction the operation range is between 0° and 360°, and for wind speed this range is assumed to be between 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. Thus, as input for the wake model the wind profile is defined as a step function, which alters within the chosen range with a defined step. For each step of the wind speed the direction is also changed from 0° to 360° with the defined step.

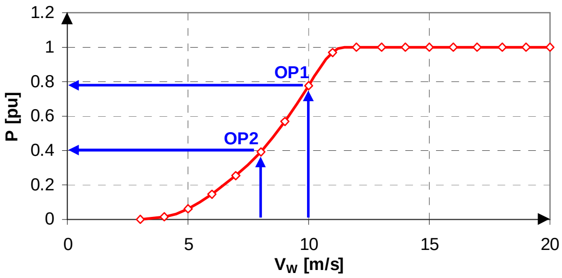

Figure 2: Power curve of pitch controlled wind turbine.

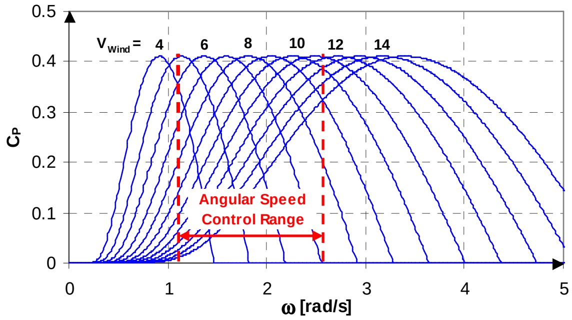

Figure 3: Power coefficient vs. angular speed for different wind speeds.

The step size for the wind speed and wind direction depends on the chosen number of intervals for both parameters in the defined range. For wind speed the step size can be calculated with Eq. (1) and for wind direction with Eq. (2).

$$\Delta v_W = \frac{v_{MAX} - v_{MIN}}{n_{WSI}} \tag{1}$$

Where: v_{MAX}, v_{MIN} – the upper and the lower limit of the considered wind speed range [m/s]; n_{WSI} – number of wind speed intervals.

$$\Delta \varphi_W = \frac{360°}{n_{WDI}} \tag{2}$$

Where: n_{WDI} – number of wind direction intervals.

As a result of this calculation the characteristic of the wind farm in the whole operation range regarding the input wind speed of individual units is obtained. Then, based on these wind speeds the groups of coherent units can be evaluated. Because the number of information obtained from the former calculation is very high, a new structure – the coherency matrix has been introduced in order to manage this information. This matrix is a 3D-object that is filled with the coherency indexes that are assigned to each WT for each considered wind speed and wind direction, see Figure 4. These indexes carry the information about the structure of the aggregated farm. It means that a single equivalent unit in the aggregated farm model can replace each group of WT, which have the same coherency indexes. Moreover, value of the index can be used to find the resulting wind speed profile for each equivalent wind turbine [15]. The size of the coherency matrix – S_{CM} depends on the number of WT within the farm as well as on the number of

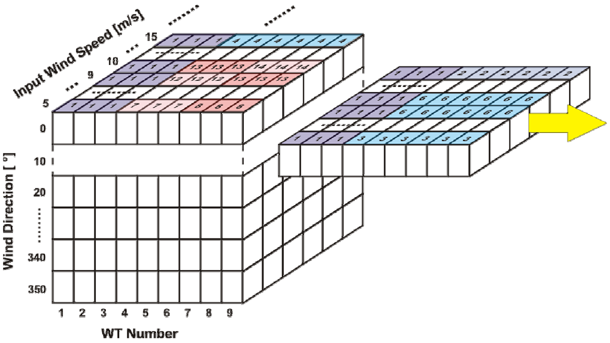

Figure 4: General structure of the coherency matrix.

intervals for wind speed and wind direction chosen for wake calculation, Eq. (3).

$$S_{CM} = n_{WDI} \ x \ n_T \ x \ n_{WSI} \tag{3}$$

For the purpose of coherency matrix identification an algorithm has been developed as discussed in [15].

3.3 *Parameters of Equivalent Wind Turbines*

In order to perform simulations using the aggregated wind farm model its adequate implementation with proper parameters in the respective simulation software is needed. In this paper all simulations were performed using PSS^{TM}NETOMAC [17]. It was assumed that all individual turbines within one wind farm are of the same type and have equal parameters. All parameters of the single machine are defined in the per unit system, where the rated apparent power of the unit and its rated voltage are used as basis values. Also the signals used in the controllers are represented in the same per unit system. This representation is advantageous for the configuration of the equivalent model. So it was accordingly assumed that the rated voltage of the equivalent WT is the same as in the case of individual units. Moreover, the rated apparent power of the equivalent unit is equal to the sum of rated apparent powers of all individual WTs whose coherency index corresponds to that of the considered equivalent unit, see Eq. (4).

$$S_{Grat\_EQ\_i} = \sum_{j=1}^{n_{CIx}} S_{Grat\_j} \tag{4}$$

Where: n_{CIx} – is the number of coherency indexes with the same considered value, S_{rat_j} – is the rated apparent power of the generator of jth – wind turbine, to which the considered coherency index was assigned.

This causes the values of the controller signals in both cases to be identical. Therefore, the structure of the equivalent WT model and its controllers will be not changed and all parameters apart from the rated apparent power are also identical. This assumption concerns the parameters of the machine as well as the gains and time constants of the controllers.

Additionally, the step-up transformers that are included in each wind turbine should be adequately represented in the aggregated model. For this purpose the same assumption was made as for the WT. This means that only the rated apparent power of the transformer has to be changed since all other parameters are in a per unit system that uses this power and the rated voltage as basis values. Accordingly, the rated apparent power of the transformer for the equivalent WT is equal to the sum of rated apparent powers of all transformers belonging to the WTs that were integrated into one equivalent group.

3.4 *Reduction of the Farm Grid*

The third inherent element of the reduction process is the determination of the structure and parameters of the internal wind farm grid. Generally, the passive network has influence on the active and reactive power losses within the farm and, therefore, has to be adequately considered especially in the large wind farms. In this paper only the wind farms with radial structure are considered. In the reduced wind farm model it is assumed that each equivalent WT is directly connected to the lower voltage side of the wind farm coupling transformer with a separate cable. To find the parameters R_{eq}, X_{eq}, C_{eq} of these cables in the equivalent wind farm grid, the approach based on conservation of the power losses has been used. This approach assumes that the active and reactive power losses of the farm have to be the same for the detailed and equivalent representation. Moreover, calculation of the participation factors takes into account the fact that the equivalent WTs obtained from the coherency matrix can include individual units that are physically connected to different strings of the wind farm grid, depending on the direction of the incoming wind.

The starting point of this method is the calculation of the active and reactive power losses within the detailed wind farm grid. For the wind farm with a radial structure, as presented in Figure 5, the active power losses of each string can be then evaluated according to Eq. (5).

$$\begin{aligned} P_{LossSt\_i} = 3 \cdot \big[& R_n \cdot I_n^2 + R_{n-1} \cdot (I_n + I_{n-1})^2 + ... \\ & + R_1 \cdot (I_n + I_{n-1} + ...I_2 + I_1)^2 \big] \end{aligned} \tag{5}$$

The total active power losses of the detailed farm are equal to the sum of the losses of each string, Eq. (6).

$$P_{LossF\_total} = \sum_{i=1}^{m} P_{LossSt\_i} \tag{6}$$

Where: m - number of strings within the farm. Similar expressions with X_i instead of R_i can be used for the representation of reactive power losses.

By analysing the equation for power losses in one string – Eq. (5) – it can be observed that the current of WTs located at the end of the string has more influence on the generation of power losses than the current of units located at the beginning of the string. Since the structure of the equivalent WTs in the farm – i.e. which individual units are replaced by the equivalent unit – depends mostly on the wind direction, it can happen that one of the equivalent WTs includes mainly the individual units that are located at the end of the grid strings and another one includes individual units that are located at the beginning of the strings. This means that the first equivalent WT integrates units that have the main contribution to the generation of power losses in the farm, and vice versa for the second equivalent turbine. Therefore, this observation has to be considered during the calculation of the line impedances for equivalent WTs. For this purpose, the participation factors of each individual WT in the generation of power losses have to be estimated.

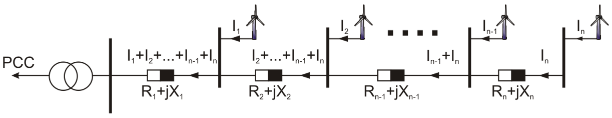

Figure 5: Power losses calculation in a radial wind farm grid.

Firstly, the vector with factors describing the share of power losses of the individual lines in the total power losses of the farm – kP_{Loss} has to be calculated with Eq. (7).

$$kP_{Loss} = \frac{P_{Loss\_Lines}}{P_{LossF\_total}} \tag{7}$$

Where: P_{Loss_Lines} – is the row vector of power losses in the individual lines, whose length is equal to the number of lines in the farm n_C. Furthermore, the matrix $n_T x n_C$ with the factors expressing the share of the current of each individual WT in the total current of each line – kI has to be evaluated, whereas n_T – is the number of WT in farm. By the means of the vector – kP_{Loss} and matrix – kI the new column vector containing the participation factors of each individual WT in the total power losses of the farm – kWT_{Loss} has to be determined. For this purpose each row of the matrix - kI has to be element-wise multiplied with the vector – kP_{Loss} and then, the elements of single rows in the resulting matrix have to be summed up as shown by Eq. (8).

$$kWT_{Loss} = \sum_{i=1}^{n_C} (kP_{Loss} \,.*\, kI)_i \tag{8}$$

Where: i – is the index that corresponds to the column number of the matrix resulting from the multiplication and n_C – is the number of lines in the farm.

The participation factors of the wind turbines in the total power losses of the farm are then used to determine the values of the equivalent impedances in the reduced wind farm model. Using assumptions about conservation of the power losses between the detailed and the aggregated model, the following equation describing losses in the equivalent grid can be written, Eq. (9):

$$\begin{aligned} P_{LossF\_totd} = 3 \cdot \big[& R_{eq\_1} \cdot I_{eq\_1}^2 + R_{eq\_2} \cdot I_{eq\_2}^2 + \ldots. \\ & + R_{eq\_n_{EQT}} \cdot I_{eq\_n_{EQT}}^2 \big] \end{aligned} \tag{9}$$

In this equation P_{LossF_total} was calculated with Eq. (6) and n_{EQT} – describes the number of equivalent turbines that represent the whole farm. The number of equivalent wind turbines is not constant and, as discussed in previous sections, depends on the wind direction and speed as well as on the farm structure. Therefore, the impedances of the equivalent farm model are also not the same for all conditions and have to be evaluated for each condition separately. For the given conditions the groups of turbines that are then replaced by the equivalent units are known from the coherency matrix. The currents of the equivalent turbines can be calculated as the sum of currents of the individual units belonging to one equivalent group. To find the values of equivalent resistances in Eq. (9) an additional assumption according to Eq. (10), which considers the participation factors of equivalent turbines in the power losses – kEQ_{Loss_i}, is introduced.

$$\frac{R_{eq\_1}}{kEQ_{Loss\_1}} = \frac{R_{eq\_2}}{kEQ_{Loss\_2}} = \ldots = \frac{R_{eq\_n_{EQT}}}{kEQ_{Loss\_n_{EQT}}} \tag{10}$$

The participation factor of i^{th} equivalent turbine in the power losses of the farm can be calculated by the summation of the participations factors of individual turbines defined with Eq. (8), which belongs to the discussed equivalent unit, Eq. (11).

$$kEQ_{Loss\_i} = \sum^{k} kWT_{Loss\_k} \tag{11}$$

Where: k – represents the index of turbines that belongs to the current equivalent unit and is used to find appropriate elements of the vector kWT_{Loss} with participation factors for individual wind turbines, which have to be summed up. The procedure for calculation of the equivalent reactance is similar, but the resistance – R has to be replaced by reactance – X in the given equations. If the connections of the internal wind farm grid are modelled taking into account the shunt elements (capacities), which are especially significant for the cables, the adequate representation within the equivalent model is required. This mainly influences the level of reactive power that is exchanged between wind farm and the superior-power system. Since the current of the shunt elements depends on the voltage level, which is normally almost equal to the rated value, it can be assumed that the shunt capacitance of the line connecting the equivalent wind turbine model will be equal to the sum of the individual capacitances of the cables that are directly connected to the individual wind turbines integrated into the considered equivalent unit [18].

4 TEST SYSTEMS

The dynamic model of the New England Test System was used to test the developed aggregation approach, see Figure 6. Additionally, the exemplary wind farm was connected to node 24 of this system. This wind farm consists of 50 variable speed wind turbines with DFIG and its rated power is 75 MW. The WTs are located at a distance of 400 m from each other and there is an additional displacement in the farm structure between neighbouring rows of wind turbines, see Figure 7. The displacement is equal to 200 m.

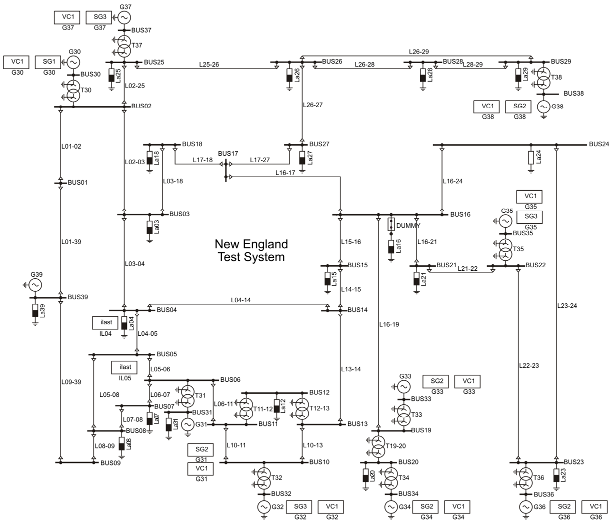

Figure 6: Structure of the New England Test System.

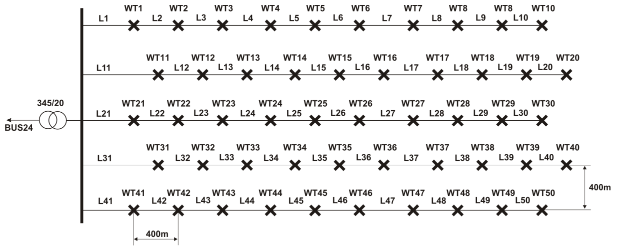

Figure 7: Structure of the 50 WT test wind farm.

5 SIMULATION RESULTS

5.1 *Methodology for Evaluation of the Approach*

In order to evaluate the aggregation method a new coefficient has been introduced. This coefficient defines the reduction grade of a farm and is given by Eq. (12).

$$RG = \left(\frac{1 - n_{EQT}}{n_T - 1} + 1 \right) \cdot 100\% \qquad (12)$$

Where: RG – is the reduction grade, n_{EQT} – is the number of equivalent wind turbines after reduction and n_T – is the number of the individual wind turbines in the original wind farm. The value of this coefficient can vary between 0 and 100 percent, where 0 % means that the number of equivalent WT after the reduction process is the same as in the original farm and 100 % means that the original wind farm was replaced with one single unit. A coefficient of 100% is the best aggregation case. Moreover, the accuracy of the aggregation method was evaluated by comparing the active and reactive power time curves in the point of common coupling. For this purpose the new indexes APR and AQR were introduced, see Eq. (13) and Eq. (14).

$$APR = \frac{\sum_{i}^{n_{STEPS}} abs(P_{\det\_i} - P_{agg\_i})}{\sum_{i}^{n_{STEPS}} abs(P_{\det\_i})} \qquad (13)$$

$$AQR = \frac{\sum_{i}^{n_{STEPS}} abs(Q_{\det\_i} - Q_{agg\_i})}{\sum_{i}^{n_{STEPS}} abs(Q_{\det\_i})} \qquad (14)$$

5.2 *Aggregation Results for Test Wind Farm*

As discussed in previous sections the aggregated model of the wind farm can change its structure depending on wind profile parameters. Therefore, the reduction grade is not constant and changes with wind direction and wind speed as shown in Figure 8. But, it can be seen that its minimal value exceeds 85 % in the whole operation range, which guarantees a significant reduction of the model complexity. Moreover, the accuracy of results obtained with the reduced model is very good since the average value of the APR factor do not exceed 0.5 % and the average value of the AQR factor is lower than 1 %. This tendency can be also observed on the curves representing results for the time domain simulation of a three-phase fault in node 16 of the New England Test System, see Figure 9.

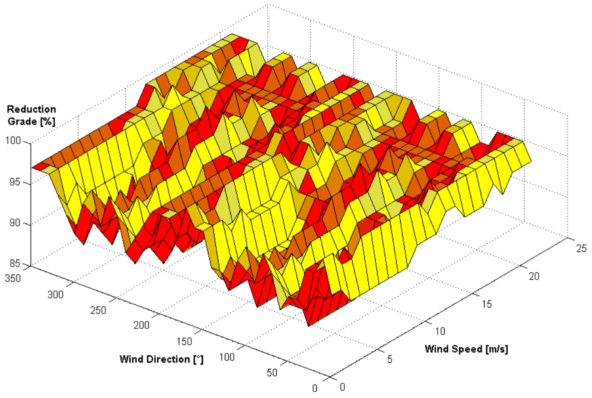

Figure 8: Values of reduction grade for different wind speeds and directions.

For the purpose of comparison the simulation of the test wind farm using a single unit equivalent, which was applied to represent the whole farm in the past, was also performed. The simulation results show that there is almost no difference between the detailed model, which is used as a reference, and the aggregated model obtained with the coherency approach. At the same time the single unit equivalent model shows significant deviations in the active power and current representation. In Figure 10 the values of the angular speed of chosen wind turbines are presented. It can be seen that as discussed at the beginning of this paper the individual wind turbines operates at different angular speeds, and this fact is considered in the aggregated model obtained with the coherency approach. The single unit equivalent does not consider this fact and therefore, deviations in the behaviour can be noticed.

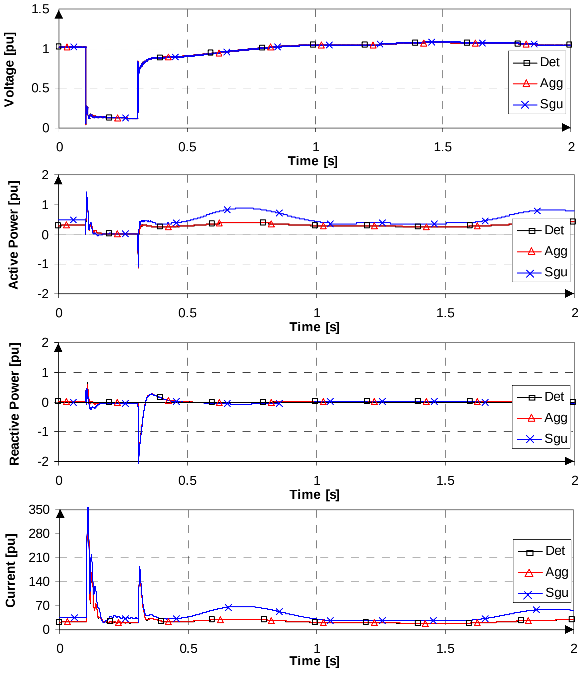

Figure 9: Parameters of the wind farm TWF50 in the point of common coupling for V_W=9 m/s and φ_W=0°.

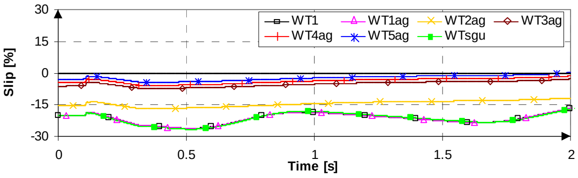

Figure 10: Slip of the chosen wind turbines in TWF50 farm for V_W=9 m/s and φ_W=0° (WT1 – unit in detailed farm; WT1ag, WT2ag, WT3ag, WT4ag, WT5ag – units obtained from the coherency matrix; WTsgu – single unit equivalent.

6 SUMMARY

In this paper a new method for the reduction of model complexity of wind farms has been introduced. This method is based on the coherency analysis of the wind turbines within a farm and allows for dynamic simulations of the power system operation. The coherent wind turbines are defined as units within a farm that obtain a similar input wind profile and, therefore, have similar operating points. It has been shown that the single equivalent wind turbine can replace such group of units during the simulation of the power system without significant influence on the dynamic behaviour of the farm. In order to determine the coherent wind turbines, the wind profiles incoming to the individual units within a farm are determined with the help of the wake effect analysis. The results of this analysis are then summarized using the coherency matrix, which includes information about the number of equivalent units representing the considered farm as well as information about the equivalent wind profile for each equivalent wind turbine. The performed simulations show that the results obtained with the reduced model of the considered wind farm deviate insignificantly from the results obtained with the detailed model, while results obtained with the single unit equivalent of the farm deviate strongly in case of partial load operation of the farm. Moreover, it was observed that if all wind turbines are in full load operation the single unit equivalent of the whole farm also provides a good representation of the dynamic behaviour. The calculated factor describing the overall error of the active power time curves in the considered test wind farm is lower than 0.5 % while the average reduction grade is higher than 85%. This means that the proposed method is well suited to represent the wind farm behaviour in the point of common coupling using models with reduced complexity and retaining good accuracy.

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