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Renewable Energy Solution of Wind Turbine Using Doubly-Fed Induction Generator for Energy Efficiency and Reliability

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Abstract

Wind power generation, which is the most reliable renewable energy resource has been wildly stalled in power systems worldwide. Towards the end of 2015, global wind energy capacity was close to 432 Gigawatts and was estimated to hit 760GW by the end of 2025. Consequently, the widespread utilization of Doubly-Fed Induction Generator (DFIG) wind turbines in power systems began with undesirable influences like decreased system inertia, converter controls using power electronics, small synchronized coupling, and displacement of synchronous generators. Due to this effect, the power system dynamic performances, like power oscillation, frequency, transient stability, signal, and voltage stability, may be affected. The potential of wind energy as a form of electricity generation has made a major impact on energy generation as the sector has undergone tremendous growth in recent years. To completely explain the stability of a wind turbine system and at the same time develop new operation strategies with a good share of renewable energy for the grid connection, there is a need for reliable models to simulate the response of wind turbines following an event in the grid. This research will use a DFIG control wind farm that will generate 9MW of power. For power system reliability of wind-generated energy, operators should understand the full model of the system and how it functions. To this effect, this research paper designed a mathematical model of a DFIG wind turbine and ran MATLAB and SIMULINK models to see the system's performance and reliability.

Keywords: *Renewable energy, Wind turbine and Energy reliability*

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Background to the Study

A wind turbine is a machine that converts the energy from the wind into mechanical energy. This mechanical energy is then converted to electrical energy for the generation of electricity. As the wind blows past the blade surface, the blade rotates. The rotation of the blade causes the inner shaft connected to the gearbox to rotate. The gears control and double the rotation of the shaft which rotates the stator of the coil by Fleming's left-hand rule. This rotation causes the generator to generate electricity. The voltage is then boosted through a step-up transformer and supplied to the power grid. Figure 1 shows the energy conversion system of a wind turbine.

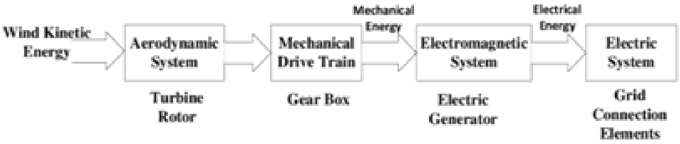


Figure 1: Block diagram of Wind Energy Conversion System

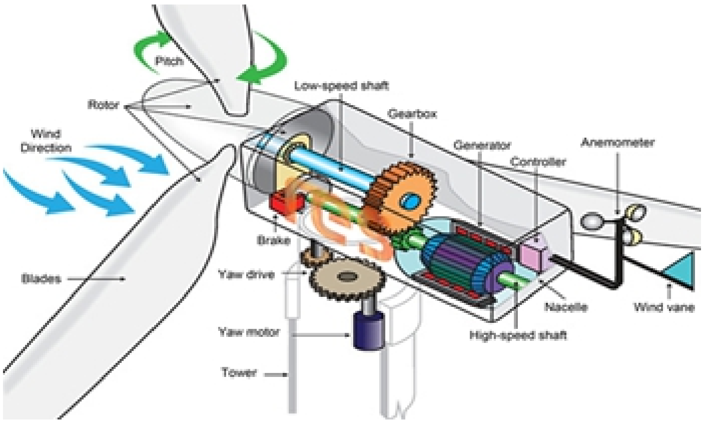


Figure 2: Pictorial diagram of the three-blade horizontal wind turbine.
Source: Safanah and Hussein: 2018

The wind generates the kinetic energy which is used to drive the turbine blade. The turbine rotor projects the aerodynamics of the system by turning the blade. The gearbox constitutes the mechanical drive train which generates the mechanical energy needed to drive the rotor of the coil. Here, by Fleming's left-hand rule, an upward force acts on one section of the coil, and a downward force acts on the order section of the coil. The whole system constitutes a couple that makes the coil rotate. Michael Faraday's first law of electromagnetic induction states that 'whenever there is a relative motion between a coil and a magnet, an e.m.f is induced (Okeke & Ndipu: 2000). These induces e.m.f constitute the electrical energy of the turbine.

Some of the parts are explained as follows;

1. ***Wind Direction***: this blows to the right and the nose of the wind turbine faces the wind.

2. ***Nose***: this is built with an aerodynamic design and faces the wind.
3. ***Blades:*** this is the point where the wind turbine is attached to the nose and the rotor. They rotate with ample wind speeds.
4. ***Shaft***: this connects the rotating blades to the interior mechanism of the machine. When the blows, it rotates with the blades and is the mechanism that transfers the mechanical energy of the blades to the electrical generator.
5. ***Brake***: this is provided to stop any mechanical failure during turbulent wind and high rotational speed conditions.
6. ***Gearbox:*** This is used to boost the speed of rotation of the turbine shaft. It has the same principle of operation as the gears on a bicycle. With changes in the gears, the speed of rotational also changes. Hence, the rotational energy is transferred to the high-speed turbine shaft and into the generator.
7. ***Turbine shaft***: it connects the gearbox to the generator of the turbine. the speed is what spins the turbine generator.
8. ***The Generator*****:** this is the most important part of the wind turbine. It is the mechanism that converts the mechanical energy from the wind that converts the mechanical energy of the shaft into electrical energy with the help of the rotating force that is transferred from the gears and turbine shaft.
9. ***Anemometer***: this device measures the speed of the wind. They instruct the controller when to stop or start the turbine in certain wind speed conditions.
10. ***Controller: it*** is used in to control the turbine at certain undesired wind speeds. At this condition, the anemometer instructs the controller to use the brake and stop the rotating of the turbine blade
11. ***Wind Vane: this*** is used to measure the direction of the wind. This is important in the turbine because up-wind turbines need to be facing the wind to function properly.
12. ***Yaw drive:*** this mechanism receives data from the wind vane and directs the wind turbine to rotate facing the wind direction.
13. ***Yaw motor***: this device physically rotates the turbine in the direction of the wind or as instructed by the yaw drive mechanism (www.turbinegenerator.org, 2022)

Figure 2 shows a pictorial diagram of a wind turbine to show the internal structure. The anemometer is for the control of the turbine. For instance, when it dictates the direction of the wind, it positions the turbine in that direction. In turbulent wind situations, the anemometer isolates the turbine from rotating thereby preventing the blade from wobbling.

More than thirty years ago, the research and development of modern wind power were a result of advancements in turbine scaling, drive technology, switching rotor fixed-speed to variable-speed operation, advanced load control, and electrical power grid integration. Big rotors per megawatt were used to achieve a lower cost of energy and accelerated cost parity with the ordinary power plant. In the late 1990s, the use of hybrid drive rotors expanded the choice between high-speed geared and direct drive. Before these developments, DFIGs had long been predicted to lose out from permanent magnet generators. Within mid-2010 permanent generator-based direct drive was predicted to become the most reliable. Recently, DFIG has been proven to be the most reliable in terms of performance and efficiency. The presence of hydraulic-drive generators has made variable rotor speed that has fixed generator speed possible (Elsevier, et al: 2013)

Conventional energy sources from fossil fuels are limited and pollute the environment. Consequently, more attention is focused on renewable energy sources such as wind energy, biomass, solar energy, etc. Among all these renewable energy sources, wind energy is the most promising renewable energy source due to its abundance in nature and reliability. For the world campaign on clean energy to come to reality, the adoption of the wind turbine as a primary means of energy generation should be adopted. This could be carried out through increasing people's awareness, government and private sector participation, and progressive development in the power electronics industry towards developing an efficient and effective means of tapping wind energy. The diversity of installation of turbines either off-shore or on-shore makes the source more reliable. Therefore, with the reliable performance of DFIG, power extraction from wind turbines is easy.

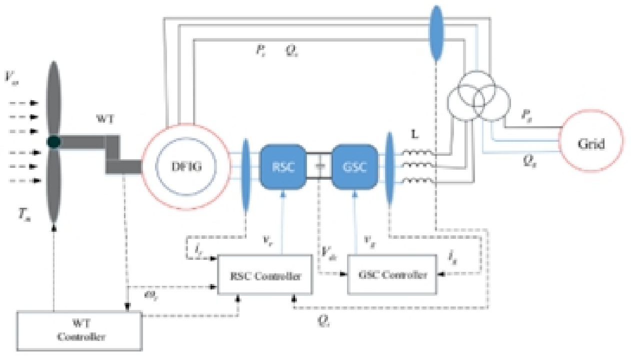


Fig 3: Schematic diagram of a doubly fed induction generator wind turbine system.
Source: Kaloi et al.: 2016

The world is gradually going green in terms of clean energy production. Almost all the industrialized nations depend on at least 30% of energy from wind. The wind is a renewable form of energy naturally in abundance in almost all the countries of the world. To harness renewable energy sources more efficiently, researchers and scientists over the years have been doing a lot of work on wind and renewable energy sources. To tap the energy from the wind is one thing and to effectively utilize it is another. To this effect, many manufacturers of turbine blades and generators have been applying many techniques and power electronics technology for the operation and control of turbine generators. Paramount among them is the Doubly-Fed Induction Generator (DFIG). Double-powered induction generators allow the operation of wind turbines in a variety of speed ranges. Therefore, pitch control is easier, mechanical stress is reduced, power quality is improved, and system efficiency is improved. Variable-speed wind turbines provide flexible control of rotor speed and generated power. Consequently, these turbines are more grid-friendly compared to fixed-speed wind turbines. In recent times, DFIG has gained market penetration more rapidly than any other system that is equipped with full-rated power converters.

History of Wind Turbine

Wind turbines have been in use by human beings for so many years' particularly to pump water for irrigation agriculture and navigation. They are also used to propel boats along the Nile River for 5000 years BC. People in Persia and China at that time were using wooden wind-powered water mills for pumping water and grinding grain (International Renewable Energy Agency, 2012). The mills at that time were small and particularly, they were used for minor works. Around the 1990s, wind energy gained commercial application as a means of electricity generation. The invention of the airplane by the Wright brothers in 1903 brought in wind energy as a commercial means of electricity generation. Its first source was the onshore wind for turbine application. Since then, progressive research stated by scientists with the adoption of the propeller of the airplane as the source of onshore wind energy (Kaldellis &, Zafirakis, 2004). With the progression in science and technology, a lot of progressive research started and the development of today's modern onshore and offshore wind turbines came to reality. Presently, the technology of wind turbines has wilder applications in power generation in developed nations. Denmark built the first ever onshore wind turbine towards the end of 1991 with an installed capacity of 450kW and a generation capacity of about 4.95MW. The first offshore wind farm was built in Denmark in 1991. It had 11 wind turbines each of 450 kW capacity capable of producing 4.95 MW (https://www.windpoweroffshore.com, 1998)

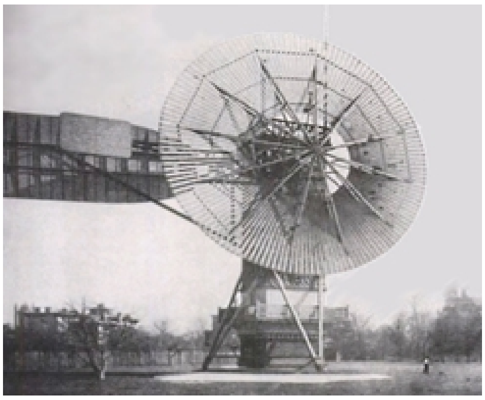


Figure 4: The first windmill was built by Charles Brush in 1888
Source: https://www.windpoweroffshore.com, 1998

Location of Wind Energy

The early discovery and development of wind energy made a headway for researchers and scientists to build more interest in the building of modern-day wind turbines. Conventionally, wind turbine has two natural sources; onshore and offshore wind turbines.

Onshore Wind Turbines

Figure 5 shows the traditional arrangement of onshore wind turbines. The global Onshore Wind market is expected to witness significant growth during the forecast period owing to the growing investments in renewables. Globally, the onshore wind turbine market started growing in 1999 (www.bing.com, 2019).

An onshore wind turbine could be defined as a turbine that is located on land and which uses onshore wind for the rotation and generation of electricity. This type of turbine is located in areas where there is no human or communal habitation. They are cheap and easily affordable in construction and installation. In terms of electrical stability, onshore wind farms have less voltage loss when compared with offshore wind turbines. Consequently, they are relatively cheap both in installation and operation when compared with the offshore wind turbine.

Figure 5: Onshore wind turbine.
Source: (www.bing.com, 2019)

In 2018, the International Energy Agency stated that onshore wind turbine electricity generation increased by an estimated 12%, and its capacity additions grew up to 7% yearly. According to the International Energy Agency (IEA), in 2018, onshore wind electricity generation increased by an estimated 12%, while capacity additions only grew by 7%. Many forces are responsible for the growth of onshore wind turbine electricity generation. These include:

Industrial Demand

The primary factor promoting the growth of wind turbines as a form of renewable energy generation is the industrial demand for clean energy. Though onshore wind power generation is not enough to match the globally growing demand for wind energy due to poor wind speed most times, its viability cannot be overemphasized. The advent of Solar PV panels as another form of renewable energy generation poses a big threat to the industry. With recent advancements in technology, the industrial demand for wind energy has increased.

Market Segmentation

Major players in the production of wind turbines are; North-America, Europe, South America, and the Middle East

Offshore Wind Turbine

As a result of the technological and economic benefits of wind turbines, wind energy generation from off-shore wind turbines has grown enormously (Subhamoy, et al: 2017). In 2016, China built in Xinjiang Province the most sophisticated off-shore wind turbine which was to generate between 5GW in 2015 and five years (2020) would increase to 30GW. Figure 3 shows the China's Xinjiang Province project of the offshore wind turbine.

Figure 6: Picture of offshore wind turbine: Source:

Offshore wind turbines are bigger than those onshore wind turbines. Since Wind turbines are extremely large machines and transporting them to an onshore site can be difficult because transportation is done by road, hence this may lead to a reduction in the size of the turbine. Offshore turbines can be of any size transportation is done by ships. Therefore, the larger the size the more power is produced. Offshore turbines have proven to be more reliable than onshore turbines. The only disadvantage of the offshore turbine is the laying of the undersea electric cables which most times are very expensive (Paul Breeze, 2017)

Power Maximization and Control

Technically, the efficiency of a wind turbine depends on its maximum power, particularly at a low-speed condition. This is determined by the control of a variable-speed wind turbine that is composed of a two-mass drive train the Squirrel Cage Induction Generator (SCIG), and voltage source converter control by Space Vector Pulse Width Modulation (SPVWM). To obtain the maximum power of a turbine, we first search for the reference speed of the generator (Safanah and Hussein: 2018).

For better performance of the Turbine, the controller is designed in such a way that it has two control loops;

i. Extremum Seeking Control (ESC): this is used to set the required reference speed to the proportional-integral controller so that it will control the operating speed of the turbine generator thereby extracting the maximum electrical power.
ii. The inner control loop: this control mechanism is based on the use of Indirect Field orientation to decouple the current.

The Proportional integral control parameters are obtained using Particle Swam Optimization. The idea of Maximum Power Tracking (MPPT) of DFIG-incorporated wind turbines is essential, particularly in locations with low speeds of wind (Abdullah, et al: 2012). The maximum power tracking of a variable-speed wind turbine has been an area of interest to researchers for decades. Different methods have been used for the control of the turbine; generator speed control and blade pitch control which lowers the mechanical load of the turbine or a combination of both control mechanisms (Soliman, et al: 2011)

In addition, the model-based control method can be used to actualize good performance for intervals of operating conditions. However, these methods have some drawbacks because the mathematical model of the system is directly integrated into the turbine controller (Barakati, et al: 2009). Furthermore, to deal with these drawbacks and lower the dependency on the mathematical model, different model-free control methods have been proposed by researchers in this field. These include;

i. Model Reference Adaptive Control (MRAC). In this control method, the output power of the turbine is maximized by adapting a good control law that directly relates the speed with torque, hence making the then MRAC adapt the torque gain for output power increase (Barakati et al, 2009).
ii. The classical MPPT methods: in this method, the control input is perturbed by a particular step size and the change in power output (Safanah and Hussein: 2018).

Advantages of Wind Turbine Power as a Renewable Energy Source

1. They are environmentally friendly. The renewable nature of wind energy is environmentally safe. Unlike other renewable sources, the wind turbine is cheap and dynamic to the environment. Fossil fuel causes ozone layer depletion and greenhouse emissions.
2. They are naturally sustainable. Therefore, it will not cost much to harness wind energy resources.

Irrespective of the natural benefits of wind turbines, there are a lot of problems in harnessing them. These may include:

1. Seasonal variations and turbulence. In some countries, the prevailing wind is sometimes seasonal and, in many situations,, may be turbulence which can damage the blade.
2. Land Use Act: in some countries, the Land Use Act also affects the location of turbines.
3. Misalignment of the turbine blade from the wind direction.
4. The effect of the turbine blade on wildlife is most times disastrous. Birds have been killed by flying into spinning turbine blades. In the UK for instance, the Red-throated diver bird stopped the second phase of the wind farm because of the turbine blade trap and killed them as shown in Figure 7

Figure 7: Birds preventing the rotation of a turbine in a small wind farm in Maiduguri, Northern Nigeria. **Source**: Renewable Energy Commission of Nigeria, 2019

Finally, both two proposed renewable energy sources are capital-intensive and the energy produced by wind turbines requires expensive storage during peak production time.

Principle of Operation of DFIG

The basic principle of operation of DFIG is mainly based on the control of the wind turbine. Practically, power electronics technology plays a vital role in the efficient operation of DFIG in wind turbines. DFIG inverter cost is relatively cheap and has a speed range of 33% to 43% when operating at its synchronous speed. It also has a System efficiency and lower cost for power factor control. Two control measures are used in DFIG; direct power control (PC), and traditionally there are two control methods for the rotor-side converter: direct torque control (DTC) and direct power control (DPC).

Dual-feed induction generators are inexpensive and offer easy pitch control. It also reduces the mechanical stress associated with the turbine. They dynamically compensate for the torque and power pulsations caused by the back pressure of the tower. This back pressure causes considerable torque pulsation at a speed equal to the speed of the turbine rotor multiplied by the number of rotor blades. In addition, double supply induction. In addition, it improves power quality, reduces flicker, reduces acoustic noise, and improves system efficiency. Traditional wind turbines have a fixed rotational speed that depends on the characteristics of the mechanical sub-circuits. e.g., Pitch control time constant, the maximum value of the main switch Switching rate, etc. The response time of some of these mechanical circuits can be tens of milliseconds. As a result, you can observe rapid and rapid changes in electrical output each time a gust hits the turbine. These load fluctuations require not only a robust power grid to enable stable operation but also a robust mechanical design to absorb high mechanical loads. This strategy leads to complex mechanical structures, especially at high nominal powers. Double-powered induction generators allow the operation of wind turbines in a variety of speed ranges. Therefore, pitch control is easier, mechanical stress is reduced, power quality is improved, and system efficiency is improved.

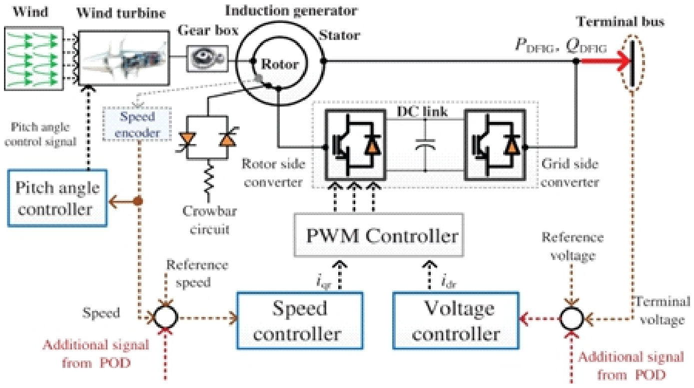


Fig 8: Schematic diagram of DFIG wind turbine system.
Source: Issarachai: 2017

Figure 8 represents the structure of the DFIG wind turbine and its control systems. It is made up of a back-to-back grid-side converter (GSC) coupled with a rotor-side converter (RSC).

The stator windings are interfaced with the power grid, while the rotor windings are connected to the power grid by RSC. With this configuration, the cost of converters and the harmonic filter are reduced to a large extent (Issarachai: 2017). The small size of the converter leads to low power loss and at the same time breeds efficiency (Milano, 2010). This achievement is a result of in-depth research conducted about DFIG YEARS AGO.

The limitation of most existing research is that the proposal is only tested in an offline simulation environment, creating a testability gap in terms of the utility of the proposal. The researcher attempts to discuss the tools and procedures needed to run in real-time. Simulation of DFIG-based WG system as the basis for conducting more practical control tests on Grid tides and strategies for maximizing grid tide reliability and performance Island WG system. However, this research work is important to the world as a whole, taking cognizance of the recent campaign on clean energy.

Doubly-Fed Electric generator is an electrical machine that supplies AC into the winding of the stator and rotor (Hlaing, 2018). The machine operates like a synchronous motor whose speed can be varied by adjusting the frequency of the AC fed into the rotor winding. In DFIGs, mechanical power at the machine shaft is transformed into electrical power supplied to the grid via the stator and rotor windings (Lab-volt, 2014). DFIG dynamic model is needed to develop decoupled control of active and reactive power. The construction of a DFIG is similar to a wound rotor induction machine (IM) and comprises a three-phase stator winding and a three-phase rotor winding.

Advantages of DFIG in Wind Turbine

Global reliance on wind energy resources as a major source of clean energy generation has led to a series of research and development in the sector. The wilder application of power electronics has contributed in no small measure toward the realization and application of DFIG in wind turbines

DFIG acts like a synchronous generator and at variable speed irrespective of the fact that its stator is directly connected to the electricity grid. Its converter effectively controls the voltage magnitude and phase angle that is applied to the rotor thereby controlling the magnetic field rotor speed. Its configuration forms an AC excitation with a variable frequency as may be seen in DC excitation machines used in synchronous generators. This process makes DFIG act as a synchronous generator (www.ukessays.com, 2017). DFIGs have different control methods for their reactive and active power, therefore, making them more grid-compatible than other turbine generator designs. It can be operated in any desired power factor using power electronic converter control. This reduces cost and lower power loss during operating conditions (Ali, 2013). Other of its advantages include:

1. Transient stability: this is the ability of a power system to remain in a state of synchronism even at the point of the subjection of disturbances which may be a short-circuit condition. With DFIG, this is achieved since the inertia of the DFIG rotor is decoupled from the power grid, and the high installation of DFIG wind turbines replaces the conventional synchronous generators (Kundur, et al: 2004).

2. Voltage stability: also, this is the ability of a power system to maintain steady state voltages at all buses within safe ranges after a disturbance. The presence of reactive power output control ability of a DFIG wind turbine brings the improvement in voltage stability (Vittal, et al: 2010)
3. Frequency control: this is categorized into two groups: inertial control and power reserve control. Inertia control releases the kinetic energy stored in the DFIG rotor to lessen the frequency required at the initial stage of a disturbance, while power reserve control is a process of injecting the reserved power into the wind turbine to supply insufficient power persistently (Naik, 2016)

Performance Operation of Wind Turbine Doubly-Fed Induction Generator

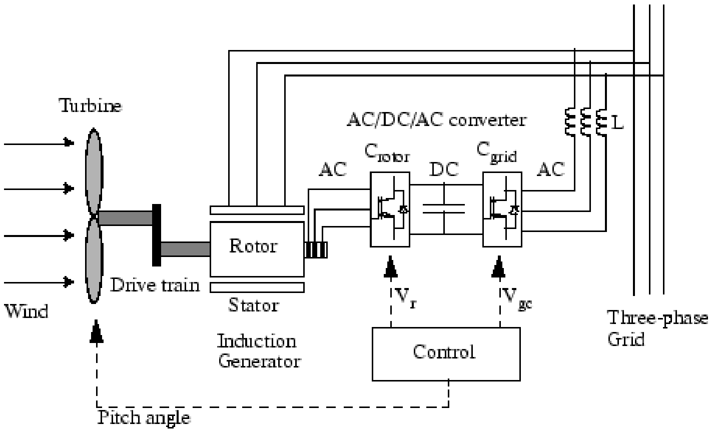


Figure 9: Structural Diagram of DFIG

Figure 9 is the sectional one-line diagram of the DFIG used. The AC/DC/AC converter is divided into two components; the rotor-side converter and the grid-side converter. Both converters are voltage-sourced controlled Converters that use insulated-gate bipolar transistors (IGBT). This IGBT is a three-terminal power semiconductor device mainly used as an electronic switch, which combines high efficiency and fast switching technology. This device is used to synthesize an AC voltage from a DC voltage source. A capacitor connected to the DC side acts as the DC voltage source. A coupling inductor L is used to connect the grid-converter side. The rotor converter-side is connected to the three-phase rotor winding using slip rings and brushes and the three-phase stator winding is directly connected to the grid. The mechanical power captured by the wind turbine is converted into electrical power by the induction generator and this is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals V_r and V_{gc} for C_{rotor} and C_{grid} respectively to control the power of the wind turbine.

Practically, the wind turbine is classified based on the axis of rotation into two main groups. They include the horizontal axis wind turbine and vertical axis wind turbine. Because horizontal axis turbines collect a higher amount of wind energy during the day and are also able to adjust its blade's pitch angle to avoid turbulent wind conditions, they are more often used in wind turbines than the vertical axis turbine. (Roshin &Mandi: 2017). The basic principle of the operation of a Wind turbine is to convert the kinetic energy of the wind into mechanical energy that rotates the rotor blades which are connected to the low-speed shaft. The generated mechanical energy is then transmitted into the high-speed shaft of the turbine through a gearbox to generate the desired electrical energy. The horizontal axis type wind turbine rotates at an axis parallel to the direction of flow of the wind. Throughout this process, Wind energy can be harvested provided that the blades are in the direction of the wind. A horizontal axis type wind turbine naturally has a taller tower which allows the turbine to withstand stronger wind since wind speed increases with height. With variable pitch angle turbines, the maximum extractable amount of wind energy is possible by increasing or reducing the blade's pitch angle depending on the electricity generated (Rigit & Ali: 2020)

Model of a Wind Turbine

After the discoveries of the drawbacks of using fixed-speed wind turbines, the variable-speed wind turbine was developed as early as the 1920s and 1930s when thousands of small wind turbines powered rural homes and farms in the US and Europe (Varies, 2013). The installed capacity at that time was within the range of 0.5MW to 10MW. The first commercial kW-size geared variable-speed wind turbine was developed in the 1980s and presently, with ongoing research, more efficient turbines have been developed. To model a system, it is paramount to understand the mode of operation and the parameters of the system. In Modelling a wind turbine, the actual power curve of is used to develop the system's characteristic equations through **curve fitting techniques and mathematical models. In this scenario, mathematical models of the system equations will be used.**

Mathematical Model of a Wind Turbine

For a clear understanding of the parameters used in this research project to model the horizontal wind turbine, table 1 represents the parameters used and their respective nomenclature. In running the simulation, the following parameters will be used.

Table 1: Parameter Nomenclature

S/No	Parameter	Nomenclature	Unit
1	P_w	Power in the wind	W
2	ρ	Air density	Kg/m^2
3	A	Area swept by the rotor blade	m^2
4	V_w	Speed of the wind	m/s
5	P_m	Mechanical output of the turbine	W
6	C_p	Power coefficient of the turbine	
7	P_t	Power output of the transmission system of the turbine	W
8	η_t	Transmission efficiency	
9	η_g	Generator efficiency	
10	P_e	Electrical power produced by the wind turbine	W
11	η_0	Overall efficiency of the wind turbine conversion system	
12	W_S	Weibull scale parameter	m/s
13	f_p	Probability distribution	
14	k	Weibull shape parameter	
15	v_1	Wind speed (m/s)at a height h_1	
16	v_2	Wind speed (m/s)at a height h_2	
17	Eff_{ad}	Efficiency of the AC – DC converter	
18	t	Time at which calculation began	s
19	R	Radius of wind turbine blade	m
20	η_t	Tip – speed ratio	
21	P_{wd}	The power density of the wind turbine	W/m^2
22	ω_m	Mechanical speed of the rotor	rads/s
23	V_c	Cut-in speed of the wind turbine	m/s
24	V_r	Rated speed of the turbine	m/s
25	V_f	Cut-out speed of the turbine	m/s
26	P_{Er}	Electrical rated power output of the turbine	W

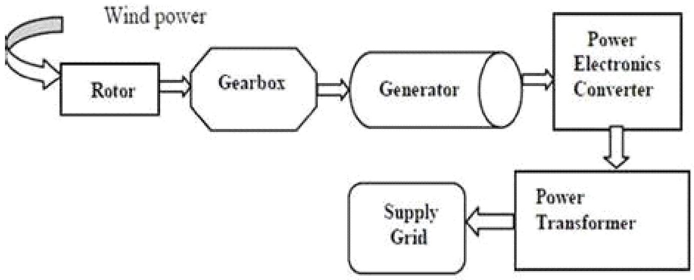


Fig. 10: Basics of wind energy conversion system: source: bing.com, 2017

For the process shown in Figure 10, the instantaneous power available to the turbine of cross-sectional area (A) perpendicular to the flow of wind stream with air density ρ moving at a speed Vm/s given as;

$$P_w = \frac{1}{2}\rho A {V_w}^3 \qquad 1$$

This wind power is then converted into mechanical power through the rotation of the blade of the turbine. The converted mechanical power is given as:

$$P_m = P_w \times C_p = \frac{1}{2}\rho A {V_w}^3 \qquad C_p \qquad 2$$

C_p is the power coefficient which is a measurement of how efficient the turbine is. This includes the combination of the losses. For this research design, $lenght\ of\ turbine\ blade = 80m wind\ turbine\ power\ coefficient = 0.5$

Therefore, the expected wind power using equation 1 would be;

$$P_w = \frac{1}{2}\rho A {V_w}^3 = P_w = \frac{1}{2} \times 1.25 \times A \times (10)^3$$

A is the swept area which is the area of the imaginary circle swept by the blade of length 8m This 68m is the radius of the imaginary circle.
Therefore;

$$P_w = \frac{1}{2}\rho A {V_w}^3 = P_w = \frac{1}{2} \times 1.25 \times \frac{22}{7} \times 80 \times 80 \times (10)^3 = 12.568MW$$

Mechanical power to be developed by the turbine would be;

$$P_m = P_w \times C_p = 12.568 \times 0.5 = 6.284MW$$

This 6.284MW is the rated capacity of the turbine that can produce 6.284MW of power per hour at the prevailing maximum wind speed continuously for one hour. Moreover, the capacity factor of the wind chosen is the ratio of the turbine's actual power over a time period to its maximum power output.

Wind power density is;

$$WPD = \frac{1}{2}\rho {V_w}^3 \qquad 3$$

In general terms,

$$P_w = \frac{1}{2}\rho A {V_w}^3 C_p(\beta, \lambda) \qquad 4$$

$\beta = pitch\ angle\ and\ , \lambda = tip\ speed\ ratio$

$$C_p(\beta, \lambda) = C_1\left(\frac{C_2}{Z} - C_3\beta - C_4\right)e^{-(C_5/Z)} + C_6\lambda \qquad 5$$

$$\frac{1}{Z} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3} \qquad 6$$

Where;

$$C_1 = 0.5176,\ C_2 = 116,\quad C_3 = 0.4,\quad C_4 = 5,\quad C_5 = 21;\ and\ C_6 = 0.0068$$

Aerodynamic Modelling

The development of the aerodynamic modelling of the wind turbine is based on the mathematical equations governing the model (Michalke & Hansen: 2010). In this model, the assumption is that the kinetic energy obtained by the blades of the wind is transformed into mechanical torque at the rotor shaft of the wind turbine. Figure 11 shows the aerodynamic situation of the blade.

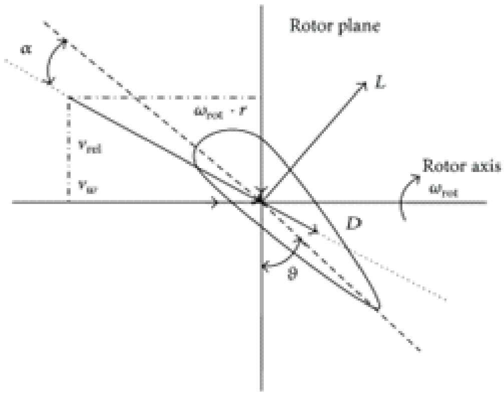


Fig. 11: Aerodynamic c
Source: Luis, et'al: 2013

The torque on the rotor shaft shown in figure 12, which is important for the axis model, can be calculated from the power with the aid of the rotational speed as:

$$T_A = \frac{P_w}{\omega_r} \qquad 7$$

$T_A = rotor\ Totque, \qquad \omega_r = wind\ turbine\ speed$

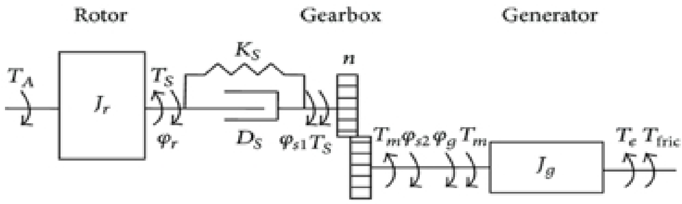


Fig. 12: Drive train schematic for the modelling of a wind turbine:
Source: Luis, et al: 2013

Figure 12 shows the model of the power transmission. All masses are grouped into low and high-speed shafts. For transient stability analysis with a fixed, this model will be used. The rotating blades produce the inertia of the low-speed shaft and that of the high-speed shaft. Small masses of high-speed shafts are considered in this model because they influence the dynamic system as a result of the transformation of the transmission ratio. Stiffness and damping of the shaft are combined in equivalent stiffness and damping placed on the low-speed side. Mass of the gearbox in neglected in this model. Input to the model for a two-mass system is defined as torque, which is obtained by the aerodynamic system and the generator reaction torque whereas the output is the changes in the rotor and generator speed.

$$\lambda = \frac{\omega_{not} \times \mathrm{r}}{V_w} \qquad 8$$

$$\mathrm{r} = \text{lenght of the blade and } \omega_{not} = tip\ speed$$

However, the dynamic of the high-speed generator can be expressed as a machine model. The differences in the mechanical drive torque, the generator torque reaction, and torque losses due to friction, cause the change of angular velocity (Muyen, et al: 2008)

$$T_m - T_e - T_{fric} = J_g \times \dot{\omega}_g \qquad 9$$

$$\dot{\omega}_g = \ddot{\varphi}_g. \qquad 10$$

The difference in angular speed $\dot{\omega}_r$ is a result of the change in the aerodynamic torque T_A and shaft torque T_s at the low speed.

Therefore;

$$T_A - T_s = J_r \times \dot{\omega}_r \qquad 11$$

$$\dot{\omega}_r = \ddot{\varphi}_r. \qquad 12$$

The mechanical driving torque Tm and shaft torque Ts are connected by the gear ratio;

$$T_m = \frac{T_s}{n} \qquad 13$$

The governing equations of the shaft can be described as;

$$T_s = (K_s \times \Delta\varphi) + (D_s \times \Delta\varphi\ ) \qquad 14$$

$$\Delta\varphi = \varphi_r - \frac{\varphi_g}{n} = \quad \omega_r - \frac{\omega_g}{n} \qquad 15$$

The final drive train dynamics is as follows:

$$\dot{\omega}_r = \frac{1}{J_r}\left(T_A - D_s.\omega_r + \frac{D_s}{n}.\omega_g - K_s\left\{\int \left(\omega_r - \frac{\omega_g}{n}\right)dt\right\}\right) \qquad 16$$

$$\dot{\omega}_g = \frac{1}{J_g}\left(-T_e - \left(D_g + \frac{D_s}{n^2}\right)\omega_g + \frac{D_s}{n}.\omega_r - \frac{K_s}{n}\left\{\int \left(\omega_r - \frac{\omega_g}{n}\right)dt\right\}\right) \qquad 17$$

K_s is the stiffness constant and D_s represents the damping constant of the shaft. To get the stiffness constant, the eigenfrequency of the drive train must be known. Assuming a two-mass free-swinging system; the eigenfrequency is as follows obtained as follows:

$$\dot{\omega}_r = \frac{1}{J_r}\left(T_A - D_s.\omega_r + \frac{D_s}{n}.\omega_g - K_s\left\{\int \left(\omega_r - \frac{\omega_g}{n}\right)dt\right\}\right) \qquad 18$$

$$\dot{\omega}_g = \frac{1}{J_g}\left(-T_e - \left(D_g + \frac{D_s}{n^2}\right)\omega_g + \frac{D_s}{n}.\omega_r - \frac{K_s}{n}\left\{\int \left(\omega_r - \frac{\omega_g}{n}\right)dt\right\}\right) \qquad 19$$

$$\omega_{os} = 2\pi f_{0s} = \sqrt{\frac{K_s}{J_{gs}}} \qquad 20$$

The total inertia of the free-swinging system at the low speed is calculated as:

$$J_{ges} = \frac{J_r \cdot J_g \cdot \; n^2}{J_r + J_g \cdot n^2} \qquad 21$$

Hence, the stiffness constant of the low-speed shaft is given as;

$$K_s = J_{ges} \cdot (2\pi f_{os})^2 \qquad 22$$

Finally, the damping constant of the turbine is calculated thus:

$$D_s = 2\xi_s \cdot \sqrt{\frac{K_s \cdot J_{ges}}{\xi_s^2 + (2\pi)^2}} \qquad 23$$

Luis, et al: 2013.

Model Description and Simulink Block of DFIG

The 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 25 kV distribution system exports power to a 120-kV grid through a 30 km, 25 kV feeder. Wind turbines using a doubly-fed induction generator (DFIG) consist of a wound rotor induction generator and an AC/DC/AC. Insulated Gate Bipolar Transistor (IGBT)-based PWM converter. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed while minimizing mechanical stresses on the turbine during gusts of wind.

Simulink Block of DFIG

DFIG is an electrical machine fed with AC currents into the stator and the rotor windings of the internal coil. They are frequently used in the industries. For this project, DFIG will be used in a wind turbine that can generate 9MW of power. The simulation model is carried on both the average model of the DFIG. Figure 13 shows the Simulink block models of the DFIG wind turbine.

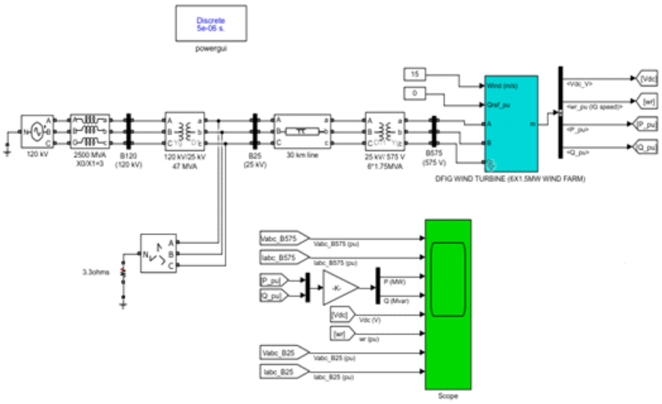


Fig. 13: DFIG wind turbine Normal model

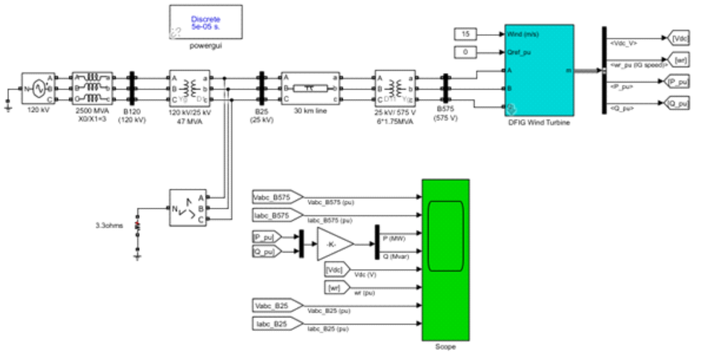


Figure 14: DFIG wind turbine average model.

Wind Turbine Power Curve

Figure 14 shows the regions of a wind turbine power curve. In region one, the speed of the wind is smaller than that of the cut-in speed, therefore, the power output of the wind turbine here is zero. Between the cut-in speed and the rated wind speed is region two. In this region, wind speed increases rapidly and the output power of the turbine also increases. The third region is the region of constant power output. In this region, no matter the speed of the wind, the power output of the turbine remains the same (rated power). This continues until the cut-off wind speed is reached. At the cut-off region four, the turbine is automatically disconnected from operation, and the power produced here is zero. The essence of this is to protect the turbine components from damage (Vaishali, et al: 2016). The power efficiency of a wind turbine is shown on the power curve. It is important to get the accurate curve of a wind turbine to design online monitoring and power forecasting. Many techniques have been used to model the wind turbine power curve to verify its performance (Kusiak, et al: 2009).

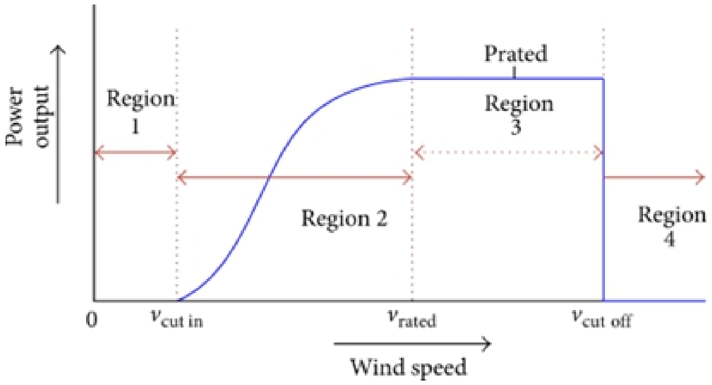


Fig. 15: Wind turbine power curve: Source: Vaishali, et'all: 2016

Grid Control System

The grid section of the converter C_{grid} is used to control the voltage of the DC bus capacitor. In addition to this, this model allows using a converter to generate or absorb reactive power. The block diagram is as shown in figure 16.

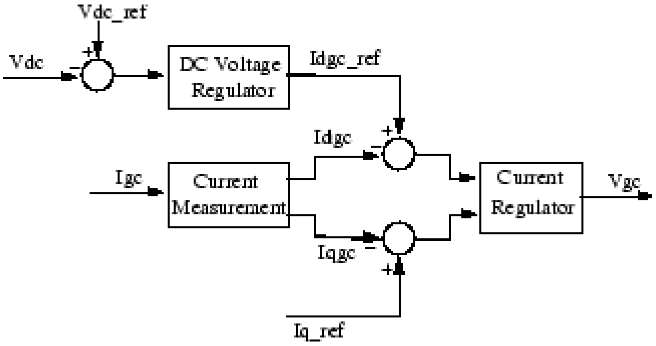


Fig. 16: Block diagram of Grid-Side Converter Control

The system control comprises;

1. Measuring d and q components of AC positive-sequence currents to be controlled as well as the DC voltage Vdc.
2. Outer regulation loop made up of a DC voltage regulator. Its output voltage regulator is the reference current $(I_{gr(ref)})$
3. For the current regulator. Idgc is the current that is in phase with grid voltage which controls active power flow.
4. The inner current regulation loop comprises a current regulator. This controls the magnitude and phase of the voltage generated by converter C_{grid}(Vgc) from the $I_{gr(ref)}$ produced by the DC voltage regulator and specified $I_{gr(ref)}$ reference. The current regulator is assisted by feed-forward terms that predict the C_{grid} output voltage.

Therefore, the magnitude of the reference grid converter current $I_{gr(ref)}$ is given as;

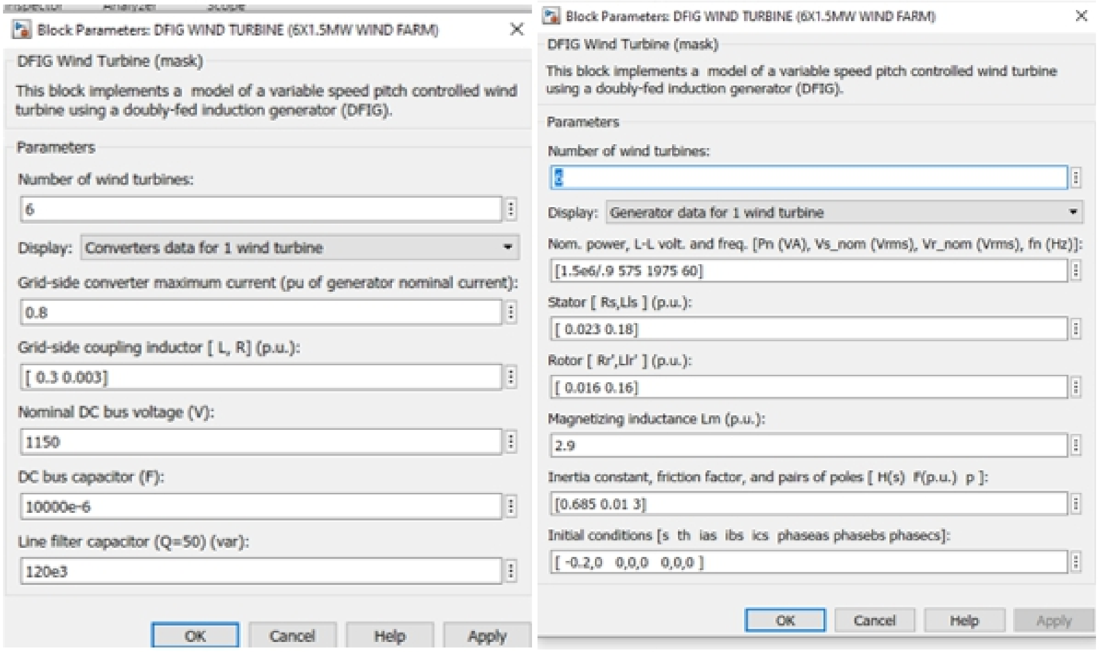
$$I_{gr(ref)} = \sqrt{I_{2dgc(ref)} + I_{2dr(ref)}} \tag{25}$$

Turbine Model

The turbine model uses the Wind Turbine blocks shown in Figures 1.17 and 1.18. The doubly-fed induction generator phasor model is the same as the wound rotor asynchronous machine. The differences are;

1. Only the positive sequence is taken into account.
2. Addition of a trip input. At high input, the induction generator is disconnected from the grid.

The tables below show the data for the realization of 9MW of power from a DFIG



DFIG Wind Turbine (mask)

This block implements a model of a variable speed pitch controlled wind turbine using a doubly-fed induction generator (DFIG).

Parameters

Number of wind turbines: 6

Display: Converters data for 1 wind turbine

Grid-side converter maximum current (pu of generator nominal current): 0.8

Grid-side coupling inductor [L, R] (p.u.): [0.3 0.003]

Nominal DC bus voltage (V): 1150

DC bus capacitor (F): 10000e-6

Line filter capacitor (Q=50) (var): 120e3

(a)

DFIG Wind Turbine (mask)

This block implements a model of a variable speed pitch controlled wind turbine using a doubly-fed induction generator (DFIG).

Parameters

Number of wind turbines: 6

Display: Generator data for 1 wind turbine

Nom. power, L-L volt. and freq. [Pn (VA), Vs_nom (Vrms), Vr_nom (Vrms), fn (Hz)]: [1.5e6/.9 575 1975 60]

Stator [Rs,Lls] (p.u.): [0.023 0.18]

Rotor [Rr',Llr'] (p.u.): [0.016 0.16]

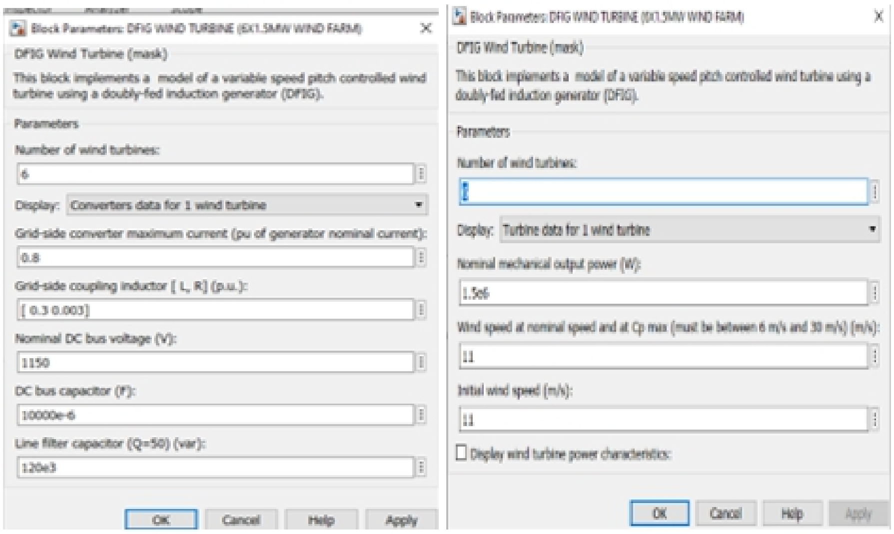
Magnetizing inductance Lm (p.u.): 2.9

Inertia constant, friction factor, and pairs of poles [H(s) F(p.u.) p]: [0.685 0.01 3]

Initial conditions [s th ias ibs ics phaseas phasebs phasecs]: [-0.2,0 0,0,0 0,0,0]

(b)

Fig. 17: (a) Block parameters for converter data of DFIG (b) Block parameters for Generator data of DFIG.



DFIG Wind Turbine (mask)

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Parameters

Number of wind turbines: 6

Display: Converters data for 1 wind turbine

Grid-side converter maximum current (pu of generator nominal current): 0.8

Grid-side coupling inductor [L, R] (p.u.): [0.3 0.003]

Nominal DC bus voltage (V): 1150

DC bus capacitor (F): 10000e-6

Line filter capacitor (Q=50) (var): 120e3

(a)

DFIG Wind Turbine (mask)

This block implements a model of a variable speed pitch controlled wind turbine using a doubly-fed induction generator (DFIG).

Parameters

Number of wind turbines: [illegible]

Display: Turbine data for 1 wind turbine

Nominal mechanical output power (W): 1.5e6

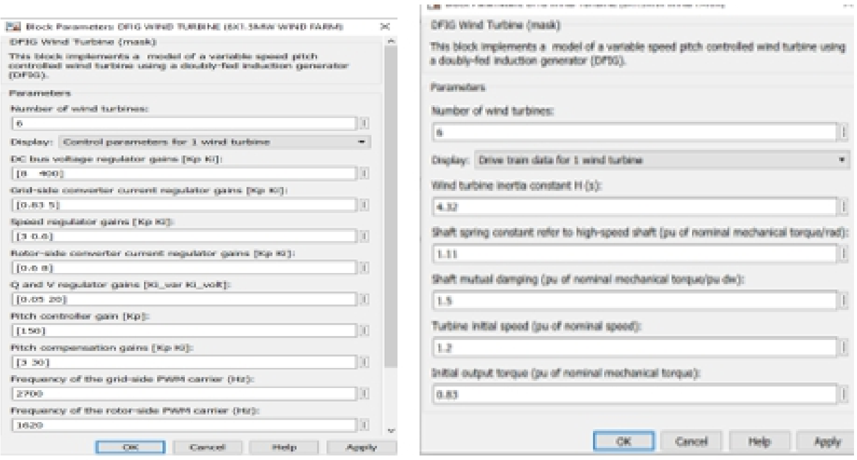
Wind speed at nominal speed and at Cp max (must be between 6 m/s and 30 m/s) (m/s): 11

Initial wind speed (m/s): 11

☐ Display wind turbine power characteristics:

(b)

Fig. 18: (a) Block parameters for converter data of DFIG (b) Block parameters for Turbine data of DFIG



Block Parameters: DFIG WIND TURBINE (6X1.5MW WIND FARM)

DFIG Wind Turbine (mask)

This block implements a model of a variable speed pitch controlled wind turbine using a doubly-fed induction generator (DFIG).

Parameters

Number of wind turbines:
6

Display: Control parameters for 1 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]

Frequency of the grid-side PWM carrier (Hz):
2700

Frequency of the rotor-side PWM carrier (Hz):
1620

DFIG Wind Turbine (mask)

This block implements a model of a variable speed pitch controlled wind turbine using a doubly-fed induction generator (DFIG).

Parameters

Number of wind turbines:
6

Display: Drive train data for 1 wind turbine

Wind turbine inertia constant H (s):
4.32

Shaft spring constant refer to high-speed shaft (pu of nominal mechanical torque/rad):
1.11

Shaft mutual damping (pu of nominal mechanical torque/pu dw):
1.5

Turbine initial speed (pu of nominal speed):
1.2

Initial output torque (pu of nominal mechanical torque):
0.83

(a) (b)

Fig. 19: (a) Block parameters for drive train data of DFIG (b) Block parameters for control data of DFIG used

Results and Discussions:

The simulation sample time used to discretize the model (Ts = 10 microseconds) is specified in the Initialization function of the Model Properties. For a wind speed of 10 m/s, the turbine output power is 0.5 pu of its rated power. Depending on the range of frequencies to be represented, three simulation methods are currently available in Power Systems to model VSC-based energy conversion systems connected to power grids

FIG Simulation Results

Normal Model

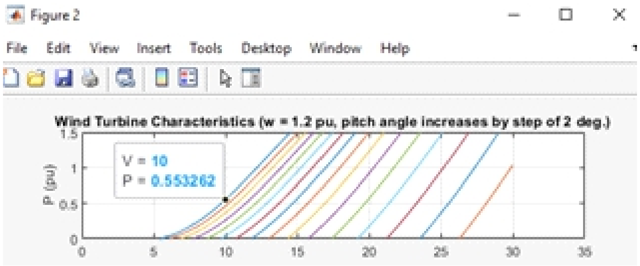


Fig. 20: Power per unit (Pu) versus wind turbine speed

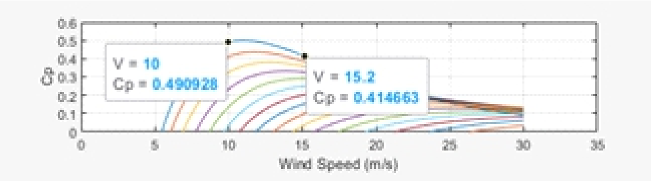


Fig. 21: Power coefficient versus wind turbine speed

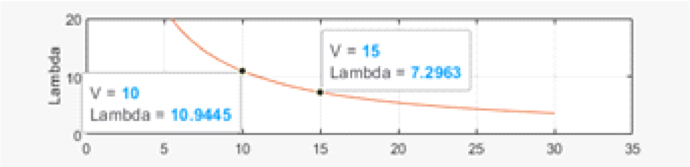


Fig. 22: Pitch angle versus wind turbine speed

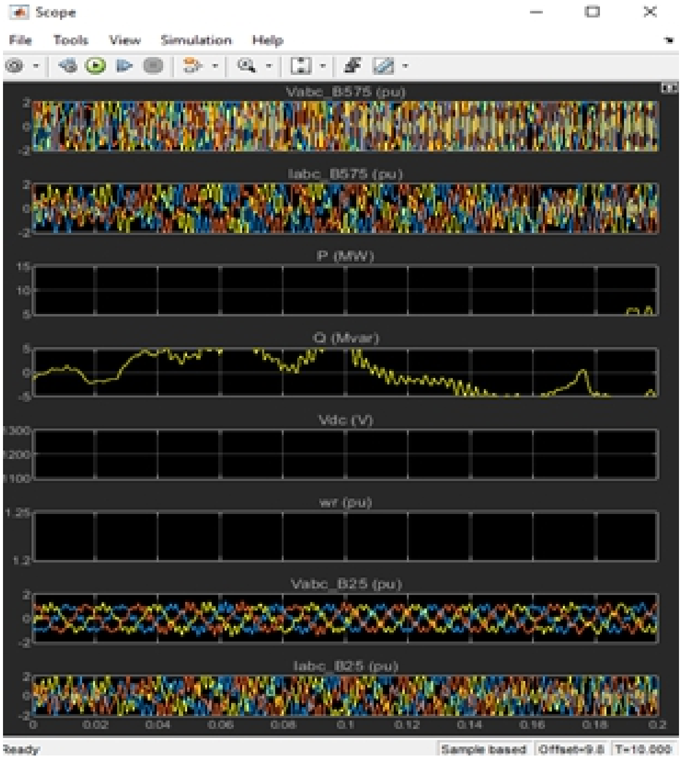


Fig. 23: Pulse width modulation (PWM) for various bus voltages of the DFIG

Average DFIG Model

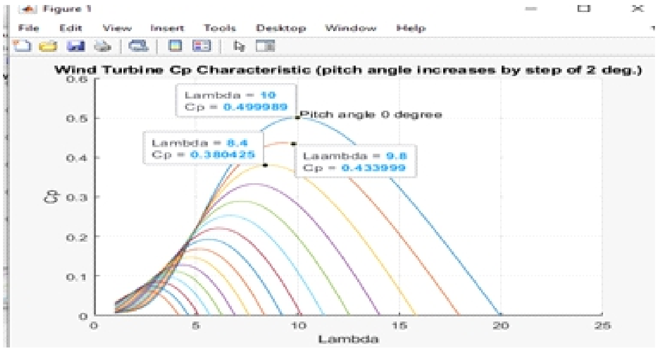


Fig. 24: Power coefficient characteristics at various pitch angles of the DFIG

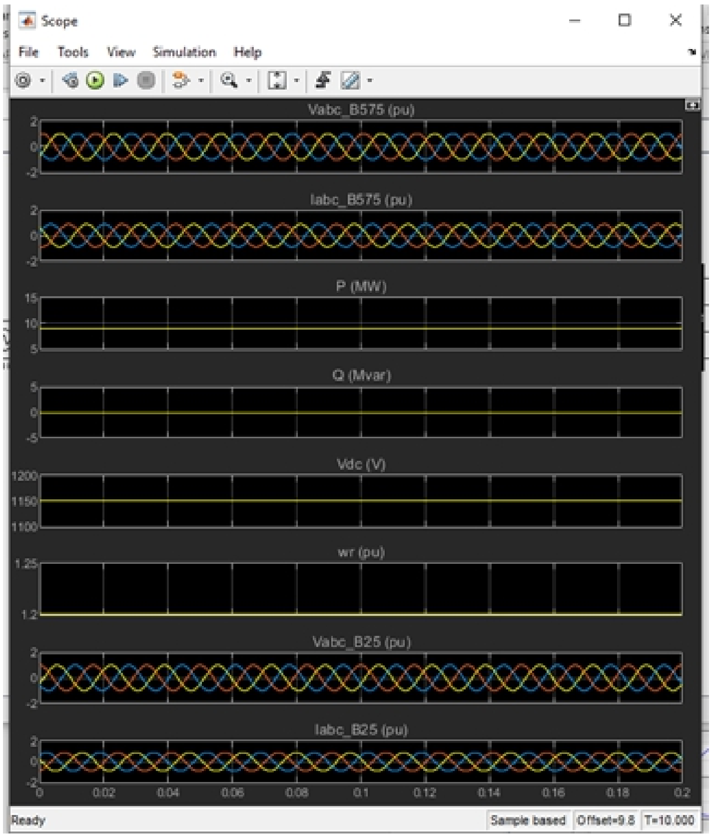


Fig. 25: Pulse width modulation (PWM) for various bus voltages of the DFIG average model

Comparison of the Two Models

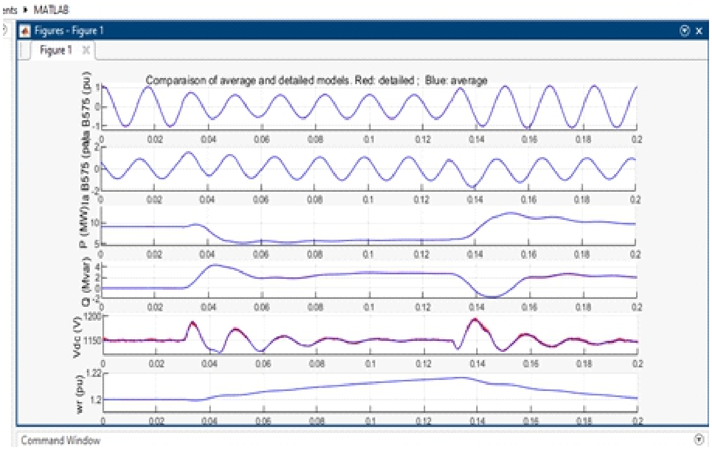


Fig. 26: comparison of the average model of the DFIG. Re signals represent the normal model while blue signal represents the average model.

Discussions

The variable speed pitch-controlled wind turbine with a DFIG is connected to the grid and the rotor is coupled to the grid through a power converter. The power converter allows the control of active and reactive power output. The grid is represented by a slack bus, into which the wind turbine's active power generation is injected at any time. For this project, the dynamics of the wind turbine are controlled through three controllers; the rotor speed controller, the pitch angle controller, and the state controller as shown in figures 1.20, 1.21, and 1.23 of chapter three respectively. Figure 1 shows the Power per unit (Pu) versus wind turbine speed. At a speed of 10m/s, pu is 0.5, and Power coefficient characteristics at various pitch angles of the DFIG shown in figure 5 is 0.5 when the pitch angle is set to zero. When the wind velocity is zero, the turbine is not generating mechanical power to the generator. Hence, the electrical output of the generator is zero. On the other hand, at maximum wind speed, the generated output is maximum. To achieve an acceptable accuracy with the 1620 Hz and 2700 Hz switching frequencies used in this project, the model is discretized at a relatively small-time step (5 microseconds). This is used to observe the harmonics and control system dynamic performance over relatively short periods (typically hundreds of milliseconds to one second).

The average model (discrete) such as the one presented in Figure 1.24, the IGBT Voltage-sourced converters (VSC) are represented by equivalent voltage sources generating the AC voltage averaged over one cycle of the switching frequency. This model does not represent harmonics, but the dynamics resulting from the control system and power system interaction are preserved. This model allows using much larger time steps (typically 50 microseconds), thus allowing simulations of several seconds.

The Normal mode (continuous) is shown in Figure 5. This model is adapted to simulate low-frequency electromechanical oscillations over long periods (tens of seconds to minutes). In the phasor simulation method, the sinusoidal voltages and currents are replaced by phasor quantities (complex numbers) at the system nominal frequency (50 Hz or 60 Hz). The Average model of the results of the simulation of the wind turbine DFIG is shown in Figure 7. A good obtained in dynamic handling and response to regulations imposed and reactive power. The fluctuations in the power are due to the PWM inverter and the dependence on these powers slips as shown in Figure 6. Figure Power per unit (Pu) versus wind turbine speed

Conclusion

Through a concrete example of the implementation of a prototype simulation of a system of wind power generation based on a doubly fed induction machine, I have highlighted some of the tools offered by Matlab / Simulink to design and help the complete study for such a system. Direct Torque Control (DTC) is an important alternative method for the doubly fed induction machine drive-based wind turbine, with its high performance and simplicity. The control of the DFIG connected to the grid with a back-to-back converter, using two control techniques: DTC for the rotor side converter and Voltage Oriented Control for the grid converter presents good performance and undulation reduction. The effectiveness of this proposed scheme control is shown by simulation using the blocks PSB of Matlab / Simulink and the results corresponding to the test of three levels of wind speed. Finally, I can conclude that the control methods applied to DFIG present the most interest and contribute to the improvement of system response performances. The first investigations, presented here, of the DFIG control prove its effectiveness and its high dynamics. It will be completed in future work by considering other control techniques particularly limiting torque undulations and resolving the problem of variable switching frequency. Additionally, I conclude that Matlab / Simulink is a powerful tool in the comprehensive study of dynamical systems and particularly in what concerns us the power generation based on renewable and new energy

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