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Mathematical Modeling and Simulation of DFIG Wind Turbine and Comparison with Industrial Data

Naveed Ullah[a]*, Yong-Taek Oh [b]

[a,b]*School of Electrical, Electronics and Communication Engineering, Korea university of Technology and Education, Cheonan,330-708, South Korea*
[a]*Email: engrnavid1988@gmail.com*
[b]*Email: ytoh@koreatech.ac.kr*

Abstract

The electrical energy consumption is rising globally, due to which the demand for electricity is increasing everywhere. The renewable energy units are being integrated to power system in large scale to fulfill the demands of electrical power. One of the most efficient and famous methods in renewable energy is wind power generation. Due to variable wind speed, the double fed induction generator (DFIG) is used in wind turbines. Double fed wind induction generator is connected with power network in large scale because of constant voltage and frequency, as when the rotor speed varies the stator supplies power to the grid. This paper presents the design and simulation of a doubly fed induction generator (DFIG) wind turbine, where the mathematical modeling of the machine written with d-q reference is established to investigate simulation. Furthermore, the simulation results are compared with the industrial data of a functional DFIG plant for realizing the accuracy of our model.

Keywords: Double Fed Induction Generator (DFIG); Wind Energy; Active and Reactive Power; Wind Turbine Control System; Mathematical Modeling.

1. Introduction

Electric energy is one of the most important and highly consumed sources of energy. Majority of our daily life applications consume electric power. Due to the increasing population and more industries coming up, the demand for electricity is escalating. To counter such a situation new forms of alternate energy generation techniques have been looked into which could provide clean energy.

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* Corresponding author.

E-mail address: engrnavid1988@gmail.com

For a few decades now, the trend of renewable energy for energy generation has been adopted all over the world. The installation of such renewable plants are visible almost everywhere now a days. Due to the global warming issue, change in climate and adoption of green energy concept, most of the countries are deviating from pollution cause sources to environmental friendly sources [1]. The best forms of renewable energy are solar energy, wind energy, tidal energy and wave energy. All of them are clean, available for most of the time in a year and efficient.

This paper discusses about harvesting energy from wind. Wind energy is one of the fastest growing industries worldwide. It is preferred due to its simplicity of design and many available geographic options for installation, be it in shore or off shore. It does not only work during day time, as does solar energy, thus can generate energy throughout the day and throughout the year. For such visible advantages of wind over other forms of energy, it will continue to grow in the coming years as the demand for energy will exceed the generation rate.

The concept of wind power originated in 1970s, and matured in 80s years, furthermore the development at big stage was held in 1990s [2]. In the beginning, wind energy generation was designed as a basic fixed pitch stall control to full control of blade pitch. The energy conversion principle and aerodynamics of wind turbines are based on systematic analysis of fixed-pitch wind turbines.

There are many types of wind generator, but this paper discusses about Doubly Fed Induction Generator (DFIG). The concept of DFIG was designed for the variable wind speed. The commercially used individual generators are mostly 1.5 MW/ 1500KW. These turbines are capable of operating with margin of ±30% around synchronous generator speed. We will discuss about the feasibility and the wind turbines required within a particular area, to fulfill the energy demands of an average size city in Pakistan. Simulation and modeling of DFIG system is done in MATLAB and the data is compared with real data from industry to inspect the accuracy of our system.

2. Types of Wind Generators

Wind generators can be used either as standalone generators, which are used as residential and industrial application, or as grid connected generators. Wind speed at the installation site is a major issue when deciding on the wind generator propellers [3]. For low wind speed, generators come with long blades or more number of blades if they are small in size. The blades are kept wide to get maximum power at minimum wind speed.

Therefore, for choosing the suitable type of wind turbine for specific area, the monitoring of wind speed measurement need at least few consecutive months or a full year to get the average wind speed and the maximum and minimum wind speed. It’s always advantageous to get long term wind measurement, as it then makes it quite easy to choose the size, numbering and type of wind turbine [4].

The type of generators used for wind power generation can be classified, based on the operating speed and architecture:

- Squirrel cage induction generators

- Wound rotor induction generators
- Variable speed operation generators

3. Double Fed Induction Generator (DFIG)

3.1. DFIG Wind Power Generator

The most commonly used type of generator for wind power generation is a Doubly Fed Induction Generator (DFIG) which is also synonymous to third type wind generator configuration. DFIG enables the extraction of maximum power available in the wind, it has the capability to operate over a range of wind speeds (±30% slip) and it can control power in a flexible way. A grid connected DFIG involves a wound rotor induction machine and has terminals on both stator and rotor. In other words, DFIG can exchange power from both stator and rotor side. But being an induction machine, the rotor frequency is dependent on the operating slip of the machine. So, an AC/DC/AC converter is used to connect the rotor terminals to the grid [5]. The AC/DC/AC converter enables the variable speed operation and also makes the output real and reactive power controllable.

(a) Rotor-Side Converter Control System: When a short-term low-voltage fault occurs, the incoming power from the wind and the power flowing into the grid are imbalanced instantaneously, resulting in the transient excessive currents in the rotor and stator circuits. The rotor side controller will increase the generator rotor speed by reducing the generator torque to zero during the fault, in order to absorb and convert the incoming energy from the wind into the kinetic energy in the WT inertia.

(b) Grid Control System: When the grid voltage may not be equal to turbine voltage due to the instantaneous unbalanced power flow between the grid and rotor side converters, and therefore the DC-link voltage may fluctuate, then to reduce the fluctuation of the DC-link voltage, the item reflecting the instantaneous variation of the output power of the rotor side controller is directly set as the reference of the during the grid fault. However, the stator voltage may reduce to zero during the grid fault [11].

(c) Pitch Angle Control System: The pitch angle of the blade is controlled to optimize the power extraction of the WT as well as to prevent over rated power production in high wind. When the generator speed exceeds, the pitch control is active and the pitch angle is tuned so that the turbine power can be restricted to its rated value.

3.2. DFIG Functioning

The power flow can be described by the given equations that are

$$P_{\mathrm{r}}=T_{\mathrm{m}}*\omega \mathrm{r} \qquad (1)$$

$$P_{\mathrm{s}}=T_{em}*\omega \mathrm{s} \qquad (2)$$

For a loss less generator the mechanical equation is

$$\mathrm{J}\,\frac{\mathrm{d}\omega \mathrm{r}}{\mathrm{dt}}=T_{\mathrm{m}}-T_{em} \qquad (3)$$

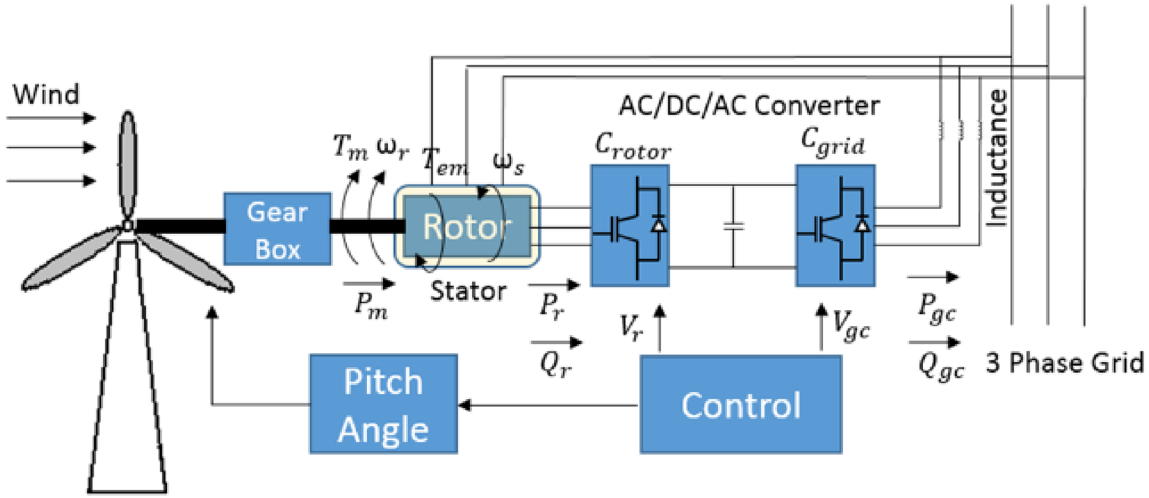

Figure 1: Schematic for Wind Turbine Power Generation

In steady-state at fixed speed for a loss less generator

T_m= T_{em} and P_m= P_s+ P_r (4)

And it follows that:

P_r=P_m– P_s=$T_m\omega_r$– $T_{em}\omega_s$=–$T_m\frac{\omega s-\omega r}{\omega s}$

Where,

ω_s=–$sT_m\omega_s$=–sP_s

$s=\frac{\omega s-\omega r}{\omega s}$ is defines as the slip of the generator.

Here the *Pm* is Mechanical power captured by the wind turbine and transmitted to the rotor, the initial equation is considered to calculate the power used for turbine which is directly proportional to Mechanical torque applied to rotor, T_m, and ω_r is for rotational speed of rotor.P_s represents the stator electrical output power, T_{em} represents electromagnetic torque applied to the rotor by the generator, and ω_s is known as rotational speed of the magnetic flux in the air-gap of the generator [6].

P_r is only a fraction of P_s. Since T_m is positive for power generation and since ω_s is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation, P_r is transmitted to DC bus capacitor and tends to rise the DC voltage. For sub-synchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage.

C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant**.** In steady-state for a lossless AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by C_{rotor}.

An induction motor is analogous to a transformer with a rotating secondary, where the coupling coefficients between the stator and rotor phases change continuously with the change of rotor position [8]. Such a model may be described using differential equations but with time varying mutual inductances. Such models are complex such as vector control based on the dynamic d-q modeling of the machine [10]. Therefore to understand vector control principle, a good understanding of d-q model is mandatory. The transformation equation from a-b-c to this d-q-o reference frame is given by:

$$F_{qdo}=K_s{*}f_{abcs} \qquad (5)$$

$$(f_{qd0s})^T= [f_{qs}\, f_{ds}\, f_{os}],$$

$$(f_{abcs})^T= [f_{as}\, f_{bs}\, f_{cs}],$$

$$K_s= \frac{2}{3}\begin{pmatrix} cos\theta & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ sin\theta & sin(\theta - \frac{2\pi}{3}) & sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

Where the variable f can be the phase voltages, current, or flux linkages of the machine.

The sum of the instantaneous input power to all six windings of the stator and rotor is given by:

$$P_{in} = V_{as} I_{as}+ V_{bs}I_{bs}+ V_{cs}I_{cs}+ V_{ar}I_{ar} + V_{br}I_{br}+ V_{cr}I_{cr} \qquad (6)$$

Using stator and rotor voltages to substitute for the voltages, we obtain three kinds of terms: i^2r (copper loss), $i\frac{d\psi}{dt}$ and $\omega\psi i$. The electromagnetic torque developed by the machine is given by the sum of $\omega\psi i$ terms divide by the mechanical speed, that is:

$$T_{em}= \left[\frac{3}{2}\right]\left[\frac{p}{2}\omega\, r\right] \quad [\omega\,(\psi ds\, iqs - \psi qs\ \ ids) + (\omega - \omega r)\,(\psi dr\, iqr- \psi qr\, idr)] \qquad (7)$$

Using the flux linkage relationships d-q Torque Equations can be calculated, which can also be expressed as follows:

$$T_{em} =\left[\frac{3}{2}\right]\left[\frac{p}{2}\right][(\psi qr\, idr-\psi dr\, iqr)] = \left[\frac{3}{2}\right]\left[\frac{p}{2}\right][(\psi ds\, iqs - \psi qs\, ids)]$$

$$= \left(\frac{3}{2}\right)\left(\frac{p}{2}\right) L_m [(idr\, iqs - iqr\, ids)] \qquad (8)$$

One can rearrange the torque equations by inserting the inserting the speed voltage terms given below:

$Eqs= \omega\psi ds$ $\qquad$ $Eds= -\omega\psi qs$

$Eqr= (\omega- \omega r)\psi dr$ $\qquad$ $Edr= -(\omega- \omega r)\ \psi qr.$

Stator circuit equations:

$$Vqss=d/dt\ (\psi qss)+rsiqss \qquad (9)$$

$$Vdss=d/dt\ (\psi dss)+rsidss \qquad (10)$$

Rotor circuit equations**:**

$$Vqrs=d/dt\ (\psi qrs)+rriqrs \qquad (11)$$

$$Vdrs=d/dt\ (\psi drs)+rridrs \qquad (12)$$

Flux linkage equations**:**

$\psi qss=Llsiqss+Lm(iqss+iqrs)=(Lls+Lm)iqss+Lm$

$iqrs=Ls\ iqss+Lmiqrs \qquad (13)$

$\psi qrs=Llriqrs+Lm(iqss+iqrs)=(Llr+Lm)iqrs+Lm$ $\qquad$ $iqss=Ls\ iqrs+Lmiqss$

$\psi dss=Llsidss+Lm(idss+idrs)=(Lls+Lm)idss+Lm$ $\qquad$ $idrs=Ls\ idss+Lmidrs$

$\psi drs=Llridrs+Lm(idss+idrs)=(Llr+Lm)idrs+Lm$ $\qquad$ $idss=Lridrs+Lmidss$

4. Industrial Data

The power generation plant with which we will be comparing our simulations with is located at Jhampir area, Sindh province of Pakistan. The model of the DFIG wind turbine is an*S-77/1500KW*manufactured by Nordex, Germany,it is also known as Hot Climate Version Turbine (HCV). The efficiency of wind turbine generators can vary depending if the type of installation is an Off-shore and On-shore one. Normally the On-shore wind turbine has an efficiency of 40-45 % and that of the Off-shore is 33-35%. Although mostly coastal areas are chosen for installation of wind turbines, however, the power generation plant in concern here is an Off-shore one, thus having an efficiency of around 33%.

To choose the area for wind turbine installation, something called micro siting is done, which means monitoringof wind mass, distances between wind turbines, power curve, and wind speed for one entire year. The number of wind turbines, the capacity of each, the span of area over which it will be laid out depends on the energy generation of the power plant. The power plant considered here has a power generation capacity of 49.5 MW using 33 wind turbines installed, making each turbine capable of generating 1500 KW. The height of the wind turbines is 80 meters, the blade length is 37.5 meters and the land area over which 33 wind turbines are installed is 4657 square meters. The plant is connected to two grids, one is theJhampir Line and other is Nooriabad Line. The meter reading taken by SCADA system on a monthly basis shows that the energy exported by plant is 10,500 MWh.

Another important parameter is the cut-in point, wind speed at which the wind turbine starts to generate power, and cut-out point, wind speed at which the wind turbine stops functioning. The plant has a cut in point of 3.5 m/s and a cut out point of 25m/s. The graph below shows the power generation by each turbine when the value of wind speed is within the cut in and cut out limits.

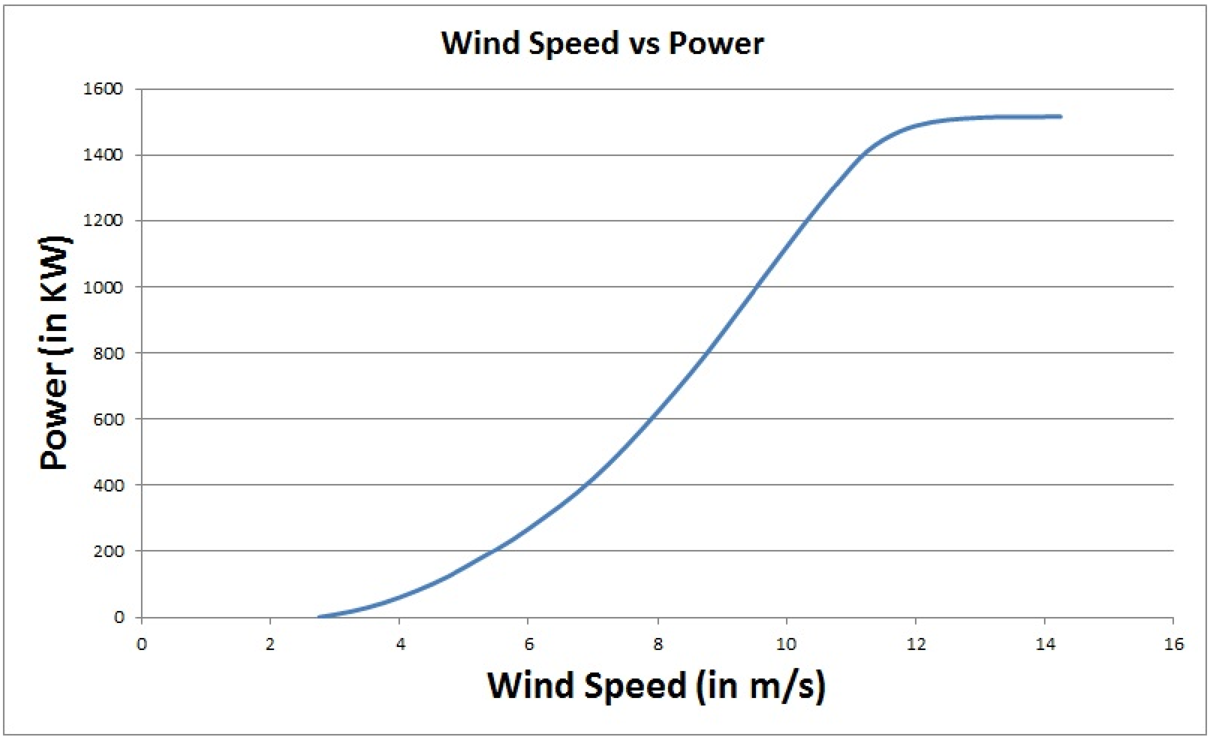

Figure 2: Industrial data for Wind Speed vs Power

5. Modeling of DFIG

A 1.5MW DFIG Wind turbine has been modelled and simulated here in which the four major systems are being monitored, namely wind speed, voltage of the generator, pitch angle of blades and velocity of the gear box.

The wind speed of an area is monitored using wind vane. This wind speed is directly proportional to pitch angle of the turbine's blades, as the wind speed increases from minimum to maximum, the pitch angle will change from maximum to minimum. Thus, the pitch angle of the blades, if the wind speed is low or zero, will be 90 degrees with respect to the wind turbine's frame. And for high wind speed, the angle of blades will be close to 0 degrees. The voltage of the generator is monitored to synchronize the generator with grid. The velocity of gear box, to maintain the speed of generator, should be synchronized [9].

The wind turbine is connected to the grid side of 11KV distribution system. The stator winding of the turbine is connected to the 60 Hz Grid, while the rotor side is connected to the AC/DC/AC converter. Therefore, 70 % of total power generated goes through the stator to synchronize generator with grid. Carbon brushes are used for this purpose due to the reason that they avoid sparking.

The DFIG wind turbine, which is rated for the 1.5 MW energy systems and which was described in this paper, shows the results comparatively at low speed and high speed of the area's wind.

Wind Turbine Ratings			
	Parameters	Design Wind Turbine Values	Practical Wind Turbine Values
1	Power	1500 Kw	1500 Kw
2	Cut In Point	5 m/s	3.5 m/s
3	Cut out Point	24 m/s	25 m/s
4	Speed	1800 rpm	1800 rpm
5	No. of Poles	4	4
6	Frequency	50 Hz	50 Hz

- Wind Speed: To get the highest energy efficiency from the wind turbine generation, speed of wind plays an important role. If the wind speed is high, the generation will be maximum. It is shown here in Fig. that the speed of wind starts at 5m/s and in 5 seconds it reaches at 14m/s. The other graph Fig. 5 shows the initial speed of the wind is 8m/s within 5 seconds it reaches at 14m/s. We use these two different speeds for our simulation which will be shown in following subsections.
- Voltage Control: The DC voltage is used to operate the control system of whole wind turbine. In Fig. 6 the voltage fluctuation is for long time as compare to Fig. 7
- PQ Value of Turbine: In this graph the yellow line shows the value of Active Power (P) and pink line shows value of Reactive Power (Q), which are obtained from the wind turbine generator. They are compared for low and high wind speeds. In Fig.8 the active value gets to the maximum power in 25 seconds, while in Fig. 9 the maximum value is covered in 20 seconds.

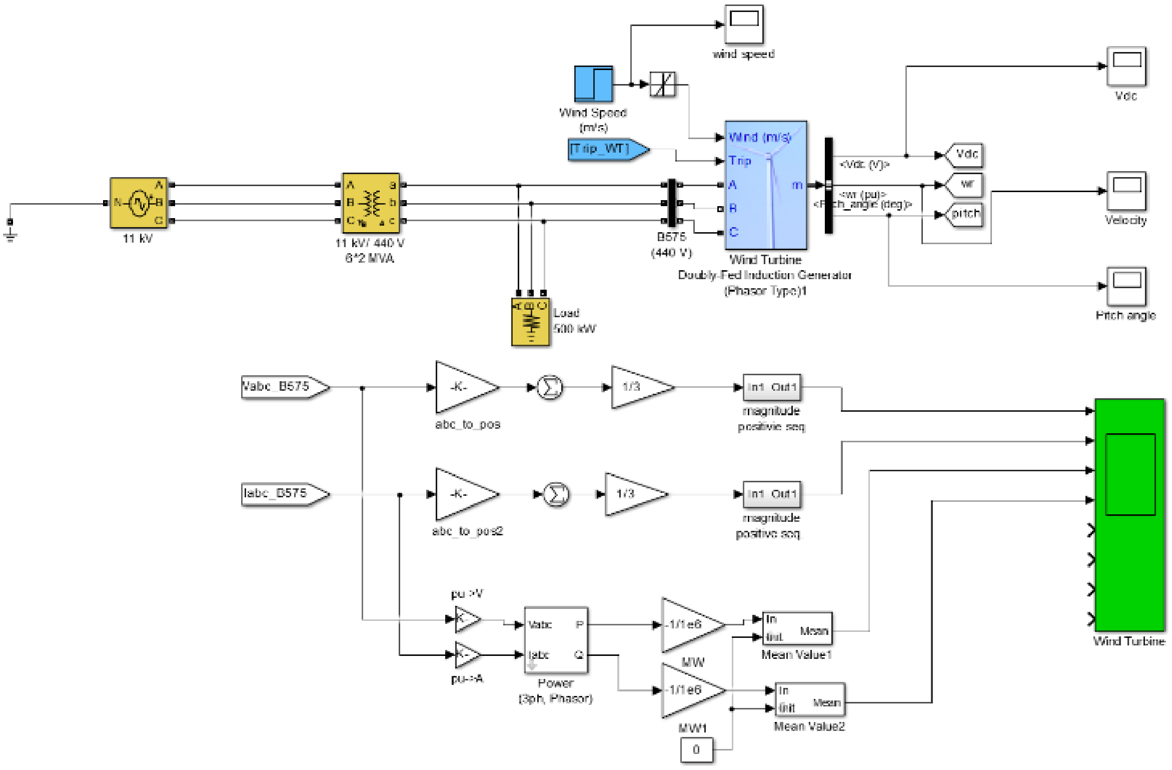

Figure 3: Modelling of DFIG Wind Turbine

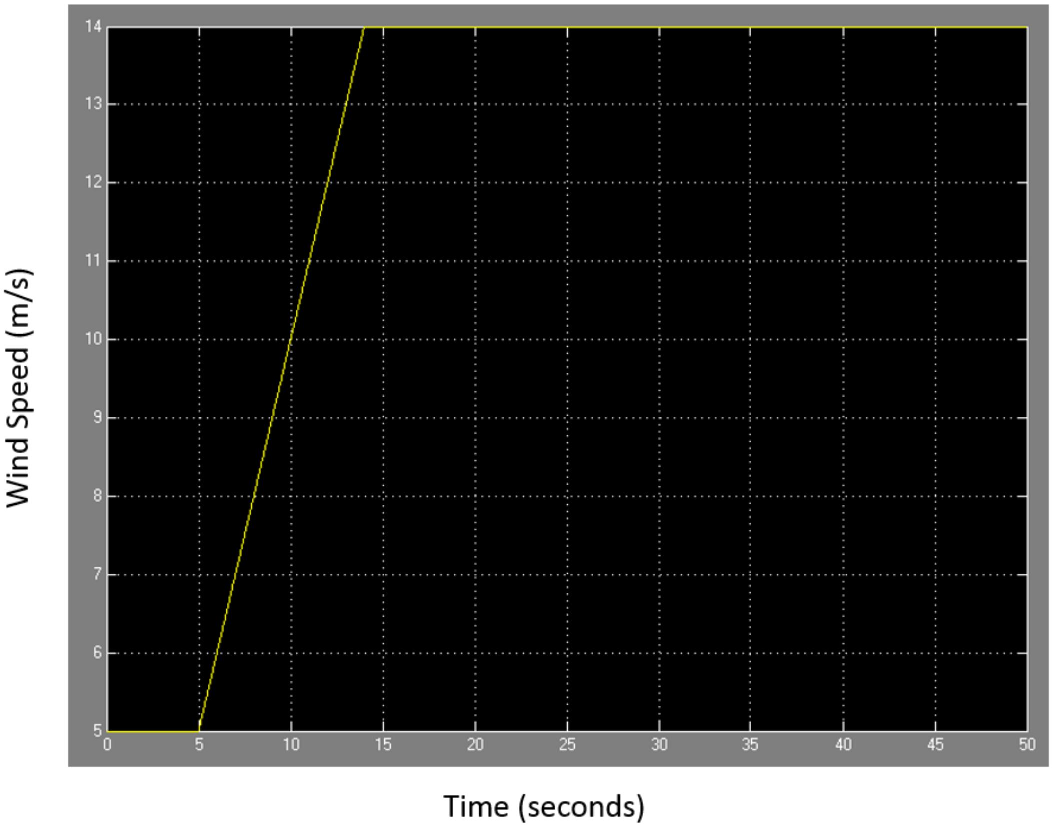

Figure 4: Simulation Time vs Low Wind Speed

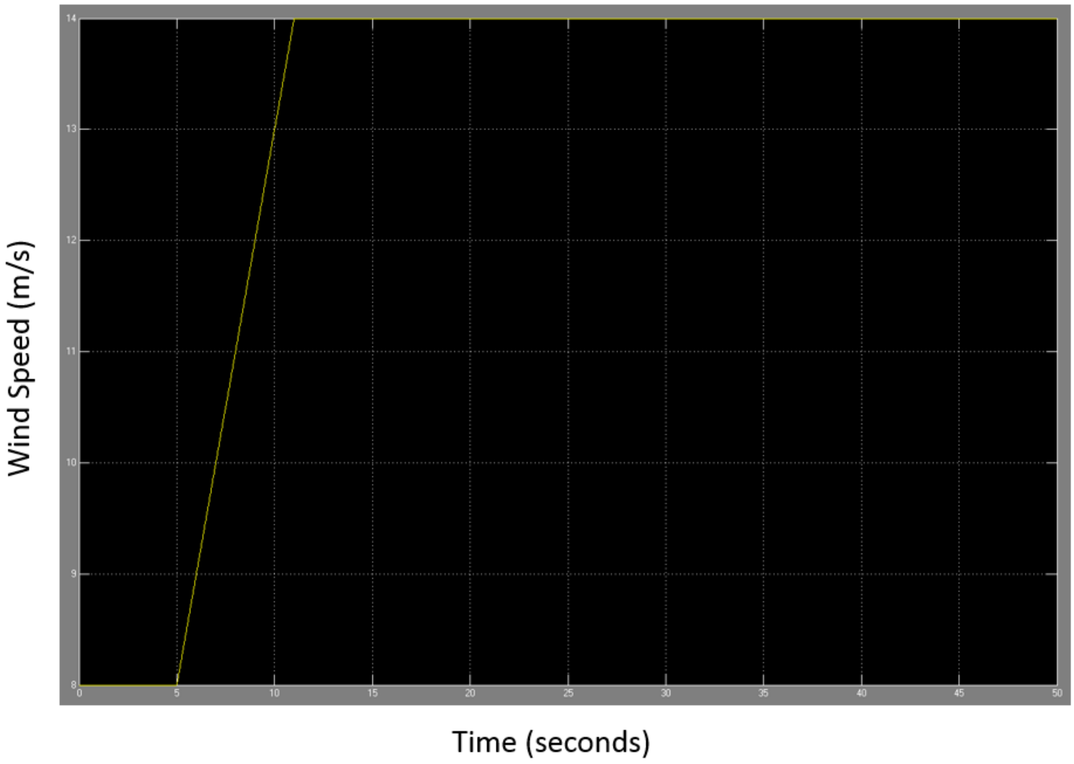

Figure 5: Simulation Time vs High Wind Speed

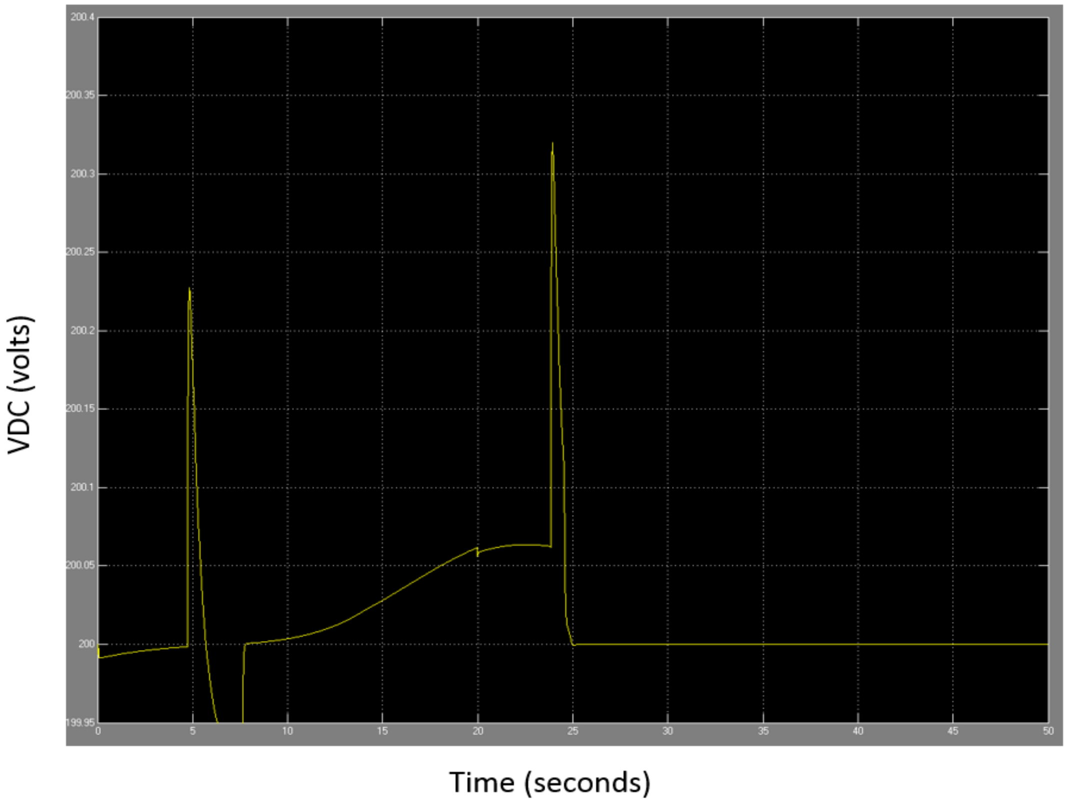

Figure 6: Simulation Time vs VDC for Low Wind Speed

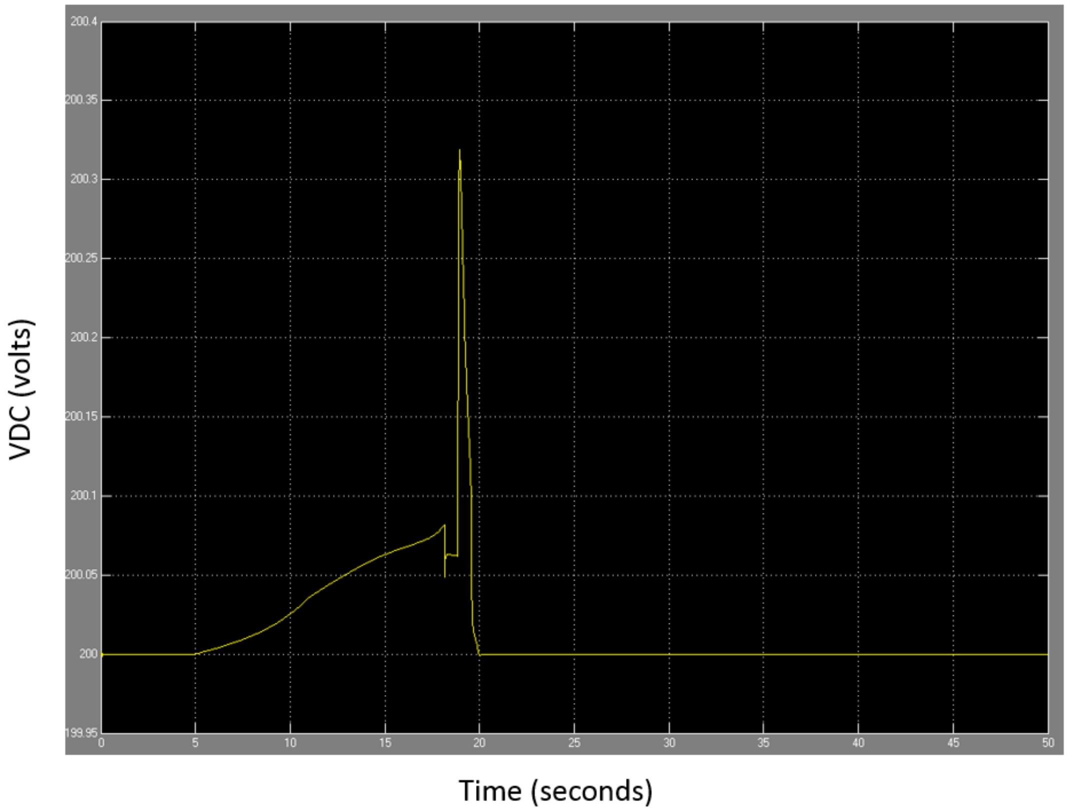

Figure 7: Simulation Time vs VDC for High Wind Speed

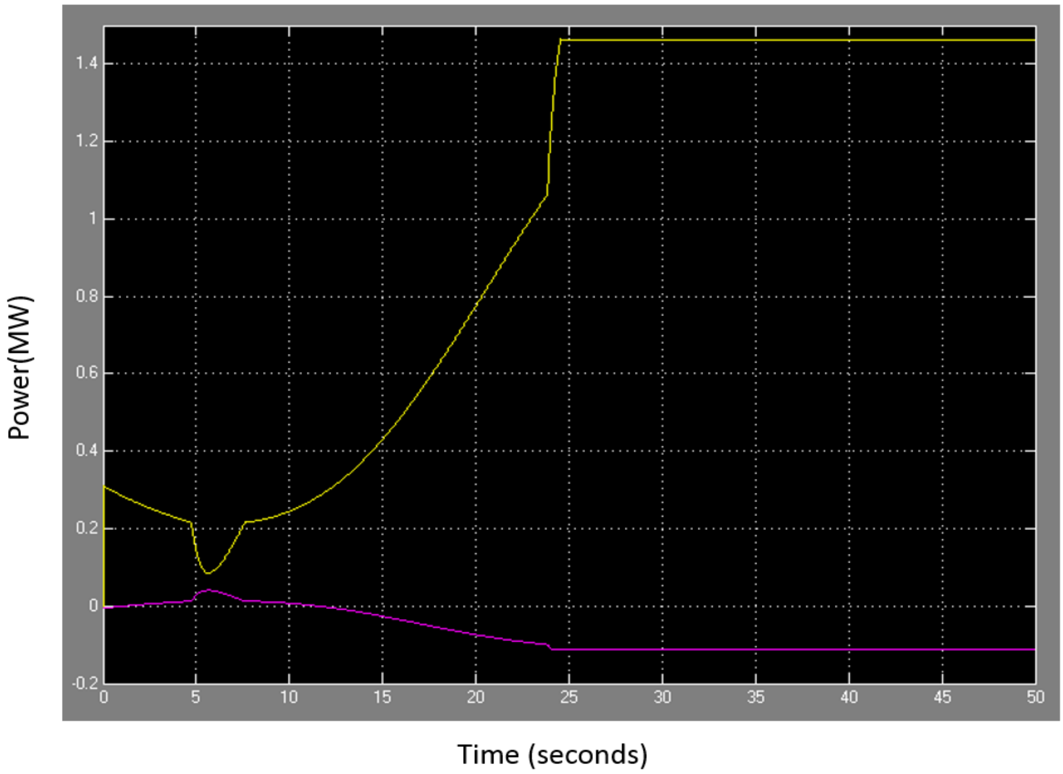

Figure 8: Simulation Time vs Power for Low Wind Speed

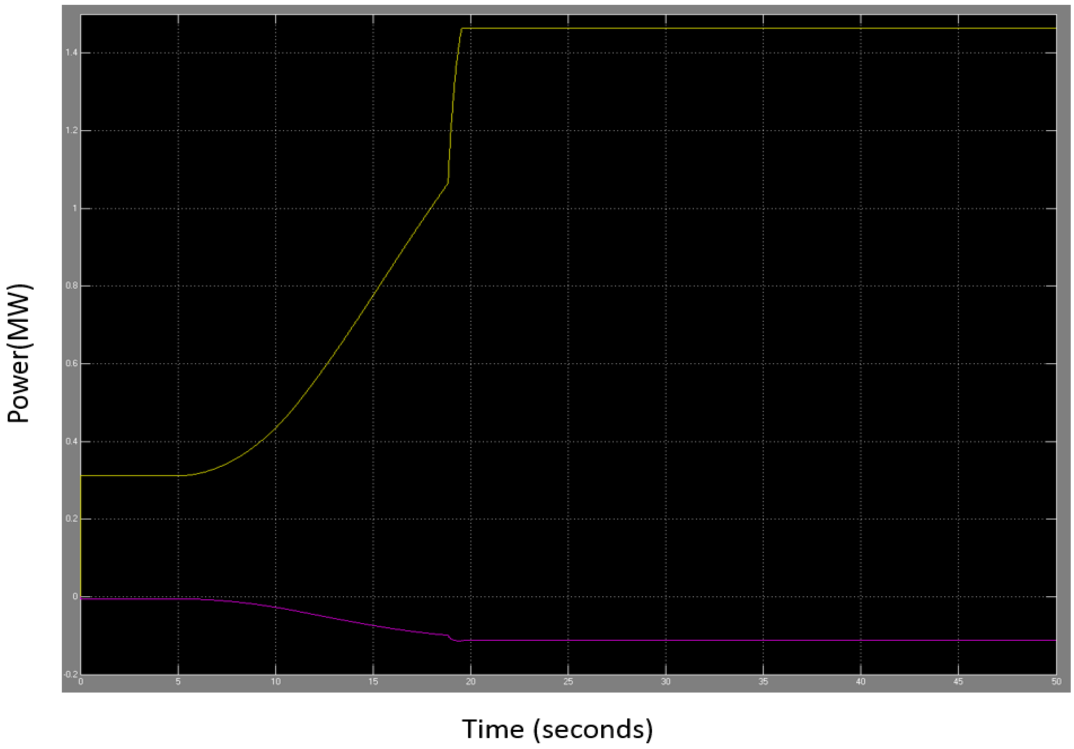

Figure 9: Simulation Time vs Power for High Wind Speed

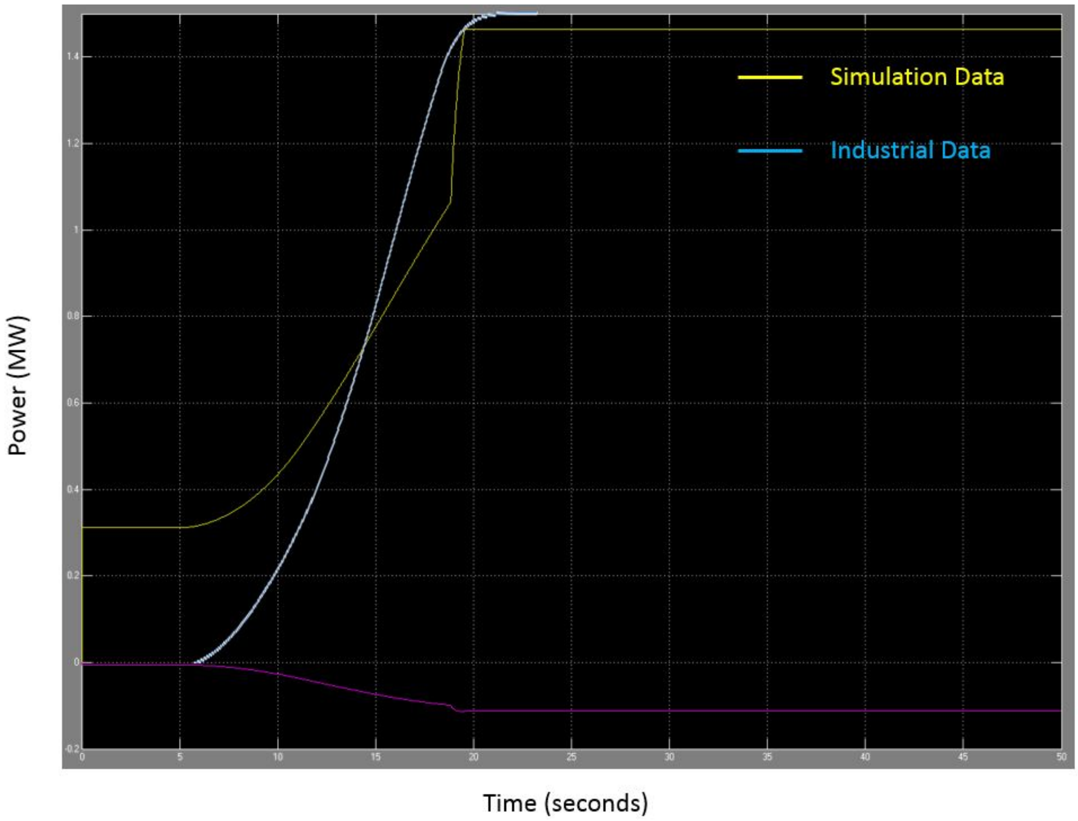

Figure 10: Comparison between simulation and industrial data for DFIG wind turbine.

- The data of the industrial and simulation were plotted in the same graph as shown in Fig. 10. It goes on to show that the simulation matches satisfactorily with the industrial data. Thus our model can be used to setup DFIG power generation plant on other coastal areas of Pakistan.
- For every project it has some constraints and limitations as well. Similarly this project is also not being feasible for everywhere. As the area we choose for the installation of the power plant is very limited, we can choose the area only where normally speed of wind should be 6m/s to 15m/s. This is only possible in coastal area or on-shore. It can't be install in plan or hilly areas. Secondly if the speed of wind is less than 3m/s or more than 22m/s, the operation of wind turbine is not possible. More over the replacement of gearbox in every 6 to 8 years, which is very costly as well.

6. Conclusion

In this paper we briefly discuss about the types of wind turbines and work on modelling the doubly fed induction generator (DFIG) coupled with wind turbine. The mathematical modeling and simulation of the generator system was discussed, and the graphical values of which were compared with the industrial data of a functional DFIG wind turbine power generation plant setup at the Jhampir, Pakistan installed by Nordex.The simulation and practical data have a close match, and we can thus conclude that theDFIG based wind turbines can be a good and economical way to fulfil the electrical energy needs, by installing them near the coastal areas of Pakistan.

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