ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Issue 6, June 2017

Performance Analysis of Grid Connected Wind Turbine Generators on the Basis of Energy Harvesting - A Case Study

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Abstract: The wind power generation technology has become one of the major matured technologies of the recent times. Despite of the limitation of the randomness of power generation, the growing investments on wind power generation indicate a pronounced future for this technology. The different wind turbine generators give different types of performance in the wind power generation. In this paper the comparison of the performance of two types of generators viz. Doubly Fed Induction Generators(DFIG) and Synchronous Generators (SG) based on the harvestable energy for the given wind conditions is analysed. The simulation is done using MATLAB SIMULINK. The results are compared with a real wind farm having conventional induction generators for the performance analysis in terms of energy harvesting.

Keywords: Wind power generation scheme; Grid connected wind farm; Energy yield; Doubly Fed Induction Generator; Synchronous Generator

I. Introduction

The increased demand for the power across the globe has resulted in the development of non-conventional sources of energy as supplement to the conventional sources. The wind power generation is one of such prominent sources for the bulk power generation. The abundant input, pollution less power generation, technological innovations in the field and support from the governments have made the concerned stakeholders to offer the wind power generation as one of the major nonconventional bulk power generation sources. Despite of the unpredictability in the output power as a consequence of its dependence on the wind speed, the recent statistics show the significant growth in the wind power installations across the globe. [1]

The different types of wind turbine generators are being deployed for the effective harvesting of the wind power for the given wind conditions. Several researchers have made comprehensive studies on the performance analysis of wind generators based on several aspects. An overview is made on various strategies applied to enhance the fault ride-through capability of the doubly-fed induction generators (DFIGs) based wind turbines during transient-state[2,3].A comprehensive review of fault ride-through strategies on DFIGs is made in [4]. The performance analysis on the pitch control of wind turbine is also made [5]. The architecture of the different schemes used to produce the electrical energy using wind turbine are presented from both electrical machine topology and control strategy points of view[6]. From these researches the Induction Generator (IG) which is fixed speed system is found to be more simple and reliable but the energy production of a wind turbine and power quality are severely limited as otherwise the generator gets overloaded or the pullout torque exceeds the limits, leading to rotor speed instability[7]. Among variable speed system the DFIGs and Synchronous Generators (SG) are found to be superior in terms of the power quality. However if compared mutually, their individual performance is further debatable [8].

Despite of addressing different issues in the comparison, none of the above methods addressed the harvestable energy level from a wind farm over a longer time frame, for different generator types used in wind turbines for the given wind conditions. Several aspects make it necessary to compare different generators under same operating conditions in terms of their energy yield. Many a times, the

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wind power not being dispatchable, needs to be operated in coordination with other dispatchable sources for its effective utilization [9].The feasibility of coordinated approach may be known if the harvestable energy from a wind turbine generated is predetermined. The other relevant aspect is about the replacement of Squirrel Cage Induction Generator (SQIG) which comes under type I wind turbines, by new models of wind turbines once their economic life is over [10]. The comparison of energy yield among the different generators can be a valuable input for the effective replacement. Whenever a new wind site is recognized for the installation of wind turbines, it is essential to assess the power potentials of the wind site for the given installed capacity and wind conditions. The wind speed in a given region being the major parameter, the harvestable energy from a grid connected wind farm also depends on the types of generators, the associated accessories, the grid profile and the transmission system parameters. Therefore it is necessary to contemplate such a model of a wind power generation scheme which considers all the necessary parameters to assess the harvestable energy from the wind farm. The energy yield of a wind farm heavily depends on the wind speed at the region of its location [11]. Apart from this, the control parameters selected for the wind turbine, generators, power converters and the transmission system also influence the energy yield. This paper discusses about such a simulation model that considers all the pertinent parameters to evaluate the energy yield for a period of one complete year. For the purpose of validation the relevant data of a real wind farm with Induction Generator (IG) wind turbine are collected and compared with that of the simulated model. The section 2 discusses about the methodology followed, section 3 discusses about the results and the last section discusses about the comparison for validation and the conclusions drawn.

II. METHODOLOGY

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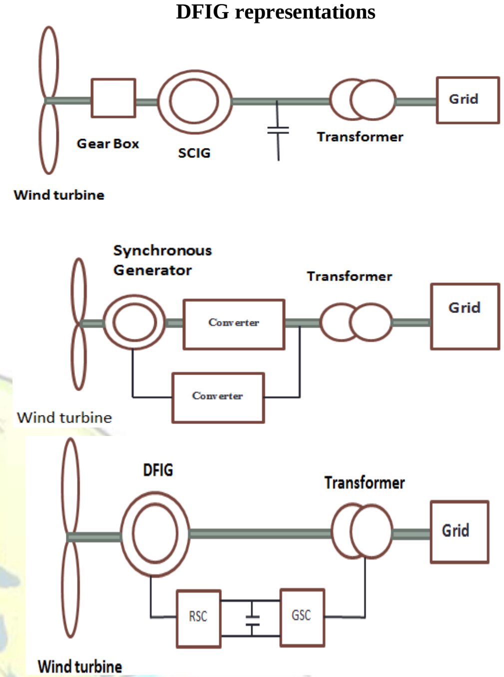
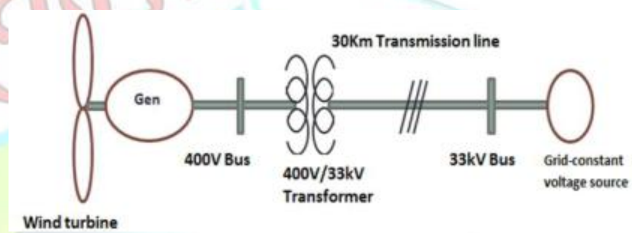
Fig. 1. Induction Generator, Synchronous Generator and DFIG representations



A. *Structure of the model*

Fig. 2. Line diagram of wind generation scheme under consideration



The schematic diagrams of the three types of wind turbine generators, Induction generator, DFIG and Synchronous Generator are as shown in the figure 1.

The figure 2 shows the line diagram of system under consideration. The generator can be of any type discussed earlier, the other sections of the system remaining same. The wind turbine with a specific generator type with a rating of 4.5 MW is connected to a 400V bus from where the power is transmitted to a 33 kV grid after stepping up the voltage to 33kV. The grid is located at a distance of about 30 km from the wind farm. For convenience the grid is assumed to be a constant voltage source. The model is developed using

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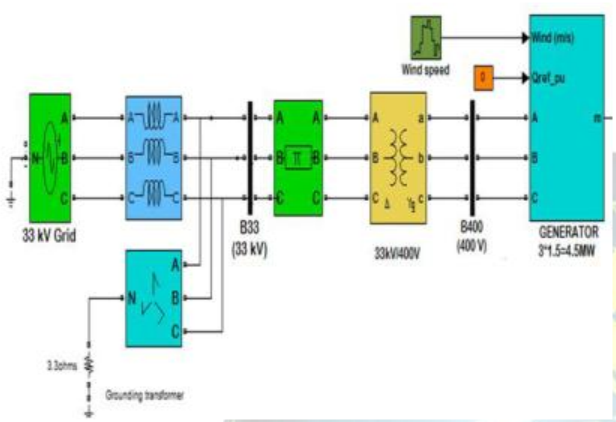
MATLAB SIMULINK for the two types of generators i.e. the DFIG and Synchronous Generator. The various control parameters for the generators are provided in the appendix. The SIMULINK model is shown in the figure 3.

Fig. 3. SIMULINK Model of wind farm under consideration



The wind turbines cannot always operate at their rated capacity due to the variation of wind speed. In order to obtain the power produced by the wind turbines the monthly average wind speed is considered for the convenience of simulation. The monthly average wind speed is collected from the concerned authorities [12] for the wind farm. This approximation will not make any notable differences in the estimated power produced compared to actual values, as both DFIG and Synchronous Generators operate mostly in the constant speed regions. Once the power produced is estimated, the annual harvestable energy is obtained from the simulation for the considered period of time. The voltage profiles at different busses, the current and the DC link voltage for both the generator schemes are also obtained in the simulation

B. Case study

For the purpose of comparison of the results of different generators, a case study of an actual wind farm with Induction Generator wind turbine is considered. The table 1 shows the details of the wind farm under consideration.

TABLE I
DETAILS OF KAPATHAGUDDA WIND FARM.

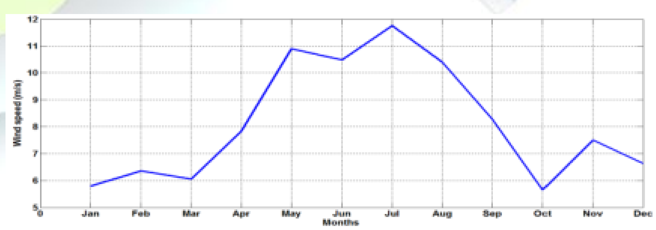
Name of the wind site	**Kapathagudda Wind Farm ,Gadag Karnataka, India**
Geographical location	Latitude:15 º 25” 56.4’
	Longitude:75 º 38” 17.7’
Nominal power rating	4.55 MW(225kWx9+230kWx11)
Power density	3.1KW/m2
Start up wind speed	4m/s
Nominal wind speed	15 m/s
Max. wind speed	25 m/s
Output voltage	400 V
Generator	Asynchronous (IG)
Grid	33kV
Location	Gadag(30 km from the wind farm)
Annual gross energy yield	12MU
Operator	Karnataka Power Corporation Ltd.(KPCL)

The annual energy harvest from this wind farm is about 12MU as per the reports of the operator with an annual capacity factor of about 35% excluding the technical losses [13]. The power produced is pooled to the network through the 33kV grid operated by the Karnataka Power Transmission Corporation Limited (KPTCL).

III. RESULTS AND DISCUSSION

The Induction generator based wind farm gives a net annual yield of energy of 8.26 MU for the considered period January-December 2016. The simulated models are designed for the wind conditions of the actual wind farm. The wind speed of the actual wind farm is as shown in figure 4 having highest average speed in the month of July of about 12 m/s..

Fig. 4. Wind speed



ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
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International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 4, Issue 6, June 2017

Fig. 4. Power Comparison

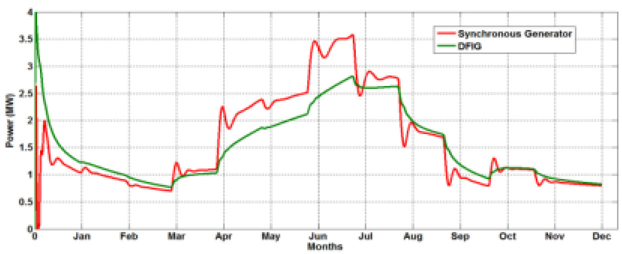

Fig. 4. Currrent at 33kV bus

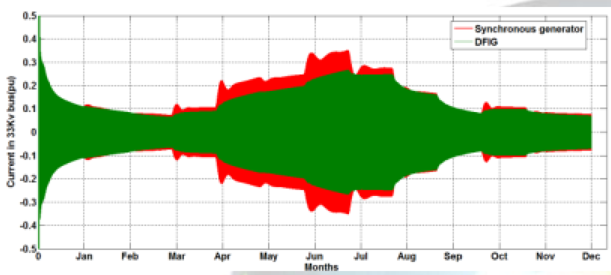

Fig. 4. Harvestable energy for the considered period

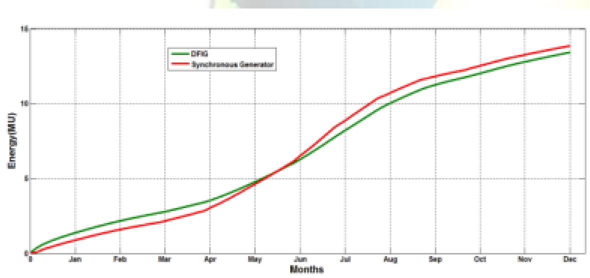

Fig. 4. Rotor speed

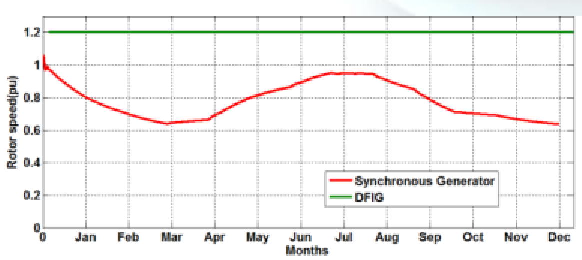

Fig. 4. DC link voltage

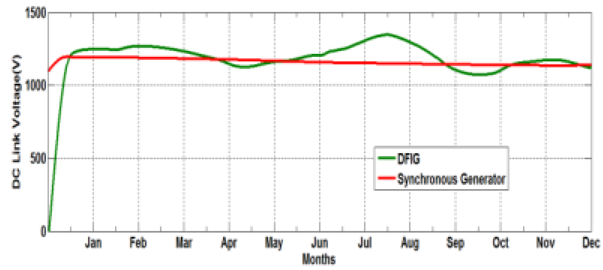

TABLE III

COMPARISON MONTHLY POWER AND ENERGY YIELD

(JANUARY –DECEMBER 2016)

Months	Synchronous Generator		
	Power (MW)	Energy (MU)	Cumulative energy(MU)
January	1.06	0.88	0.88
February	0.82	0.71	1.586
March	1.22	0.59	2.17
April	2.24	0.87	3.04
May	2.28	1.6	4.64
June	3.35	1.9	6.54
July	2.48	2.36	8.90
August	1.95	1.83	10.73
September	0.94	1.1	11.83
October	1.12	0.69	12.52
November	0.96	0.74	13.26
December	0.80	0.60	13.86

Months	DFIG		
	Power (MW)	Energy (MU)	Cumulative energy(MU)
January	1.221	1.362	1.362
February	0.954	0.8	2.162
March	0.899	0.618	2.78
April	1.370	0.749	3.529
May	1.880	1.24	4.769
June	2.442	1.52	6.289
July	2.605	1.915	8.204
August	1.981	1.846	10.05
September	1.177	1.2	11.25
October	1.121	0.77	12.02
November	0.922	0.77	12.79
December	0.820	0.62	13.41

Months	Actual wind farm	
	Energy (MU)	Cumulative energy(MU)
January	0.34	0.34
February	0.35	0.69
March	0.34	1.03
April	0.38	1.41
May	0.62	2.03
June	1.10	3.13
July	1.31	4.44
August	1.31	5.75
September	0.8	6.55
October	0.44	6.99
November	0.69	7.68
December	0.58	8.26

TABLE 3: COMPARISON OF ENERGY YIELD

Parameters	Actual wind farm	Simulated wind farm	
		Synchronous Generator	DFIG
Rated capacity	4.55 MW	4.5MW	
Generator type	Asynchronous	Synchronous	
Gross Annual energy yield	12MU	13.86MU	13.41MU
Net energy yield considering technical losses.	8.26MU	9.54MU	9.23MU
Actual Capacity factor	20.72%	24.2%	23.4%
Relative Energy produced	1 pu	1.1398 pu	1.1174 pu

The monthly energy yield details of the actual wind farm are made available from competent authorities [14]. However in the simulation, the monthly energy yield is calculated for both Synchronous Generator and DFIG wind far as shown in Table 2.The results shown in Table 3 reveal that in comparison with the Induction Generator based wind farms, the DFIG and Synchronous Generator based wind farms produce 11.74% and 13.98 % more energy respectively for the same wind conditions, capacity and period (calculations are shown in appendix). The comparisons show that Synchronous generator and DFIG of similar rating can significantly enhance energy capture in comparison with Induction Generators. Apart from this, it is important to note that the DC bus voltage remains constant irrespective of the system condition as seen in figure 10. It can be observed that the power produced, as a result of change in the wind speed is changed with the change in current only at both the busses as seen from figures 5, 6 and 7, keeping the system voltage at the busses constant

IV. CONCLUSION

A SIMULINK model of a wind farm consisting of two different types of generators viz. the DFIG and Synchronous Generator is developed. The various control parameters including the ratings of the Generators are selected such that they match with that of an actual wind farm with Induction Generator. The energy yield for both the generator types is estimated for the period of one year with the given wind conditions. The performance of the Synchronous generator is found to be superior with 13.98 % extra energy yield for the same condition followed by DFIG wind turbine with 11.74 % more energy in comparison with Induction Generator based wind farm. As the annual wind speed pattern does not vary significantly for a given region the developed Simulink model would be very useful during the planning of commissioning new wind farm with the known wind conditions. The various model parameters can be changed as per the requirements to assess the energy yields for different operating conditions. In the energy balancing strategies where the wind farms are to be operated in coordination with dispatchable sources, this simulation model could be very useful to commission new wind farms having the geographical proximity with dispatchable sources.

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Appendix

Appendix A.

Model parameters of Synchronous Generator Wind Turbine

A.1. **Wind Turbine:**

Nominal mechanical output power (W):1.5MW
Wind speed at nominal speed and at Cp max: 11 m/s
Initial wind speed: 5 m/s

A.2. **Generator:**

Nom. power, L-L volt and frequency: 1.5MW/0.9, 400V, 1975 V, 50 Hz
Reactance [Xd, Xd', Xd" ,Xq , Xq" Xl] (p.u.) :1.305, 0.296, 0.252, 0.474, 0.243, 0.18
Time constants [Tdo', Tdo'', Tq''] (s): 4.49 0.0681 0.0513
Resistance Rs (p.u.): 0.006
Inertia constant, friction factor, and pairs of poles: 0.62, 0.01

A.3. **Converters:**

Grid-side converter maximum current (pu): 1.1
Grid-side coupling inductor [L, R] (p.u.): 0.15,0.15/50
Nominal DC bus voltage (V): 1109
DC bus capacitor (μF):10000
Line filter capacitor (var): 150e3

A.4.**Control parameters for wind turbine**:

DC bus voltage regulator gains [Kp Ki]: 1.1, 27.5
Grid-side converter current regulator gains [Kp Ki]: 1, 50
Speed regulator gains [Kp Ki]: 3.0.6
Rotor-side converter current regulator gains [Kp Ki]: 0.6, 8
Q and V regulator gains [Ki_var Ki_volt]: 0.05,20
Pitch controller gain [Kp]: 15
Pitch compensation gains [Kp Ki]: 1.5,6
Field excitation gain: 10, 20
Maximum pitch angle (deg): 27
Maximum rate of change of pitch angle (deg/s):10

A.5. **Transmission system parameters:**

Type, length and frequency: π model, 30 KM, 50 Hz
Positive- and zero-sequence resistances (Ohms/km) [R1, R0]: 0.1153, 0.413
Positive- and zero-sequence inductances (H/km) [L1, L0]:1.05e-3, 3.32e-3
Positive- and zero-sequence capacitances (F/km)[C1,C0] :11.33e-9, 5.01e9

Appendix B.

Model parameters of DFIG Wind Turbine

B.1. **Wind Turbine**:

Nominal mechanical output power (W):1.5MW
Wind speed at nominal speed and at Cp max: 11 m/s
Initial wind speed: 5 m/s

B.2. **Generator:**

Nom. power, L-L volt and frequency: 1.5MW/0.9, 440v, 1975 v, 50 Hz
Stator resistance and inductance (p.u.): 0.023, 0.18
Rotor resistance and inductance referred to stator (p u) : 0.016, 0.16
Magnetizing inductance (pu): 2.9
Inertia constant, friction factor, and pairs of poles: 0.685, 0.01, 3

B.3. **Converters :**

Grid-side converter maximum current (pu): 0.8
Grid-side coupling inductor [L, R] (p.u.): 0.3,0.003
Nominal DC bus voltage (V): 1150
DC bus capacitor (μF):10000
Line filter capacitor (var): 120e3

B.4. **Control parameters for wind turbine:**

DC bus voltage regulator gains [Kp Ki]: 8,400

Grid-side converter current regulator gains [Kp Ki]: 0.83, 5
Speed regulator gains [Kp Ki]: 3.0.6
Rotor-side converter current regulator gains [Kp Ki]: 0.6, 8
Q and V regulator gains [Ki_var Ki_volt]: 0.05,20
Pitch controller gain [Kp]: 150
Pitch compensation gains [Kp Ki]: 3.30
Maximum pitch angle (deg): 27
Maximum rate of change of pitch angle (deg/s):10

B.5. **Transmission system parameters:**

Type , length and frequency: ∏ model, 30 KM,50 H
Positive- and zero-sequence resistances (Ohms/km) [R1, R0] : 0.1153, 0.413
Positive- and zero-sequence inductances (H/km) [L1 ,L0] :1.05e-3, 3.32e-3
Positive- and zero-sequence capacitances (F/km)[C1,C0] :11.33e-9, 5.01e9

Appendix C.

Capacity Factor calculation

C.1. Capacity factor=Actual energy produced/ (rating of the wind farm X no of hours in an year)

i) Actual wind farm CF=20.72%   ii) DFIG wind farm CF=23.4%   iii) S G wind farm CF=24.2%

C.2. Percentage enhancement in the energy yield
For DFIG wind farm
= (9.23-8.26) X 100/8.26
= 11.74
For Synchronous Generator wind farm
= (9.54-8.26)x100/8.26
= 13.98