Abstract

These days, the wind turbines have devoted themselves a great part of the market of the renewable energies. What is significant here is the necessity of optimal control of power (active and reactive power) and receiving the maximum mechanical power that can be absorbed from turbine in proportion to environmental conditions. Operation of control systems for wind systems has a basic goal, that is, generator control, which is performed by various methods. The present thesis investigates a wind system with a doubly fed induction generator that is connected through a power electronic converter. In this thesis, a new method for direct control of active and reactive power using second order sliding mode control is proposed. The proposed control method directly calculates the control voltage required for rotor using the non-linear sliding mode controller, so that the instantly errors of the active and reactive powers will be equal to zero and there is no need for current control loops, as a result of which, the design of system will become simpler and transient performance will be improved. The proposed method has a fast dynamic response and is resistant to parameter changes in addition to the possibility of simultaneously supplying two control purposes, i.e. omitting active and reactive power fluctuations. Proposed method has been implemented by MATLAB/Simulink which represents the accuracy of proposed scheme. The related results are compared with the results of the normal voltage vector control method and the results obtained from the control table of direct power.

Keywords: doubly fed induction machine, sliding mode control, wind energy, dynamic model.

Chapter 1

1-1-Introduction

Ever-increasing growth in energy consumption and restrictions of fossil fuels have led to various societies to think about other source of energy. Exploitation of renewable resources and the use of energy production methods with more efficiency are more significant than ever. Renewable energies refer to those kinds of energy resources that nature is always regenerating them and thus there is no limitation in using these energy resources. Wind energy, solar energy, heat energy of earth, and waves energy are the most important renewable energy resources which have been used so far.

The first attempts for using wind energy were begun by Iranians in applying the mills. At present, also among the renewable energy resources, wind systems have more economic justification than other energy resources, another advantage of this kind of energy is that if they are used at a variable speed, they are 20 to 30% more energy efficient than constant speed systems [1-3].

The most important issue in using this category of energy resources is to control and extract the optimal power from it so that the maximum output power can be extracted without interruption and with high quality in proportion to the changes of the environmental conditions and transferred to the throughout grid or to feed the local consumptions. To achieve the optimal power in different wind speeds, the speed of turbine must be variable in a wide range. In order to operate the system at the optimal speed, in addition to selecting the type of turbine, generator, converter and type of controller, other factors such as the type of machine specifications, the intensity and speed of the wind at the installation place, the price of equipment and maintenance are also significant.

Todays, the efficiency of exploitation of electricity energy generated by these resources can be maximized by using effective control methods, as a result of which the generating of energy becomes more economical in this way and also the cost of the generated electricity is reduced to a considerable extent.

The upcoming plans in developed and developing countries represent that the contribution of these resources in supplying the energy required by the world will considerably increase in the future, so that investment in this field will be highly promoted. Although it is possible to further develop the power of wind turbines, but the structural, installation, and mechanical restrictions of the market have made favorable for two megawatt turbines that are still the bestseller range of turbine for wind farms.

1-2-Research motivation

The main issue in the wind energy conversion systems is to control the power which ensures both quality and quantity of generated electricity. In fact, by using the power controllers, we increase both the quality of generated power and the maximum amount of energy that can be extracted from the turbine to its maximum value.

By progressing technology in the field of power electronic devices, the use of converters provided the possibility of holistic control of wind turbines. In fact, with the help of these converters, the generator and finally turbine can be desirably controlled.

From the beginning of studies conducted in the field of the wind systems technology, the various control methods were stated in the scientific articles that improved the performance of the wind turbines. Considering the dependence of the turbine performance on the environmental conditions and the non-linear curve of its power, control methods are always used to adapt instantly the working point of turbine with the maximum power point, which is also referred to the Maximum Power Point Tracking. In fact, the reactive power or aerodynamic power generated by the turbine is continuously adapted to the maximum generated power at variable wind speeds, which is the reference value of active power. Reactive power control is another significant aspect of power control in these systems in order to preserve power quality. Since wind systems are non-linear systems along with parametric indefinite, thus the best way to control them is to use non-linear controller that also have desirable resistance against system disturbances and uncertainties.

The generators that are most used in modern wind power generation systems are Doubly-Fed Induction Generators, because they have many advantages such as the variable speed performance, possibility of independent adjustment of active and reactive powers, low cost converter.

In this research, with regard to above cases, the active and reactive powers of doubly-fed induction generators is properly controlled by the proposed sliding mode controller directly. The control signal that is the optimal voltage of the generator rotor of wind turbine is applied to the converter of power-electronic and finally to the generator by the Space Vector Modulation. In this research, the converter is switched with a constant switching frequency by using the Space Vector Modulation which causes the design of the power converter to be simple. One of the innovation aspects in the present study is to model dynamically the doubly-fed induction generator in the reference frame of rotor which has led to the design of the controller without transforming the parameters to synchronous coordinates. By comparing the simulation results, we can notice the proper performance of the proposed controller compared with other designed cases.

1-3-Innovation and the purposes of thesis

The purpose of this thesis is to investigate and develop the control strategy of sliding model for DFIG. The applications of the variable speed of target which must be considered are the wind turbines connected to the grid. The purposes of thesis are as follows:

-Two-order sliding control strategy is considered and investigated for the variable speed application.

-Computer simulations are done in MATLAB/Simulink to initially compare the performance of a doubly-fed brushless wind turbine.

1-4-The structure of thesis

In this research, the content is given in five chapters and in the following order:

First chapter includes introduction. In the second chapter, the principal statement about wind turbines and constituent components is discussed. In the third chapter, the research background in the field of the power control of doubly-fed induction generator such as vector control, direct torque control, and direct power control is investigated, and the evolutionary process of controllers designed to maximize the productivity of wind systems is presented. The chapter 4 is devoted to explaining the proposed control method, so that the design procedure and implementation method of the desired plan, from the dynamic modeling of the doubly-fed induction generator in the reference frame of the rotor to the stating of sliding surfaces in controller, how to use Lyapunov's law, designing controller and proof of its stability and resistance against external disturbances and the investigation of the simulated results of the controller and desired system are discussed. In the last chapter, the conclusion is addressed and some proposed plans will be stated to need for continuing research.

Chapter 2

2-1-Introduction

In this chapter, by classifying the prior studies conducted on the wind and solar systems, a summary of these activities is examined in each section. At the end of conducted studies, the process of desired research in this thesis is investigated and strengths and weaknesses are stated.

2-2- power control methods of doubly-fed induction generator

The generator operation can be controlled by controlling the rotor side converter and the grid side converter. Various control methods operate by using the relations governing the generators by generating the pulse for switching of converters in such a way that favorable conditions are created.

The control of wind power plants equipped with doubly-fed induction generator is traditionally based on the vector control of stator flux. The control of active and reactive power is obtained by the control of rotor current. The direct control method of induction machine torque is another kind of vector control that reduces the use of machine parameters and does not involve the complexity of the vector control algorithm.

In this non-linear method, the current control loop has been completely eliminated and the control signal is directly commanded from a table. Although the direct control method of torque operates a little slow in the starting time, but this method presents a better performance compared to the vector control method due to less use of machine parameters, less complexity of control algorithm, and also the improvement in the transient response speed of system.

The principle of direct power control is also based on the choice of a proper rotor voltage vector, in order to instantly control the active and reactive power. The advantages of this controller include high dynamic, powerful performance, and its simple implementation.

1-2-3-Vector control (VC)

For the first time, vector control was used for squirrel cage induction machines. The vector control methods are based on rotor flux orientation and stator flux orientation and control the active and reactive powers of the stator instantly by the control of rotor current using the proportional-integrator controllers. The main disadvantage of proportional-integral controllers is not being resistant to partial changes in system parameters.

In [17], the neural network controller has been used, but the necessity of separating dq components of the rotor current is considered as one of the drawbacks of this method.

Among the problems of vector control method, the following can be mentioned:

-the necessity to transfer to a synchronous reference device

-the need for accurate adjustment of proportional-integral controller parameters

-the need to follow the phase angle and grid voltage

-it is based on the machine model, for this reason, it depends on the system parameters

-its implementation is complex

In fact, the active and reactive powers are independently controlled by using vector control in converter on the rotor side in direction of stator flux [18].

If the reference frame is considered in the same direction with the stator flux λ_s , it is obtained [19]:

$$\overline{\lambda_s} = \lambda_s = \lambda_d \text{ and } \lambda_q = 0 \text{ and } \frac{d\lambda_q}{dt} = 0 \quad (2\text{-}1)$$

If the frame along the stator flux is named dq frame, by supposing constant stator flux and considering zero stator resistance, active and reactive powers of stator will be equal to the following values:

$$P_s = \frac{3}{2} v_{qs} i_{qs} = \frac{3}{2} |\overrightarrow{v_s}| i_{qs} \quad (2\text{-}2)$$

$$Q_s = \frac{3}{2} v_{qs} i_{ds} = \frac{3}{2} |\overrightarrow{v_s}| i_{ds} \quad (2\text{-}3)$$

For components of stator current, there is:

$i_{ds} = \frac{L_m}{L_s}(|\overrightarrow{i_{ms}}| - i_{dr})$ **(2-4)**

$i_{qs} = -\frac{L_m}{L_s}(i_{qr})$ (2-5)

Finally, for active and reactive powers of stator, there is:

$P_s = -\frac{3}{2}\frac{L_m}{L_s}|\overrightarrow{v_s}|i_{qr}$ (2-6)

$Q_s = \frac{3}{2}\frac{L_m}{L_s}|\overrightarrow{v_s}|(|\overrightarrow{i_{ms}}| - i_{dr})$ **(2-7)**

As it can be seen in relations (2-6) and (2-7), the active power of stator is controlled by q-axis current and reactive power is controlled by d-axis current of rotor independently. In fact, this issue is the principle of the concept of vector control. In the other words, to control the active and reactive powers, first, the components of the rotor current must be isolated, but considering that the main purpose is to control the active and reactive powers by injecting the rotor voltage, the current components must be specified by voltage components.

2-2-3- direct torque control DTC

Direct torque control strategy which first was widely used for the squirrel cage induction machines, also used to control the electrical torque in the doubly-fed induction machines due to proper dynamic performance. The ABB company developed the first low power converter to control doubly-fed induction machines for wind applications using this technique [20].

In order to implement this strategy, it is essential to know the angle and amplitude of the rotor flux vector. Then, the rotor flux is obtained as follow by using the rotor and stator current stated in the rotor reference frame.

$|\psi_r| = \sqrt{\psi_{\alpha r}^2 + \psi_{\beta r}^2}$ (2-8)

$< \psi_r = \tan^{-1}(\psi_{\beta r}/\psi_{\alpha r}$ (2-9)

$\psi_{\alpha r} = L_0 i_{\alpha s}^r + L_r i_{\alpha r}$ (2-10)

$\psi_{\beta r} = L_0 i_{\beta s}^r + L_r i_{\beta r}$ (2-11)

In the relations (2-10) and (2-11), $i_{\beta s}^r$ and $i_{\alpha s}^r$ are the stator currents in axes β-α in the rotor reference frame. In this method, the electrical torque is equal to:

$T_e = K(\psi_{\alpha r} i_{\beta r} - \psi_{\beta r} i_{\alpha r})$ ***(2-12)***

2-2-3-Direct power control (DPC)

The Direct power control method was propounded about 15 years ago to control the 3-phase rectifiers of PWM. Due to the non-linear nature of inverters, limitation of switching modes and the variation of machine parameters during operation, the Direct power non-linear control has been presented in the last decades. This method was developed for controlling the doubly-fed induction generator based on the principles of direct torque control method for motor drives using hysteresis controllers.

In this case, first, the active and reactive powers are compared with the reference values, and their errors are injected to the hysteresis controllers. Finally, switching of the converter on the rotor side is done based on the controller output and flux situation of rotor or stator and with regard to the predetermined switching table.

The switching frequency is variable in this method that causes the increase in the costs related to power-electronic devices. Another problem of this method is a lot of harmonics which are generated as a result of its implementation. The principle of the Direct power control method is to control the stator powers by using proper voltage vector for the machine rotor [20].

Direct power control methods are not as complicated as vector control methods and have a faster response and higher accuracy. Moreover, although it is a model-based method, they are more resistant to variations of machine parameters. But they have variable switching frequency due to the fact that whose switching pattern is directly selected from an optimum switching table.

The active and reactive powers of stator are extracted from the following relations:

$P_e = K_{transf}(v_{\alpha s} i_{\alpha s} + v_{\beta s} i_{\beta s})$ (2-13)

$Q_e = K_{transf}(-v_{\alpha s} i_{\beta s} + v_{\beta s} i_{\alpha s})$ ***(2-14)***

Some of direct power control methods include hysteresis control of power or torque, and the converter outputs are selected by the switching table. In some other methods, the vector modulation is used to keep the frequency constant. It should be mentioned that in each of above methods, in case of desiring to track the maximum power, it is needed the speed to be measured.

2-3- A review on the previous research

Sliding mode control is appropriate for the non-linear systems in which there is the uncertainty such as wind systems. The advantages such as high resistance, simple implementation, and fast response of this control method is also considerable. The application of sliding control is given in [21] for driving electrical machines. In the references [22-24], this controller has been used in the wind and water turbines to control the powers of doubly-fed induction generator.

The main problem in these references is the necessity of separating the rotor current components to control the active and reactive powers. In the references [25-27], this problem has been solved by using direct power control method and applying sliding mode. Control strategy in these references is such a way that the generator should track the maximum power that turbine can be absorbed at each moment. Generator control using the high-order sliding mode control methods is of the widely used control methods. In the article [28], the high-order sliding mode control method due to the advantages such as the reducing of mechanical stress, and resistance to the non-modeled dynamics, and external disturbances.

In this paper, a second-order vector sliding surface is used to generate the control signals which is for creating the error dynamic, use of rotor current, and electrical torque for maximizing the output power.

The article [29] investigates the control of generated power in the wind turbines with variable speed that has two working regions dependent on the rate of speed peak. the high-order sliding mode control method is used to ensure the stability of system in both working regions and to impose ideal feedback control despite model uncertainty.

This control method has good specifications such as resistant to the uncertainties of system parameters. In this method, the rotor speed and torque is obtained by a sliding mode observer, and its difference with optimal torque creates the error required for sliding mode controller to control the output power.

In article [30], an adaptive-fuzzy-integral controller that has variable structure has been used. In this control system, the controller is based on the sliding-integral mode controller that the adaptive-fuzzy method is used for estimating the uncertainties in the switching gain. Also, at the end, the controller stability has been proved by the Lyapunov method.

In the article [31] (3-1), a power control method for the variable-speed wind turbine connected to the grid has been presented. In this method, control goals change based on the changing of turbine regions created by the change of wind speed. In this case, the goal is to maximize the active power in the partial load zone and to keep it constantly when the system operates in the full load zone. Moreover, the reactive power must supply the needs of the grid.

The method used in this article is based on the second-order sliding mode control and the Lyapunov, which the improved algorithm of Super Twisting Algorithm along with the variable coefficient for the non-linear multi-input multi-output system has been used. The applied algorithm has the known features such as resistance, algorithm simplicity, and adaptive characteristic.

Figure (2-1): control system of wind turbine [31]

The article [32] proposes a non-linear feedback/feedforward controller on the wind turbines with variable speed along with the doubly induction generators. By adjusting the rotor voltage and the bending angle of the blades, the active power can be controlled in both modes of the tracking maximum power and adjusting power, and also the reactive power can be controlled in such a way that the optimal power factor is kept.

In the article [33], an improved direct power control method is proposed for the wind turbine connected to the grid when the grid voltage is not balanced. This method is stated based on the concept of sliding mode control which is responsible for adjusting the active and reactive powers needless to follow the phase angle and grid voltage. A new combinational power method is presented during the grid imbalance period in order to achieve the following control goals:

Achieving the resistant and sinusoidal stator current, eliminating of stator reactive power ripples, and also preventing stator output active power fluctuations. The components of active and reactive powers can be obtained by a simple method and by considering the three mentioned control objectives and without the need for expanding negative sequence of stator current components. Also, in the article [34], figure (2-2), the second-order sliding mode control is used to control the power in synchronization of the grid. In this article, a second-order sliding mode controller is used to control the wind turbine. Two various algorithm is designed for instructing to the rotor side converters at the constant switch frequency which is responsible for controlling the power of grid synchronization. Also, this method ensures the proper transmission between two controllers at the moment of connection between turbine and grid.

Figure (2-2): sliding mode controller of active and reactive power [34]

In the article [35], due to the high impact of the bending angle adjustment on the quality of the adjusting power, a sliding-fuzzy-adaptive mode controller that uses the feedback linearization is used for the generator of wind turbines with variable speed. The sliding mode control law is obtained and also the stability is proved.

Due to the good characteristics of sliding mode control including the lack of sensitivity against disturbance and changes of parameters, a sliding mode controller is used over the bending angle, control law of which is obtained by the feedback linearization. The fuzzy-adaptive technology along with the sliding mode controller are used to ensure the stability and desirable efficiency. The fuzzy estimator is applied to avoid using the mathematical model and insensitivity to external disturbances. An adaptive law is also used to adjust the parameters in such a way that to reach the error of tracking to zero asymptotically. Overall stability of system is also proved by Lyapunov’s stability theory.

2-4-concepts of wind turbine

Since their inception, various types of wind turbine concepts have been introduced. Two main types of wind turbines are: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). The HAWTs are the dominant types and are used around the world for different reasons such as efficiency and ease of installation.

The wind turbines can be categorized based on the various specifications that are described in the following:

There are two types of wind turbines in terms of speed control:

1: fixed-speed wind turbines (FSWT)

2: variable-speed wind turbines (VSWT)

2-6-1- fixed-speed wind turbines (FSWT)

These wind turbines rotate at a constant speed under any wind condition. The lower efficiency of wind turbines is with the variable speed, because rotating speed cannot be changed with regard to the change of wind speed. Thus, these types of wind turbines are installed in locations where a certain wind speed prevails throughout the year. The advantage of wind turbine with fixed speed is that its manufacture is relatively simple, and its cost is cheaper than the wind turbine with variable speed. However, the manufacturing requirements are stronger. Since the rotor speed cannot be changed, the fluctuations of wind speed is directly converted to the drive train torque fluctuations which can create the higher structural loads.

2-6-2- variable-speed wind turbines (VSWT)

VSWT can change its rotation speed with the help of the earth control. This allows the turbines to adapt to different wind speeds. The turbine follows various power factor curves (C_p) for various wind speeds. In VSWT, the mechanical stress is less because the rotors act as flywheels (store the energy as a shield) and reduce the changes in the drive train torque. Figure (2-3) shows the power factor of a usual VSWT, in which the turbine follows the different curve at the various wind speeds. The tip of each curve is related to maximum output power of wind turbine at a certain wind speed value. The black line passes through all outputs of maximum power.

2-6-3- taxonomy based on the screw control

In terms of the earth control, the types of wind turbines are given below:

1: stall-regulated

2: pitch-regulated

Figure (2-3): C_p curve for VSWT

Stall-regulated wind turbine:

The stall regulation is obtained by shaping the wind turbine blades which are stopped at high wind speeds, so the torque is reduced and the turbine is stopped. They are simple and cheap and does not have the pitch control mechanism.

Regulated wind turbines

The regulated wind turbines have the pitch mechanism usually in the form of servo motor (control motor) that change the angles of the turbine blade around its axis, and hence they change the angle between the input wind and the front edge of the blades.

2-5- types of IEC standards

International Electrotechnical Commission (IEC) has been defined the types of $HAWT_s^1$ standards. (Ackermann, 2012).

They are:

1: A-model wind turbine

2: B-model wind turbine

3: C-model wind turbine

4: D-model wind turbine

Table (2-1): the types of wind turbines based on the earth control and stall

pitch angle	Rotational speed	Wind turbine concept
fixed	fixed	Disabled stall control
variable	fixed	Enabled stall control
variable	variable	pitch control (earth)

The table shows a summary of taxonomy

Table (2-2): types of wind turbines

Speed control		Power control		
		stall	pitch	Active stall
Fixed speed	A type	typeA0	A1 type	A2 type
Variable speed	B type	typeB0	B1 type	B2 type
	C type	typeC0	C1 type	C2 type
	D type	typeD0	D1 type	D2 type

A Model:

The A-type wind turbine is a fixed-speed wind turbine which is directly coupled to the generator, and each type of fluctuation at mechanical rotations is converted directly to the fluctuations at the electrical output. The turbine has been designed for the rotation with fixed speed, and often is accompanied with a capacitor bank to supply the reactive power.

The A-type wind turbines use the squirrel-cage induction generator (SCIG) for generating electricity.

Figure (2-4): A-type wind turbine

The A-type wind turbines are mostly categorized in the A0 class. The A1 and A2 types are based on stall, pitch, and Active Stall Control.

B Model:

This type of wind turbine is known as the wind turbine with limited variable characteristics. It has the wound rotor induction generator (WRIG) to generate power. The generator has a variable resistor which helps to control the rotation speed.

Figure (2-5): B-type wind turbine

C Model:

The c-type wind turbine is equipped with wound rotor induction generator (WRIG) along with partial scale frequency converter. This type of wind turbine provides the better control on the dynamic speed of wind turbine. Depending on the partial scale frequency converter, c-type turbine can provide a speed from 30% to 40% of synchronous speed.

Figure (2-6): c-type wind turbine

D Model:

The D-type wind turbine is a full variable-speed wind turbine, in which the generator is connected to the grid via the full scale frequency converter. The generator that is usually used is a permanent magnetic synchronous generator (PMSG) or doubly-fed induction generator (DFIG). 4-type wind turbine allows extracting maximum power from the wind turbine by optimizing the speed of the turbine rotor at low wind speeds and minimizing the stress on the wind turbine drive train during windstorm (Gagnon, 2018). The power-electronic interface provides supporting from the required reactive power and also softer connection to the grid. Full scale frequency converter in D-type wind turbine converts the electricity generated at various levels of voltage and frequency to a standard grid voltage.

Figure (2-7): D-type wind turbine

Frequency: this includes a power electronic circuit consisting of rectifiers, inverters, and other components of power-electronic. It consists of a rotor-side converter and a grid-side converter. The rotor-side converter controls the torque and reactive power of wind turbine generator, while the grid-side converter is responsible for changing the level of voltage and frequency of output power. For this thesis, D-type wind turbine has been used. The values of power factor C_p and power curve are taken of a 2-megawatt reference wind turbine used in the part of wind energy of Denmark technical university. The reason for use of this wind turbine is that it is the last type of VSWT which is used in the most wind farms. This type of wind turbine is equipped with the full frequency converter which controls the output power of wind turbine completely.

2-6- working principle of wind turbine:

In this section, performance physic of wind turbine has been presented. Like other production processes, the wind turbine converts the wind kinetic energy to the rotating of turbine blades. This torque is converted to the spin motion of generator which in turn, converts it to the electrical energy. The main difference is in the main energy source that is natural source about wind turbine, i.e. wind. A three-blade standard HAWT consists of various components that have a role in converting the wind kinetic energy to electrical energy. Figure (2-4) represents the main components of wind turbine. Aerodynamic rotors absorb the current wind energy and are connected to the generator through an axis and a gearbox that rotates and generates electrical force. The modern wind turbines are equipped with power electronic circuits in the output. The generator output is mostly connected to the transformer to increase the voltage so that the wind power plants can be connected to different levels of grid voltage (transmission, sub-transmission, or distribution). (Hansen, 2016).

Figure (2-8): source wind turbine components (Hansen, 2016)

Rotor Aerodynamic:

The rotor of wind turbine consists of three blades that are connected to the hub at the base. The power generated from wind turbines is stated as follow:

$P = \frac{1}{2}\rho\pi R^2 U^3 C_p(\lambda, \theta)$ (2-15)

Where,

'ρ' is air density which is considered 1.225 Kg/m^3.

'R' is the turbine rotor radius in terms of meter.

'U' is wind speed in terms of meter per second.

'C_p' is power factor.

'λ' is the tip speed ratio

' θ' is the pitch angle.

Power factor ($\boldsymbol{C_p}$) is the wind turbine curve that shows the percentage of power it can extract from the wind. The mechanical power p_{mech} can be shown in terms of total power in wind p_{wind}:

$$p_{mech} = C_p . p_{wind}$$

The upper limit of theory $\boldsymbol{C_p}$ according to Betz's limit formula is 16/27 or 0.59 that means that a wind turbine can extract maximum 59% of power from the input wind.(wan quick, 2007). $\boldsymbol{C_p}$ is tip speed ration (TSR) function, and the pitch angle is β.

$$C_P = f_{c_p}(\lambda, \beta)$$

Formula used for calculation of "C_P":

$$C_P = \frac{1}{2}(\lambda_i - 0.022\beta^2 - 56)e^{-0.17\lambda_i} \quad (2\text{-}16)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}) \quad (2\text{-}17)$$

Where, λ is the tip speed ration(TSR), and β is the pitch angle.

TSR(λ) is defined as the ration of the tip speed of the turbine blades (w_{rotor}) to the speed of the input wind (U).

$$\lambda = \frac{w_{rotor}R}{U}$$

Figure (2-9) shows a typical performance factor curve C_P of a wind turbine.

Power curve

The power curve shows the relation between wind speed and output power of wind turbine. Figure (2-11) shows aerodynamic power and power curve of a standard wind turbine. The dotted curve is the maximum aerodynamic power which can be extracted by the turbine.

Figure (2-9): the tip speed ratio curve versus C_P

Figure (2-10): C_P, curve of a two-megawatt reference wind turbine at various wind speeds

The rotors in accordance with (2-16), while the integrated black line indicates the real or practical power extracted by the wind turbine as a result of the restrictions and control of the wind turbine.

Figure (2-11): the power curve of a source wind turbine (Hansen, 2016)

Power curve consists of two zones:

1: power optimization zone

2: power limitation zone

2-6-1- power optimization zone

The power curve part between V_{cut-in} (cut wind speed) and V_{rated} (rated wind speed) is called the power optimization zone. The wind turbine generates maximum power with regard to wind speed in this zone.

- V_{cut-in} is minimum wind speed which is necessary for beginning the rotation of wind turbine and generating electric force.

- V_{rated} is the rated wind speed in which the wind turbine reaches its maximum power and confines any further increase in output power.

- $V_{cut-out}$ is the last value of the wind speed after which the turbine must stop to avoid flowing water conditions that may cause permanent mechanical damage.

2-6-2- power limitation zone

This zone is the power curve between the rated wind speed and stopped wind speed. Over this part of the curve, output power is confined to maximum turbine rating.

2-6-3- Generator

Generator is a mechanical device that converts the rotational motion of the rotors to output electrical energy. As it is mentioned before, the generators used in a wind turbine can be synchronous, asynchronous, or induction generators. For D-type wind turbine, the permanent magnetic synchronous generator (PMSG) is usually used.

Electrical angular velocity by:

$$\omega_{e0} = 2\pi f_0 \qquad [rad/s] \qquad (2\text{-}18)$$

Where, "f_0 " is the grid frequency 50HZ.

To convert rotation speed in revolutions per minute:

$$\omega_{gen0} = \frac{\omega_{e0}}{N_{pp}} = \frac{2\pi f_0}{N_{pp}} \qquad (2\text{-}19)$$

In which,

'N_{pp}' is the number of pole pairs in the generator.

To convert rotation speed in revolutions per minute:

$$n_{gen0} = 60\frac{f_0}{N_{pp}} \quad \text{gearbox} \qquad (2\text{-}20)$$

The gearbox is a mechanical device that converts the slow rotation of the rotor to the high rotation of generator. The ratio of gearbox by

$$N_{gear} = \frac{\omega_{gen}}{\omega_{rotor}} \qquad (2\text{-}21)$$

This ratio is different from the change of number of pole pairs in the generator.

2-6-4- Power electronic converter

The existing the power electronic converters depends on the type of the wind turbine. The traditional fixed-speed wind turbine consists of the cheap power electronic interface, while the VSWT wind turbine has a complicated power electronic interface which separates turbine and generator from grid practically. D-type wind turbine has a full-scaled frequency converter (including a rotor side converter and a grid side converter). This power electronic interface provides the capabilities of better grid control and enables the wind turbines to change the output based on the grid requirements.

Chapter 3- control of doubly-fed induction generator using the proposed method

3-1- Introduction

Wind energy technology has been significantly increased in the past few decades. The capacity (ranking) of a single wind turbine has been raised from few ranges of KW to the plants generating 1-5 MW [50,90]. Generating the wind energy can be categorized to the wide three categories based on the total power generation capacity.

A) Tool scale which is related to large wind turbine (900KW-3.5MW), mainly used for bulk power generation for the market of energy.
B) Industrial scale which is related to medium turbines (50KW-600KW) mostly used by the industries for generating remote grids for responding the local needs.
C) Residential scale which is related to small turbines (both 1-phase and 3-phase)

The increasing reliability of large wind turbines system (wind farm) as an inseparable part of the grid has led to a corresponding reduction in cost, with the availability of modern devices reached 97-99%. Many advancements have been made in the components related to grid integration, electrical device, electricity converters and capability of control. However, there are many challenges, and the problems have not been solved. At the present, the real and reactive power of the device may be controlled for the variable operations of speed. This zone of the control strategy has turned into a very challenging research topic, and technology is developing that presents many future capabilities. This requires to understand the total power systems and integrating system, machinery and applications of power electronic converters and control plans that are in a common platform.

Wind turbines are widely used around the world based on the technology of doubly-fed induction generator (type 3). In comparison with the wind turbines using fixed induction generator (type 1), wind turbines based on DFIG provide various advantages such as speed variable operations and active abilities and a quadrilateral. Such a system causes also the reduction in costs of converter and less losses compared to a system based on a full synchronous generator (type 4) with full converter. Commonly, in comparison with other similar rating devices, DFIG has considerable costs compared to the full converter with regard to the lower power rating of the rotor converter.

3-2- Doubly-fed induction generator

DFIG, as mentioned before, is basically a conventional-rotor induction device in which the stator is directly connected to the grid through a transformer, and connection of the rotor to the stator and grid is through a recursive voltage supply converter. The rotor converter system includes a grid side converter (GSC) and the rotor side converter (RSC) is connected via DC linkage. A simple simulation diagram of wind energy generation system based on DFIG has been shown in figure 3-1.

Figure 3-1. configuration of wind energy conversion system DFIG (single generator) by using the recursive converter.

The generator is called DFIG, because the power is fed to the grid form both stator and rotor circuits. The rotor circuit usually controls about 25 to 30% of the generator property power. This percentage allows the DFIG to have about 30% of the operating speed around the synchronous speed and reduce the rating and cost of the rotor converter [28,36]. The converter size is not related to the total generator power, but it is related to the range of selected speed and hence to power of slip. Thus, the cost of converter will increase when the range of speed becomes broader. Therefore, selecting the speed range is based on economic optimization of investment costs and increasing the productivity. Since the DFIG is connected to the grid, the high transient currents may destroy the power electronic devices of rotor converter due to grid disruptions. The protection system called "crowbars" is used, in which wound rotor can be released in short-term during fault period via a small resistor and when the error is removed.

3-3- principle of operation of doubly-fed induction generator

Reciprocal electric machines in industry are 3-phase rotor type. Although their principles of operation are known for decades, the large plan only has been recently entered and almost is due to the emergence of the wind power technologies. DFIG operates in both sub-synchronous (rotor speed is lower than synchronous speed) and super-synchronous (rotor speed is higher than synchronous speed) that gives to a wide range of operational speed about 30% around the synchronous speed.

Main advantage of double induction generator during using in the wind turbines is the ability to keep the amplitude and frequency of the output voltage basically constant in the grid values regardless of wind turbine rotor speed. For this reason, two-dimensional induction generator can be directly connected to AC power grid and always be in sync at all times. The other advantages include the ability to control the reactive power from the rotor circuits to the grid which allows the DFIG to support voltage stabilization and power factor correction at the common connection point (PCC).

The rotor speed control characteristic is used to overcome wind speed changes by adjusting the frequency of AC voltage and currents fed to the wound rotor. This principle cab be understood by explaining the sub-synchronous and super-synchronous modes of operations discussed below.

3-3-1- sub-synchronous mode

When the generator rotor speed n_{rotor} is less than synchronous speed n_s, the rotor frequency f_{rotor} of induction voltage increases accordingly and (according to usual contract) has the positive pole. The positive pole means that the phase sequence of the AC currents injected into the windings of the generator rotor causes the rotor magnetic field to rotate in the same direction of the generator rotor, and as a result of controlling the phase sequence of the injected current of rotor, it receives electricity from the grid through the rotor converters (GSC & RSC). This approach for controlling the power flow in the wound rotor of DFIG in the sub- synchronous mode can be described by understanding the power flow equations of an induction machine, as it is explained below [24,71].

$$P_g = P_m + P_r = (1 - s)P_g + sP_g$$

P_g is air gap power, P_m is the mechanical power transferred between rotor and axis, and P_r is the slip power (sP_g) transferred between the rotor converters and electric grid in case of DFIG. The slip “S”:

$$s = \frac{n_s - n_{rotor}}{n_s}$$

The ordinary induction motor with short circuit rotor windings operates at a speed lower than its synchronous speed. Mechanical power P_m is considered as positive when transferring from rotor to axis, and then conducts mechanical load (such as pump or fan). In this case, the slip is positive $(0 < s < 1)$, the air gap power will be positive when transferring from stator to rotor. If the direction of current is reversed for both P_g and P_m, (i.e. they are negative values), the machine will operate in the generator mode (DFIG in sub-synchronous mode). Also, the slip power will be negative, and it is supplied by the converters (GSC & RSC) to a rotor that rotor side converter (RSC) operating as an inverter and the grid side converter (GSC) operating as a rectifier. Reversing the direction of slip power in the rotor circuit is done by reversing the phase sequence of voltage or AC current injected into the wound rotor of DFIG. Figure 2.2 shows the current direction of slip power of DFIG in two modes of sub- synchronous (grid to rotor) and super-synchronous (rotor to grid).

3-3-2- Super-synchronous mode

Similarly, When the generator rotor speed n_{rotor} is higher than synchronous speed n_s, the frequency of currents f_{rotor} that must enter the generator rotor windings increases accordingly and now it has the negative pole. The negative pole means that the phase sequence of the AC currents injected into the windings of the generator rotor causes the rotor magnetic field to rotate in opposite to the direction of the generator rotor. It means that the slip (s) is higher than negative synchronous speed $(s < 0)$. DFIG operates in the super-synchronous mode, where the slip power p_r is controlled by controlling phase sequence of currents injected into the rotor windings of DFIG. In this mode, the slip power will be positive and is transferred from the rotor of generator to the grid through the rotor converters of DFIG, where RSC operates as a rectifier and GSC operates as an inverter.

3-4- general control plan for DFIG

Currently, DFIG is widely used in many applications of wind energy with variable speed and occupies about 50% of wind power generation industry. Due to the popularity of DFIGs for generating wind energy, the appropriate control systems have been widely investigated for this application. Figure 4.1 represents an ordinary control plan of a DFIG which exists in the market currently. Control plans are categorized to three main levels based on the connection to the grid. By increasing wind capacity and the number of the wind turbines, the grid operators should ensure that the quality of the consumer's electricity is not endangered. To enable the widespread use of wind energy without endangering the stability of the power system, the turbines must remain connected and help to the grid even if there is a disruption such as an unbalanced 3-phase voltage.

The wind farms must operate like conventional power plants for local loads and supply the active and reactive powers for recovering frequency and voltage immediately after the error occurs. So, some of the first variables that must be controlled are grid frequency ($f_{grid-ref}$), voltage ($V_{grid-ref}$), and power factor (PF_{ref}) that are specified in figure 4.1 as "Control Level III". These reference values cause the wind turbines to request a certain values of active and reactive powers from the wind turbine control strategy labeled as "control level II" in figure 4.1. The inputs of this control level are: wind speed V_{wind}(via anemometer), pitch angle β, rotor shaft speed ω_r. The pitch angle is the longitudinal axis of the wind turbine blades which can be controlled to change the aerodynamic feature of the blades. Considering these inputs, the pitch angle is adjusted for achieving desired wind power.

Depending on the wind turbine, its physical structure and the wind speed, control level II can detect maximum power point (MPP). This maximum power point must be processed by DFIG as a load. To achieve this, the control level I plays the role of rotor control and grid side converter as shown in figure 2-3. The rotor side converter adjusts the developed torque T_{em-ref}, active power P_{ref}, and reactive power Q_{ref}, while grid side converter presents the voltage of the fixed DC linkage. This part of control has been denominated as side converter control of rotor and grid. The circuit switches CB#1 and CB#2 are used during setup process, and in case of error, they are used for separating DFIG from the grid and local loads.

Figure 3-2: wind energy system based on doubly-fed induction generator

The standard power electronic converter used in the wind energy system based on DFIG is a consecutive converter which consists of two 3-phase voltage supply inverters (VSI) that share DC linkage.

Figure 3-3 shows the simplified circuit diagram for a general back-to-back 3-phase inverter.

Figure 3-3: general back-to-back schematic inverter

In figure 3-3, each converter consists of six switches S_{r1} to S_{r6} for rotor side converter and S_{g1} to S_{g6} for grid side converter. When the converter converts a AC grid voltage with fixed value and frequency to an adjustable DC voltage, it is usually known as an active rectifier or PWM rectifier which holds for grid side converter. When the converter converts a constant DC voltage to a 3-phace AC voltage with variable value and frequency for AC load, it is often called inverter. When it operates as an inverter or rectifier, electricity flow is reciprocal in converter circuit. The electricity can flow from its DC side to AC side and vice versa. Thus, the back to back converter is considered as bidirectional indirect AC/AC converter. [8]-[6] ‹[4].

Grid side converters and rotor side converters are reciprocal converters that generate 3-phase voltage or current with arbitrary magnitude and frequency for applying on the rotor windings. The considered voltages and currents are consequent of control approach that can be vector control and direct control of power or torque which is the main concentration of this research work. As it is shown in figure 3-2, the outputs of controllers are command signals ($S_{abc,s}, S_{abc,r}$) which can be commands of voltage or current. These command signals determine how the switches turns on or off in each phase to modulate the voltages or currents that follow the command signals at the various control levels.

3-5-evaluation of control methods for DFIG

Almost all advanced control methods which have been created for studying the induction motor in 1974 can be applied for DFIG [9]. However, DFIG control is more complicated than control of a standard induction motor. In the next chapter, it will be shown that each 3-phase quantity such as connection of voltage, current or flux can be stated as a rotational single vector [10]. Vector control acts to control these spatial vectors in size and phase [12]-[11]. Many different compounds can work and each of which has various advantages and disadvantages. [31]-[13]. Figure 3-4 shows the taxonomy of control strategies in the DFIG market. Field orientation control (FOC) [10],[13],[24], direct torque control (DTC) [25],[28], and direct power control (DPC) [29],[37] are practical control strategies that have been developed well since 1996 for wind energy generation systems based on DFIG. The following sub-section discusses mostly about the evolution of these control methods.

Figure 3-4: taxonomy of control methods of induction machines

3-5-1- Field orientation control

Field orientation control (FOC) was invented in 1970s based on the DC machine control method with separate excitation. In a DC machine, the field flux is generated by the field winding perpendicular to armature field supplied by stator windings. Due to the separation relationship between the stator space vectors and the field flux, when the torque is controlled, the change of the field flux does not affect the armature flux. The same concept has been expanded for induction machine [13] using three-phase transforming (abc) to two-phase (dq-frame), in which sinusoidal variables are predicted to DC values in the rotational direct axis (d) and square axis (q).

Vector control method that is applied for squirrel-cage induction motor [13] can be expanded to DFIG [8], [14]. In squirrel-cage machine, power electronic converter is connected to the stator windings to control the input currents in the dq frame aligned with the rotor flux [13]. Similarly, as the figure 3-5 shows, in DFIGs, the rotor side converter is connected to the rotor windings. Thus, control strategies are applied on the rotor currents by using a rotating frame aligned with the rotor flux called rotor flux orientation [8],[14][15], or by the air gap-flux orientation[16],[17]. The reference rotor current is calculated based on the active power P_s and reactive power Q_s. Then, the rotor currents can be divided into two parts. One is in the direction of the stator flux i_{rd}(direct axis) which is responsible for helping it, the other is i_{rq}(quadruple axis) which is orthogonal. The power can be controlled by changing the value of i_{rq} and yet, keeping the field flux constant. To do this, the magnitude and phase angle with respect to the stator flux vector must be controlled. Thus, there is a linear relationship between power and control variable. It can be shown that i_{rq} can be related to real power P_s, and i_{rd} be related to the reactive power Q_s that provides the possibility for the separated control from these important variables. [8]. The difficulty of the flux estimation in the stator-flux orientation method causes researchers to develop orientation based on grid voltage data [18]-[20]. For orientation of the grid voltage, all variables must be transferred from 3-phase synchronous reference frame ABC to 2-phase dq. To transform, the axis rotation angle θ_r and stator voltage phase θ_s are required which can be achieved by encryption and phase locked loop (PLL) respectively.

Figure 3-5: orientation-based field control schematic

Artificial intelligence (AI) is an advanced controller which is based on professional knowledge (human knowledge) and implicit inaccuracy [21]. Fuzzy logic controller (FLC) and artificial neural network (ANN) were known as the AI controllers which were widely used in power electronic applications. [22]-[24]. In [23], Fuzzy logic controllers are used instead of PI controller to prevent from the dependency of controller on the machine parameters. The pitch angle control for the wind turbine of DFIG was discussed through neural network in [24]. Since the FOC is based on the rotor current vector control which is in the framework of the voltage reference or the stator flux, it requires the change of voltage, current, and output variable of stator among the constant and synchronous reference frames. Also, FOC requires exact information of DFIG parameters such as stator, rotor resistor, and cross inductance. Thus, when the real values of the parameters are different with the values used in FOC control system, the control performance may be reduced. Also, the rotor current controllers must be accurately adjusted to have a good dynamic response [20]. These drawbacks of FOC motivated the researchers to develop a newer control method that is less dependent on machine parameters and also requires less efforts to adjust the compensator. This new control method was known as direct torque control (DTC) [27].

3-5-2- direct torque/power control

To reduce the difficulty of control and regulation efforts in FOC, direct torque control was developed for squirrel-cage induction motor in the late 1980s. [26].[25]

This controller was extended to DFIG in 2002 [27]. DTC technique is based on a spatial vector representation of the output AC voltages that can be achieved for rotor side converter which is used for a two-level voltage supply inverter. Figure 3-6 shows the main schematic of DTC method. The DTC control part consists of three blocks: estimation block, hysteresis-based controllers, and DTC replacement table. The torque T_e and rotor flux amplitude ψ_r are the initial control variables .[28].[27]. The spatial vectors of the rotor flux and the stator flux rotate clockwise (sub-synchronism) or counterclockwise (super- synchronism) up to a distance called the torque angle, which are estimated in the estimation block using the rotor and stator currents. Also, the real torque is estimated using the rotor and stator currents and measured voltage value. The torque can be controlled by correcting the angle between the stator and rotor flux space vectors. In order to affect the direction and amplitude of the rotor flux, different voltage vectors are injected from DTC to the rotor of the device. The reference torque and rotor flux are compared with their real values, and progress through three-level and two-level hysteresis controllers respectively, to provide the error signal status for the switching table to select the proper rotor voltage vector. These voltage vectors are presented by the two-level voltage supply converter known as the rotor side converter which supplies the electricity of the rotor windings.

Figure 3-6: ordinary block diagram of direct torque control (DTC)

Based on DTC, the direct power control technique (DPC) was developed to control three-phase rectifiers about over a decade ago [29]. In the DPC approach, the initial variable signals are the stator active power P_s and reactive power Q_S. [32] ‹[31] ‹[30]. Also, there is the block in DPC and there is no need to estimate control variables. Because the stator active and reactive powers can be calculated using the stator voltage and current.

Figure 3-7 shows the main schematic of the direct power control (DPC). As it is shown, DPC is based on how the switching vectors of the inverter are selected from the DPC switching table using the flux situation of rotor or stator and the errors of the active and reactive powers. Thus, high performance, strength, and low sensitivity to the system parameters changes can be considered as the main advantages of the DPC method [31].

Figure 3-7: ordinary block diagram of DPC

By comparing DTC with DPC, it can be determined that DPC does not require the information of the rotor current and estimation block of control variable. Both of them have the high dynamic performance due to using the hysteresis-based controllers. Yet, use of the hysteresis-based controllers has a fine of high ripple in the developed torque or power. Also, they operate inconstantly at the switching frequency which is a source for the non-linear behavior. In the second chapter, it will be shown that the switching frequency of the rotor side converter is intensely affected by the axis speed which mostly is due to the power pitch that depends on the rotor speed. Also, the variable switching frequency may generate the considerable acoustic noise with a variable intensity, uneven distribution of switching losses for each semi-conductor switch in the power inverter and the currents that have non-deterministic harmonic content. [33] ،[32] .

The harmonic at the stator currents complicates the design of an AC filter with the capability to absorb a wide spectrum of frequency components and also the design of a heat sink. Hence, some researchers have worked on DPC and DTC for DFIG to reduce the output waves and keep the rotor side converter switching constant. -[32] [40]. They include using space vector modulation (SVM), discrete vector modulation technique (DSVM), design of prediction direct power control (PDPC), and sliding mode control (SMC). The fuzzy logic was used in the direct power control of DFIG by replacing the hysteresis-based controller, and ordinary switching table by fuzzy-based controllers. [42] ،[41]. All these contributions allow to improve the DPC performance, but yet lead to more complicated designs. In [32], the rotor voltage vectors required are calculated and implemented by the space vector modulation at a constant period. Although this method adds the constant switching frequency characteristic to DPC system, but calculating the duty cycle of each voltage vector at each sample time increases mathematical computations. In discrete SVM method (DSVM), three rotor voltage vectors applied in switching period are selected by using the modified lookup table and five-level hysteresis comparator.

In the model-based predictor direct power control (PDPC), three sequences of rotor voltage vectors are injected to wound rotor at a constant period. These vectors are selected based on the minimizing of the cost functions of the active and reactive powers errors. The online calculation problems from the microprocessor’s point of view and complexity in control are the main disadvantages of PDPC. In [43], the use of sliding mode control strategy (SMC) was proposed for DPC drive. In DPC strategy, by selecting the proper second-order Lyapunov’s function, the controller is designed in such a way that to provide output voltage reference of the rotor side converter as an input to the SVM module.

3-6- independent operational mode WECS based on DFIG

As mentioned in the literature of the DFIG’s grid-connected mode, the stator is connected to the grid voltage tightly to provide the power vectors used in superior feedback. Yet, in case of absence of grid voltage in grid failure or supplying the electricity to an outback region without grid, grid-connected control strategies are no longer valid. These cases are the independent modes of DFIG, in which the grid voltage is not connected to the stator. This case can be shown by closing CB#1 and opening CB#2 in figure 3-8. An independent generator system must provide the adjusted voltage and frequency for the loads [44]. There are two different control methods for independent system which are known as indirect stator flux orientation (ISFO) [47]-[43] and direct voltage control (DVC) [49][48]. Figure 10.1 shows block diagram ISFO & DVC independent control approaches.

a) indirect stator flux (ISFO)
b) direct voltage control (DVC)

figure 3-8: block diagram of independent control systems

in ISFO, corresponding stator flux or voltage is controlled by the rotor current. The stator voltage angle is regulated by freely integrating of reference stator voltage frequency. In DFIG controlled by ISFO, the values of voltage and current are referred to the reference frame aligned with the stator flux. The rotor current axis is obtained from the magnetic current using a PI controller. The main drawback of ISFO control is the absence of direct electric torque or active power control of DFIG. This is because under ISFO control, the square component of the stator current (i_{sq}) is regulated by the load, and for maintaining the DFIG field direction, the q component of rotor current (i_{rq}) must be kept proportional to i_{sq}. Thus, i_{sq} cannot be used for controlling T_e or P_s. The direct voltage control (DVC) is an alternative method that can directly control the voltage and frequency of stator side of a DFIG, as shown in figure 3-8 (a). In DVC, the reference stator space vector has been shown in a rotating polar reference frame with arbitrary speed, as shown in figure 3-8 (b). the frequency and amplitude of rotor current are directly calculated from the stator voltage regulator. The main advantage of this method is that there is no need to measure the axis speed. The axis speed is obtained from the compensator output of stator frequency error.

3-7- synchronization process and gap-free transfer between SA and GC modes:

Most DFIG control methods do not deal with grid synchronization. This an important issue that is implemented at the same time as protection. [7].[6]. the created method for the grid synchronization using the field control orientation (FOC) uses an outer voltage loop and inner rotor current loop for achieving the synchronization of frequency, phase, and magnitude between the DFIG and grid.

Figure 3-9 represents the block diagram of FOC method for the synchronization process. When the voltage and frequency of the stator are equal to the voltage and frequency of the grid ($v_s = v_g and f_s = f_g$), the circuit breaker is closed. The phase locked loop system can calculate the stator voltage and phase values and grid side which is used for controlling the rotor current at the direct axis of i_{rd}. The square axis of rotor current i_{rd} is kept zero during the synchronization process, because no power flows between both sides of the stator and grid.

Figure 3-9: block diagram for synchronization process based on FOC

These methods inherit all the defects of FOC and require to measure grid and stator voltage, rotor current, and position, which results in complicated control algorithms. A direct voltage control plan was proposed in [51]-[54] using the integral variable structure control without current control loop. However, it still requires to measure the grid and stator voltage. Moreover, due to its complexity, transient response is endangered. The grid synchronization was proposed using DTC in 2002 [53]. In comparison with FOC, a better transient performance was obtained. This method used of three PI regulators and needed to measure the rotor position and current and the grid and stator voltage. In 2009, the fast grid synchronization was obtained needless to PI regulators and measuring the stator voltage by introducing the concept of virtual torque.

Unfortunately, the stator voltage waveform is distorted due to the flux waves and high torque. This is a large barrier for a smooth connection to the grid. Yet, the switching frequency is variable. The other important issue is the need for fast and flexible regulation of active and reactive powers after connecting to the grid. This issue allows DG units to contribute in the energy management and improve the power quality in a DG system. A grid synchronization strategy based on DPC was proposed in 2009 that was able to obtain the smooth transfer between the synchronization and normal operation by adjusting active and reactive powers without changing of control configurations [55]. This control strategy is almost similar to something given in [54] except that it uses virtual force instead of virtual torque, and also the prediction control is used for presenting the fixed switching frequency.

The load of a DFIG may include many sensitive devices such as life support equipment, precision instrumentation devices, hospital equipment, and microwave broadcast that need to the clean input voltage with low total harmonic distortion (THD). WECS based on DFIG connected to advanced grid (GC) must be able to operate in the GC mode and independently (SA) to supply the emergency load when the power cut off. A transferring method without the gap from connection to grid independently and vice versa for critical loads are explained in [57]. This algorithm matches the inverter voltage value and phase and grid voltage when disconnecting or reconnecting to the grid to minimize any kind of sudden voltage change (surge) in the load.

3-8-dynamic model of doubly-fed induction generator

The rotor and stator linkage flux vectors in the stator static reference model are given below:

$$\psi_{S\alpha\beta}^{s} = L_s I_{s\alpha\beta}^{s} + L_m I_{r\alpha\beta}^{s} \qquad \text{(3-1)}$$

$$\psi_{r\alpha\beta}^{s} = L_r I_{r\alpha\beta}^{s} + L_m I_{s\alpha\beta}^{s}$$

According to relation (2-3), rotor linkage flux vector based on the stator linkage flux and current can be rewritten as follow:

$$\psi_{r\alpha\beta}^{s} = \sigma L_m I_{s\alpha\beta}^{s} + \frac{L_r}{L_m}\psi_{s\alpha\beta}^{s} \qquad \text{(3-2)}$$

Where, $\sigma = 1 - L_s L_r / L_m^2$ is the link parameter.

According to figure (1-3), the rotor and stator voltage vectors are as follow:

$$U_{s\alpha\beta}^{s} = R_s I_{s\alpha\beta}^{s} + \frac{d\psi_{s\alpha\beta}^{s}}{dt} \qquad \text{(3-3)}$$

$$U_{r\alpha\beta}^{s} = R_r I_{r\alpha\beta}^{s} + \frac{d\psi_{r\alpha\beta}^{s}}{dt} - j\omega_r \psi_{r\alpha\beta}^{s} \qquad \text{(3-4)}$$

According to the relations (3-3) to (3-5), the instantaneous variations of stator current can be stated as below:

$$\frac{dI_{s\alpha\beta}^{s}}{dt} = \frac{1}{\sigma L_m}\left[U_{r\sigma\beta}^{s} - R_r I_{r\sigma\beta}^{s} - \frac{L_r}{L_m}\left(U_{s\sigma\beta}^{s} - R_s I_{s\sigma\beta}^{s}\right)\right] + \frac{j\omega_r}{\sigma L_m}\left(\sigma L_m I_{s\alpha\beta}^{s} + \frac{L_r}{L_m}\psi_{s\alpha\beta}^{s}\right)$$

(3-5)

Also, the instantaneous variations of active and reactive powers of stator output which are injected to the grid are calculated as below:

$$P_s + jQ_s = -1.5U_{s\alpha\beta}^{s} \times \widehat{I_{s\alpha\beta}^{s}} \qquad (3\text{-}6)$$

And

$$P_s = -1.5(u_{s\alpha} i_{s\alpha} + u_{s\beta} i_{s\beta} \qquad (3\text{-}7)$$

$$Q_s = -1.5\left(u_{s\beta} i_{s\beta} - u_{s\alpha} i_{s\beta}\right) \qquad (3\text{-}8)$$

When $P_s > 0$, it means that the induction machine operates as the generator, and when $P_s < 0$, it means that the machine operates as a motor. Also, electromagnetic torque can be stated as the following relationship:

$$T_e = \frac{3}{2}\frac{pL_m I_m(\psi_{s\alpha\beta}^{s} \times \widehat{\psi_{r\alpha\beta}^{s}})}{(\sigma L_s L_r)} = \frac{3}{2}\frac{pL_m(\psi_{s\beta}\psi_{r\alpha} - \psi_{s\alpha}\psi_{r\beta})}{\sigma L_s L_r} \qquad (3\text{-}9)$$

Where P is the number of poles pair. The mechanical equation of wind turbine equipped with DFIG is equal to:

$$\frac{J}{p}\frac{d\omega_r}{dt} = T_m - T_e \qquad (3\text{-}10)$$

Where J is the inertia constant of wind system, T_e is the electrical torque obtained from the relation (3-10) and T_m is the mechanical torque of turbine which is obtained from the optimal speed-torque characteristic according to the references [32] & [33].

$$T_m = K_{opt}(\frac{\omega_r}{p})^2 \qquad (3\text{-}11)$$

Where, k_{opt} is the optimal torque constant of wind turbine. The variations of active and reactive powers are equal to:

$$\frac{dP_S}{dt} = -\frac{3}{2}\left(u_{s\alpha}\frac{di_{s\alpha}}{dt} + i_{s\alpha}\frac{du_{s\alpha}}{dt} + u_{s\beta}\frac{di_{s\beta}}{dt} + i_{s\beta}\frac{du_{s\beta}}{dt}\right) \qquad (3\text{-}11)$$

$$\frac{dQ_S}{dt} = -\frac{3}{2}\left(u_{s\beta}\frac{di_{s\alpha}}{dt} + i_{s\alpha}\frac{du_{s\beta}}{dt} - u_{s\alpha}\frac{di_{s\beta}}{dt} - i_{s\beta}\frac{du_{s\alpha}}{dt}\right) \qquad (3\text{-}12)$$

As it is obvious from the relations above, the variations of grid voltage are needed. There is in an ideal grid:

$$u_{s\alpha} = U_s \sin(\omega_1 t) \qquad (3\text{-}15)$$

$$u_{s\beta} = U_s \sin(\omega_1 t - \frac{\pi}{2}) = -U_s \cos(\omega_1 t) \qquad (3\text{-}16)$$

So, there is for the variations of grid voltage:

$$\frac{du_{s\alpha}}{dt} = \omega_1 U_s \cos(\omega_1 t) = -\omega_1 u_{s\beta} \qquad (3\text{-}17)$$

$$\frac{du_{s\beta}}{dt} = \omega_1 U_s \sin(\omega_1 t) = \omega_1 u_{s\alpha} \qquad (3\text{-}18)$$

3-9- coordinate reference conversion

In order to simplify the analysis, the studies of simulation and designing the controller, the dq transformation is used for the brushless doubly-fed reluctance induction generator. The spatial distribution MMF (i.e. currently spatial vector) at the fixed coordinate reference dq by supposing the phase sequence like the figure (3-4) can be written as below:

$$i_s = \frac{2}{3}(i_a + e^{\frac{2\pi}{3}}.i_b + e^{-\frac{j2\pi}{3}}.i_c) = i_{ds} + ji_{qs} \qquad (3\text{-}19)$$

Figure (3-4): ABC phase sequence of a general three-phase coil [34]

By using (3-11), the components of d-q current can be stated in terms of three-phase currents:

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3\text{-}20)$$

Or vice versa, by applying a reverse transformation:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \qquad (3\text{-}21)$$

Transformation from constant to the rotating coordinates reference (and vice versa) in figure (3-5) can be carried out using the famous relations below:

Figure (3-5): angular displacement of the rotational coordinates reference ("e") and constant of d-q ("s") [34]

$$\begin{bmatrix} i_{de} \\ i_{qe} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (3\text{-}22)$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{de} \\ i_{qe} \end{bmatrix} \quad (3\text{-}23)$$

Where, θ_e represents the angular position of the rotating coordinates reference relative to the fixed counterpart shown in figure above.