Doubly Fed Induction Generator Model for Power Quality Studies

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***Abstract*—Integration of wind power plant into power grids introduces power quality problems. The use of Doubly Fed Induction Generator into wind farm cause a distortion of the waveforms of voltage and current. The percentage of harmonic distortion is greater if the number of wind turbines is large. If the simulation model are not defined properly, the harmonic distortion result would be incorrect. For power quality studies, it is required that the model represent the wind turbine in a detail form. However, when the wind farm has a high power capacity, a detail simulation model exceed the computational capacity of the software. As an alternative solution, aggregation methodologies of wind turbines are considered. To determine the precision of the simulation, an analysis of detail and aggregate model is being made based on IEC Std. 61400-21: *Measurement and assessment of power quality characteristics of grid connected wind turbines*. The comparison shows that an aggregate model could represent properly the behavior of large-scale wind farm for power quality studies.**

***Index Terms*—Doubly fed induction generator (DFIG), harmonic distortion, power quality, wind power generation.**

I. Introduction

Wind power generation is an attractive solution in the searching of clean energy source because of the high resource availability and the technology development. Currently, the implementation of a high portion of Wind Power Plant (WPP) is made with Doubly Fed Induction Generator (DFIG). The increasing of WPP projects has carried out to extend the research in the modeling of wind turbines to represent properly the static and dynamic behavior of wind farms. However, WPP is composed of hundreds of wind turbine units and a detailed model of each machine increase the complexity of the simulation. In this way, the model needs to be simplified to improve the simulation performance. The simplification should not affect the results of power quality studies. The aggregation of wind turbines should guarantee that the harmonic current and harmonic voltage distortion produced in the Point of Common Coupling (PCC) is similar as the distortion produced by a detailed representation of the wind farm.

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Different authors have developed methodologies for aggregation the WPP model for transitory stability studies and load flow calculation. The aggregation is carried out for reducing the simulation time and the model complexity [1], [2], [3], [4]. The simulation time is improved with the developing of new controllers of the power converters commutation [5], and the modification of the DFIG model to decrease the number of state variables [6]. In addition, harmonic mitigation techniques have complimented the aggregation model with active filters to reduce the power quality problems [7]. This aggregation has the purpose of size the renewable energy impact over the power systems [8]. With the aggregation model was analyzed the problem of Low Voltage Ride Through (LVRT) of the WPP [9]. Finally, the impact in the aggregation model of wind turbine parameters has been studied in transitory stability [10].

Others authors have considered a WPP aggregation model for frequency stability studies [11]. These studies are complemented with the analysis of resonant effect produced by the harmonic injected by WPP [12], [13]. In the other hand, authors have developed wind turbine aggregation models for short circuit studies to analyze the behavior of WPP during contingencies [14].

Different researchers have studied the Equivalent Wind Method (EWM) to propose new aggregation methodologies based on wind speed data in the zone [15]. The wind profiles are classified to determine which turbines could be aggregate in the same group [16].

Regarding power quality studies, authors have analyzed the stochastic behavior of wind speed to define the relation between the harmonic distortion and power generation of WPP [17]. In addition, based on the stochastic analysis, probability density functions have been defined to estimate the total harmonic voltage and current distortion respects to wind fluctuations [18]. Power quality studies for WPP have been oriented to validate the summation law presented in IEC Std. 61400-21. This validation is carried out based on measurements of wind turbines currently in operation

[19], [20]. In addition, the summation law has been studied for a wind turbine model in a WPP composed of five DFIG [21]. Finally, harmonic distortion evaluation of wind farm has been tested for WPP where the harmonic current and voltage spectrum was characterized [22], [23].

This paper presents an analysis of the aggregation methodology of wind turbines for large-scale WPP in power quality studies. The comparison of the aggregation model and detailed model of the wind farm is carried out based on the DFIG library in SimPowerSystems/MATLAB.

The benefits of the analysis consist of the introduction to large-scale WPP aggregation model for studies different of transitory stability, frequency stability, and load flow calculation. Also, this research extends the power quality studies made for WPP from few DFIG units to larger wind farms. This analysis is focused on harmonic distortion calculation of voltage and current and it is validated with the IEC Std. 61400-21 based on the summation law of individual harmonics.

The paper is organized as follows. Section II presents the harmonic summation law and the aggregation method used in SimPowerSystems/MATLAB. Section III shows the study case of the research. Section IV presents the results of the harmonic distortion for the detailed model and the aggregation model and the generalization for large-scale WPP. Finally, the last section presents the conclusions.

II. Summation Law and DFIG Aggregation Method

The IEC Std. 61400-21: Measurement and assessment of power quality characteristics of grid connected wind turbine [24] introduces the summation law. It consists of the estimation of the individual harmonic current of a WPP with a number of DFIG units. In this standard, the measurement point is located at the PCC of the wind farm. The PCC is on the medium voltage side of the WPP substation. The harmonic distortion at the PCC may be estimated by:

$$I_k = \sqrt[\beta]{\sum_{i=1}^{N_{wt}} \left(\frac{I_{k,i}}{n_i}\right)^{\beta}} \quad (1)$$

Where,

- N_{wt} number of wind turbines connected to the PCC
- I_k h^{th} order harmonic current distortion at the PCC
- n_i the ratio of the transformer at the i^{th} wind turbine
- $I_{k,i}$ h^{th} order harmonic current distortion of the i^{th} wind turbine
- β exponent with a numerical value to be selected according to Table I

Regarding the estimation presented in (1), IEC Std. 61400-21 gives some clarifications about the harmonic current distortion calculation. First, if the wind turbines are equal and their power converters line commutated, it can be assumed that the harmonics are to be in phase and β = 1 for all harmonic orders. Second, the estimation does not consider the use of transformers with different vectors groups that may mitigate particular harmonics. Finally, the estimation can be generalized for current interharmonics and higher frequency components. For these components, it is recommended to use β = 2 for aggregation of these.

TABLE I
Specification of Exponents According to IEC 61400-21

Harmonic order	β
$h < 5$	1.0
$5 \leq h < 10$	1.4
$h > 10$	2.0

The DFIG model implemented in SimPowerSystem/ MATLAB corresponding to the detailed configuration presented in Fig. 1. These units are aggregated in simulation based on the number of turbines fixed by the user as an input parameter. The DFIG detailed model received as input parameters the data of generator, converters, turbine, drive train and control.

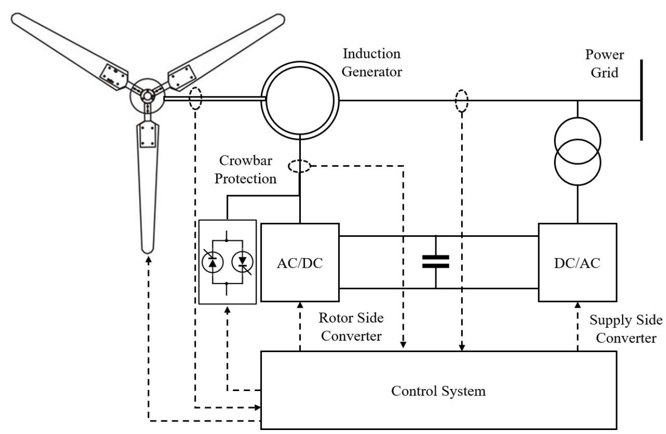

Fig. 1. Wind turbine DFIG configuration

There are three techniques of aggregation of wind turbines: a multi full aggregate model using equivalent wind speed, semi aggregated model and mixed semi full aggregated model [25], [26]. These techniques are divided regarding the strategy to calculate the equivalent torque of the wind farm. If the wind speed is equal for all the machines, the torque is the same for each DFIG unit. However, when the wind speed varies among turbines, the aggregated torque is calculated by the sum of the torque of each machine according to the configuration of the wind farm [27].

The multi full aggregate model using equivalent wind speed corresponding to the aggregation method used in SimPowerSystem/MATLAB. It assumes that all the units are equal and are in parallel connected through equal series impedances to the same node as shown in Fig. 2.

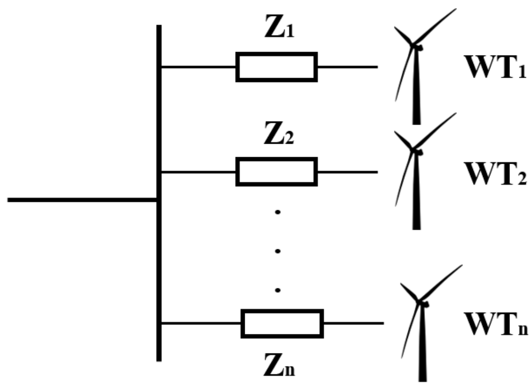

Fig. 2. Parallel connection of n wind turbines

For this method, equivalent wind turbine, and equivalent generator aggregate the capacity of individual wind turbines and the compensating capacitors are, respectively:

$$S_{eq} = \sum_{j=1}^{n} S_j = nS_j \tag{2}$$

$$C_{eq} = \sum_{j=1}^{n} C_j = nC_j \tag{3}$$

III. Study Case

The test system is composed of one power grid equivalent and a wind farm. The wind farm contains five DFIG units connected to the grid equivalent. The WPP configuration corresponds to a parallel connection between the wind turbines. The study case is divided into two scenarios. The first one is presented in Fig. 3. It is defined by the aggregation model of the wind farm. In this case, the WPP cluster five DFIG units in one simulation block. The second one is a detailed model of the WPP as shown in Fig. 4. In this case, the wind turbines are made by five DFIG simulation blocks connected in parallel to the power grid equivalent.

The WPP capacity is 16.5 MW. Each DFIG unit generates 3.3 MW. The connection is made through a 575 V link. The wind speed is constant and defined to 15 m/s.

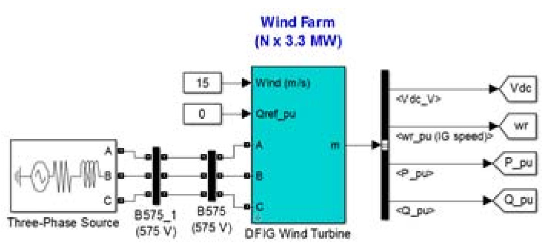

Fig. 3. Scenario 1: Five DFIG units aggregated

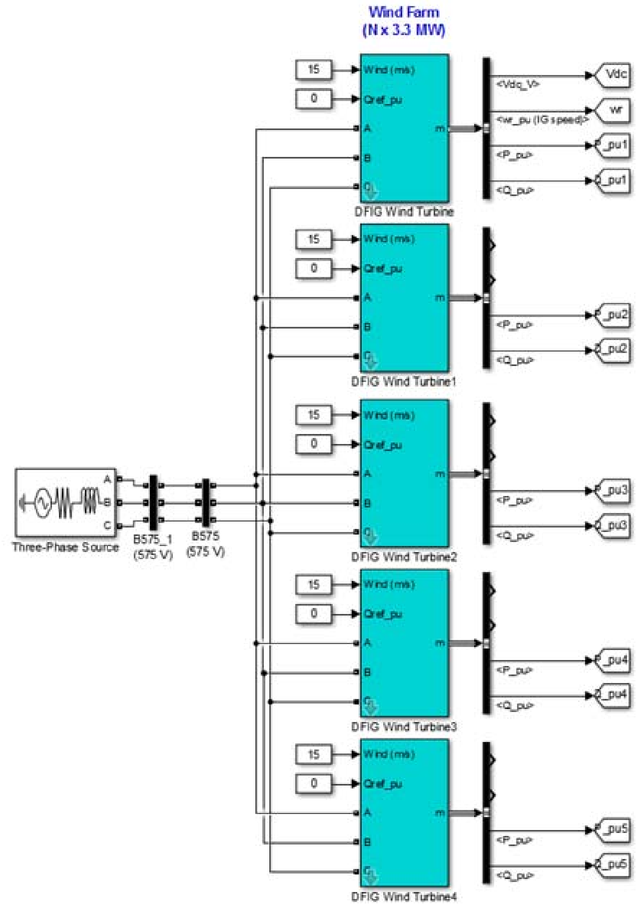

Fig. 4. Scenario 2: Five DFIG units detailed

IV. Harmonic Distortion Results

The power quality study is performed respects to the Summation Law. The harmonics measurement is made at the node of 575 V. The comparison between the harmonic current and harmonic voltage distortion at the WPP output is made for the two simulation scenarios. However, the differences between the simulation times required for the two simulation scenarios is considerable.

Table II presents the harmonic current and voltage distortion for one DFIG unit connected to power grid equivalent. This data is the base for the computation of the Summation Law for comparing the two Scenarios with the IEC Std. 61400-21. Moreover, the harmonic voltage distortion is compared with the harmonics voltage measured at the WPP output in the simulation scenarios. These results were obtained from SimPowersSystems/MATLAB after setting the number of turbines to one.

A. Scenario 1: Aggregated WPP model

Table III presents the harmonics current and voltage distortion for the aggregated model. Compared with

TABLE II
HARMONIC CURRENT AND VOLTAGE DISTORTION FOR ONE DFIG

	Harmonic current distortion [%]			Harmonic voltage distortion [%]		
Phase	A	B	C	A	B	C
THD	4.25	4.16	4.20	3.80	3.77	3.79
h1	100.0	100.0	100.0	100.0	100.0	100.0
h2	0.56	0.39	0.71	0.04	0.02	0.03
h3	0.52	0.28	0.35	0.04	0.01	0.01
h5	0.21	0.13	0.17	0.03	0.03	0.03
h7	0.10	0.31	0.19	0.01	0.06	0.04
h11	0.19	0.22	0.18	0.05	0.04	0.05
h13	0.12	0.08	0.11	0.02	0.04	0.04
h15	0.05	0.07	0.09	0.02	0.03	0.03
h17	0.09	0.05	0.14	0.04	0.04	0.06
h25	0.64	0.63	0.59	0.34	0.34	0.32
h29	0.56	0.67	0.52	0.33	0.39	0.31
h43	3.13	3.13	3.14	2.79	2.81	2.83
h47	2.61	2.50	2.53	2.54	2.46	2.48

TABLE III
HARMONIC DISTORTION FOR AGGREGATED MODEL

	Harmonic current distortion [%]			Harmonic voltage distortion [%]		
Phase	A	B	C	A	B	C
THD	2.05	2.01	2.12	3.62	3.51	3.60
h1	100.0	100.0	100.0	100.0	100.0	100.0
h2	0.23	0.07	0.17	0.01	0.03	0.09
h3	0.24	0.24	0.14	0.13	0.07	0.04
h5	0.29	0.37	0.52	0.20	0.19	0.33
h7	0.33	0.31	0.32	0.29	0.24	0.22
h11	0.05	0.17	0.21	0.04	0.22	0.28
h13	0.16	0.06	0.12	0.26	0.09	0.22
h15	0.22	0.16	0.25	0.37	0.27	0.45
h17	0.09	0.09	0.23	0.20	0.18	0.35
h25	0.37	0.36	0.32	1.03	0.92	0.90
h29	0.21	0.15	0.18	0.62	0.45	0.57
h43	0.58	0.57	0.58	2.58	2.55	2.58
h47	0.44	0.43	0.42	2.15	2.13	2.13

data presented in Table II, the current Total Harmonic Distortion (THD) decrease and the voltage THD does not change significantly.

B. Scenario 2: Detailed WPP model

Table IV presents the harmonic's current and voltage distortion for the detailed model. In comparison between the results for one DFIG (see Table II) and similar to Scenario 1, the current THD decrease and the voltage THD does not show any significant change.

C. Comparison and validation based on Summation Law

The comparison between the simulation scenarios required the theoretical calculation of the harmonic current distortion for five DFIG turbines based on the summation law. Applied (1) to the harmonic current data from Table II, the harmonic spectrum for five turbines is estimated based on the measures obtained for one DFIG unit.

TABLE IV
HARMONIC DISTORTION FOR DETAILED MODEL

	Harmonic current distortion [%]			Harmonic voltage distortion [%]		
Phase	A	B	C	A	B	C
THD	2.47	2.37	2.42	4.07	3.98	4.00
h1	100.0	100.0	100.0	100.0	100.0	100.0
h2	0.54	0.28	0.54	0.05	0.02	0.05
h3	0.18	0.24	0.21	0.02	0.03	0.03
h5	0.06	0.17	0.30	0.01	0.04	0.06
h7	0.22	0.43	0.23	0.06	0.13	0.06
h11	0.23	0.04	0.13	0.11	0.01	0.06
h13	0.12	0.09	0.03	0.06	0.05	0.03
h15	0.04	0.20	0.04	0.02	0.12	0.03
h17	0.18	0.10	0.04	0.12	0.07	0.04
h25	0.86	0.70	0.79	0.88	0.73	0.82
h29	0.57	0.51	0.64	0.68	0.61	0.76
h43	1.69	1.69	1.65	2.99	2.99	2.93
h47	1.30	1.26	1.27	2.52	2.45	2.48

TABLE V
APPLICATION OF SUMMATION LAW FOR DFIG HARMONIC CURRENT DISTORTION

Phase	A [%]	B [%]	C [%]
THD	2.02	1.91	2.01
h1	100.0	100.0	100.0
h2	0.56	0.39	0.71
h3	0.52	0.28	0.35
h5	0.13	0.08	0.11
h7	0.06	0.19	0.12
h11	0.08	0.10	0.08
h13	0.06	0.04	0.05
h15	0.02	0.03	0.04
h17	0.04	0.02	0.06
h25	0.29	0.28	0.26
h29	0.25	0.30	0.23
h43	1.40	1.40	1.41
h47	1.17	1.12	1.13

Table V presents the theoretical estimation for the harmonic current distortion of five DFIG turbines connected in parallel. For this estimation N_{wt} is 5, β is obtained from Table I and $I_{h,i}/n_i$ correspond to the results presented in Table II.

Analyzing the data presented in Table II, Table III, Table IV and Table V, it can be deduced the following results: with the assumption that the wind speed is the same for all the DFIG units, there are not significant differences in the harmonic current and voltage distortion between the aggregated and detailed model. However, the simulation time required for the detailed model make inefficient the power quality study.

Also, when the number of wind turbines increases, the current THD at the PCC decreases. This behavior is obtained for the two scenarios and it is consistent with the summation law. Based on the IEC Std. 61400-21, the current THD is:

$$THD_C = \frac{\sqrt{\sum_{k=2}^{4} I_k^2 + \frac{\sum_{k=5}^{10} I_k^2}{N_{wt}^{4/7}} + \frac{\sum_{k=11}^{50} I_k^2}{N_{wt}}}}{I_n} \quad (4)$$

TABLE VI
HARMONIC CURRENT DISTORTION ABSOLUTE ERROR

Case	Scenario 1 vs. Scenario 2 [%]			Summation Law vs. Scenario 1 [%]			Summation Law vs. Scenario 2 [%]		
Phase	A	B	C	A	B	C	A	B	C
THD	0.42	0.36	0.30	0.03	0.10	0.11	0.45	0.45	0.41
h1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
h2	0.32	0.21	0.37	0.33	0.32	0.54	0.02	0.11	0.17
h3	0.06	0.00	0.07	0.27	0.04	0.21	0.33	0.04	0.14
h5	0.23	0.20	0.22	0.16	0.29	0.41	0.08	0.09	0.20
h7	0.12	0.12	0.09	0.27	0.12	0.20	0.16	0.24	0.11
h11	0.18	0.13	0.09	0.04	0.07	0.13	0.15	0.06	0.04
h13	0.04	0.03	0.09	0.10	0.02	0.07	0.06	0.06	0.02
h15	0.17	0.04	0.21	0.19	0.13	0.21	0.02	0.17	0.00
h17	0.09	0.01	0.19	0.05	0.07	0.17	0.14	0.07	0.03
h25	0.49	0.35	0.47	0.08	0.08	0.06	0.57	0.42	0.53
h29	0.36	0.36	0.46	0.04	0.15	0.05	0.32	0.21	0.41
h43	1.11	1.12	1.07	0.82	0.83	0.83	0.29	0.29	0.24
h47	0.86	0.83	0.85	0.73	0.69	0.71	0.13	0.14	0.14

TABLE VII
HARMONIC VOLTAGE DISTORTION ABSOLUTE ERROR

Case	Scenario 1 vs. Scenario 2 [%]			DFIG Distortion vs. Scenario 1 [%]			DFIG Distortion vs. Scenario 2 [%]		
Phase	A	B	C	A	B	C	A	B	C
THD	0.45	0.48	0.40	0.18	0.27	0.19	0.26	0.21	0.21
h1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
h2	0.03	0.01	0.04	0.02	0.01	0.07	0.01	0.00	0.03
h3	0.10	0.03	0.02	0.08	0.06	0.03	0.02	0.03	0.01
h5	0.19	0.15	0.28	0.17	0.16	0.30	0.03	0.01	0.03
h7	0.23	0.12	0.17	0.28	0.19	0.19	0.05	0.07	0.02
h11	0.07	0.20	0.21	0.01	0.18	0.23	0.05	0.03	0.01
h13	0.20	0.04	0.20	0.24	0.06	0.19	0.04	0.01	0.01
h15	0.34	0.14	0.42	0.35	0.24	0.42	0.00	0.09	0.00
h17	0.08	0.12	0.32	0.16	0.14	0.29	0.09	0.03	0.02
h25	0.15	0.19	0.08	0.69	0.57	0.59	0.54	0.38	0.50
h29	0.07	0.17	0.19	0.28	0.06	0.26	0.35	0.23	0.45
h43	0.40	0.44	0.35	0.21	0.26	0.24	0.20	0.18	0.10
h47	0.37	0.32	0.35	0.39	0.34	0.35	0.02	0.02	0.00

Where I_k is calculated based on (1) and I_n is the nominal current at the PCC. THD_c is derivate from the β values specified in Table I. If the value of N_{wt} grows, the individual harmonics greater than or equal to fifth harmonic decreases according to β. This results can be seen in the comparison between the harmonic current distortions for one DFIG, scenario 1, scenario 2 and summation law. On average, the current THD decreases from 4,20% to 2,15% when N_{wt} is five DFIG for the two scenarios and the estimation based on the summation law. Also, the high order harmonics decrease, while the low-frequency components tend to be equal.

Finally, the harmonic voltage distortion at PCC does not change significantly between the aggregated and detailed WPP model. Table VI shows the comparison between the aggregated and detailed model for harmonic current distortion, and Table VII for harmonic voltage distortion. These tables show the absolute error for the individual harmonic distortion and THD in different study cases.

Table VI compares the harmonic current distortion between scenario 1 and scenario2, scenario 1 and summation law and scenario 2 and summation law. The greater absolute error in the harmonic current distortion results for case Scenario 1 vs. Scenario 2 is 1,12%. Also, the summation law estimated accurately the distortion because the greater absolute error respects to scenario 1 and scenario 2 are 0,83% and 0,57% respectively. To conclude, the absolute errors presented in Table VII shows that the harmonic voltage distortion is independent of the WPP model and the number of DFIG units. The cases Scenario 1 vs. Scenario 2, DFIG Distortion vs. Scenario 1 and DFIG Distortion vs. Scenario 2 were studied. The harmonic voltage distortion does not change because the greater absolute error for all the cases is 0,69%.

V. CONCLUSION

The paper presented an analysis of WPP modeling for power quality studies. The aggregated model consists in the cluster of five turbines connected in parallel to a power grid equivalent. The detailed model consists of the implementation of five DFIG units in independent simulation blocks. Also, the two models are validate based on the summation law presented in IEC Std. 61400-21.

The comparison between the models shows that the differences are small. The harmonic current distortion presents a maximum absolute error of 1,12% among the THD and the

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individual harmonics. Also, the change in the simulation time between the aggregated and detailed model is notorious. The detailed model made the simulation very complex and the Power Quality study inefficient.

The model validation based on the summation law shows that it is an accurate estimator of the harmonic current distortion when the number of wind turbine increases. The maximum absolute error of the estimation is 0,83% among the current THD and the individual harmonics. The small absolute errors values for harmonic current and voltage distortion and the accurately of the summation law in the estimation of the current spectrum allow extending the aggregated model for Power Quality studies applied to large-scale WPP.

Finally, the results show that the total harmonic current distortion decreases with the number of wind turbines and the harmonic voltage distortion are independent of the number of wind turbines inside the WPP.

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