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Omar H. Abdalla
Hussein M. Kamel
Hady H. Fayek

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Omar H. Abdalla
Electrical Power and Machines Dept
Faculty of Engineering,
Helwan University
(Cairo,Egypt)
ohabdalla@ieee.org

Hussein M. Kamel
Electrical Power and Machines Dept
Faculty of Engineering,
Helwan University
(Cairo,Egypt)
husseinmagdy16@gmail.com

Hady H. Fayek
Electromechanics Engineering Dept
Faculty of Engineering,
Heliopolis University
(Cairo,Egypt)
hadyhabib@hotmail.com

***Abstract*— Penetration of wind energy plants into power grids has been growing from installations with a few wind turbines to large wind farms with more than hundreds of MW capacity. Modeling of these wind farms with individual wind turbines increases the complexity of the model and consequently leading to long time for planning studies. Simplified models which simulate wind farms are usually used for performing grid connection planning studies to evaluate alternative scenarios.**

This paper presents an aggregation model for a 500 MW wind farm to simplify steady-state and transient simulation studies. The aggregated modeling converts each group of wind farm components into a single equivalent representation. These groups include generators, pad mounted transformers, collector system and station transformers. Results of simulation studies are presented to show comparisons of aggregated equivalent model and detailed model of the wind farm. The results include steady-state (power flow, short circuit, contingency) and transient analyses.

***Keywords*—wind farm, model aggregation, detailed model, equivalent collector system.**

I. NOMENCLATURE

N_{G}:	Number of wind turbine generators.
P_{eq_G}:	Equivalent real power in MW for all wind generators.
Q_{eq_G} :	Equivalent reactive power in MVAR for all wind generators.
S_{eq_G} :	Equivalent apparent power in MVA for all wind generators.
Z_i :	Impedance of the ith pad mounted transformer, i = 1, 2… n
Z_{eq_PT}:	Equivalent Impedance of pad mounted transformers.
N_{PT}:	Number of pad mounted transformers.
S_{eq_PT}:	Equivalent apparent power in MVA of the pad mount transformers.
Z_{eq_c}:	Equivalent impedance for collector system that connecting the equivalent wind turbine to the station transformer.
Z_{ST}:	Station transformer impedance.
N_{ST}:	Number of station transformers.
B_{eq_C}:	Equivalent susceptance for collector system that connecting the equivalent wind turbine to the station transformer.
I:	Total number of branches in the collector system.
Z_i:	Impedance ($R_i + jX_i$) for i_{th} branch.
B_i:	Susceptance for i_{th} branch.
n_i:	Total number of wind turbines connected to the branch i.

II. INTRODUCTIONION

Wind farm performance in power systems has received considerable attention in recent years. Integration of large-scale wind farms into grids may cause significant consequences in system operation. In order to reduce computational complexity, analysis time and the risk of errors, it is important to obtain an aggregated model for the wind farm to avoid complexity of detailed modeling with a large number of wind generators and associated collector system. Aggregated modeling of the wind farm converts all wind farm components including generators, transformers, underground cable, overhead lines (if any) and station transformers into single equivalent representation of each group of the components.

Aggregation models of various types of wind turbine generators (WTG) and the wind speed modeling is performed in [1] to study high penetration of large-scale wind farms in smart grid. Dynamic modelling of fixed speed WTG is simulated in [2]. The significance of integrating the shaft system modelling into grid-connected wind turbines is described in [3]. An equivalent collector system with different configurations for a wind farm is developed in [4]. The impact of aggregation model on power quality was described in [5]. An aggregated wind farm model for analyzing power quality issues, with a case study, is described in [6]. Model aggregation of large wind farms for dynamic studies is presented in [7], where a large off-shore wind farm of 150 wind turbines is simulated by three equivalent clustered generators. Model aggregation of wind farms is presented in [8] based on the perturbation theory of model aggregation for ensembles of identical dynamical systems. It guides the construction of an aggregate model of

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a wind farm and provides bounds for its accuracy. In [9] the MaWind-tool for the aggregation of wind farm models is proposed based on mathematical approach to represent wind generation in system analysis. Simplified model of wind farms are presented in [10] to study voltage dip transients. Aggregated models of large wind parks with different configurations are developed in [11] for power system studies. Detailed models of doubly-fed induction generator and full converter schemes are analyzed. Aggregated models for wind farms are presented for use in power system transient stability studies [12]. A method for dynamic weighted aggregation equivalent model is developed in [13] based on the conventional aggregated dynamic equivalent modelling, considering the weighting factors for each generator which are calculated according to the Weibull distribution of wind speeds. A proposed equivalence method for distributed multiple wind farms in a power system is presented in [14], based on dynamic analysis of wind farms for determining coherence of different generators. A method for dynamic aggregation of doubly-fed induction generators is presented in [15] for stability analysis of wind farms. Permanent magnet synchronous generators wind farm aggregation algorithm is presented in [16] based on the principles of power equivalence. Model aggregation of a wind farm based on probabilistic clustering is presented in [17]. Adequacy of dynamic aggregated modelling of wind farms is presented in [18]. An alternative technique to obtain equivalent models of dynamical systems is to use system identification. [19], [20]. Parameter identification of multi-machine equivalent models of a wind farm consisting of doubly fed induction generators based on measured data is presented in [21].

The main objective of this paper is the development of an aggregate model of a large-scale wind farm for steady-state and transient studies at the planning stage, where specific type of wind generators is still under study. The model represents all wind farm components including wind turbine generators, pad mounted transformers, collector system and station transformers. The following assumptions [6] are considered while representing the aggregation modeling:

- All wind turbine generators shall have the same parameters and wind speed.
- Each wind turbine has the same voltage, current, and power under all operating conditions.

Simulations studies of detailed and aggregation models are performed and compared using DIgSILENT software [22]. The results include steady-state and transient analyses.

The arrangement of the paper is as follows. Section I outlines the previously performed research on the aggregation technique of wind farms. Section II illustrates the concept of the aggregation techniques and an illustrative example is presented. Section III presents the application of model aggregation to a 500 MW wind farm consisting of 200 wind turbine generators, each with a rating of 2.5 MW. The wind farm is connected to a 220 kV power grid. Section IV provides a comparison between the detailed modeling and aggregated modeling. Section V summarizes the main conclusions.

III. AGGREGATION MODELING METHODOLOGY

A. Aggregation Modelling in Power Systems

Besides wind farms, aggregation modeling of power systems has been used in many applications. Aggregation of static and dynamic loads which usually represented in the power system studies as induction motors are described in [23] and [24]. Modelling and aggregation of LED lamps load is developed in [25] for harmonic analysis in a distribution network. Studies are presented in [26] to demonstrate a proposed structure-preservation aggregate modelling of two-stage inverters in large PV system. Model aggregation for a multi-machine power system with thermal and hydro generators is described in [27] based on frequency response analysis.

B. Aggregation Modelling of Wind Turbine Generators

Figure (1) illustrates the aggregation modelling method, in which all wind farm components are turned into a single equivalent representation.

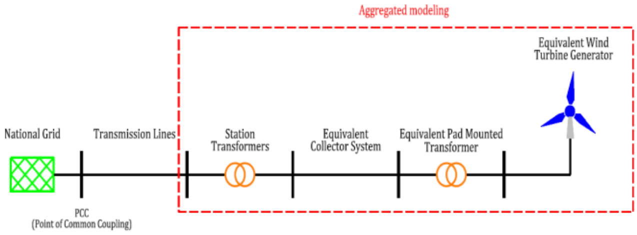

Fig.1: Aggregation technique to represent large wind farm into a single equivalent representation.

In order to construct the aggregation model for wind a farm having a large number of wind turbine generators into a single machine equivalent representation as described in Figure (2). The aggregation technique shall be expressed as per the following equations:

$$P_{eq\_G} = N_G \times P_G \tag{1}$$

$$Q_{eq\_G} = N_G \times Q_G \tag{2}$$

$$S_{eq\_G} = N_G \times S_G \tag{3}$$

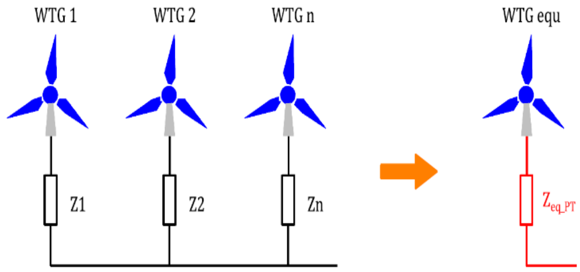

Fig.2: Aggregation of WTG and pad mounted transformer.

C. Equivalent Model of Pad Mounted Transformers

In order to convert the pad mount transformers to a single equivalent transformer representation, the equivalent apparent power in (MVA) and the equivalent impedance shall be as follows:

$$S_{eq\_PT} = N_{PT} \times S_{PT} \tag{4}$$

$$Z_{eq\_PT} = \frac{Z_{PT}}{N_{PT}} \tag{5}$$

D. Equivalent Model of the Collector System

The configuration of the wind power plant, as well as the size, type and arrangement of underground cables and overhead lines (if any) all have an impact on the performance of the collector system within the wind power plant.

National Renewable Energy Laboratory (NREL) created a simple approach that can be used for calculating the equivalent impedance for the collector system [28] as the following:

$$Z_{eq\_c} = \frac{1}{N_G^2} \sum_{i=1}^{I} Z_i n_i^2 \tag{6}$$

$$Z_{eq\_c} = \frac{1}{N_G^2} \sum_{i=1}^{I} (R \times n^2 + \mathrm{X} \times n^2) \tag{7}$$

$$B_{eq\_C} = \sum_{i=1}^{I} B_i \tag{8}$$

E. Equivalent Model of Station Transformers

Figure (3) shows an equivalent representation of the station transformers, the equivalent impedance shall be expressed as per the following equation:

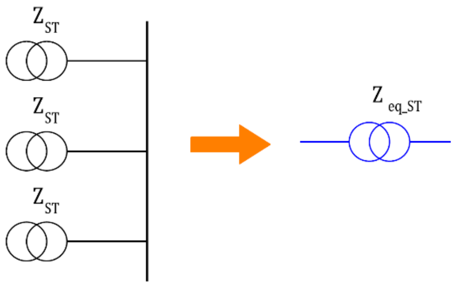

Fig.3: Aggregation of station transformer.

$$Z_{eq\_ST} = \frac{Z_{ST}}{N_{ST}} \tag{9}$$

F. Illustrative Wind Farm Example

An illustrative example for a collector system of a medium-scale wind farm with 40 MW capacity is presented to demonstrate the technique for calculating an equivalent collector system. Figure (4) shows the layout of the wind farm which consist of 16 WTG, each has a 2.5 MW rating, 16 pad mounted transformers, rating is 3.2 MVA, 0.69/20 kV and a station transformer with rating 50 MVA. Table I summaries calculations of the equivalent collector system, where:

$$Z_{eq\_c} = \frac{\sum_{i=1}^{I} (\mathrm{R} \times \mathrm{n}^2 + j\,\mathrm{X} \times \mathrm{n}^2)}{N_G^2} = \frac{222.044 + j123.375}{16^2}$$

$$Z_{eq\_c} = 0.8673 + j\,0.4819\ \Omega$$

$$B_{eq\_C} = \sum_{i=1}^{I} B_i = 7596.370\ \mu\mathrm{S}$$

IV. AGGREGATION MODELING FOR 500 MW WIND FARM

A. System Description and Modelling

As a case study, aggregation modelling for a large-scale wind farm with 500 MW capacity connected to a 220 kV power grid is performed. The 220 kV power grid is simulated by an equivalent generator with capacity 20 GW.

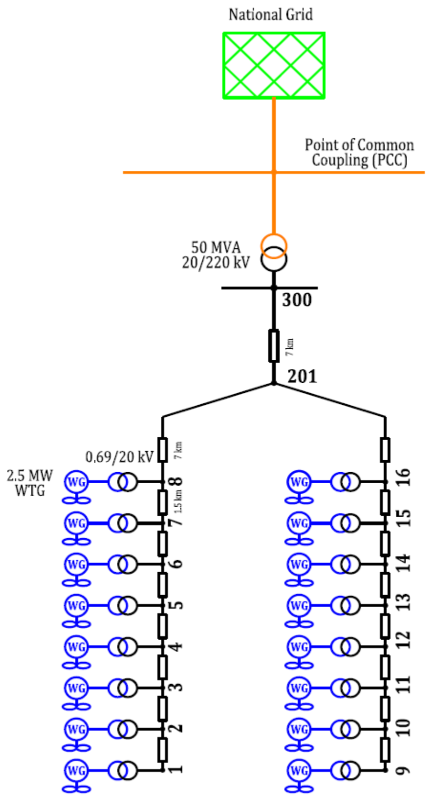

Fig.4: Layout for 40 MW wind farm

TABLE I. EQUIVALENT COLLECTOR SYSTEM FOR 40 MW WTG.

Branch From	Branch To	R (Ω)	X (Ω)	B (μS)	n	$R \times n^2$	$X \times n^2$
1	2	0.2092	0.1744	122.522	1	0.3138	0.1744
2	3	0.2092	0.1744	122.522	2	1.2552	0.6974
3	4	0.2092	0.1744	122.522	3	2.8242	1.5692
4	5	0.2092	0.1744	122.522	4	5.0208	2.7897
5	6	0.1046	0.0872	245.044	5	3.9225	2.1795
6	7	0.1046	0.0872	245.044	6	5.6484	3.1385
7	8	0.1046	0.0872	245.044	7	7.6881	4.2718
8	201	0.1046	0.4068	1143.540	8	46.8608	26.0378
9	10	0.2092	0.1744	122.522	1	0.3138	0.1744
10	11	0.2092	0.1744	122.522	2	1.2552	0.6974
11	12	0.2092	0.1744	122.522	3	2.8242	1.5692
12	13	0.2092	0.1744	122.522	4	5.0208	2.7897
13	14	0.1046	0.0872	245.044	5	3.9225	2.1795
14	15	0.1046	0.0872	245.044	6	5.6484	3.1385
15	16	0.1046	0.0872	245.044	7	7.6881	4.2718
16	201	0.1046	0.4068	1143.540	8	46.8608	26.0378
201	300	0.0418	0.1627	2858.849	16	74.9773	41.6586

Figure (5) shows the configuration of the 500 MW wind farm. It consists of 200 × 2.5 MW capacity WTGs and five 125 MVA, 20/220 kV station transformers which connect the wind farm to the 220 kV transmission system. The equivalent collector system for the 500 MW wind farm is obtained by using equations (7) and (8) and the same criteria as indicated in the illustrative example described in Section II. The results are: Z_{eq_c} = (0.0752+ j 0.0418) Ω and B_{eq_C} = 87807.505 μS.

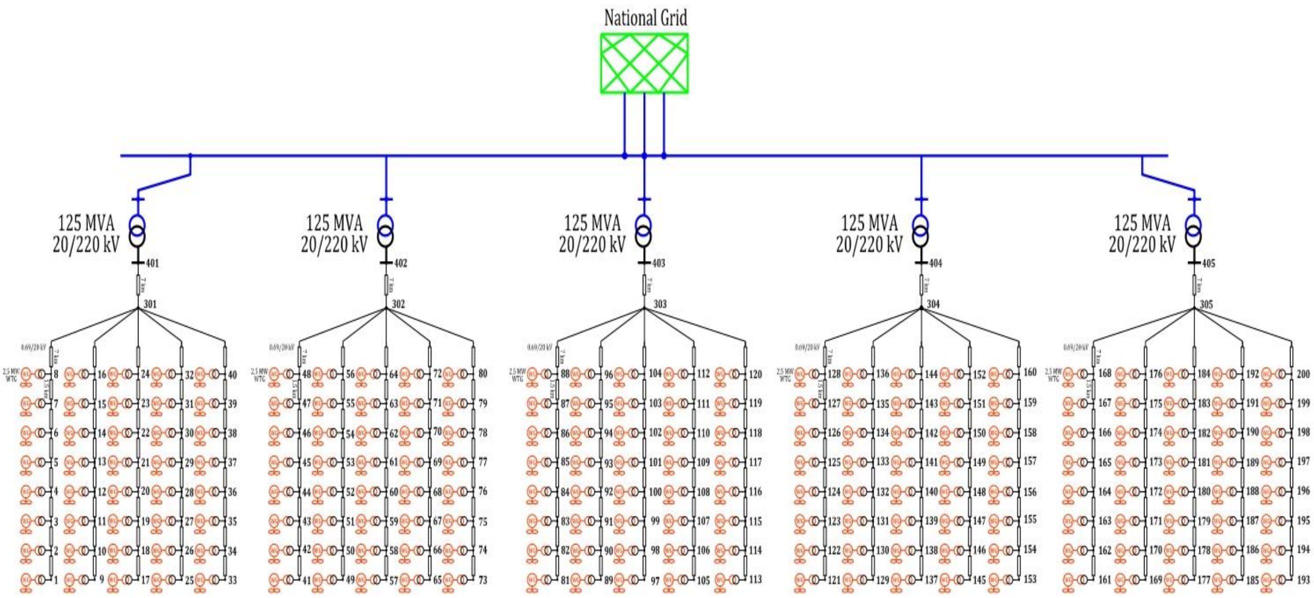

Fig.5: Detailed model for 500 MW wind farm.

Figure (6) shows the simulation of the 500 MW wind farm aggregation model using the DIgSILENT PowerFactory software. The simulated model will be utilized for further steady state analysis and transient analysis such as load flow, short circuit, contingency analysis, and transient stability analysis.

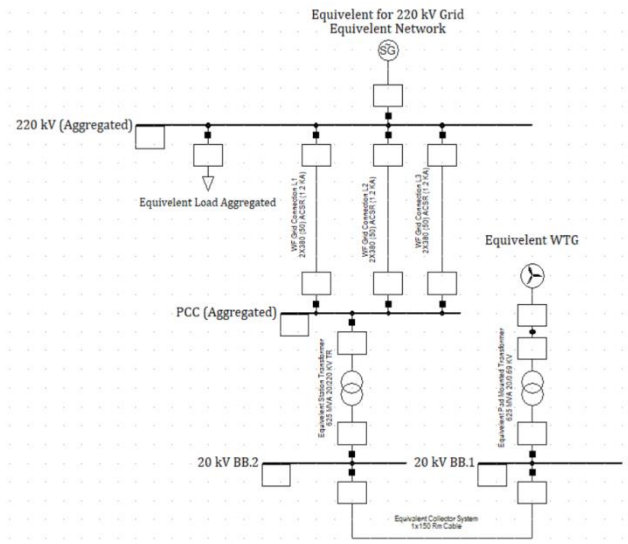

Fig.5: Aggregated modeling simulation in DIgSILENT.

TABLE II. BUS VOLTAGES FOR AGGREGATED MODEL

Bus name	Voltage in (p.u.)
220 kV (Agrregated)	1.00
PCC (Agrregated)	1.00
20 kV BB.1	1.08
20 kV BB.2	0.99

B. Load Flow Analysis

Load flow calculations are performed to acquire voltages at various buses, loading of transformers and overhead lines. Tables II, III, and IV reveal that the voltages for all bus and line loadings shown in Figure (5) are acceptable for all operating conditions.

TABLE III. LINE LOADING FOR AGGREGATED MODEL

Line name	Line loading (%)
WF Grid Connection L1	33.6
WF Grid Connection L2	33.6
WF Grid Connection L3	33.6
Equivelent Collector System	73.7

TABLE IV. TRANSFORMER LOADING FOR AGGREGATED MODEL

Transformer name	Transformer loading
Equivelent Station Transformer	73.7%
Equivelent Pad Mounted Transformer	75.4%

C. Short Circuit Analysis

The purpose for this analysis is to calculate the short circuit fault current at various buses and to determine the short circuit withstand current ratings of the busbars. Values of the short circuit currents are shown in Table V when a three-phase short circuit is applied at point of common coupling (PCC). The calculations are based on the method C of the IEC 60909 standard [29] using the equivalent frequency in calculating the peak short circuit current.

TABLE V. SHORT CIRCUIT CURRENT MAGNITUDE FOR AGGREGATED MODEL

Bus Name	Short circuit current (KA)
PCC (Agrregated)	46.033

D. *Contingancy analysis*

(N-1) contingency analysis is performed to investigate the effects of a single component outage such as a transmission line, power transformer, or generating unit on power system operation. The calculated branch flows of transmission line, maximum loading of transformers and voltages at network nodes are compared to permissible deviations from nominal values.

The contingency analysis performed on the aggregated model reveals that all transmission lines and transformers are within their permissible thermal capability limitations ensuring the security and reliability of the system. Table VI shows the lines loading in percentage in the case of WF Grid connection line L1 outage.

TABLE VI. LINE LOADING FOR (N-1) CONTINGENCY IN CASE OF ONE LINE OUTAGE

Line name	Max line loading in (N-1) contingency (%)
WF Grid Connection L2	50.4
WF Grid Connection L3	50.4
Equivelent Collector System	73.7

E. *Modelling of Small-Scale and Medium-Scale Wind Farms*

In simulation studies of small-scale wind farms with limited number of wind turbine generators detailed models can be conveniently used. In the case of studies of medium-scale wind farms (in the range of 20-50 MW), detailed or aggregated models may be used. Grid impact studies of a 50 MW wind farm are performed using a detailed model [30]. Grid code compliance studies for integrating a 50 MW wind farm into a power grid are described in [31]. Power quality studies of the same wind farm are presented in [32], where detailed model is employed.

V. COMPARISON BETWEEN DETAILED MODELING AND AGGREGATED MODELING

The detailed modeling for 500 MW wind farm shown in Figure (5) is simulated in DIgSILENT PowerFactory software to assess the level of accuracy and efficacy of the aggregated model.

Comparisons between the aggregated model and the detail model are performed in terms of steady-state and transient conditions. Table VII shows voltage a comparison between detailed and aggregated model. Table VIII shows a comparison between the WF grid connection lines loading in each model.

TABLE VII. COMPARSION BETWEEN BUS VOLTAGES FOR DETAILED MODEL AND AGGREGATED MODEL

Bus Name	Voltage in (p.u.)	
	Detailed Model	***Aggregation Model***
PCC	1.0002	1.0014

TABLE VIII. COMPARSION BETWEEN LINE LOADING FOR DETAILED MODEL AND AGGREGATED MODEL

Line Name	Loading (%)	
	Detailed Model	***Aggregation Model***
WF Grid Connection lines	33.5	33.6

A 3-phase short circuit is also applied based on IEC 60909 standard at point of common coupling (PCC) in both the aggregated and detailed models. Table IX shows a comparison between short circuit current values of both detailed and aggregated model.

TABLE IX. COMPARSION OF SHORT CIRCUIT CURRENT BETWEEN DETAILED MODEL AND AGGREGATED MODEL

Bus Name	Short circuit current (KA)	
	Detailed Model	***Aggregation Model***
PCC	47.39	46.03

Table X shows a comparison of the calculated power losses of the collector system in the aggregated model and the detailed model.

TABLE X. COMPARSION OF POWER LOSSES BETWEEN DETAILED MODEL AND AGGREGATED MODEL

Feeder Name	Power Losses			
	Detailed Model		**Aggregation Model**	
	MW	***MVAR***	***MW***	***MVAR***
Collector system	41	13.3	39.9	16.1

Transient stability analysis is used to further investigating the system dynamic responses when it is subjected to a large disturbance.

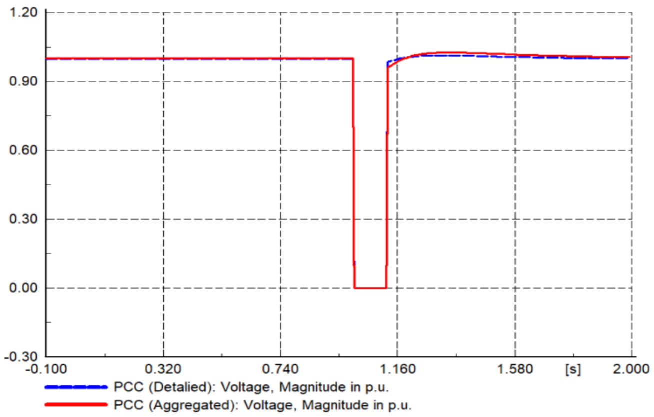

Fig.6: Comparison between voltage response of detailed model and aggregated model.

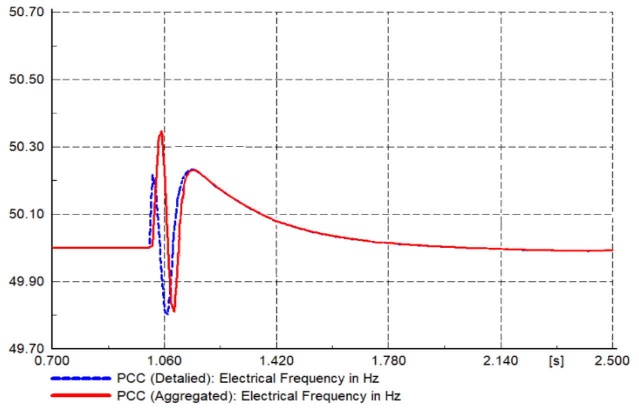

Fig.7: Comparison between frequency response of detailed model and aggregated model.

Three phase short circuit of 120 ms period is applied at the PCC terminals followed by one line outage of the WF grid connection lines.

Figures (7) and (8) show the responses of the voltage and frequency, respectively, at the PCC in both detailed model and aggregated model. Figures (9) and (10) show comparisons of active and reactive power responses of the detailed and aggregated models.

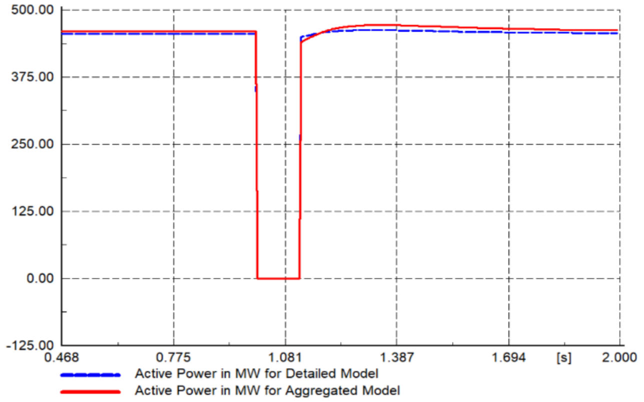

Fig.8: Comparison between active power in (MW) between aggregated and detailed model.

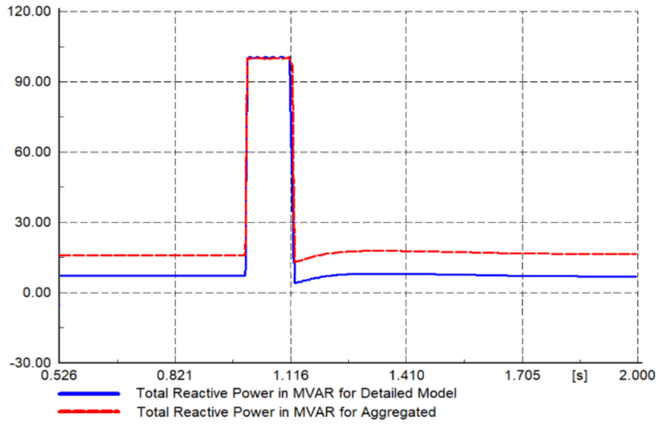

Fig.9: Comparison between Reactive power in (MVAR) between aggregated and detailed model.

It can be observed form above simulation studies that the system responses of the aggregated model are closely identical to that of the detailed wind farm model in the cases of steady-state operation and transient conditions.

CONCLUSION

The paper has provided an overview on the methodology of aggregation technique for large-scale wind farms. The aggregation concept has been applied to convert wind farm components into a single equivalent representation. The aggregated model will assist in planning simulation studies for connecting wind farms to power systems. The aggregated wind turbine model consists of a single WTG, a single pad mounted transformer, a single station transformer, an equivalent line of the collector system, and four buses. The aggregated model, developed here, provides a simple model representing a detailed wind farm model of 200 WTG, 200 pad mounted transformer, 5 station transformers and 206 buses. This implies a 98% reduction in the size of wind farm model that offers a significant reduction in the simulation time and estimating the impact of the wind farm on the grid under steady-state operations and transient conditions. The simulation of the detailed model and aggregated model of the 500 MW wind farm has been performed by using the DIgSILENT PowerFactory software. The results have proved the validity of the aggregated model of the wind farm. The aggregated model is intended to be employed in future studies concerning planning of large wind farms grid connection studies.

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