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Wind Power Plant Model Collection Network Representation in an Aggregated Wind Power Plant Model

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Abstract—**Wind power plants may need to be modeled as aggregated models for power system studies. The modeling is typically done by scaling up the wind power plant components, and representing the wind power plant collection network either by equivalent or zero impedance. The collection network representation in aggregated wind power plant model may have influence on the precision of wind power plant internal power losses and reactive power capability, especially in the vicinity of reactive power capability requirement limits. This paper analyses the aggregate model collection network representation in the case of different wind power plant topologies and wind power plant operating states. The study shows that the equivalent collection network impedance in aggregate model provides very accurate results for reactive power in the case of identical operation of the wind turbines in the wind power plant. The error of reactive power in aggregate model representation in the case of un-identical operation of wind turbines is analyzed.**

Keywords: aggregate wind power plant model, collection network, PSS®E

I. INTRODUCTION

The wind power plant (WPP) models required by the grid operators are generally aggregated models instead of detailed wind power plant models. The aggregated model with possibly a single scaled-up wind turbine generator, step-up transformer and a connection impedance, however, have to be able to present the performance of the actual wind power plant accurately.

The aggregated wind power plant model assumes identical operation of each individual wind turbine (on-line) and the collection network impedance is calculated assuming all the individual wind turbines are in operation. In some simulation cases some of the wind turbines may be off-line, or their operating points may be different from each other – and the collection network impedance assuming identical operation is used. In alternative case, the wind power plant collection network impedance may be assumed zero.

The aggregation of the collection network impedance has influence on the precision of power losses and reactive power capabilities of the wind power plant model.

Yang and Zha have presented an aggregation method for wind power plant in [1], including the calculation for the collector network. Also Akhmatov and Knudsen have studied aggregate model of a large wind power plant in [2].

The requirements – also concerning reactive power capability – set by TSOs vary greatly from TSO to TSO and the size of the wind power plant. Sourkounis and Tourou have reviewed in [3] some of the Grid Code requirements of European TSOs. The reviewed European requirements on reactive power suggest at most stringent, the Q/P_N 0.41 (inductive) and 0.48 (capacitive) – that correspond respectively to 0.925_{ind} and 0.9_{cap} power factor at nominal active power.

This paper presents a sensitivity study of aggregated wind power plant network presentation of different sizes of wind power plants and different collection network topologies and aggregated collection network influence on the reactive power capability simulation results.

II. WPPs AND REACTIVE POWER REQUIREMENTS

The WPP collection networks are often cable networks. There are different network topologies used depending on the individual WPPs.

Common to most of the modern wind power plants, the individual wind turbines (WT) have their own dedicated wind turbine step-up transformers, and the whole wind power plant has its own high voltage step-up transformer connecting the WPP to the power system. A typical WPP collection network contains multiple daisy-chain-type collection branches (e.g. Figure 1), and may also contain tree-type parts (e.g. Figure 2).

The reactive power requirements set in the grid codes are for the whole WPPs and must be fulfilled at a specified reference point, typically the grid connection point, e.g. at the high voltage side of the WPP step-up transformer.

Generally, the most likely problematic area (in case there is any) of fulfilling the reactive power capability requirements is in the capacitive reactive power capability at nominal active power.
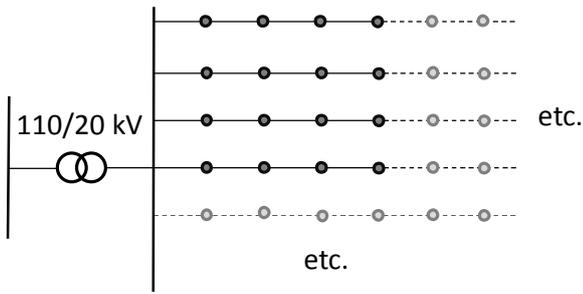
Figure 1.   An example of a wind power plant array layout, consisting of parallel collection branches and a number of wind turbines in each branch. The collection branches are of daisy-chain type, as in each circle of the diagram, there is a parallel connected WT with a step-up transformer.
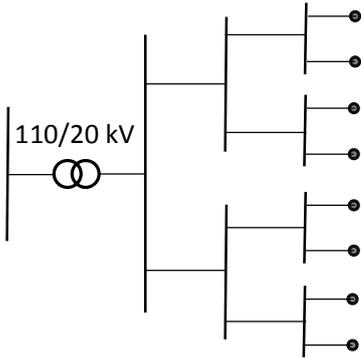

Figure 2.   An example of a wind power plant tree layout. In each circle of the diagram, there is a WT connected with a step-up transformer.

Cable networks – that transmit the power from WTs to the WPP connection point – produce capacitive reactive power. In addition to the WPP internal collection cable network, the WT and WPP step-up transformer impedances influence the reactive power at the WPP grid connection, or reference point. The influence of the transformer impedances is generally more significant than that of the cable collection network, but in the borderline cases of WPP fulfilling or not fulfilling the reactive power capability, the network impedance may play an important role.

III.   WPP SIMULATION MODEL

A generic wind power plant model was built for this analysis by selecting generally most typical WPP and wind turbine features and components. The simulations were run with PSS®E.

Two WPP models are created for each study case. A so-called topology model comprises the individual wind turbines (generators), wind turbine step-up transformers, the collection network cables and the WPP step-up transformer(s). An aggregated WPP model for each corresponding study case is created, and it is composed of a single scaled-up wind turbine (generator), a scaled-up WT transformer, an equivalent WPP step-up transformer (in the case the original topology model contained multiple parallel WPP step-up transformers or individual transformers per collection branches), as well as the collection network as a branch with equivalent collection network impedance.

A.   WPP topology model

1)   Wind turbines
The average size wind turbine delivered to the market today is about 2 MW of capacity. Thus 2 MW wind turbines

are used in this study. The typical rotor diameter for a 2 MW wind turbine is 80 m.

The typical turbine type is variable speed wind turbine that is equipped with power converters and thus is capable of reactive power control. Reactive power control capability depends on the wind turbine type, i.e. if the turbine is a DFIG – doubly-fed induction generator – (Type 3) or a full power converter equipped wind turbine (Type 4), as well as the turbine manufacturer and the specific wind turbine type etc. The capability is to control the reactive power between inductive and capacitive reactive power within certain limits, and may be dependent on the active power production. Generally the most challenging reactive power performance operating states may be at nominal active power operation, when the reactive power control need may be emphasized. In addition at the same time the wind turbine reactive power may be more limited on nominal active power than at partial power operation.

Power factors (pf) of 0.90 and 0.95 are mentioned in typical reactive power requirements (for nominal power operation), and many wind turbines may have these power factors as their design limits or characteristics. Thus this study is conducted assuming full 2 MW active power production and reactive power limits are used according to 0.9 and 0.95 ind/cap power factors. Pf 0.95 signifies reactive power of ±0.657 MVAr ($S_n = 2.11$ MVA) and pf 0.9 signifies ±0.969 MVAr ($S_n = 2.22$ MVA). For 0.9 power factor the Q/P_N is 0.48 and for pf 0.95 Q/P_N is 0.33.

2)   Wind power plant
The wind power plant was selected an array layout (as presented in Figure 1) with equal spacing between adjacent wind turbines. The collection network is assumed of the type of parallel daisy-chain collection branches. This may be the common WPP layout especially for the larger wind power plants.

The spacing of the wind turbines affects the collection cable lengths. In this study, the collection cable length between individual wind turbines is assumed to be determined by the used wind turbine spacing.

The spacing of wind turbines in the wind power plant may vary, both by design (i.e. the selection of the sufficient spacing) as well as within a single wind power plant (e.g. due to locational reasons). According to Meyers [4], the optimal average turbine spacing may be considerably higher (i.e. ~15D, D signifying the turbine diameter) than conventionally is used in current wind power plant implementations (e.g. ~7D). In the simulation and analysis of this paper, a 10D spacing of wind turbines is assumed.

Thus with 10D spacing and 80 m diameter wind turbines, the spacing of wind turbines in the WPP is 800 m. This is also used as the length of cable branches between the turbines. Also the same cable length is used between the WPP substation and the first WTs in the collection branches.

The wind power plant collection network is medium voltage network of 20 kV that is a typical medium voltage level used in Finland.

Different sizes of wind power plants are considered in the simulations. The PSS®E WPP model in this study is possible to be constructed and parameterized for 1…9 collection branches and 1…19 wind turbines in a single collection branch connected in daisy-chain manner. I.e. the

wind power plant of capacities 2…342 MW are possible to be studied.

3) WPP step-up transformers

The wind power plant is assumed to be connected to the high voltage grid in 110 kV level, that is commonly used high voltage level in Finland.

The 110/20 kV step-up transformer is selected according the WPP size from a list of typical 110/20 kV transformers presented in table 1. In the case of the WPP being larger than the highest rated step-up transformer in the list of available transformers, multiple transformers with appropriate rating are used (identical transformers in parallel).

TABLE I. THE WPP 110/20 kV STEP-UP TRANSFOMER OPTIONS AND DATA USED IN THE STUDY WPP MODEL. (ABB TRANSFOMERS)

S_n [MVA]	r_k [%]	x_k [%]
10	0.510	9.987
20	0.435	9.991
31.5	0.387	9.992
40	0.365	11.994
50	0.350	11.995
63	0.333	11.995

4) WT step-up transformers

Each wind turbine has a dedicated 20.5/0.69 kV step-up transformer of 2.5 MVA rating. The transformer parameters are shown in table 2.

TABLE II. THE DATA FOR WT 20.5/0.69 kV STEP-UP TRANSFOMER USED IN THE STUDY WPP MODEL. (ABB TRANSFOMERS)

S_n [MVA]	r_k [%]	x_k [%]
2.5	0.720	5.957

5) Collection network cables

A cable network is typically used as the collection network in WPPs. In this study, the WPP is assumed to be located at land (i.e., the cables a buried in ground and the cable characteristics are accordingly).

The cable network of the WPP layout of the type in figure 1, is parameterized for the defined wind power plant size and the choice of wind turbines in collection branches optimally.

Parameters of a selection of typical (and available) cable types are used, as presented in table 3. The cables for the branches are selected by using the following equation for the calculation of the minimum current carrying capacity for a branch

$$I_{rat.min} = \frac{S_{n,WT}}{\sqrt{3}U_{n,min}} \cdot 150\ \%, \qquad (1)$$

where $S_{n,WT}$ is the rated wind turbine capacity (now assumed $S_N = P_N = 2$ MW), and $U_{n,min}$ the minimum normal operating voltage, i.e. 0.9 pu of the nominal 20 kV. In addition the cable is over-dimensioned by (approximately) 50 % to be on the safe side.

TABLE III. THE 20 kV CABLE TYPES AND DATA USED IN THE STUDY WPP MODEL FOR BURIED INSTALLATION.

Cable type	r [Ω/km]	l [mH/km]	c [uF/km]	Irat [A]
AHXCMK-WTC 3x70/16 [1]	0.52	0.55	0.18	175
AHXCMK-WTC 3x120/25 [1]	0.30	0.52	0.22	230
AHXCMK-WTC 1x185/35 [1]	0.36	0.54	0.26	330
AHXCMK-WTC 1x300/35 [1]	0.33	0.52	0.31	435
AHXCMK-WTC 1x400/35 [1]	0.32	0.50	0.35	510
AHXCMK-WTC 1x630/35 [1]	0.30	0.49	0.41	635
AHXCMK-WTC 1x800/35 [1]	0.30	0.48	0.47	695
CX5-T101-U80 1x1000 [2]	0.0234	0.481	0.455	1188
Single core arm. Cu 1000 [3]	0.0295	0.283	0.584	1010

[1] Reka cables
[2] Doha cables
[3] Nexans cables

In the case a higher rated cable type would be needed, than the available ones in the list, multiple identical parallel cables of appropriate type are used.

B. WPP aggregate model

The wind power plant model is aggregated as a single–turbine–transformer–collection–network model from the data of the WPP topology model.

The most troublesome aggregation task is to aggregate the collection network. The network aggregation for this study is done mainly according to the method presented in [1]. The method is based on the assumption of identical WTs (with identical operation points) connected in the same (virtual) WT bus, and connection from each WT to the WPP collection point being parallel connections.

There are power losses on these parallel connections, and the equivalent impedance of the parallel connections for a daisy-chain topology according to [1] is

$$Z_S = \frac{\sum_{m=1}^{n} m^2 Z_m}{n^2}, \qquad (2)$$

where $m = 1$ is the wind turbine at the further end of the daisy-chain collection branch, n the number of WTs in the collection branch, and Z_m the impedance of individual branch between two daisy-chain connected turbines.

Similarly, the equivalent impedance on parallel connected collection branches is

$$Z_P = \frac{\sum_{m=1}^{n} n_m^2 Z_m}{n^2}, \qquad (3)$$

where n_m is the number of wind turbines connected via the Z_m (that is e.g. Z_S from (1), and n_m is n in (1).)

IV. STUDY CASES

The point of interest in the study is the WPP output at the connection point of the WPP, i.e. the HV bus of the 110/20 kV transformer(s), where the grid code requirements must be fulfilled.

The different WPP topology cases run were (no. of collection strings x no. of WTs in a collection string):

- 3 x 3; 5; 7
- 4 x 4; 6; 8
- 5 x 5; 7; 9
- 6 x 6; 8; 10

- 7 x 7; 9; 11; 13
- 8 x 8; 10; 12; 14; 16
- 9 x 9; 11; 13; 15; 17; 19

Thus the WPP capacities varied from 18 MW to 342 MW with the different above listed WPP collection network topologies.

The simulation cases were initialized for individual WTs operating at nominal 2 MW active power, and at their maximum reactive power capability: 0.9_{ind} or 0.9_{cap}.

The simulations were run for the topology model, as well as the aggregate model with aggregate WPP collection network impedance. The results of the simulations, i.e. the active power and reactive power output, were identical in the topology model and aggregate model simulations in the case of identical individual WT operation (the largest errors of 0.3 MW and 0.1 MVAr being in the case of largest 9 x 19 WPP). This justifies the representation of aggregate collection network in the case of identical wind turbine operation.

In order to assess the importance of the modelling of the collection network, the simulations were run with the aggregate model for respective study cases with zero impedance of the aggregate network.

The WPP aggregate model was assessed in the case of some of the WPP WTs being off-line while other WTs were operating at full active power, and 0.9_{cap} pf. Symmetrical array (i.e. N x N) layout WPPs of size 3 x 3 … 9 x 9 were studied. All the cases were calculated with

- the first WT in each collection string being switched off (case F)
- the last WT in each collection string being switched off (case L)
- a whole single collection string being switched off (case S).

In each of the above described cases F, L and S, the WPP production for a N x N WPP is equal. However, in the case of smaller WPPs, the share of switched-off capacity and power production is larger. I.e. 1/3 in the case of 3 x 3 (18 MW capacity) case, and 1/9 in the case of 9 x 9 (162 MW capacity) case.

V. SIMULATION RESULTS

The simulation results of the pf 0.9_{ind} cases (i.e. the WTs operate at 0.9_{ind} pf) showed that in the case of all the different WPP topologies and capacities the Q/P_N was -0.6 or less. Thus, reactive power capability is well kept. However, the capacitive reactive power capability of the WPPs is low, as Q/P_N is below 0.9 pf requirement in all cases, and below 0.95 pf requirement in some cases, as seen in figure 3. According to these results, it is evident that if the WTs' reactive power capability were 0.95_{cap}, the study WPPs would have even more difficulties in complying with the 0.9_{cap} reactive power requirement at the grid connection point.

The results show (e.g. in figure 3) that the consideration of the collection network impedance has a capacitive impact on the WPP reactive power capability. If using zero
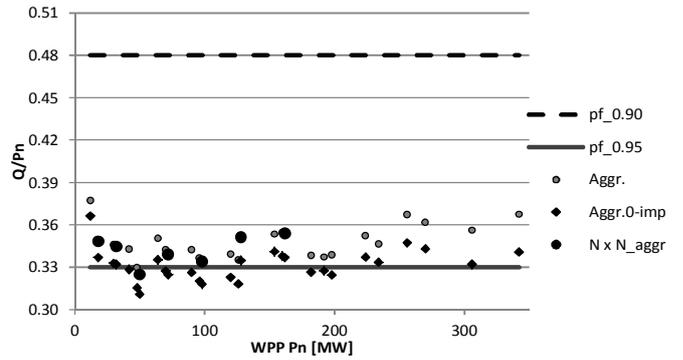

Figure 3. WPP Q/Pn of the simulation results of different WPP sizes and network topologies compared to the 0.9cap and 0.95cap reactive power requirements. Aggregated model represents the accurate results. Symmetrical N x N WPP array layout results are highlighted. The aggregate model with zero impedance WPP collection network results are shown for comparison and demonstration of the importance of proper modelling of the collection network in an aggregate model.

impedance for the collection network, the WPP reactive power capability is transferred slightly to inductive direction. In the case of WPP being close to the reactive power capability limits, omitting collection network impedance by assuming zero impedance, might erroneously sway the conclusion of the simulation results to WPP not fulfilling the requirements.

In addition to reducing the capacitive reactive power capability by assuming zero impedance collection network in WPP aggregate model, the active power losses in the WPP collection network are also overlooked. In the largest studied WPP cases the active power losses were > 2%, thus reducing the actual maximum power of the WPP at the connection point from the cumulative of the nominal power of individual WTs.

Symmetrical array WPP models (i.e., N x N turbines) were simulated in order to analyze the errors of aggregate model, and differences of different WTs of the WPP being switched off.

The aggregate model simulation results were compared to the topology model simulation results. The aggregate model was again simulated with the whole WPP collection network equivalent impedance, as well as zero impedance. The errors of the aggregate model simulation results are presented in figure 4.

Conclusions from the sensitivity analysis simulation results of the aggregate model impedance in the case of some WTs in the WPPs being switched off are:

- The selection of switched-off WTs in the WPP (i.e. F, L or S) does influence significantly the error in reactive power.
- The error in active and reactive power is smallest when the last turbines in the collection branches are switched off (case L) instead of the first ones or a whole collection string.
- As the share of the switched off WTs is large, the error in reactive power is larger. However, the percentage error in active power is not affected by the size of the WPP (and the decreasing share of switched-off WTs).
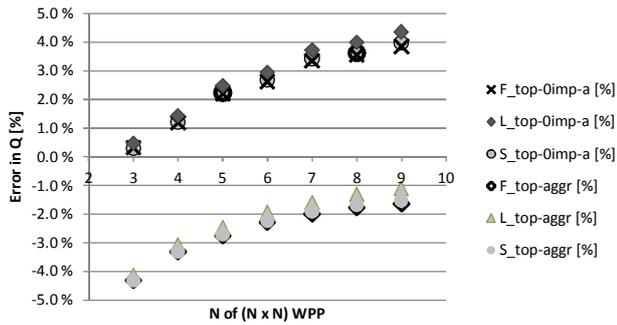
Figure 4.   Aggregate model WPP reactive power error in the case of different WPP sizes (N x N) when part of the WPP WTs are being swithed off. F – the first WTs in the collection branches are being swithed off, L – the last WTs in the collection brances are being swithed off, and S – a whole single connection branch is being swithed off. Aggregate model impedance according to the equivalent collection network impedance (aggr), and zero impedance (0imp-a).

- Zero impedance aggregate model gives more accurate results than the equivalent aggregate network impedance model in the cases when large share of WTs are being switched off.

VI.   CONCLUSIONS

The wind power plant collection network impedance representation in an aggregated WPP model is shown to be important. Although the aggregate network impedance being relatively small compared to the transformer impedances – the individual wind turbine transformers and wind power plant step-up transformers – its role should not be overlooked. It may play a significant role when considering reactive power capability analysis of the WPP.

The calculation of the aggregate collection network impedance was proven accurate in the case of identical wind turbines and their identical operation. In the case of un-identical operation, e.g. some of the WTs being switched off, there occurs some error. It is important to know the potential error sources and margins when using aggregated wind power plant models for different power system analysis cases.

REFERENCES

[1]   Y. Yang, and X. Zha, "Aggregating Wind Farm with DFIG in Power System Online Analysis," IEEE 6th International Power Electronics and Motion Control Conference, 2009, pp. 2233–2237.

[2]   V. Akhmatov, H. Knudsen, "An aggregate model of a grid-connected, large-scale, offshore wind farm for power stability investigations – importance of windmill mechanical system ," Electrival Power and Energy Systems, vol. 24, no. 9, 2002, pp. 709-717.

[3]   C. Sourkounis, and P. Tourou, "Grid Code Requirements for Wind Power Integration in Europe", Hindawi Publishing Corporation, Conference Papers in Energy, vol. 13, 2013, Article ID 437674, http://dx.doi.org/10.1155/2013/437674.

[4]   J. Meyers, and C. Meneveau, "Optimal turbine spacing in fully developed wind farm boundary layers," Wind Energy, vol. 15, no. 2, March 2012, pp. 305–317.