Chapter 5
Reactive Power Control in Wind Power Plants

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Abstract Studies in this chapter have been performed on the interaction between wind farm, reactive power compensation, and the power system network. The fluctuation of the loads and the output of wind turbine units in power system have made the reactive power compensation an effective procedure. Considering the wind turbine power plant as a distributed generation unit, there would be some positive effect on the network, i.e. distributed system and upper hand grid reliability improvement, improving the environmental issues and development of power grid planning. In order to achieve better condition of reactive power in the network the existing conventional Asynchronous Induction motor (Constant Speed) should be replaced by Wound Rotor Synchronous Induction motor (variable speed), namely, Doubly Fed Induction Generator (DFIG). The control system of a DFIG wind turbine is usually comprised of two parts: electrical and mechanical control. The former includes the control of converter in the rotor side and control of converter in the grid side and the latter includes the control of the angel of turbine blade. The standard IEEE 30-bus System is Consider as the test system. Three methods are applied. Newton-Raphson algorithm, using second generation of smart genetic

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algorithm with non-dominated sorting without any power plant, and the last is using second generation of smart genetic algorithm with the non-dominated sorting with the assumption of the presence of wind power plants. Results show that the presence of wind power plant is effective in improving the reactive power in the grid.

5.1 Introduction

The daily increase of need to electrical energy has been converted into a serious problem and taking into consideration the environmental problems of electricity generation by the fossil fuel power plants, the development of renewable energy resources seems to be the only logic way.

Today, concurrent with the development of the new technologies, electricity world is facing noticeable changes from the viewpoint of issues such adjustment, social and environmental regulations. The prevailing power plant is equipped in particular with special instruments for the control of grid frequency, in order to guarantee the system balance. A similar controlling structure has been developed in the area of voltage control, though its use has been less prevailing.

With regard to the increase of the share of renewable energy systems from energy generation, such as photovoltaic systems and wind farms, the grid management has been converted into one of the very important necessities in creation of a balance between generation and consumption in an ideal and highly output form [1].

In addition, the energy generation based on renewable energy systems causes to make the process of forecasting and control of load distribution in the grid to be much more difficult. In such a scenario, the load distribution management is changed into a determining factor in the connection of generated energy by non-centralized renewable resources to the grid.

At present, renewable energy resources exist in a broad but non-centralized form at the sub-distribution and distribution systems. They are very frequent and their accessibility is predictable but they are not fully reliable. However, these resources have not been utilized fully yet to be able to detect their weak points and strengths. In a separate form, these resources cause the reduction of ability to control the voltage. These units are mostly managed by distribution system operators and have a difficult coordination with the transmission system operators.

With the fast expansion of the technology of wind energy and considering the national policies on renewable energy resources, wind energy has been noticed vastly in energy generation. The wind units in a useful and noticeable rate of energy are available. They have a zero fuel cost and the energy generation by these units is very ideal from the environmental viewpoint.

The wind farms at a large scale will have a great impact on the reliability and stable performance of the power system for two main reasons. First, the areas which are under the blowing of rich resources of wind energy and can be used in order to develop the generation of energy from wind power. In most of the cases, they are located in a region that the power grid faces problems and weakness for connection. Secondly, it is the nature of the wind energy which has been identified as an unstable energy. So, the active power from the generator connected to the wind turbine changes with the wind speed. The serious problem is the intensive reduction of voltage quality of the local electricity grid in the place or near wind farm. The power grid causes fluctuation of reactive power and in the continuation; it will have impact on system voltage and even causes a global blackout.

The adjustment of the reactive power is one of the important issues in connection with the large wind farms which should receive a specific notice. The rate of the reactive power absorption or injected by the wind units in the farm and electricity grid is changing constantly and its reason is the constant changes of power due to change in wind speed. By the way, considering the fact that the size and number of wind farms which contribute in the generation of electrical energy is increasing, it is not possible to ignore the reactive power which is generated in wind farms in large scales.

With the development of use of wind energy resources in larger scales, all effects which this energy has on the power quality and tolerated by the electricity grid, is not economic and even sometimes seems to be unbearable. So, proper compensation of reactive power besides the wind turbine units seems to be an essential issue. The compensation of reactive power can cause the increase of adjustable ability of the reactive power which may lead to the voltage stability in wind farms.

Optimization and control of reactive power in the power system through suitable allocation of reactive power resources and rational compensation of the reactive loads is the best effective method to reduce the losses of power in the grid and control of voltage level at power grid.

The units of wind turbines in power station scales could be able to adjust the voltage by the dynamic supply of reactive power. From the viewpoint of utilization of power system, wind farms should have the control ability in agreement with other resources of electricity generation. The ability of voltage adjustment of wind turbines units is different depending on the technology used in the construction of generation and also its manufacturer. The units of wind turbines of the type of 1 and 2 which are based on induction generator, do not have any control ability of voltage in nature. Type 3 and 4 of wind turbine units include power electronic converters, so they have the ability to adjust the reactive power and consequently they have the ability of voltage control. For some reasons, in most of the cases, this ability is not used in the type 3 units, but mostly they are used in the mode of unity power factor. When the adjustment of reactive power is employed, coordination is made among the reactive adjustment points of wind turbine units usually by a central controller which determines an ideal program for all existing units in the wind farm [2].

5.2 Indices Affecting the Wind Turbine Units from the Reactive Power Viewpoint

The increase of wind power share and larger wind turbines have made the evaluation of voltage conditions of connection to the wind turbine grids with further details and using the load flow analysis, an interesting issue. In load flow analysis, voltage of each knot is determined by the given load. In a radius grid consisting of wind units and consumers, the minimum voltage occurs mainly when there is zero generation and maximum consumption and the maximum of voltage occurs in minimum load and maximum generation. If the minimum and maximum of the voltage, both are in an acceptable level, it can be said that the situation of the grid is confirmed, otherwise, the grid should be reinforced.

Having precise and confirmed information on the maximum output power and reactive power and other indices related to that are the calculation requirements which have been mentioned before.

- **Maximum of Output Power**

The maximum of output power of wind turbine is the necessary feature in determining the strength necessary for the grid in the connection point of the place where the wind turbine unit is installed. On this basis, the following data seems to be necessary.

The reference power which based on definition is the highest point of curve for the power according to IEC 1400-12/2 standard.

The maximum of continues power includes the maximum of continues power which the system of turbine control permits and the output power irrespective of atmospheric conditions (wind and air density) and the grid should not surpass that. In practice, it means that the wind turbine should be equipped with a mechanism to control its own performance, so that this continues output power will never exceed a certain limit. The maximum of continues power can be obtained with the evaluation of the controlling system of turbine or calculations in accordance with the IEC 1400-12/12 standard [3, 4].

The maximum instantaneous power is the maximum of instantaneous output power from turbine in the normal operating condition and standard air density. Measuring this power is also taken place according to IEC 1400-12/2 standard.

Wind turbines with fixed speed, with the controlling system of pitch and stall have the ability to produce the peak power output, i.e. higher than nominal power and at the same time, the wind turbines of flexible speed and Optislip, due to speed or flexible slip, have certain limits in their own moment output power.

- **Reactive Power**

The reactive power of wind turbines (generation or consumption) has also important and necessary features in determining the rate of strength of the grid in the joint connection point of the place where the turbine is installed. The reactive power (or power factor) can be determined through measuring special functions which are related to the output of the wind turbines power.

The reactive power consuming in the wind turbine units which are connected to frequency converter (variable speed wind turbines) is usually zero. Whereas the consumption of reactive power in prevailing types of wind turbine with induction generations varies according to a function of their generation active power. Wind turbines with induction generator are usually used along with compensators. So the coefficient of their power depends on the size and type of generator design is variable from 1 in zero generations to 0.98 in nominal generation. In the event of need, it is possible to achieve the coefficient of unity power factor through connection of larger capacitor bank to the wind turbine [3].

- **Flicker**

Flicker is a description of the fast changes of voltage on incandescent lamps. Fast changes of voltage are created due to change in the consumption of grid loads which leads to the creation of fluctuation in the active and reactive power. Wind turbines are also sources of power fluctuations which mainly are due to the impact of disruption (turbulence) of wind and tower shade which leads to the periodical fluctuation of power in a frequency in which the rotor blades passes through vertical pivots of the tower. Flicker also depends on the ratio of X/R and level of short circuit (fault level) in the Point of common coupling (PCC) [3, 5].

- **Harmonic**

Voltage deviation from the 50 Hz full sinusoidal shape curve leads to creation of harmonic and noise in the network. Harmonic and noise causes the increase of losses in the power system. In some cases, they can lead to the creation of overload on batteries, transformers and other electrical equipment. The creation of disruption in telecommunication systems and fault of controlling equipment are other outcomes of these two phenomena. Since the frequency converters create a current with an incomplete sinusoidal wave shape, the of the variable speed wind units equipped with the frequency converter can lead to the harmonic generation in the power network and the current harmonic leads to the creation of harmonic in the voltage waveform. The amplitude of voltage harmonic is related to the current harmonic amplitude and impedance of the grid in the current frequency [3, 5].

5.3 Types of Wind Turbine Connection to the Power Grid

Wind Turbine Structure

The main parts of wind turbine unit contain the main tower, blades, gearbox, generator and axel of the turbine. In order to control the speed of rotating shaft of the generator, the gearbox is used.

In order to gain the maximum energy from the wind, it is necessary that the angle of blades changes with the change in the wind speed, and this function is done by controlling the angle of the blade. Also after measuring the wind direction, a small engine called Yaw, turns the whole upper part of the turbine tower to be placed in proper line with the wind blowing direction.

Types of Wind Turbines

- *Fixed Speed Wind Turbines*

By the early 1990, the standard of installation and utilization was based on wind turbines with fixed speed. In these types of turbines, irrespective of wind speed, the speed of turbine rotor (shaft) is fixed. This speed depends on the frequency of the generator construction grid and also the ratio of gears in the gearbox.

These types of turbines have Squirrel-cage induction generator or with the wounded rotor which are directly connected to the power grid. These generators are equipped with a soft starter and capacitor banks for the reactive power compensation. These generators have been designed such that in a specific speed of wind could have the greatest output. In order to increase the generation power of generator, these wind turbines have two types of adjustment on the stator windings.

One is used in low speeds of wind (mainly 8 poles) and the other is used in the average or high speed (4 poles or 6 poles). These types of turbines have advantages such as simplicity, reinforcement and high reliability and many scientific and research works have been made on them. The price of electrical parts and their drive is also low. The important disadvantages of these turbines also include the uncontrollable consuming reactive power, mechanical stress and limited control of power quality. Due to the performance of their fixed speed, all fluctuations in the wind speed emerge in form of fluctuations in the mechanical moment and thereby in form of fluctuations in the electrical power of the grid. As for the weak grids, the power fluctuations can lead to large voltage fluctuations which cause the considerable losses in the transmission lines [6].

- *Variable Speed Wind Turbines*

In recent years, wind turbines with variable speed have formed the dominant majority (among the installed turbines). In this status, it is possible to adjust the rotor rotating speed (with the increase or reduction of acceleration). The fixed speed is kept and stabilized in a fixed and pre-determined rate to be able to achieve a high power factor. In this status, the generator torque is kept relatively fixed and changes in the wind blowing leads to changes in the generator speed.

The electrical system of wind turbines with variable speed is more complex than turbines with fixed speed. These types of turbines mainly have induction generator or Synchronous one and are connected to the grid through a power converter. The advantages of these types of turbines include: the increase of energy obtained from the wind, improvement of the power quality and reduction of mechanical stress. Their disadvantages also include: losses in the electronic drives equipment, using more devices and increase of cost resulting from the equipment of electronic systems. In these types of turbines, the power fluctuations resulting from wind fluctuations mainly appear in form of changes in the rotor speed of turbine and generator [6].

- *Power Control Concepts*

The most simple, strong and cheap control method is the inactive control in which the blades are screwed inside the ball with a fixed angle. The rotor design is such that in the event that the wind speed exceeds a certain limit, rotor could loss the wind power. So the aerodynamic powers of blades are limited. Such an adjustment of aerodynamic power causes to have less power fluctuations proportional to the adjustment of power in a fast steps. Some of the deficiencies of this method are the low output in low speeds of wind, lack of auxiliary start and changes in the maximum power of the stable status as a result of changes in air density and network frequency.

Other type of control is the step control (active control) in which the blades can be twisted in the times when the output power is very low or high towards the wind direction or opposite to it accordingly.

In general, the advantages of this type of control are the good control of power, auxiliary restart and emergency stoppage. From electrical viewpoint, the good control means that in high speeds, the main rate of output power to be close to the nominal rate of generator. Some of its disadvantages are the additional complexity resulting from the step mechanism and more fluctuations of the power in high speeds. During storm and limited speeds of the step mechanism, the instantaneous power fluctuates around the nominal rate [6].

The third controlling strategy is active fatigue control. In the low speeds of wind, in order to have access to the maximum output, the blades are turned like a step controlled wind turbine. In the high speeds, blades are into a deep and slow fatigue and in the direction opposite to the controlled turbine with pace. With this type of control, a clearer limited power (without high fluctuations of controlled wind turbines with pace) is obtained. This type of control has advantages such as ability to compensate the air density changes. Combination with the step mechanism has eased the stoppages of the emergency status and start of wind turbines [6].

5.4 Types of Modern Generators

Type A: Fixed Speed

As the SCIG constantly extracts the reactive power from the grid, this arrangement uses a capacitor bank to compensate the reactive power. The soft, smooth and clear connection to the grid is obtained through a soft starter. As it was mentioned, on the case of weak grids, the wind fluctuations are converted into voltage fluctuations. These types of turbines can absorb variable quantities of power from the grid and this also increases the voltage fluctuation and line losses. So, some of the most important deficiencies of this generator and related systems include:

- Lack of control over speed
- A need to having a strong grid
- A need to having a strong mechanical structure to be able to bear the high mechanical stresses.

Type B: Limited Variable Speed

That category of wind turbines which are limited with the variable speed have variable resistance in the rotor and are identified with the name of Opt slip. In this type of arrangement, the wounded rotor induction generation is used. Generator is directly connected to the grid, and in order to have a better connection, a soft starter is used. The variable resistance of rotor of these types of generators can be adjusted with the controlled converter by optic pulses which have been installed above the rotor axel. This optic equipment is in need of expensive slip rings (which demands brush and maintenance).

In this case, the rotor resistance can be changed and thus control the slip in this way. By this means, the output power of the system is controlled. The range of dynamic speed control depends on the size of the rotor variable resistance. Typically, the speed limit is zero to 10% over the Synchronous speed. The energy resulting from the conversion of additional energy is lost in form of heat. In 1998, two engineers, namely Wallen and Oliner introduced the concept of replacement in which, passive parts has been put forth instead of power electronic converters. This concept has a 10% slip but unfortunately had no control on slip [6].

Type C: Variable Speed with Frequency Converter with Fractional Capacity

This type of generator is known as doubly fed induction generator (DFIG). The converter capacity (frequency converter with fractional capacity) is about 30% of the nominal power of the generator. This converter does the compensation of reactive power and by the way, at the time of connection to the power grid, it gives a clear and smoother state. This type of arrangement has a broader limit as compared with Optislip in the dynamic control of voltage. The limit of their speed is usually in a broader limit as compared with Synchronous speed. Smaller frequency converter is more economic from the economic point of view. The main deficiency of this method is the use of slip rings and their protection against the grid faults [6].

Type D: Variable Speed with Frequency Converter with Full Capacity

In this method, generator is connected to the grid through a converter (frequency converter with full capacity). The frequency converter does the compensation of reactive power and at the time of connection to the grid has a clear and smoother feature. This type of generator can be motivated in electrical form like WRIG, WRSG's or to be incited through a permanent magnet (PMSG). Some of the wind turbines of full variable speed do not have any kind of gearboxes. In these cases, the multi-polar generators which receive commands directly (in a large diameter) are used [6].

Asynchronous Generators (Induction)

Asynchronous generator is the most prevailing generator which is used in wind turbines. The mechanical strength and simplicity and cheap price are some of its advantages and need to magnetizing current is among its disadvantages. Its consuming reactive power is supplied either by capacitor bank or power electronic devices. The created magnetic field in it is rotating with a speed which is determined by the windings poles and grid frequency and is called Synchronous speed. If rotor turns with a speed more than Synchronous speed, in that magnetic field, voltage is induced and the current is flowing in its windings.

In SCIG generators whose speed changes only about many percent due to changes of wind speed, so that they are mostly used along with the turbines of type "A" (fixed speed). SCIG generator has a sharp torque-speed characteristic, so that the vibrations of wind power are directly transferred to the power grid. These transient states especially at the time of connection of wind turbine to the grid are critical because they give rise to the creation of inrush current of seven to eight times of the nominal flow. In the weak grids, this rate of inrush current can cause intensive disruption. So, connection of SCIG generators to the grid is done slowly and by a soft starter to limit the inrush current.

In SCIG generators, there is a liner relation between the rate of necessary capacitor bank, active power, terminal voltage and rotor speed. That means, in the event of intensive winds, the turbine can produce a more active power if it could absorb more reactive power from the grid. In these types of generators, if a fault occurs, due to the unbalance of mechanical and electrical powers, the rotor speed increases. So by removing the fault, SCIG extracts more reactive power from the grid which causes the greater reduction of the voltage [6].

In the wounded rotor induction generator, the electrical specifications of the rotor can be controlled from outside and affects its voltage. The rotor winding can be connected through a brush and slip rings to the outside or through power electronic devices which might need to slip rings and brushes or might not need, generator can become magnetic through stator or rotor. There is a possibility for retrieval of slip energy from rotor circuit and rotating to the stator outlet. In wind turbines, most of the following arrangements which are related to WRIG are used.

1. Induction generator of (Optslip) which is used in type (OSIGB).
2. Doubly fed Induction Generation which is used in type C.

In Optislip generators, converter is controlled in optic form (The converter which changes the rotor resistance), so that there is no need to slip rings. Stator is also connected directly to the power grid. The range of operating speed in this case as compared to SCIG generators is greater and more advanced from the viewpoint of system. For a specific spectrum, this concept can reduce the mechanical loads and power vibrations resulting from storms. The disadvantages of this method include:

1. Speed limit. Mainly it is about zero to 10% and this is independent from the rate of variable resistance of rotor.
2. It has a weak control on active and reactive powers.
3. Slip power against flexible power is annihilated in form of loss.

The doubly fed induction generator (DFIG) is an interesting option or an increasing market and with demand. DFIG is a WRIG in which its stator is directly connected to the three phase grid with fixed frequency and rotor winding is fed through a voltage source converter with back to back single direction IGBT switches. The doubly fed phrase refers to this reality that stator gives voltage for the loads fed to the power grid and rotor voltage is created by the power converter. The performance speed of this system is in a vast scope but limited. Converter compensates the difference of electrical and mechanical frequency by injecting the current into the rotor with a flexible frequency. Both during the normal operating condition and during faults, the generator behavior is adjusted by the power converter and its controllers.

Power converter is comprised of two converters, the converter in the side of the grid and converter in the side of rotor, which are controlled independently. The main idea is that the converter of the side of rotor controls the powers of active and reactive power by controlling the rotor flow. Whereas the converter of the line side, controls the voltage of DC side to be assured of the performance of converter in the coefficient of unity power factor (zero reactive power). Depending on the operating conditions of drive, power is entering into the rotor or exited from it. In the over-Synchronous condition the power can be flowed towards the grid and in under-Synchronous conditions, power flows from grid towards rotor. In both cases, power goes from stator towards grid side. The advantages of DFIG generators include:

1. Having ability to control the reactive power
2. Having ability to make an independent control of active and reactive powers with rotor flow control
3. Ability of magnetism by rotor side
4. Ability to produce the reactive power which is delivered to stator.

As it was mentioned, converter in the side of grid operates at the unity power factor and does not involve itself in the exchange of reactive power. Of course on the case of weak grids, in the event of voltage fluctuations, DFIG generators might be commanded to exchange the reactive power with the grid, and the ability to control voltage is not related to the overall generator power but related with speed limit and slip power. Converter price is proportional to the range of speed around the Synchronous speed. The inevitable deficiency of DFIG generators is the use of slip rings [6].

Synchronous Generator

Synchronous generator in comparison with the induction generator with similar specifications and similar size is more expensive and complex. Its most important advantage is lack of need to a flow for magnetizing and thereby, through a converter (power electronic), it is connected to the main grid. Converter has the following two important objectives too:

1. For acting as a reinforce of power against the power vibrations (resulting from flexible energy of wind and storm and transit states of the side of power system
2. For the control of magnetic field to maintain Synchronism and prevent from Synchronization problems with the power grid.

The application of such a generator, gives permits to work with a variable speed to wind turbines. These types of generators are either of the type of winded rotors (WRSG) or of the type of permanent magnetic rotor (PMSG).

Due to known state of stable and transit performance of these types of generates, no much discussion are made on them. Other generators in use for wind turbines include [6]:

1. High voltage generators
2. Switched reluctance generators
3. Diagonal flux generators.

5.5 Wind Turbine Requirements During Connection to the Grid Considering Reactive Power Aspects

Deciding about the system of reactive power compensation in the area of wind turbine power plants design, many cases should be taken into consideration. Most of the wind power stations for connection to the grid are bound to observe certain principles which has been confirmed through a series of agreement under the supervision of the management of all-nation electricity grid and necessary parameters for this connection is defined in accordance with the agreement. These necessities can be taken from the world, local standards or cases necessary for the local grid. Some of the necessities can be the result of the study of effects of the system which had been conducted earlier. For example, in some standards, the minimum coefficient of power and Voltage ride through (VRT) for the connection of wind turbines to the grid is considered as the main requirements. The wind power plants designers should be aware that a reactive power compensator cannot solely be a guarantee for low voltage ride through in the wind turbine power plant [5].

After meeting the main conditions for the connection of wind turbine to the grid, other cases such as the time of responding, voltage control requirements, necessities for the control of power factor, stable susceptance requirements, low voltage ride through, high voltage ride through, post emergency requirements and voltage retrieval requirements are considered as another part of the requirements for the set of wind power plant and reactive power compensation system.

- **Power Factor**

The agreement of the wind power plant power factor usually should be measured with POI. Wind power is authorized to meet the condition of power factor through the abilities of wind turbine generator (WTG), fixed or parallel reactors/capacitors or a combination of both states. For example FERC institution makes wind power plants bound to observe the power factor from 0.95 lead to 0.95 lag, of course, provided that the system studies by the officials of the transmission system indicates that such a condition is necessary to guarantee the security of utilization. Wind power plant usually pursues the voltage planning (static voltage) imposed from the transmission system which following it, the power factor of wind power plant is determined in the operating state and desired time. It is possible that the wind power plant be unable to secure the all conditions of the power factor limitation in all possible operating scenarios [5].

- **Voltage Dynamic Backup Requirements**

Some institutions believe that the sufficiency of voltage dynamic supply, like stabilizer of power system and automatic voltage regulations in the conventional power plants units is one of the requirements of wind power plants. Such obligations can be imposed when the authorities of transmission system has come to this conclusion through system studies that the dynamic capability of wind turbine power plant is necessary for maintaining the security of system operating condition [5].

- **Low Voltage Ride through (LVRT) Requirements**

Low voltage ride through ability in wind power plants is one of its requirements for the connection to the power transmission grid. Wind turbine power plants are bound to remain in the state of connection to the grid during the occurrence of 3 phase faults with the time to remove the faults of 4 to 9 cycles. In the other words, the wind turbine unit should not be outage for the state in which the voltage in the side of high voltage of the wind unit transformer substation is up to the time of 0.15 s in zero quantity. Also, wind power plants should remain in the circuit during the phase to the ground faults with the removing delay time and retrieval the post fault voltage to the pre fault amount. LVRT requirements are not applied for the faults among the generator terminals of wind turbine and the side of high voltage of wind power plant transformer [5, 7].

- **High Voltage Ride Through (HVRT) Requirements**

Wind power plants are exposed to high voltages and these voltages might occur due to reasons such as removal and clearance of faults, losing large loads or other system transient states in the grid. Some institutes intends to include certain obligations about HVRT. In many European countries, wind power plants bound to remain in the generation circuit in situations in which the high voltage is up to 110% of nominal voltage at the POI. Also these power plants should remain in circuit for higher voltages if the fault time is less than the pre-determined time [5, 7].

5.6 Wind Turbine Power Plant from Distributed Generation Viewpoint

Considering the wind turbine units as the distributed generation at the distribution and sub-distribution levels, it is possible to achieve good results in different areas related to electricity energy and environmental effects. In the continuation of the discussion, some of these effects are pointed out briefly.

- **Effect of Wind Turbine Units in the Role of Distributed Generation Resources on Reliability of Distribution System**

One of the most important feature of distribution system is its level of reliability. As we know, one way to improve the distribution system reliability is to reduce the outage time or in the other words, the reduction of load retrieval time for a part of consumers which have been detached from the electricity grid as an incident. Distributed generation resources can improve the reliability in this way. When there is a failure in the main grid, they can supply part of the load in island form which is not in the failure area and has been in outage as a result of fault in the grid. Thus, the time of load retrieval in these consumers, from the time of the repair of out-of-service part of the grid, will reduce to the duration of switching and DG re-running.

This state of DG performance, is also called backup state. In this state, it is possible that DG acts prior to failure in parallel form with the main grid and after the fault occurs in the grid, enters the island form. In this event, it should be noted that after the fault occurs, first DG is detached from the grid and after detaching the failure cause, it is connected to the grid for supplying a part of the load once again. The reason for doing this process is to prevent from the lack of protective coordination in the grid and also formation of unwanted islands which in addition to technical problems will bring about the personnel security issues too. Another issue which should be noticed is that the DG should have required capacity for supplying the load inside the island [7–9].

- **The Impact of Wind Turbine Units in the Role of Distributed Generation on the Reliability of Upper Hand Grid**

As the presence of a distributed generation unit can have impact on the reliability of distribution grid, it could influence on the upper hand grid reliability, because with the installation of a unit in distribution grid, the load curve seen in the side of the distribution substation changes. As this curve contributes in the trend of reliability calculation, so that with the installation of each DG in the distribution grid, as much as the reduction of the substation load curve, the reliability index of upper hand grid will change [8, 10].

- **The Effect of Wind Turbine Units in Improving the Environmental Issues**

Employing the wind turbine units in the role of resources for distributed generation in the power grid can be effective in improving environmental issues in two ways:

1. Limiting the dissemination of greenhouse gases: Using the distributed generation resources in particular, the resources based on renewable energies such as wind and co-generation of heat and power (CHP), limits the dissemination of greenhouse gases which is itself one of the stimulants for the use of these resources in the power system.
2. Preventing from the construction of transmission lines and new power plants: One of the other important effects of the distributed generation resources from the environmental viewpoints is to prevent from construction of transmission lines and new power plants whose performance increases the public opposition because the construction of these power plants reduces the environment beauty and capture a large space too [8, 11].

- **The Effect of Installation of Wind Turbine Units in DG Role in Planning for the Development of Power Grid**

The effect of distributed generation resources on the planning for the development of power grid should be studied from some aspects. These cases include the development of power grid for the grid load supply or in other words the study of system sufficiency at two levels of distribution and generation.

One of the important effects of the presence of distributed generation resources in the distribution grid is the concurrent replacement or delay of investment for the development of distribution and sub-distribution of substations. As these resources by themselves as the small power plants deal with the supplying the grid loads, so the rate of electrical power received from the generation and transmission system is reduced and investment for the promotion of substations capacity or construction of new posts are postponed. The important point which should be taken into consideration on this case is to determine the level of sections of distribution cables.

As the rate of load growth is determined with the measurement of grid load in distribution substations, the presence of distributed generation resources might cause the misleading of system designers and some of the distribution lines face overload gradually. As the occurrence of this issue will cause the disconnection of distribution lines and reduction of reliability, more accurate assessments should be done on this issue. Another issue which is put forth at distribution level is to study the sufficiency of power system at the level of distribution grid. The issue is put forth in this way that the presence of wind turbine units in the role of distributed generation resources can to which extent be an alternative for the power purchased from the transmission grid. In order to respond to this question, certain studies have been done to study the sufficiency of the distribution system in the presence of distributed generation resources [8].

5.7 Doubly Fed Induction Machine

The presence of wind energy resources in the power grids is expanding and in many wind farms, the doubly fed induction machines are used for the generation of electrical energy. When the power grid faces a serious disruption, the wind turbine generations in the wind farms are not able to adjust the reactive power dynamically because they are under operation with the unity power factor. So, this status lead to the intensive fall of voltage to the extent that the wind turbine generators makes tripping and are outage and this issue has directly impact on the regular performance of wind farm and threaten the grid security. So, the study of the quality of contribution of wind farms in the voltage regulation of power grid and quality of full utilization from the adjustment ability of the wind turbines reactive power is an effective way to reduce the voltage fluctuations and control of voltage durability in the common connection point of the grid and assurance of the secure performance of the power grid system [12].

As the power generation in distributed and uncontrolled form increase the risk of power system operation and may lead to reduction of power quality (placing the electrical variables outside the limit of use, risk of de-functioning or exit of equipment, etc.), so the power generation companies try to control the reactive power of wind farms through doubly fed machines and on this basis, it is possible to achieve the control of voltage level at distribution grids. It is worth mentioning that in these types of generations, the control of active and reactive power is possible and consequently, they can be used as a source for the continuous reactive power in the electricity generation institutes [12, 13].

5.7.1 Doubly Fed Induction Generator (DFIG) Modeling

The main structure of a DFIG is shown in Fig. 5.1. Wind turbine is connected to DFIG through a mechanical system and this mechanical system includes a low speed shaft (axle) and a high speed shaft which have been detached from each other by a gearbox. The induction generator and wounded rotor in this structure, fed from both sides the rotor and stator of electrical grid. In this machine, stator has been directly connected to power grid whereas the rotor has been connected to grid through AC/DC/AC variable frequency power electronic converter. In order to generate the power in the fixed voltage and frequency for a power grid in the speed limit between upper Synchronous and lower-Synchronous speed, it is necessary to control the transfer power between rotor and grid both from the viewpoint of quantity and direction. The variable frequency converter is comprised of two pulse modulation width converter (PMW) which includes Rotor Side Converter and Grid Side Converter (GSC).

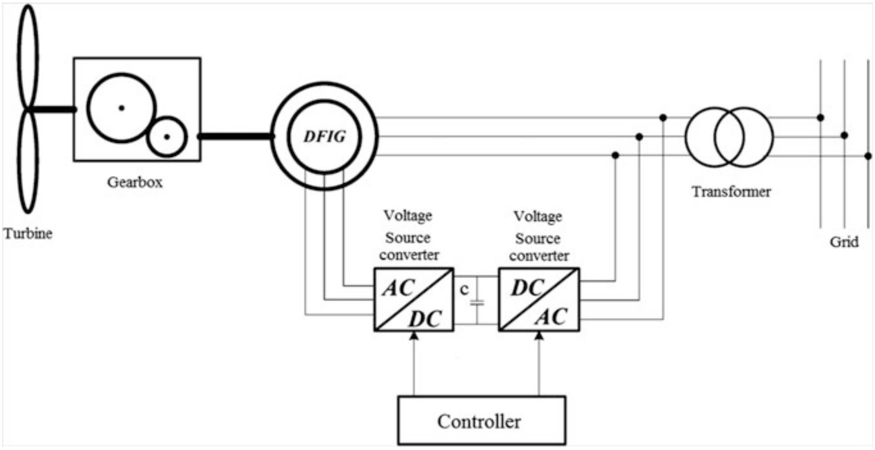


Fig. 5.1 DFIG structure

These converters have been connected back to back through a DC link capacitor. The Crow-bar system which exists in most DFIG is used to short circuit the rotor circuit at the time of fault in order to protect the rotor windings and RSC (Rotor Side Converter) against over-currents of rotor windings.

For a more precise discussion on this case, the following cases can be taken into consideration [14]. In DFIG system, the frequency of stator is fixed and equal to the grid frequency. As it was said, with the control of applied frequency to rotor, with regard to the change in the wind speed, it is possible to control the system.

In the event that rotor is fed with a variable frequency and voltage by the power electronic converter, the generator will provide a variable frequency and voltage in stator.

With regard to the explanations presented, it can be shown that in the remaining state, the mechanical speed of axle ω_{sh} is obtained from the following relation:

$$\omega_{sh} = \omega_s \pm \omega_r \tag{5.1}$$

where ω_{sh}, ω_s and ω_r, accordingly include the angle speed of stator voltage, angle speed of applied voltage on rotor and angle speed of rotor shaft.

Positive sign in the above relation is when the sequence of rotor and stator phase are similar and $\omega_{sh} < \omega_s$. This state is called sub-synchronous performance. The negative sign in this state is corresponding with the state in which the rotor phase sequence is negative (opposite to the sequence of stator phase) and $\omega_{sh} > \omega_s$. This state is called the over-synchronous mode.

With the assumption that DFIG function in the steady state, the existing relation between mechanical power, electrical power of rotor and electrical power of stator has been shown in Fig. 5.2. In this figure P_m indicates the mechanical power delivered to generator, P_r indicates the rotor power, P_{airgap} is the power of generator

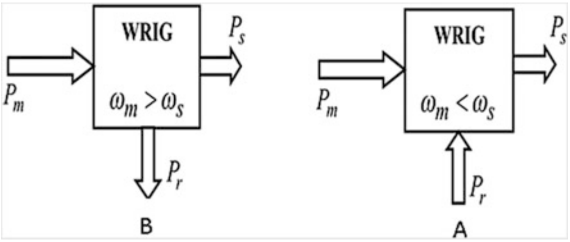


Fig. 5.2 DFIG power flow diagram

air distance and P_s is equal to the power delivered to the grid by stator. In this figure and relations of P_g indicate the total generating and delivered power to the grid.

$$P_m = P_s \pm P_r \tag{5.2}$$

Considering the DFIG equations, simply it can be shown that the following relation is established between stator power, rotor power and the power applied on generator shaft.

One system including DFIG can deliver the electrical power through both ways of stator to the grid but through rotor circuit can absorb energy and power from the grid too.

Delivery or absorption power by rotor depends on the speed of generator turn. If generator is in the over-Synchronous mode, power through rotor and through converters will be injected to the grid and if the generator is in sub-Synchronous mode, in this case rotor will absorb the power through converters. These two working modes are shown in Fig. 5.2 in which ω_s is equal to Synchronous speed and ω_r is equal to rotor speed.

With regard to the Fig. 5.2, it can be learned that in the event that the stator losses is ignored, the Eq. (5.3) and in the event of ignoring the rotor losses, the Eq. (5.4) is obtained.

$$P_{airgap} = P_s \tag{5.3}$$

$$P_{airgap} = P_m - P_r \tag{5.4}$$

From the above two and equation, the stator power is stated by using the following relation:

$$P_s = P_m - P_r \tag{5.5}$$

The above relation can be written in form of generator torque:

$$T\omega_s = T\omega_r - P_r \tag{5.6}$$

In which $P_s = T\omega_s$ and $P_m = T\omega_r$. With the right arrangement of the above relation, it is possible to achieve the following equation:

$$P_r = T(\omega_s - \omega_r) \tag{5.7}$$

Then the rotor power can be related to slip in the following form:

$$P_r = -sT\omega_s = -sP_s \tag{5.8}$$

In which slip means the same s, in terms of phrases of ω_s and ω_r are stated as follows:

$$s = \frac{\omega_s - \omega_r}{\omega_s} \tag{5.9}$$

With the combination of the above relations, the mechanical power i.e. P_m is stated as follows:

$$P_m = P_s - P_r = P_s - sP_s = (1 - s)P_r \tag{5.10}$$

Finally, the total delivered power to the grid, i.e. P_g is stated by using the following relation:

$$P_g = P_s + P_r \tag{5.11}$$

With regard to the equation $P_r = -sP_s$, it is seen that the direction of flow in rotor depends on the rotor performance speed. The direction of power includes to two states of sub-Synchronous and super-Synchronous performance. So, the rotor circuit in the generator state can both absorb the electrical power and inject the electrical power to the grid. Table 5.1 shows different working modes for the doubly fed induction generator [15].

The dynamic equation of a doubly fed induction generator with three phases in the Synchronous rotating reference frame of d–q is written as follows [15]:

$$V_{ds} = V_s I_{ds} - \omega\lambda_{qs} + \frac{d\lambda_{ds}}{dt} \tag{5.12}$$

Table 5.1 Possible states for the doubly fed induction generator

Under sync		Upper sync		
Motor	Generator	Motor	Generator	Functional status
0>	0<	0>	0<	P_m
>0	0>	0>	0<	P_r
0>	0<	0>	0<	P_s

$$V_{qs} = V_s I_{qs} - \omega \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \tag{5.13}$$

$$V_{dr} = V_s I_{dr} - s\omega \lambda_{qr} + \frac{d\lambda_{dr}}{dt} \tag{5.14}$$

where ω_s shows the Synchronous reference frame rotating speed and $s\omega_s = \omega_s - \omega_r$ shows the slip frequency and the linking flow of DFIG is specified with the following relations.

$$\lambda_{ds} = L_{ls} i_{ds} + L_m (i_{ds} - i_{dr}) = L_s i_{ds} + L_m i_{dr} \tag{5.15}$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qs} - i_{qr}) = L_s i_{qs} + L_m i_{qr} \tag{5.16}$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m (i_{ds} - i_{dr}) = L_m i_{ds} + L_r i_{dr} \tag{5.17}$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m (i_{qs} - i_{qr}) = L_m i_{qs} + L_r i_{qr} \tag{5.18}$$

where $L_{lr},\ L_m,\ L_{ls},\ L_r = L_m + L_{lr},\ L_s = L_m + L_{ls}$ of the rotor and stator linking inductances and counterpart. DFIG electromagnetic torque is shown as follows:

$$T_e = \frac{3}{2}\frac{p}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{5.19}$$

where p shows the number of poles of induction machines. Ignoring the losses of the power related to the stator resistance, active and reactive powers of stator are obtained in form of the following equations:

$$P_s = \frac{3}{2}(V_{ds} i_{ds} - V_{qs} i_{qs}) \tag{5.20}$$

$$Q_s = \frac{3}{2}(V_{qs} i_{ds} - V_{ds} i_{qs}) \tag{5.21}$$

And the active and reactive power of rotor is specified with the following equations:

$$P_r = \frac{3}{2}(V_{dr} i_{dr} - V_{qr} i_{qr}) \tag{5.22}$$

$$Q_r = \frac{3}{2}(V_{qr} i_{dr} - V_{dr} i_{qr}) \tag{5.23}$$

5.7.2 DFIG Shaft System Model

DFIG wind turbine shaft system has been formed in form of *an* integrated shaft or in form of two high speed and low speed axels which have been connected to each other by a gearbox. In the first model, the fix of total inertia of the system is specified as follows:

$$H_m = H_t + H_g \tag{5.24}$$

where H_g is generator inertia and H_t is turbine inertia. The electromechanical equation of DFIG wind turbine generator is shown as follows:

$$2H_m \frac{d\omega_m}{dt} = T_m + T_e - D_m\omega_m \tag{5.25}$$

which T_m shows the mechanical torque applied on turbine in pre-unit, T_e is the electromagnetic torque of machine and ω_m is the revolving speed in the per unit and m shows the mortal coefficient of shaft system. Due to the fact that there is a possibility of risk of rotating fluctuation of wind turbine and electrical quantities, in shaft system, mostly two models of shafts are used which one has a low speed and related to turbine and the other has a greater speed and related to generator and these two parts have been connected to each other by a gearbox. This type of model has been shown in Fig. 5.3.

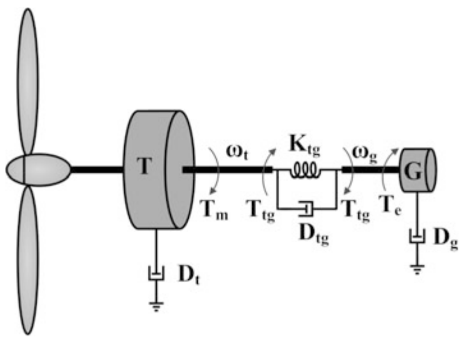
Electromechanical equations of this system are obtained as follows:

$$2H_t \frac{d\omega_t}{dt} = T_m - D_t\omega_t - D_{tg}(\omega_t - \omega_r) - T_{tg} \tag{5.26}$$

$$2H_g \frac{d\omega_r}{dt} = T_{tg} - D_g\omega_r + D_{tg}(\omega_t - \omega_r) - T_e \tag{5.27}$$

$$\frac{dT_{tg}}{dt} = K_{tg}(\omega_t - \omega_r) \tag{5.28}$$

Fig. 5.3 DFIG wind turbine two part shaft system model



where ω_t and ω_r show the turbine and generator rotor speed in per unit and T_{tg} the local torque, D_{tg}, D_t and D_g show the turbine mortality coefficient, generator and gearbox and K_{tg} shows the strength of gearbox. Ignoring the mortality coefficient of turbine and generator, the function of transfer from electrical torque of the generator with the speed of ω_r rotor for DFIG wind turbine has been shown as follows. In Fig. 5.3, N_1/N_g specifies the ratio of gears of gearbox.

$$\frac{W_r}{T_e} = \frac{1}{2(H_t + H_g)s} \frac{2H_t s^2 + D_{tg}s + K_{tg}}{\frac{2H_t H_g}{H_t + H_g} s^2 + D_{tg}s + K_{tg}} \tag{5.29}$$

5.7.3 DFIG Wind Turbine Generator Control

The control system of a DFIG wind turbine usually is comprised of two parts: The part of electrical control and the part of mechanical control. The part of electrical control includes the control of converter in the rotor side and control of converter in the grid side.

The part of mechanical control includes the control of the angel of turbine blade. Figure 5.4 shows the system of simulated wind power plant in MATLAB software which is connected to a power grid.

Rotor Side Control Converter

The necessity of the rotor side control converter is to achieve the following objectives: [16]

1. Adjustment of DFIG rotor speed for maximum power absorption
2. Maintaining the output frequency and voltage of DFIG stator in fixed quantity
3. Control of DFIG reactive power.

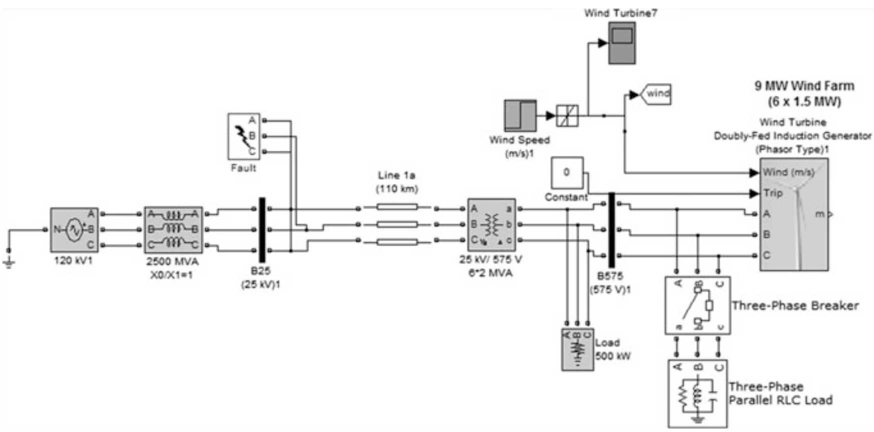


Fig. 5.4 Wind power plant system in MATLAB software

In DFIG, the mentioned objectives are usually obtained by adjusting the rotor current in the revolving frame of reference stator flux. In the rotating reference frame, the stator flux of d axel matches with the linking flux of stator Fig. 5.4 shows the design of RSC vector control [16].

In the d–q reference frame, there prevails a mathematical relation among the components of d and q axel which is shown as follows:

$$i_{qs} = \frac{-L_m i_{qr}}{L_s} \tag{5.30}$$

$$i_{ds} = \frac{L_m(i_{ms} - i_{dr})}{L_s} \tag{5.31}$$

$$T_e = \frac{-\frac{3}{2}\frac{p}{2}L_m^2 i_{ms} i_{qr}}{L_s} \tag{5.32}$$

$$Q_s = \frac{3}{2}\omega_s L_m^2 i_{ms}(i_{ms} - i_{dr})L_s \tag{5.33}$$

Such that

$$V_{dr} = r_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - s\omega_s \sigma L_r i_{qr} \tag{5.34}$$

$$V_{qr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} - s\omega_s(\sigma L_r i_{dr} + \frac{L_m^2 i_{ms}}{L_s}) \tag{5.35}$$

$$i_{ms} = \frac{V_{qs} - r_s i_{qs}}{\omega_s L_m} \tag{5.36}$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{5.37}$$

The above equations show that the DFIG (ω_r) rotor speed as a result of stator active power can be controlled with the adjustment of the component of q (I_{qr}) axel current and Eq. (5.23) shows that the Q_s stator reactive power is controlled by adjusting the component of d axel of I_{dr} rotor current. So that, the reference quantities of I_{qr} and I_{dr} are obtained directly from the adjustment of stator reactive power and rotor speed or DFIG stator power.

Considering Fig. 5.5 from the comparison of real measured flows and reference currents obtained and their reinforcement by PI controllers, the reference components of d and q of rotor voltage are obtained. In Fig. 5.5, V_{qr} and V_{dr} components only depend on I_{dr} and I_{qr} currents. So, they can be adjusted independently by I_{dr} and I_{qr}. Then, these quantities are compared with the simplified quantities in Eqs. (5.30) and (5.31). Then they are modulated by PWM for IGBT.

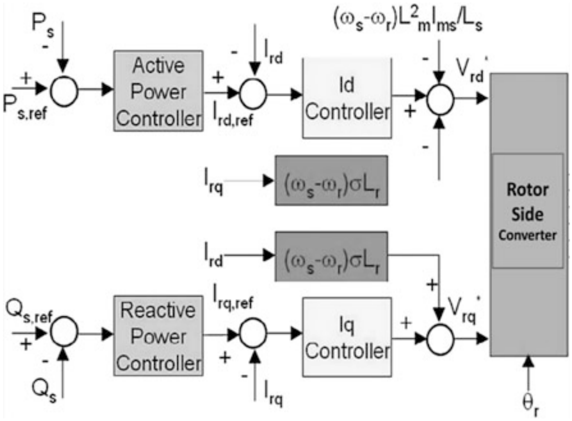


Fig. 5.5 RSC controlling circuit

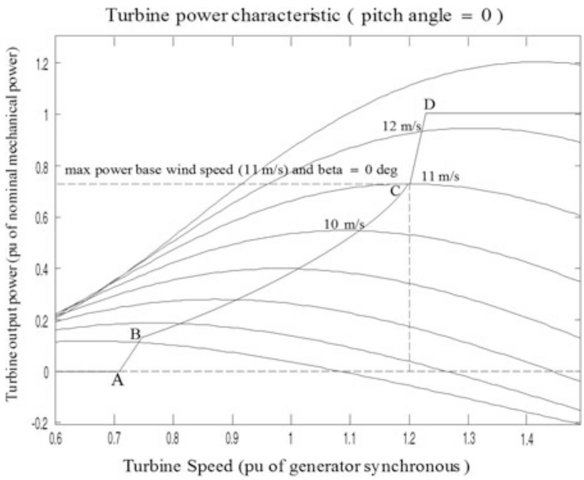


Fig. 5.6 Curve of feature of power absorption

The reactive power control can be used to achieve the coefficient of ideal power in the DFIG connection point. When WTG feeds a strong power system, the reference reactive power can be adjusted for simplicity in zero. For the control of active power, the curve of feature of power-speed is used which is known as the curve of feature of absorption. [Calculations for the wind turbine power].

This feature has been shown in Fig. 5.6 by ABCD curve. In this curve, first the turbine speed is measured. Then the mechanical power related to the same speed is used as the reference power for the control circle of active power P_s^*. The point between B and C is the geometrical place of the maximum of turbine power and power in D point and higher than that is equal to one per unit.

The reactive power causes changes in the systemized stabilized voltage and also indirectly causes the increase of costs of power system. Thus, the optimal distribution of reactive power which is a sub-problem of optimal load flow (OPF) and mainly is done through suitable control of reactive power resource is of great significance.

5.8 Calculation of Power Resulting from Wind

The wind kinetic energy is proportional with the square of its speed or when it hits the surface; its kinetic energy is converted into pressure (power) over that surface.

As we know, the multiplication of power in speed gives the power and as the wind power is proportional with the square of its speed, the wind power will be proportional with the cubic of its speed.

$$E_c = 0.5MV_w^2 \tag{5.38}$$

$$P = 0.5pAV_w^3 \tag{5.39}$$

As it is specified from the Eq. (5.38), the mechanical power of wind power has a direct connection with the cube power of wind speed. The high speeds of wind are not usually repeated and are non-economic to be able to put the accessible power and also the controlling systems based on using these types of speed, as a result, with the aerodynamic design of blades, the increase of the power in lieu of high speed will be prevented. The curve of Fig. 5.7 shows the changes of output power of wind turbine in lieu of changes of wind speed.

One of the most prevailing methods to stabilizing the output power of wind turbine is to use the change of angle of blades paces. Usually for modeling, the mutual effect of wind and turbine blades, a coefficient of power in Eq. (5.39) is used. Thus, the following relation is obtained:

$$P_m = 0.5pAV_w^3 C(\theta, \lambda) \tag{5.40}$$

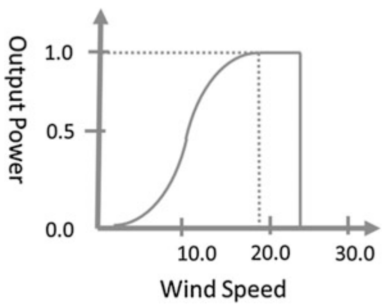


Fig. 5.7 Curve of output power in lieu of change of wind speed

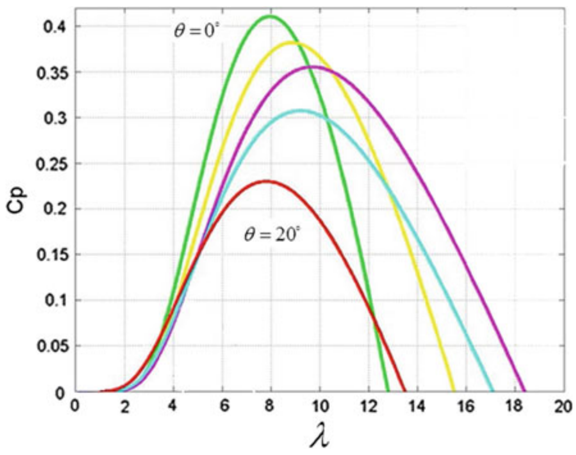


Fig. 5.8 Change of power coefficient in terms of λ variable

where $C(\theta, \lambda)$ is the power coefficient of θ angle of blades pace and λ is the ratio of speed of blade top to the wind speed. Figure 5.8 shows the method of change of power coefficient in terms of λ variable.

Theoretically, the maximum of wind power in a wind turbine which might be changed into mechanical energy, 16.27 is almost 3.59% of wind kinetic energy and this issue in 1972 was put by Betez. The aerodynamic deficiencies in practical machines and mechanical and electrical loses cause the real power to be less than the rate calculated through theory and in practice, the fixed coefficient of 593.0 cannot surpass 4.0.

5.9 Air Density Changes Proportional with the Height and Temperature Degree

Air density changes with the height changes and also with the changes of temperature degree.

Air density in regular conditions of 60 F is equal to 5.15 C near the sea 21.1 kg/m^3.

Air density in the height over the earth lowers. The ratio of air density in different heights to the air density in zero height of the sea surface is called the ratio of density in height.

Air density in different degrees of temperature changes such that in the degrees higher than 60 F, air density reduces. The ratio of air density in different temperature to the air density in 60 °F is called the ratio of density in temperature.

Changes of Wind Speed Proportional with the Height

Wind speed in the heights of about some thousands meters is basically related to the difference of atmosphere pressure. The closeness of wind to the earth makes the wind speed to be reduced noticeably. Though finding a precise relation between wind speed and its distance from the earth due to the situation of the earth from the viewpoint of ups and downs is difficult, but in this line, the experimental relations have been presented. One relation by Helman to obtain the speed in the inaccessible heights is as follows:

$$V_{h_2} = V_{h_1}\left(\frac{h_2}{h_1}\right)^a \tag{5.41}$$

where h_1 is the measured height, h_2 the concerned height, V_{h1} is the wind average speed in the measured height, V_{h2} is the wind average speed in the ideal height and a is the sign of Helman whose quantity depends on unsmooth statuses of heating classes and its quantity is obtained experimentally. For example, the quantity of a in the seashore areas is less than points far from the sea such that in the surrounding areas it is almost 1429.0 and in the forest and hills areas it is usually between 2.0 and 3.0.

As we see, the wind speed increases with the increase of height from the land surface. The 10 m height has been identified as a suitable height for the installation of average wind turbines in the world.

5.10 Load Control, Frequency and Voltage-Reactive Power in Diesel Generators

The main part of the system of frequency-load control is the system of adjustment of diesel engine speed which receives the frequency deviation or frequency or power and converts it into a suitable reaction to control the rate of input fuel into the diesel engine.

For adjusting the diesel engine speed to control load-frequency, three types of control can be employed which include:

- Speed manual changer
- By governor
- Through feedback.

For the control of voltage—power reactive, the simplest solution, is to control the Synchronous generator inciting which is point out at the following lines:

The current to incite the Synchronous generators is usually supplied by a DC generator which is the same shaft with turbine-generator.

The full control system is known as automatic voltage regulator (AVR). In the simplest way, the output voltage of Synchronous generator is sampled and after, it is compared with the reference voltage and the resulting error after reinforcement is applied on the inciting field of an Amplidyne which the Amplidyne also will incite and control the main field of generator.

In the large systems of wind power for the control of load-frequency and voltage-power control of reactive, it is possible to use the microprocessor methods to increase the easiness and accuracy of the job which is beyond the scope of the present discussion.

Traditionally, OPF issue is used in form of economic load flow. In this case, the object function is to minimize the fuel cost, but the functions of other objective can also use in this issue. In some cases, it is possible that a number of functions concurrently become optimal as the target functions which in this case, the issue takes the form of target multi-function. The formulation of the issue is as the following form:

$$\min/\max\left\{ F(x,u) = \begin{bmatrix} f_1(x,u) \\ f_2(x,u) \\ \cdot \\ f_n(x,u) \end{bmatrix} \right\};\ n = 1,2,\ldots,N_{obj} \tag{5.42}$$

$$\text{s.t.}\begin{cases} h(s,u) \le 0 \\ g(s,u) = 0 \end{cases} \tag{5.43}$$

where u is the vector of controlling or independent variables of grid including the generative powers apart from reference bass, generators voltages, transformer tap and injected reactive power by parallel elements and can be expressed in the following form.

$$u = (P_G, V_G, T, Q_{sh}) \tag{5.44}$$

$$x = (P_{Gref}, V, \delta, Q_G) \tag{5.45}$$

Also, x is the vector of status or dependent variables of the grid including load bass voltage, base voltage phase, generators reactive power, generative power in reference bass and can be expressed as follows:

$G(x,\ u)$ represents the equal constraints which indicates the equations of system load distribution. With the adjustment of u as the controlling variable in each stage and solving the non-linear equations of load flow, the corresponding x quantities are calculated.

$H(x,\ u)$ indicates the unequal constraints and includes the following cases:

Equal constraints:

$$P_{Gi} - P_{Di} = \sum_{j=1}^{N_{Buses}} V_i V_J Y_{ij}\, Cos(\theta_{ij} - \delta_i + \delta_j)]\ \forall i,\, j \in N_{Buses} \tag{5.46}$$

$$Q_{Gi} - Q_{Di} = \sum_{j=1}^{N_{Buses}} V_i V_J Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j)]\ \forall i,\, j \in N_{Load\ Buses} \tag{5.47}$$

$$\sum_{i}^{N_g} P_{Gi} = P_D + P_{Loss} \tag{5.48}$$

$$\sum_{i}^{N_g} Q_{Gi} = Q_D + Q_{Loss} \tag{5.49}$$

Unequal constraints:

(A) Capacity limits of generation units which includes the high and low limit of voltage rate, generation power of active and reactive. The output power of each generator should not be more than its nominal rate and also it should not be less than the quantity which is necessary for the durable use of steam boiler. So, the generation is limited such that it could place between the two predetermined limits of minimum and maximum:

$$V_{G_i}^{\min} \leq V_{G_i} \leq V_{G_i}^{\max} \tag{5.50}$$

$$P_{G_i}^{\min} \leq P_{G_i} \leq P_{G_i}^{\max} \tag{5.51}$$

$$\begin{aligned} &Q_{G_i}^{\min} \leq Q_{G_i} \leq Q_{G_i}^{\max} \\ &i = 1, 2, , \ldots, N_g \end{aligned} \tag{5.52}$$

(B) Compensational power limits by parallel elements

$$Q_{sh_i}^{\min} \leq Q_{sh_i} \leq Q_{sh_i}^{\max} \tag{5.53}$$

(C) Limit of tap transformer

$$t_i^{\min} \leq t_{i_i} \leq t_i^{\max} \tag{5.54}$$

(D) Limit of equipment use which includes the acceptable scope for the voltage and loading rate:

$$V_i^{\min} \leq V_{i_i} \leq V_i^{\max} \tag{5.55}$$

$$\begin{cases} P_{Li} \leq P_{Li}^{\max} \\ Q_{Li} \leq Q_{Li}^{\max} \end{cases} ; \; i = 1, 2, 3, \ldots, N_{Branches} \tag{5.56}$$

In this discussion, the optimization of reactive power is concerned which the objectives can be stated as follows [17–19].

5.10.1 Minimizing the Real Losses

One of important goals of optimal use of reactive power is to minimize the losses of real power in the transfer grid which in this chapter has been considered as the function of the goal of optimization problem. The rate of losses in the transfer grid can be calculated as follows [18, 20, 21]:

$$P_{Loss} = \sum_{k=1}^{N_L} g_k [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \tag{5.57}$$

where V_i and V_j are the primary and last bus bar voltage, θ_{ij} is the angle difference between bus bar i and j and g_{ij} is the conductive media between bus bar i and j.

5.10.2 Durability Indicator Calculation

There are many indicators for the analysis of the voltage improvement in power systems including *P–V* curve analysis, *Q–V* curve analysis and *L*-index indicator. In this research, the *L*-index indicator is used to analysis the durability and voltage sensitivity. For this purpose, one system of n bus bar is divided into two groups of generative and load bus bars. The bus bars 1 to g are the generative bus bars and bus bars g + 1 are load bus bars.

$$\begin{bmatrix} I_g \\ I_l \end{bmatrix} = \begin{bmatrix} Y_{gg} & Y_{gl} \\ Y_{\lg} & Y_{ll} \end{bmatrix} \begin{bmatrix} V_g \\ V_l \end{bmatrix} \tag{5.58}$$

With regard to the admittance matrix, the L indicator for load bus bars is obtained from the following relation.

$$L_j = \left| 1 - \sum_{i=1}^{N_g} F_{ij} \frac{V_i}{V_j} \right|, \quad j = N_g + 1, \ldots, n \tag{5.59}$$

$\left[F_{ij}\right]$ can be calculated with regard to the admittance matrix in the following form.

$$\left[F_{ij}\right] = -[Y_{LL}]^{-1}[Y_{LG}] \tag{5.60}$$

L is an index between zero and one. To the extent that this index is closer to one, to the same extent it indicates the instability and disruption of voltage and the more this index is closer to zero, the more durability it has.

$$L = \max(L_j), \quad j \in \alpha_j \tag{5.61}$$

5.10.3 Voltage Profile Indicator

As voltage is one of the most important standards from the viewpoint of power quality in presenting services by the electricity companies, so that in the distribution networks, great attention has been made to study the impact of units on voltage. The optimization of voltage profile in power systems is of great significance.

In the power grids, there is an effort to minimize the voltage profile. In V_i^{ref} calculations, 1 per-unit is considered.

$$\Delta V_L = \sum_{i-1}^{N_{PQ}} \left| V_i - V_i^{ref} \right| \tag{5.62}$$

5.11 IEEE Standard 30-Bus Test System

The single line 30-bus bar standard system is shown in Fig. 5.9. As it is obvious in Fig. 5.9 it has 6 generator buses bar. The specifications of these generator units are shown in Table 5.2. As it is clear, the limits of active power generation and cost coefficients and coefficients of pollution rate of each of the units have been pointed out.

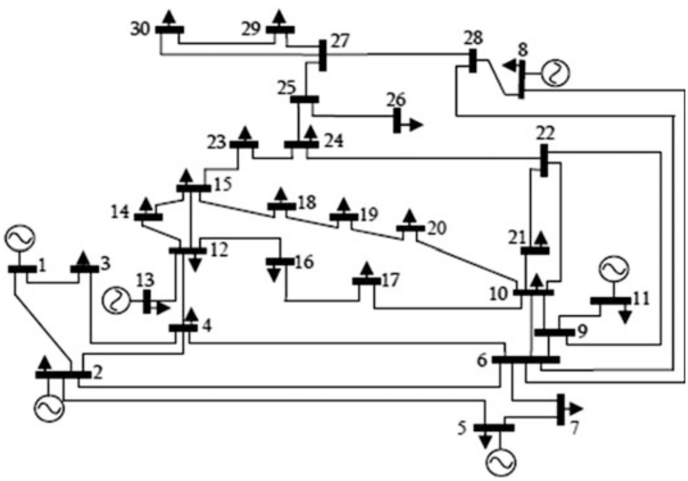


Fig. 5.9 IEEE standard 30-bus test system

Table 5.2 Specifications of the system generator units [22]

No.	λ	ξ	γ	β	α	c	b	a	$P_{G\min}$	$P_{G\max}$
P_{G1}	2.857	2e-4	0.0649	−0.05543	0.04091	100	200	10	5	150
P_{G2}	3.333	5e-4	0.05638	−0.06047	0.02543	120	150	10	5	150
P_{G5}	8	e-6	0.04586	−0.05094	0.04258	40	180	20	5	150
P_{G8}	2	2e-3	0.0338	−0.0355	0.05326	60	100	10	5	150
P_{G11}	8	e-6	0.04586	−0.05094	0.04258	40	180	20	5	150
P_{G13}	6.667	e-5	0.0515	−0.05555	0.06131	100	150	10	5	150

Table 5.3 N.R. results

Method	N.R.
Loss	4.6174
Voltage deviation	0.6783
Voltage stability	0.1171

The first method is to use the algorithm of N.R. whose results can be observed in Table 5.3.

The next step is to calculate the system calculations with the smart algorithm of the second generation of genetics with non-dominated sorting.

In this scenario, it is assumed that no wind power plant is placed in the grid and we have no limitation on this case and the problem is defined inform of a three-target problem to reduce the losses, voltage profile and voltage durability. It is clear that the reading of the problem in this state has three dimensions. With the implementation of algorithm of the best reading in the tridimensional space, they have formed a curve which totally none of the spots have a priority over the other one and the selection of the best response is done merely based on the indicators of losses, voltage profile and voltage durability and their preference is made with the employment of algorithm system.

Here it is worth pointing that from the viewpoint of Pareto superiority, the extreme points of Pareto front in fact is the optimal solution to the optimization issue, when each of the objectives are studied exclusively.

So, considering this issue, it is possible to study the quality of responses resulting from the suggested algorithm can be studied during the analysis of responses.

Figure 5.10 shows the set of optimal Pareto. After optimization, it is observed that the best reading of the last repetition of Algorithm has N-member which none of them has priority over the other one. The lack of existing continuity is due to the disrupted nature of optimization process. The resulting optimal point based on algorithm output is a suggestion. The best responses which optimize each of the three objectives in this state exclusively are displayed in Table 5.4.

The next step is to calculate the system with the smart algorithm of the second generation of genetics with the non-dominated sorting with the assumption of the presence of wind power plants with 10 MW active powers with power coefficient of 0.9.

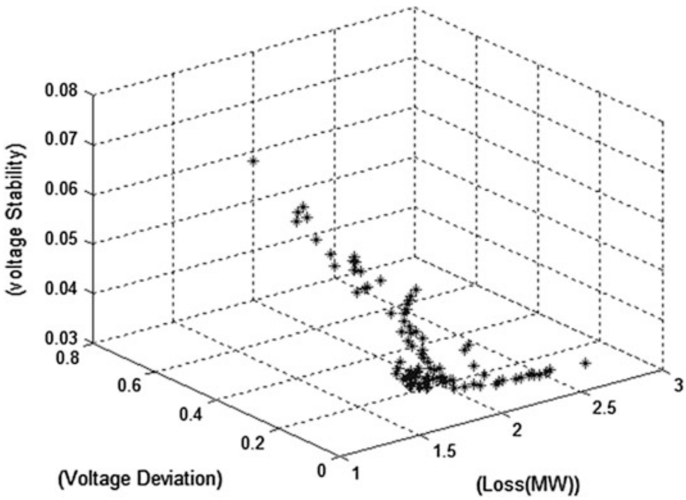


Fig. 5.10 Curves of the first Pareto front without wind turbine

Table 5.4 Results without wind turbine

Method	Best loss	Best voltage deviation	Best voltage stability
Loss	1.5198	4.1485	5.3467
Voltage deviation	0.5392	5.6788e–06	0.5073
Voltage stability	0.0486	0.0589	0.301

In this scenario, it is assumed that one power plant has been placed in the grid and the capacity generation limit of 10 MW active powers with power coefficient of 0.9 and the goal is to improve the reactive power. The problem is defined in for of a three-target problem to reduce the losses, voltage profile and voltage durability. It is clear that the reading of the problem in this state is three dimensional.

With the implementation of the best algorithm of reading in tridimensional space, they have formed a curve which totally none of the points is preferred to the others and the selection of the most suitable response is merely done based on the indicators of loss indictors, voltage profile and voltage durability and their preference is done by employing the algorithm system.

Figure 5.11 shows the optimal Pareto of this system. After optimization, it is observed that the best reading of the last repetition of Algorithm has N member and none of them has priority over the others. The resulting optimal point based on algorithm output is a proposal. The best response which optimizes exclusively each of the three objectives put forth in this state is displayed in Table 5.5.

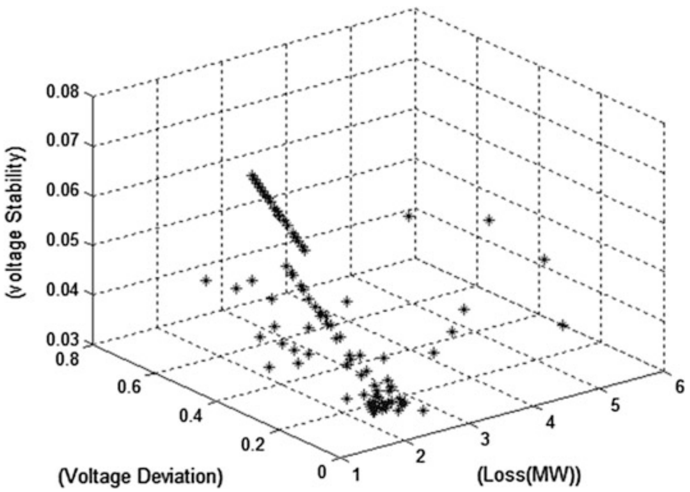


Fig. 5.11 Curves of the first Pareto front with wind turbine

Table 5.5 Results with wind turbine

Method	Best loss	Best voltage deviation	Best voltage stability
Loss	1.4503	1.7768	2.4338
Voltage deviation	0.5167	9.7316e–05	0.3332
Voltage stability	0.0709	0.0447	0.0305

Comparing the results, it is clearly learned that the presence of wind power plant is effective in improving the reactive power in the grid.

5.12 Conclusion

The role of wind power plant in today's environmental and energy dependable development is so crucial. Lots of studying and researches have been performed on wind power technologies and numbers of wind farm have been utilized around the world. The performance of overall wind power plant depends on the subsystem such as reactive power compensation and energy storage to maintain stability. However, with the increasing capacity of the wind power plant the cost and benefit of these subsystems became unfeasible. By increasing the wind farm capacity the cost for reactive power and energy storage increases. In future works, it could be feasible to test wind power plant using combined capacitor and reactive power compensation which could low the cost. The overall development of these subsystems in wind power plant depends on their cost.

It is also concluded that a DFIG is a wound-rotor doubly-fed electric machine (similar to a Synchronous generator), and as its rotor circuit is controlled by a power electronics converter, the induction generator is able to control import and export reactive power. The control of the rotor voltages and currents enables the induction machine to remain Synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine compared to a fixed speed wind turbine utilizes the available wind resource more efficiently, especially during light wind conditions. The converter cost is not as high as other variable speed solutions because only a fraction of the Mechanical Power is fed to the grid through the converter, the rest being fed to grid directly from the stator. The mechanical efficiency in a wind turbine is dependent of the power co-efficient. The power co-efficient of a rotating wind turbine is given by the pitch angle and the tip speed ratio. Adjustable speed will improved the system efficiency since the turbine speed can be adjusted as a function of wind speed to maximize output power.

Performing simulations and by looking through real experiments it can be concluded that the wind turbine unit utilizing double fed induction generator is an important and effective tool from the voltage regulation point of view. So it plays a significant role in supplying the reactive power of the network.

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