PWM Controlled Double-Fed Induction Generator for Wind Energy Applications

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Abstract

In this paper, a wind power system using a double fed induction generator (DFIG) was modelled and simulated by using MATLAB/Simulink environment. At the beginning of the study DFIG and its control methods are introduced. After simulative approaches, it will be aimed that how DFIG response to speed changes in different load conditions with pulse width modulation (PWM) control method. The system is analyzed in terms of electromagnetic torque, rotor speed, voltage, current and control signals at constant DC Link voltage.

1. Introduction

The energy production based on fossil fuels such as coal, oil and gas, lose their importance and push the humanity to find new way for producing energy. As a main reason of that, it can be shown the rapidly depleted reserves, greenhouse gases emissions, and also increased cost sourced from lack of reserves. Additionally, the negative effects on human health and natural habitats make the fossil fuels intolerable and unsustainable. Even though all these harmful sides of fossil fuels, they have a great portion of the energy production levels on earth. However, coal, oil, gas, thorium, uranium and all other fossil fuels will be depleted in a close future because of the increasing energy demand of the world day by day. Therefore that great need on energy causes that the renewables become more daily issue.

In recent years, renewable energy systems become more popular, because they can offer new solutions to increasing energy demands with less environmental impact. They are also increasing their importance in the national energy production pie. As a result in the Fig. 1, the world energy production source types are given as pie chart.

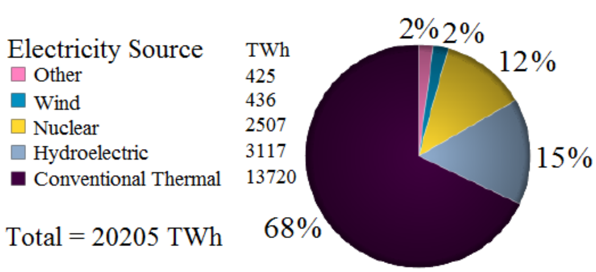

Fig. 1. World electricity production from all energy sources in 2011 [1]

In developing countries, the renewable especially wind energy takes a small share for energy production. However, wind energy is a growing energy type, so wind energy could be a proper solution for the relatively small consumers. Main concern of wind energy generation process is to find a proper solution for variable wind speed applications. To find this solution DFIG is a good option due to extremely wide usage in wind energy applications.

DFIGs are one of the most preferred generators in wind energy applications because of their fast response ability to changes in wind speed. In early 80's DFIGs started to use for variable speed applications in industry. Electrical engineers realized that DFIG is proper for wind energy applications and DFIGs became more popular in wind energy applications. Therefore, researches about DFIGs are increased. Besides, DFIGs have different control methods to use the maximum energy of wind, and applications of these control method are also widely studied by researchers [2, 3, 5, 6].

In this study, MATLAB/Simulink program is used for observing the behaviors of generator with dynamic outputs. By modelling the DFIG as a wound rotor induction machine and applying the proper control circuits on the systems, the some output are collected at different loads as a result of the simulation. During the simulation process, PWM control method is applied by taking the voltage and current values on the simulation and results are compared.

2. Double Fed Induction Generators

DFIG is an asynchronous machine that is used for wind applications especially. There is a wound rotor induction generator and an AC/DC/AC switch-based converter inside the DFIG base wind turbine model. A direct connection exists between stator windings and 50Hz grid, meanwhile a swinging frequency feeds rotor through the back-to-back converter.

2.1 Equivalent Circuit

DFIG is an asynchronous machine in basis of its structure; therefore its equivalent circuit can be drawn similar as an induction machine. In the Fig. 2, equivalent circuit of the DFIG is given with magnetization losses.

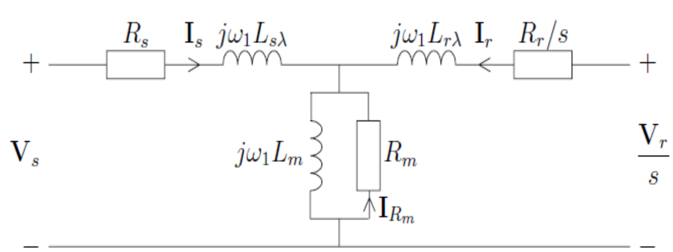

Fig.2. Equivalent circuit of DFIG [3]

This equivalent circuit is proper for each branch of wye connected phase, while steady-state conditions are valid. If the setup of DFIG is prepared as delta connected, the machine can be still represented with a wye connected one. In the figure, calculations of the component values of equivalent circuit are made in frequency domain. As a key point of calculation, if rotor wounds are short-circuited and rotor voltage (V_r) is taken as zero, equivalent circuit model of DFIG will be same with squirrel cage induction generator [3].

2.2 Operating Principles

A wind turbine diagram with a DFIG and converter circuits is shown in Fig.3. In this circuit C_{rotor} is rotor side converter (RSC), C_{grid} is grid side converter (GSC) and V_r, V_{gc} are the control signal of switches inside the converters. The back-to-back converter is a basic PWM converter which driven by sinusoidal PWMs provided by control signals.

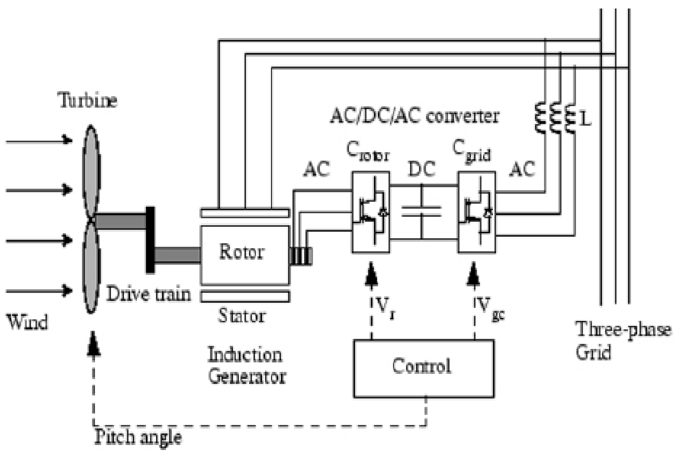

Fig.2. DFIG model [3]

In construction of DFIG, there can be observed to connection points affect the operation of machine. One of them is stator connections which are directly engaged to the AC grid line, and the other connection point rotor connections are fed from the grid over the power electronics converters by slip rings for operating the DFIG in variable speeds and allow fast response dramatic change on the wind speed. This concept is preferred instead of a frequency converter between the grid and induction generator, that have fixed and variable frequencies respectively. Power storage is provided by the capacitor between the RSC and GSC, for next generation cycles. Boosting the DC link voltage to a higher level than absolute value of the V_{L-L} of grid, allows that the take full control of the grid current. Power flow of the slip can be in both directions either from rotor to supply, if the rotor rotates in super-synchronous speed or vice versa if it rotates in sub-synchronous speed. Thus, DFIG can be controlled in both modes as a generator or a motor. While DFIG is operating in generator mode under or over the synchronous speed function of RSC is defined as rectifier and the GSC is defined as inverter and slip power is gone to grid. If the synchronous speed conditions will be examined, power on the slip ring is taken from the grid only for excitation of the rotor windings; hence the machine operates as a synchronous machine.

2.3 Control of DFIG

There are many different methods to control the DFIG, some and well-known of them can be listed as PWM control, frequency control, vector control, speed control, direct torque control, direct power control, and pitch control.

2.3.1 Rotor-Side Converter Control

In induction machines, rotor should be excited for the initial movement. In DFIG, this initial excitation is provided by the rotor-side converter (RSC). This RSC allows that to control the torque and speed as a result of controlling torque, by applying a PWM. Moreover, the power factor at the stator connections also can be controlled by this method.

2.3.2 Grid-Side Converter Control

Direction of the converters between slip rings and grid transformer can be in both ways. If the power flow is from grid to rotor GSC is operating as a rectifier, a control signal may not be required. However, if the power flows from rotor to grid, GSC operates as inverter. Hence, in that condition, it requires control signals to trigger the switches. One of the primary duties of GSC is to stabilize the DC-link voltage, apart from the magnitude and the rotor power direction. Thus, the real and reactive power flow from rotor to grid can be controlled by the GSC [4].

2.3.3 Frequency Control

In frequency control method grid frequency is taken as the feedback frequency. Inside of the frequency regulator block in simulation, a phase locked loop (PLL), comparator and a proportional-integral (PI) controller exist. Three phase grid voltage is converted into a proportional frequency signal by PLL and the frequency signal is transferred to comparator. In the comparator, input frequency signal that came from grid and the reference frequency are compared. Consequently, PI controller decides the control action according to comparison result of the comparator and gives an output which called as I_{dc_ref} this part is same with conventional control block.

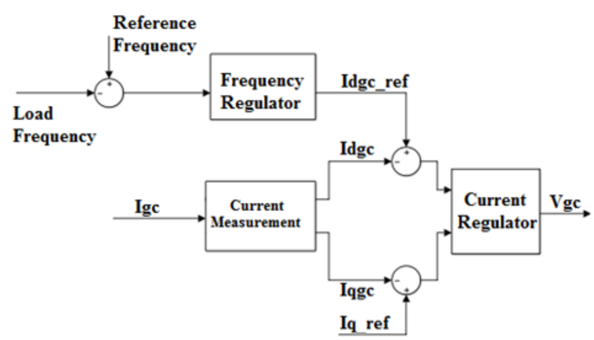

Fig.4. Frequency control method comparator [5]

2.3.4 Vector Control

Vector control is another well-known and commonly used version of the DFIG control methods. In this method, signals that are taken from lines are decoupled and processed with different methods or blocks, after then they are used for generating control signals.

2.3.5 Speed Control

Speed control is a method to evaluate rotor speed to achieve the highest efficiency. Therefore the instantaneous rotor speed is measured and compare with a pre-defined reference value. There are two different control strategy can be used according to operating region of the wind turbine. Using all available power from wind is the main target for partial loads. As an example strategy Maximum Power Point Tracking (MPPT) can be used, and the only requirement of this system is a rotation speed sensor. Wind speed always has variable values, due to its nature.

2.3.6 Direct Torque Control

Stator flux vector has a rotational movement at synchronous speed ω_0, because there is a direct connection between the stator windings of DFIG and power grid. First, voltage drop on the stator winding resistance and supply voltage fluctuation should be taken as zero. Moreover, a constant magnitude is considered for the stator flux. Thus, torque of DFIG, can be controlled by the rotor flux vector. When it has been considered that rotor flux $\Box_r$ has a circular trajectory, there would be a direct proportion between T and θ. It means the direct torque control is provided by controlling θ angle [6]. In that condition, changing on the θ angle will affect the torque produced; if the θ increases, the torque will also increase, vice versa torque will also reduce.

2.3.7 Direct Power Control

If the applied voltage vector on the real and reactive power states and position of stator flux is determined, a dynamic control of the power can be established. While active power state (S_p) and reactive power state (S_q) are generating, two of the three-level hysteresis comparators are used as can be found in Fig. 5. It can be realized that active and reactive power are impacted from zero voltage vector in a different for different running rotor speeds. Zero voltage vectors may cause much complicates issues because of rotor resistance itself, in particular near the synchronous speed. Hence, zero voltage vectors should not be used unless both power values are zero [7].

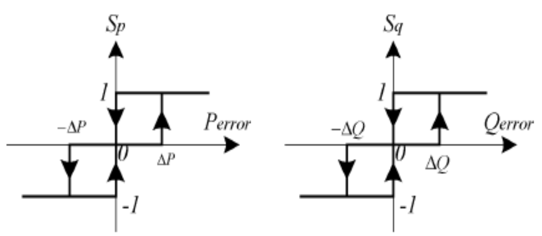

Fig.3. Hysteresis control signal [7]

2.3.8 Pitch Control

Pitch control is another method that influents the power coefficient C_p. For the wind speeds which are considered as low and medium speed, the pitch control is not necessary, usually pitch control is set on ideal value. However, for high wind speeds, maximum available wind power is transferred to the turbine generator by the controlling of the pitch angle, in the limits of the turbine. A sample block diagram of the pitch control is given in Fig. 6 [8].

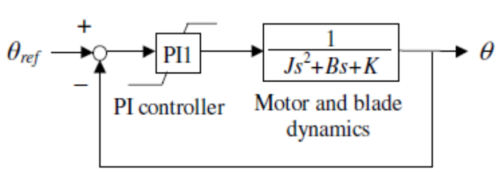

Fig. 4. Pitch control block diagram [8]

3. Methodology

General view of a DFIG base wind turbine model is given in below. As it seen in Fig. 7, a resistive load is connected to the wind turbine, and this load is a variable load that will take value between 0- 1,5MW.

Moreover, there is a programmable AC voltage source is added into simulation to provide the initial excitation for movement of electrical machine inside the turbine. This AC source cannot be linked directly to the wind turbine, thus an isolation transformer is added between the source and the turbine. This transformer has a 1:1 transforming ratio and it is set at 1.66 MVA apparent power. Both side of transformer have wye connection, and neutral points are grounded.

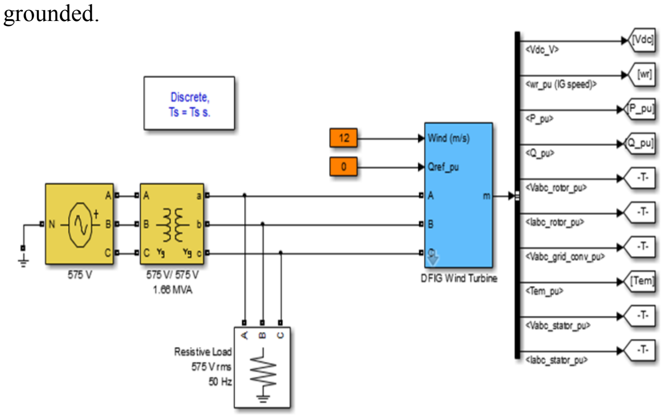

Fig.5. General view of simulation model

3.1 Determination of Parameters

DFIG parameters are one of the most important things in this simulation. To get accurate results, these parameters are taken from a previous example prepared in Simulink by Nicholas W. Miller, William W. Price, Juan J. Sanchez-Gasca in October 27, 2003 (GE-Power Systems Energy Consulting). As you can find in Table 1, the parameters of DFIG are given as tables.

Table 1. Generator parameters

P_n [MVA]	V_s [V]	V_r [V]	f_n [Hz]	p
1.66	575	1975	50	3

3.2 AC/DC/AC Converter Model

Back-to-back converters are the most important part of the DFIG control systems. Applied signals determine the behaviors of current and voltage outputs. For stabilization, control arguments are very important.

Essentially, back-to-back converter includes 12 switches, which are IGBT for this simulation, and 12 diodes for operating in both directions.

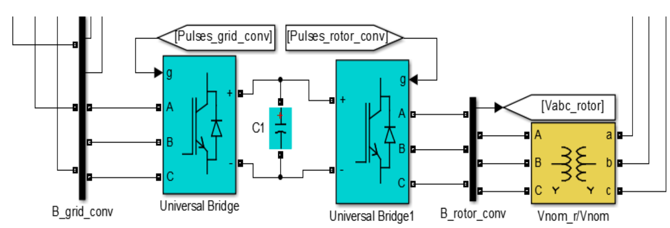

Fig. 6. Converter model in simulation

In establishing of converter circuit, two universal bridges are used to provide inverting and rectifying operations. To satisfy triggering on switches inside the universal bridges, six synchronized signals are applied to universal bridges.

To control the voltage and current signal, switches inside the universal bridges should be triggered with continuous pulses. These pulses are named as control signal, and they are generated by discrete 3-phase PWM generators. Control signal generation for converters can be examined under two subtitles.

- RSC Control signal generation
- GSC Control signal generation

4. Simulation Results

In this paper, modelled system is simulated at 9m/s, 11m/s and 13m/s wind speeds. During this simulation, constant DC link voltage, torque change, speed characteristics and voltage outputs are examined.

The following results are collected for 13m/s wind speed.

4.1 Results for 13m/s

At this wind speed level, electromagnetic torque increases due to increase in rotor speed. The rotor speed is related with wind speed especially.

It can be observed that the electromagnetic torque value is stabilized around the -0.75 p.u. value.

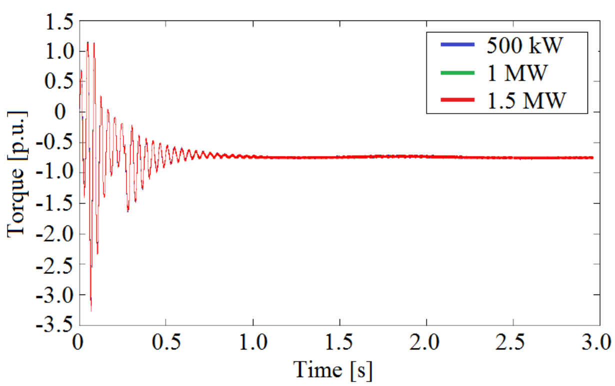

Fig. 9. Electromagnetic torque values for different loads

As it preferred, the DC link voltage stabilization level can be observed at approximately 1150 V level. In the Fig.10, DC link voltage characteristic is given.

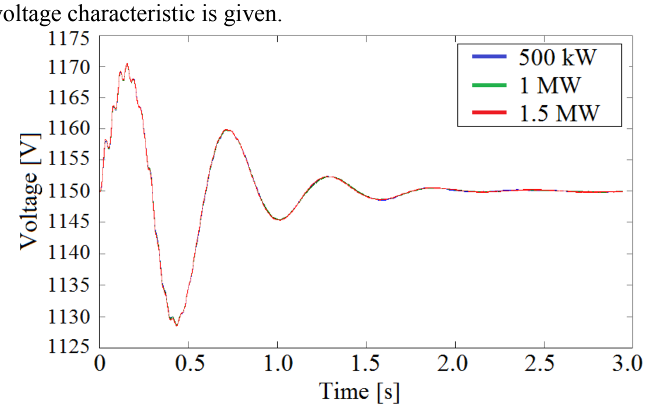

Fig. 10. DC link voltage values for different loads

When the rotor speed is examined for 13m/s wind speed, it can be realized that is the closest one to stabilize in all outputs. For this wind speed level, the rotor speed is set near 1.21 p.u. value.

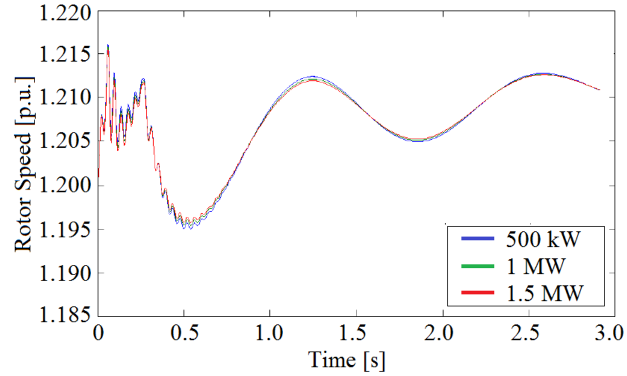

Fig. 11. Rotor speed values for different loads

Finally, the voltage and current outputs of the DFIG are examined and as given in Fig.12 and Fig.13 both uncontrolled and controlled situations of the voltage and current signals from the rotor and stator side are obtained, respectively.

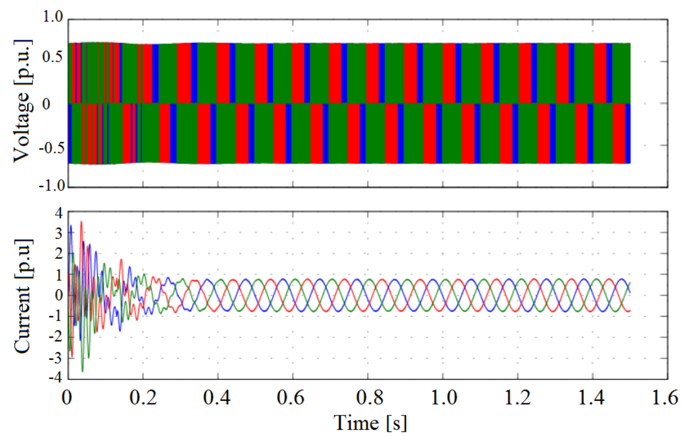

Fig.12. Uncontrolled situation of voltage and current signals from the rotor side

When these signals are processed with proper signals, the following voltage and current outputs are collected.

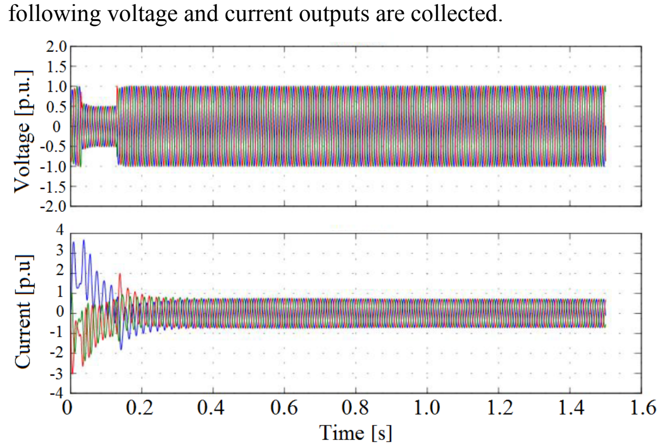

Fig.13. Controlled situation of voltage and current signals from the stator side

4.2 Comparison Results

As a result of the comparison in different loads and different wind speeds, it can be said that the chosen DFIG is more proper for high wind speed, and changes on load has no significant effect on the outputs of DFIG. Because, when DFIG is on operation, load can be considered as infinite. Load shows grid characteristics in operation. On the other hand stabilization of the system is most important thing for energy production.

Table 2. Stabilization Values

Wind Speed	Torque	DC Link Voltage	Rotor Speed
9 m/s	-0.51 p.u.	1149.8 V	1.07 p.u.
11 m/s	-0.65 p.u.	1150 V	1.17 p.u.
13 m/s	-0.75 p.u.	1149.9 V	1.21 p.u.

In back-to-back converter system, the DC link voltage should be stable, because required voltage is provided from here and also to stabilize the voltage that given to grid, keeping the DC link voltage is most wanted issue for this application. In this simulation, DC link voltage values are all set on the 1150V line with less than 0.02% error.

According to results of simulation rotor speed and electromagnetic torque outputs are compared and given in Fig.14.

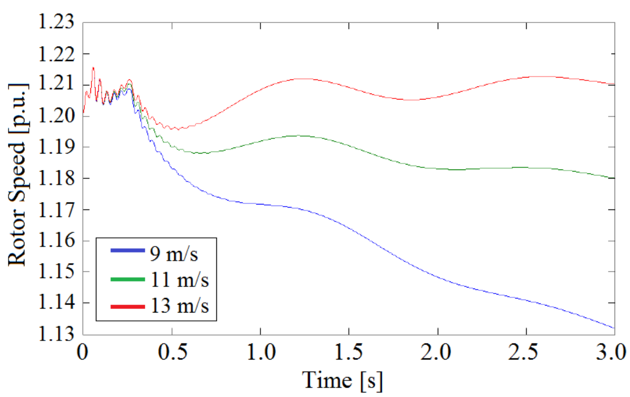

Fig. 14. Comparison of rotor speed values for different wind speeds

The reducing on rotor speed as a result of reduction in wind speed could be seen in the Fig 14.

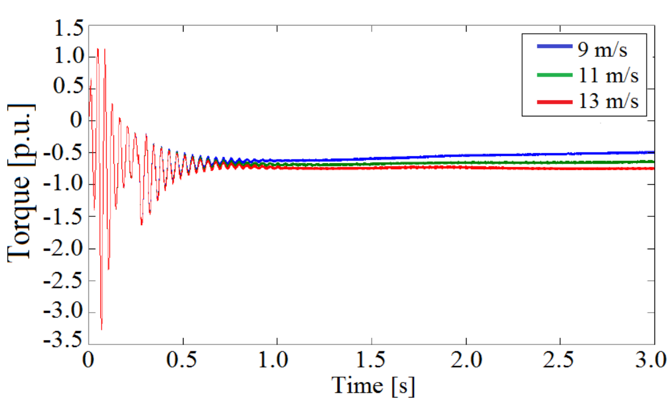

Fig. 15. Comparison of electromagnetic torque values for different wind speeds

When the comparison is examined for each graphic, all the electromagnetic torque outputs are affected from initial start ripples of rotor speed. The ripple on the rotor speed is a consequence of the mechanical system and feedback time of the drive train blocks.

Electromagnetic torque is directly proportional with the rotor speed. Therefore, changes in the rotor speed affect the stabilizing point of the electromagnetic torque as seen in the Fig.15.

5. Conclusions

In this study, it was aimed that control systems of a DFIG is examined for variable speed wind turbine applications. To achieve this aim, different models are simulated in the MATLAB/Simulink environment. First, the DFIG is modelled as a wound rotor induction generator and whole DFIG model is implemented on it. This model also includes wind turbine and drive train models.

Second, the DFIG model is run and the results are obtained in different wind speeds and loads. Therefore, the behaviors of the chosen DFIG are observed in defined conditions.

Finally, it is realized that chosen DFIG is more proper for high speed applications and back-to-back converter system is proper in terms of stable DC link voltage that supplied to grid for variable wind speed values.

7. References

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