Chapter One
Introduction

1-1 Background

Power systems have been in operation since the late 19^{th} century. They were used for powering street lighting and were soon expanded to include mechanical loads. Originally direct current systems were used to deliver power, but these limited the distances that load could be placed from generation. This was because at usable voltage levels the losses and voltage drops were very high, and there was no convenient method for voltage transformation. The development of the transformer led to the introduction of alternating current systems, which became standard for power systems. Longer transmission distances became possible and, after current frequencies were standardized, interconnection between neighboring power systems also became possible. Interconnection led to increased security, since loads could be supplied by many different generators, and higher system efficiency, since each generator could be utilized to a larger extent.

Electric power systems are often described as consisting of generation, transmission and distribution. Generation usually consists of synchronous generators which produce electricity. Prime movers convert thermal energy or pressure to rotating mechanical energy, which is in turn converted into electrical energy by the generator. The transmission system connects major generators and distribution systems together by means of transmission lines. Voltages are transformed from generator voltage up to higher transmission voltage levels, and then stepped down again for loads.

Traditionally only synchronous generators were used to generate power. However wind power is now becoming an increasingly important source of energy. The community is looking more and more towards wind power to provide a renewable source of energy, with rising fuel prices and growing concern over the presence of greenhouse gases in the atmosphere. During the last decade, wind power capacity has increased at an astounding rate, and the costs of harnessing wind energy have been continually decreasing.

1-2 Problems

It is possible to state that the significant impact of wind power started in the beginning of eighty's very much related to the mid seventy's oil crises. During the period, a simple and robust wind turbine includes a three bladed wind turbine rotor, a gearbox, and an induction machine directly connected to the grid and control system.

The nineties represented an important breakthrough: new concepts emerged because of a demand for more efficient power production and to comply with power quality requirements. During these times, the wind turbines (and farms) grew in size and ratio from the few hundred kilowatts to the megawatts size. Most of the decade has been dedicated to voltage quality analysis of wind power and economics of the power systems including wind power.

Nowadays, some power system start to face problems of integrating thousands megawatts of wind power, which are decentralized spread over large extensions.

At this, the problem of planning, operation and control of the power system with a large wind power become very important. On these problems, the main challenges are classified in long term planning and energy management systems, and power system performance.

1-3 Objectives

Integration of wind power into the power system has been studied by many authors before, but most of them focused on different characteristics and issues of the power system. Wind power influences several power system characteristics from economic dispatch to stability and quality issues.

Someone pointed out main factors to utility integration of solar and wind power, provided a starting point and general classification of the most relevant power system aspects.

A project report, aimed to establish insight and to orient works in the integration of renewable power in the European Network. It characterized the impacts of large amount of renewable energy on European conventional utility practice (not only operation but institutional aspects also).

1-4 Methodology

A more recent report reviews the technical options and constrains of integration of distributed power generation. One of the focuses was on a new power system structure to deal with the imbalance on consumption and production from the stochastic nature of wind power.

On the dynamic subject, several works have been done on the analysis of power quality and on the transient stability from wind turbines to the power systems.

Other one developed an extensive analysis of the potential impacts of wind turbines on the small scale integration.

Someone, presented simple models to wind turbines and argued that contributions of wind turbines components must be modeled into the overall simulation but the total accuracy was not essential to obtain an adequate representation.

Dynamic simulations of very large power systems are very expensive. Voltage stability has been pointed out as another problem to large integration of wind power because wind farms demand reactive power.

1-5 Thesis outline

In this thesis by going through the main problems of power system that are related to the wind turbines.

Chapter3 presents, a suitable wind speed model to assess the power quality from wind turbines.

Chapter4 presents the case studies; the dynamic wind turbine is implemented in "NEPLAN" program. In the last part of the chapter we discuss the results.

Chapter5 presents the conclusions.

Chapter Two

Modeling of Wind Turbine

2-1 Wind Power Basics

The wind turbines are composed of an aerodynamic rotor, a mechanical system, an electrical generator, a control system, limited reactive power compensation and a step-up transformer. The conventional wind turbine is even at the present time, the most common type of wind turbine installed. Figure2.1 presents the basic components of a conventional wind turbine [1].

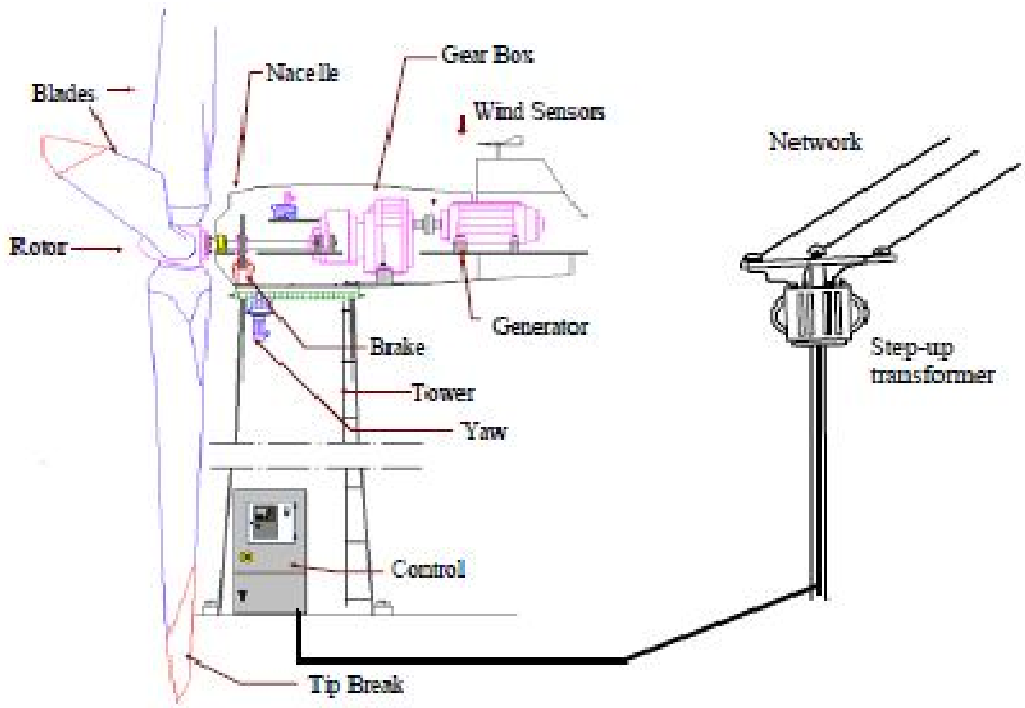


Figure.2.1 Basic Component of wind turbine Unit

The conventional wind turbine is connected directly to the grid and the generation is “synchronized” to the network. This technology has been named fixed rotational speed wind turbine because the induction generator allows small mechanical speed variation.

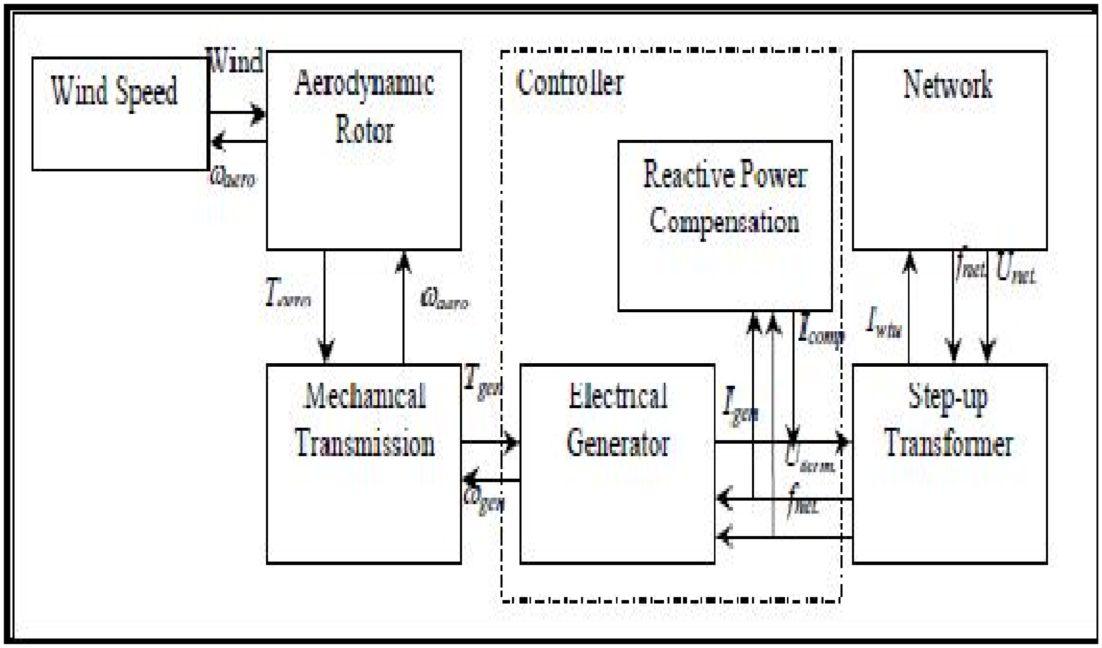


Figure2.2 Interaction between each components of wind turbine unity

Where:

w is rotational speed aero aerodynamic rotor

T is the torque wtu turbine unity wind

U is the voltage comp compensation unity

I is the current net network

f is the frequency gen electrical generator

The wind turbine components are classified in electrical and aerostatic part. The aerostatic part comprises the aerodynamic rotor and the mechanical transmission system. The electrical part comprises all the electrical components i.e. the generator, reactive power compensation, step-up transformer, and network.

2.2 The aerostatic system Components

Each component of the wind turbine has some relations with other components. Figure 2.2 [2] presents the main relations among different components. The aerodynamic rotor depends on the transmissionsystem; the transmission system depends on the electrical generator and aerodynamic rotor; and so on.

2-2-1 Aerodynamic rotor

The aerodynamic power on the main shaft can be expressed in per unit as [1].

Paero= $-\frac{1}{2}\frac{P.\pi.R^2.W^3.Cp(\lambda.\theta pitch)}{Pbaserotor}$ (2.1)

Where

P = air density

R = rotor radius

W = wind Speed

Cp = aerodynamic power coefficient

P base rotor= Rated power of the rotor

θpith= pitch angle

λ =Tip speed ratio

The aerodynamic torque in per unit can be expressed as [1].

Taero = $\frac{\boldsymbol{P}aero}{\boldsymbol{W}rotor.\boldsymbol{P}baserotor} = \frac{P.\pi.R^2.W^3.Cp(\lambda)}{2.\boldsymbol{W}rotor.\boldsymbol{P}baserotor}$ (2.2)

Where

W rotor = Rotational speed of the rotor

Cp = is a function only of the λ because stall regulated wind turbines have a fixed pitch angle.

2-2-2 Drive Train

The drive train connects high speed in the electrical generator side and slow speed in the aerodynamic rotor using a gearbox. The drive train includes a gear box, shafts and disc brakes that can be positioned in the low or in the high- speed shaft depending on the size of the wind turbine. On small wind turbines the brakes are positioned in the low speed shaft that reduces the stresses on the gear box during shut down of wind turbines, on large wind turbines, however, the torques in low speed shaft are very high hence the disc brakes are located in the high speed shaft.

Figure 2.3 [3] presents a simplified dynamic drive train model where the gear box is considered ideal hence omitted here and the speeds and torque are in p.u.

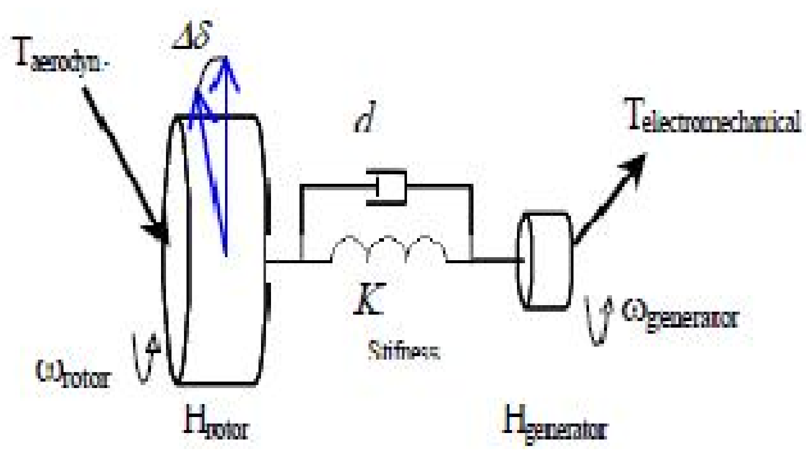


Figure 2.3 Dynamic representation of the drive train model

In figure 2.3 Taero is the aerodynamic torque computed from the aerodynamic module, Wrotoris the rotational speed of the aerodynamic rotor, Wgenis the rotational speed of the induction generator, T electromechanically the electromechanical torque in the induction generator , K stiffness's the equivalent stiffness of the shaft connecting the two masses, d is the equivalent damping coefficient that includes the losses are the torque losses in the system damping and damping losses are the torque losses related to the damping coefficient.

The equations of motion in to the dynamic drive train can be expressed according to [3].

$\frac{d(\delta rotor)}{dt}$ = Wrotor. W_0(2.3)

$\frac{d(\delta generator)}{dt}$= W gen. W_0 (2.4)

The inertia is then converted to the high speed side of the shaft and finally converted to the per unit system using the following equation [3]

H rotor=$1/2.\frac{Jrotor(W^0)^2}{q^2 gear.Sbase}$(2.5)

Where

J rotor= rotor inertia in physical unit on the low speed side

H rotor= Total inertia of the aerodynamic rotor

q gear= is the ratio between low and high speed in the gearbox

$W_0 = 2\pi f_0$ poles in the mechanical synchronous speed on the generator side

S base= base power of the electrical generator

2-3The electrical system Components

The electrical components comprise the electrical generator, the reactive power compensation, control system, step-up transformer

2-3-1Electrical generator

The asynchronous generator is the most common type of electrical machine. It is mostly applied as motor. As generator, however, it has been used for many years in wind turbines. The reliability, low price, and low maintenance made this type of machine the most suitable for wind turbines. Allied to those characteristics, the speed flexibility (slip), when compared to the synchronous machine, reduces the current spikes due to the wind gusts.

In the asynchronous generators, the rotational speed of the rotor is not fixed as it is in the synchronous machines, but it is related to the torque from the prime mover and to the network frequency.

The rotational speed of a synchronous generator must be above the synchronous speed in order to force the power flux to the network.

Keeping the active power constant and increasing the voltage lead to an increase in the reactive power because the excitation is a shunt element proportional to the voltage. Still keeping the active power constant and at this time reducing the voltage lead to a small reduction on the reactive power consumption, however decreasing further the voltage leads to an increase in the reactive power because of the losses that are increased due to the higher currents flowing in the machine.

Using a standard dq-reference frame and the notation [3].

$\acute{f} = f_{\mathrm{d}} + \mathrm{j}f_{\mathrm{q}}$(2.6)

We can write the electrical dynamics of the fifth order model as [3].

$\grave{v}_s = -R_s \acute{\iota}_s + \frac{1}{\omega_s}\frac{d\acute{\psi}_s}{dt} + j\acute{\psi}_s$(2.7)

$\acute{v}_r = -R_r \acute{\iota}_r + \frac{1}{\omega_s}\frac{d\acute{\psi}_r}{dt} + j(\frac{\omega_s - \omega_{r)}}{\omega_s})\acute{\psi}_r$(2.8)

With the relationships between the currents and flux linkages given by [3].

$\acute{\psi}_s = -X_s \acute{\iota}_s - X_m \acute{\iota}_r$(2.9)

$\acute{\psi}_r = -X_r \acute{\iota}_r - X_m \acute{\iota}_s$(2.10)

Where the subscripts s and r denote stator and rotor values for voltages v, resistances R, currents i, flux linkages per secondψ and reactance'sX, X_m is the mutual reactance, ω_s is synchronous speed, and $\omega_r$is the electrical rotor speed [3].

$\omega_r = \mathrm{P}\omega_m$(2.11)

Where p is the number of pole pairs of the machine and $\omega_m$is the mechanical speed of rotor.

Can relate the stator voltage to the network bus voltage $\acute{V}_s$ by [3].

$\acute{v}_s = \acute{V}_s$(2.12)

Reduced order models for DFIGs which are suitable for classical phases domain dynamic studies .The fifth order model includes high frequency dynamics$\frac{1}{\omega_s}\frac{d\acute{\psi}_s}{dt}$ in the stator, which are not suitable for including in fundamental frequency simulation. It is also common practice to neglect the stator resistance R_s since it is small.

If you neglect the stator resistance here, you can then write the electrical dynamics of a third order model as:

$\acute{v}_s = j\acute{\psi}_s$(2.13)

$\acute{v}_r = -R_r\acute{\imath}_r + \frac{1}{\omega_s}\frac{d\acute{\psi}_r}{dt} + j(\frac{\omega_s-\omega_r}{\omega_s})\acute{\psi}_r$(2.14)

2-3-2 Polar notation

It is useful in this study to represent the stator side of a DFIG as a voltage$\acute{E}$ behind a transient impedance$R_s + j\acute{X}$, so that [1].

$\acute{v}_s = \bar{\acute{E}} - j\acute{X}\acute{\imath}_s$ (2.15)

Equation (2.12) can then be rewritten as [1].

$\frac{d\bar{\acute{E}}}{dt} = \frac{1}{T_0}\left(jT_0\omega_s\acute{V}_r - jT_0(\omega_s - \omega)\bar{\acute{E}} - \frac{X_s}{\acute{X}}\bar{\acute{E}} + \frac{X_s-\acute{X}}{\acute{X}}\acute{V}_s\right)$(2.16)

Where

$T_0 = \frac{X_r}{\omega_s R_r}$(2.17)

is the transient open-circuit time constant and [1].

$\acute{V}_r = \frac{X_m}{X_r}\acute{v}_r$(2.18)

Could also write (2.16) in polar coordinates by making the substitutions [1].

$\bar{\acute{E}} = \acute{E}e^{j\delta}$(2.19)

$\acute{V}_r = V_r e^{j\theta_r}$(2.20)

$\acute{V}_s = Ve^{j\theta}$(2.21)

and comparing real and imaginary part. Then

$\frac{d\delta}{dt} = \frac{1}{\acute{E}T_0}\left(-T_0(\omega_s - \omega_r)\acute{E} - \frac{X_s-\acute{X}}{\acute{X}}V\sin(\delta - \theta) + T_0\omega_s V_r\cos(\delta - \theta_r)\right)$(2.22)

and

$\frac{d\acute{E}}{dt} = \frac{1}{T_0}\left(-\frac{X}{\acute{X}}\acute{E} + \frac{X_S-\acute{X}}{\acute{X}}V\cos(\delta - \theta) + T_0\omega_s V_r\sin(\delta - \theta_r)\right)$(2.23)

The mechanical equation can also be written as

$$\frac{d\omega_r}{dt} = \frac{1}{M}\left(P_m \frac{\omega_s}{\omega_r} - \frac{\acute{E}V}{\acute{X}}\sin(\delta - \theta)\right)(2.24)$$

The electrical equations then take a similar form to the standard representation of the synchronous generator. This is useful for drawing comparisons between synchronous and asynchronous generators.

2-4 Mechanical dynamics

The mechanical dynamics of a turbine system can be represented by a two mass model, which takes into account torsional oscillations found in the turbine shaft. The high and low-speed shafts and the gearbox are assumed to be infinitely stiff

If protection is not to be examined during the simulation, then a lumped mass model of the shaft can be used. This is because the mechanical and electrical parts of a turbine are decoupled to a large extent by the converters in variable speed wind turbines

Let us write the combined moments of inertia of the system as [4].

$$J = J_m + \frac{J_t}{\eta^2}(2.25)$$

Where the subscripts m and t denote the machine and turbine moments of inertia J and 1:η is the gearbox ratio. Then the lumped mass model describing the rotation of the turbine is

$$J\frac{d\omega_m}{dt} = (T_m - T_e)(2.26)$$

whereω_m is the mechanical speed, T_m is the mechanical torque, and

$$T_e = \frac{P}{\omega_s}\left(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}\right) = \frac{P}{\omega_s}(\psi_{qr}i_{dr} - \psi_{dr}i_{qr})(2.27)$$

is the electromagnetic torque.

Using the relationship

$$T_m = \frac{P_m}{\omega_m}(2.28)$$

Between the mechanical torque and the mechanical power in the machine, we can rewrite (2.26)

$\frac{d\omega_r}{dt} = \frac{\omega_s}{2H}\left(P_m \frac{\omega_s}{\omega_r} - P_e\right)$(2.29)

where

$H = \frac{1}{2} J\omega_n^2$(2.30)

is the inertia constant of the turbine shaft and generator in seconds

$P\omega_n = \omega_s$(2.31)

and

$P_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds} = \psi_{qr} i_{dr} - \psi_{dr} i_{qr}$(2.32)

Use the lumped mass model (2.29) in this thesis, since our investigation is more concerned with the dynamics of generators than with the dynamics of wind turbines.

This, together with the equations (2.13) and (2.14) form the third order model.

2-5 Dynamic Wind Turbine Model Remarks

A dynamic wind turbine model has been presented, which is intended to power quality assessment of wind turbines. This section focuses on the aerodynamic model because the electrical components are modeled by a dedicated conventional power system simulation program.

The main differences are related to basic assumptions done in the model. The first difference is related to the tower bending moment that is not

Included in the aero elastic model therefore the differences were expected.

Finally, the model is suitable to power quality assessment. The model can be applied to different simulation tools with small modifications. The model also is fast and permits the simultaneous simulation of several wind turbines representing wind farms.

2-6 Current wind turbine types

The vast majority of the wind turbines that are currently installed use one of the three main types of electromechanical conversion [3].

2-6-1 Fixed speed induction generator

The first type of turbine uses one or two asynchronous squirrel cage induction generators, or a pole switchable induction generator, to convert mechanical energy into electricity. The generator slip varies slightly depending on the amount of power generated and so is not entirely constant. However this type is normally referred to as a fixed-speed turbine because the speed variations are in the order of 1% . Today the constant-speed design is nearly always combined with a stall control of aerodynamic power.

This turbine uses one of the most common machines in power systems. Because of its simple construction, it is cheap, robust and easy to maintain. However it does experience mechanical stresses in its drive train, and because of its lack of power electronics, cannot deliver a steady output power to the grid or contribute reactive power which is important for voltage stability.

2-6-2 Double fed induction generator

The second type of turbine uses a DFIG instead of a squirrel cage induction generator. Like the first type, it needs a gearbox. The stator winding of the generator is coupled to the grid, and the rotor winding is coupled to a power electronics converter, which is usually a back-to-back voltage source converter (VSC).Through the use of this equipment, the electrical and mechanical rotor frequencies are decoupled, because the power electronics converter compensates for the difference between mechanical and electrical frequency by supplying a rotor voltage with a variable frequency. In this way variable speed operation becomes possible. The rotor speed is controlled by regulating the difference between the mechanical input and the generator output power. In this type of conversion system, the required control of the aerodynamic power is normally achieved by controlling the pitch of the blades.

While variable speed turbines were designed to extract more energy from the wind than fixed-speed induction generators, their variable speed operation is essential for decreasing the mechanical stresses in the turbine system. The converters in DFIGs are only a fraction of the rated power of the turbine, and can be used for active and reactive power control. These turbines can contribute to rotor angle stability and frequency control if their active power is controlled. They may also be able to contribute to rotor angle stability and voltage stability if their reactive power is controlled.

2-6-3 Full converter synchronous generator

The third type of turbine uses a synchronous generator with a full-scale power electronics converter. It may use either a fast speed synchronous generator with

a gearbox, or a direct drive low speed multi-pole synchronous generator with the same rotational speed as wind turbine rotor. The generator can have either a wound rotor equipped with permanent magnets. The stator is not connected directly to the grid but to a power electronics converter, which is in turn connected to the grid. The converter may consist of a back-to-back VSC or a diode rectifier with a single VSC and makes variable speed operation is possible. Power limitation is achieved by pitch control, as with the doubly fed induction generator.

This type of turbine shares the advantages of the DFIG, but its converter is a fully rated power converter can absorb or provide a larger amount of reactive power than a DFIG turbine, but is more expensive. If the synchronous generator is directly driven, then the turbine requires less maintenance, has reduced losses and costs, and a higher efficiency.

2-7 Stand-alone system

In many places, wind power is the least-costoption for providing power to homes and businesses that are remote from an established grid. It is estimated that wind produces more power at less cost than diesel generators at any remote site with a wind power density above 200 W/m^2at 50 m elevation.

Table 2.1 gives a representative idea of power requirements of some household appliances. Wind turbine performance depends primarily on rotor diameter and wind speed. Table 2.2 gives an estimate of a wind turbines output, based on wind speed rotor diameter, in Whr/day.

Table 2.1 Household appliances details [3].

Item description	*Power, Watt*	*Daily energy Whr/Day*
Incandescent light	60	1,800-720
Fluorescent light	15	45-180
Refrigerator	80-500	2,000-10,000
Television	15-100	30-600
Village household	60-300	300-1,200

Table 2.2 Output of wind turbine [3]

Rotor diameter,	*Wind speed, m/s*			
(m)	*4*	*5*	*6*	*7*
1.5	35	70	94	117
3	152	269	386	468
5	421	761	1,053	1,287
7	831	1,522	2,107	2,575

Chapter Three
Wind Power Integration

3-1 Introduction

The power quality and stability problems, and means of coping with them, are not new to the power system engineers. However, those problems related to wind power are not well described when it comes to large –scale integration.

The problem is introduced by pointing out the relevant power quality characteristics of a small wind farm (or a single wind turbine) and after it is scaled to represent the large-scale case.

First, the scales of integration are defined as follow:

- Small – scale wind power integration:

The power system is assumed to have enough spinning reserve of active and the frequency is kept constant therefore only voltage problems are concerned.

- Large – scale wind power integration:

Cause power quality or stability problems and, in some particular cases, the frequency affected by the wind turbines. Hence, the voltage and frequency problems are concerned.

3-2 Small – Scale Integration of Wind Power

In this case, the power system is considered strong and the main problems from connecting wind farms come from the voltage control. The wind farm is composed by several wind turbines. Each wind turbine has as basic electrical components: an induction generator, local reactive power compensation and step – up transformer. The wind farm limit is defined by the point of common coupling (PCC), additionally the wind farm may use an integration transformer to connect to a higher voltage level.

Figure3.1 presents the relevant electrical components of a conventional wind farm. In this thesis, the focus is on the direct connected wind turbines type (So called "fixed" rotor speed). On those types of wind turbines, the reactive power that comes from the wind is transferred to the power system without strange devices

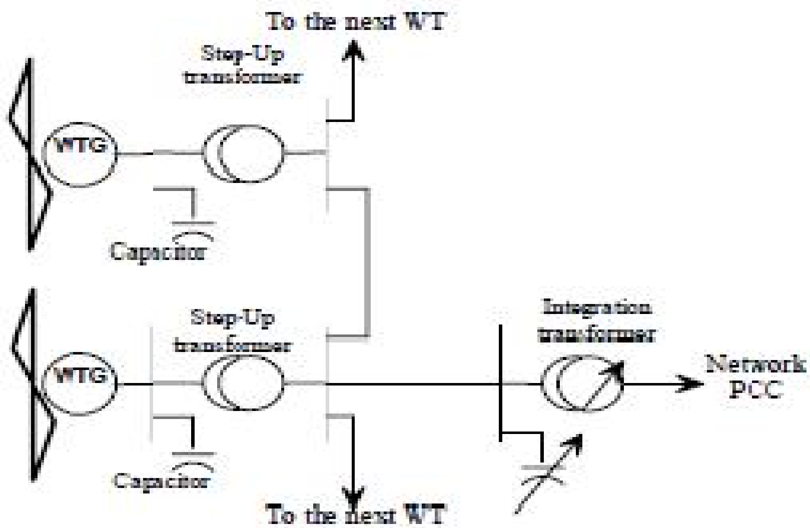


Figure3.1Electrical Component of a Conventional Wind Farm[5].

Induction (or asynchronous) machines applied as generators demand reactive power from the network, which is partially compensated with shunt capacitor banks. In special configurations, special reactive power compensation is demanded and installed at the PCC (e.g variable reactive power compensation). In special installations, the voltage level variations at the PCC can demand a variable tap change transformer.

Wind farms have very little control of the active power due to the stochastic behavior of the wind; in addition, the voltage control on this type of wind turbine can be done only by changing the amount of reactive power compensation (shunt capacitor installed). The lack of control on the active and reactive powers can disturb the voltage on the PCC.

The disturbances on the voltage from wind turbines are classified in different time scales. The classification presented as follow:

- Stead-state-does not include dynamics (very slow dynamics representing periods above 10 minutes to hour);
- Dynamic-include the dynamics in the time frame from milliseconds to 10 minute;
- Harmonics- include voltage variations in high frequency, due to the electronic equipment installed in the wind turbines; this part is not related to the wind speed. The harmonics are not an important issue because this report focus on the direct connected wind turbine type that does not emit harmonics on current, therefore it is not included in the thesis.

3-2-1 Steady State Operation

The steady state operation analysis assures that the:

- The currents will not exceed the thermal limits nor will the protections act during extreme powers;
- The voltage levels will not exceed limits. In near future, wind turbines can be certified to power quality. From these certifications a set of data will help to verify the steady – state operation of the wind turbines and wind farms.

Table 3-1present the main steady state parameters to wind turbines certified to power quality [5].

Parameters
Rated active power
Rated Reactive power
Rated apparent power
Rated current of the wind turbine at rated voltage
Rated voltage of the wind turbine
Maximum Permitted Power set –up in the controller
Maximum Measured power in 60 second average period
Maximum Recorded power in 0,2 second average period
Reactive power demand / supply as function of active power

Based on the parameters specified on table 3-1 and with electrical characteristic of the network it is possible to determine the impacts on the voltage quality as well as the maximum currents on the cables and transformers.

The impacts on the voltage quality to the different condition as expressed in table 3-1 can be computed with help of a load flow program or by simple equations. Following, simple equations to determine the voltage levels are introduced. Figure3.2 presents the electrical representation of the wind turbine and the power system, where the reference node and the equivalent impedance represent the entire power system at the wind turbine terminals.

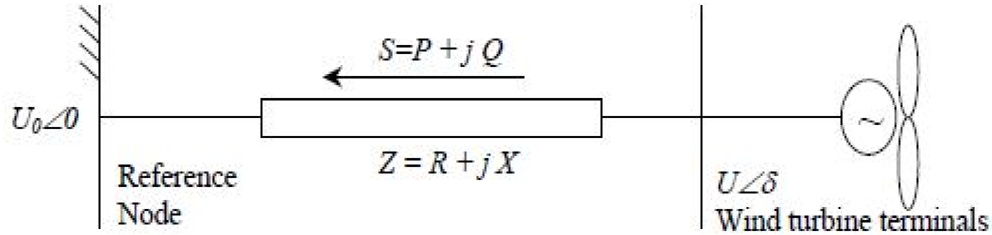


Figure3.2 Single line equivalent for a wind turbine connection

P and Q are the active and reactive power respectively from the wind turbine, there are no load or shunt element installed at the wind turbine terminals the voltage at the wind turbine terminals U can be determined as follow [6]

$$U=U0 + \Delta U \qquad (3.1)$$

Where, U0 at the reference node, U is the voltage at the wind turbine terminals and ΔU can be computed as [6].

$$\Delta U = \frac{(PR+Qx)}{U0} + \frac{(PR-Qx)}{U0} j(3.2)$$

Where, R and X are the resistance and reactance inductive characteristics of the electrical network respectively. The voltage can increase or decrease depending on the amount of reactive and active power flux and on the network characteristics.

Using equation (3.2) it is possible to compute the voltage level and compare to preset limits imposed by the local network operator.

However, in most cases, it is important to detail the network and include the load installed and use a load flow program to compute the voltage and currents on the relevant nodes and lines respectively.

3-2-2 Dynamic Operation

The wind turbines dynamically produce power that varies in a board range of frequencies and amplitudes. These continuous variations of active and reactive power from the wind farm cause dynamic voltage variations. The dynamic voltage variations from the wind turbines during operation are quantified by flicker and step change.

The flicker emissions during continuous and switching operations and the voltage step change are the voltage quality indicators influenced from small number of wind turbines connected to the grid. The flicker emission is a measure of the human perception of the bulb light variation consequent of the voltage low frequency variation. The value is computed to short term (10Minutes) and long term (120 minutes). The flicker emission includes voltage variations in frequencies up to 25Hz that are weighted with an eye perception function.

Figure 3.2 presents the voltage fluctuations as a function of frequency that will represent a unity of short term flicker perceptivity (Period start) to two different conditions

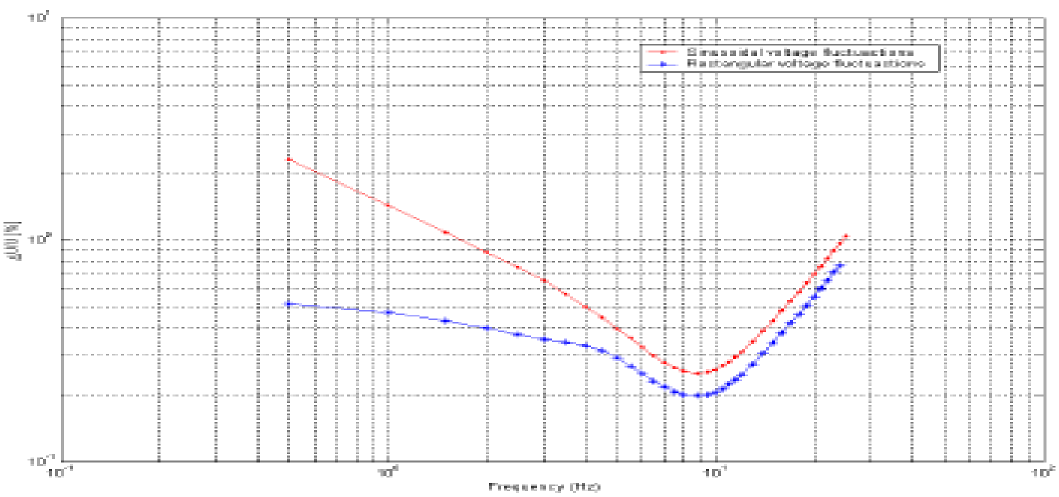


Figure3.3 Voltage fluctuations corresponding to flicker emission unity

From Figure3.3 [7], the maximum flicker perception comes from around 8Hz where the voltage fluctuations must be reduced in order to respect the flicker limits. The limits on Figure3.2 consider that voltage variations lead to light intensity variations in light bulbs.

In order evaluate the flicker contribution from wind turbines; Figure 3.3 presents the power spectral distribution (PSD) of the power produced from a three bladed wind turbine

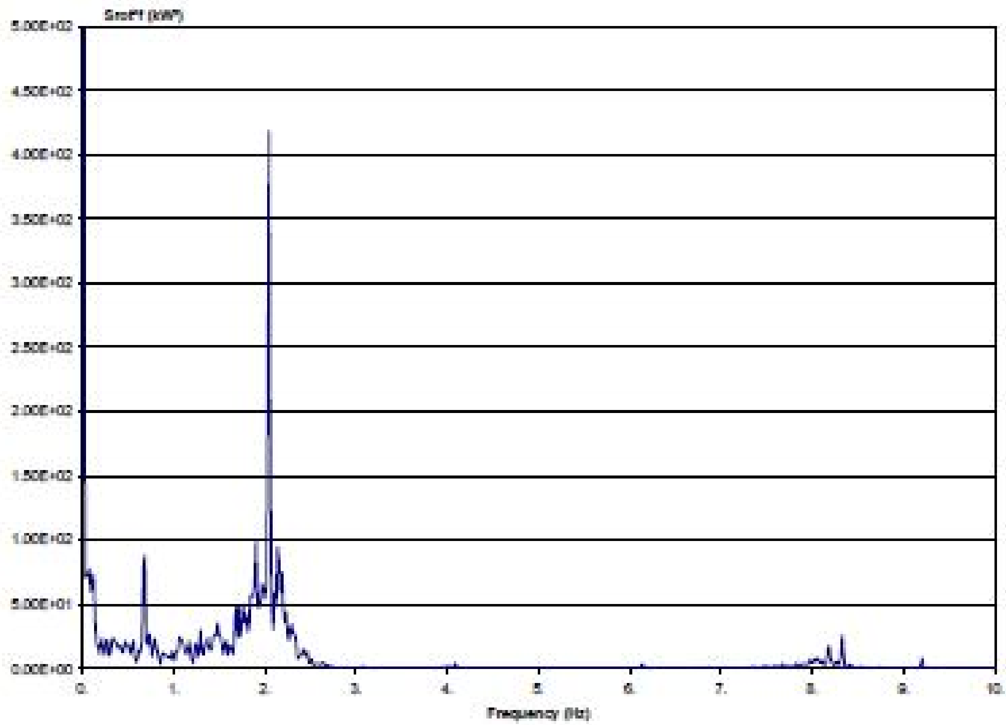


Figure3.4 Measured power spectra of the electrical power from a 225KW pitch regulated wind turbine

The PSD in Figure3.4 [7] includes contributions from deterministic and stochastic parts. The fundamental frequency of rotation (1p- one time the rotational speed of the rotor) is approximately0.7Hz, at this frequency there is a small contribution related to some asymmetry in the rotor. At the frequency of 2.1Hz (3p-three times the rotational speed of the rotor) there is a large contribution to the power variation. The 3P effect is related to rotational turbulence and the blades passing the tower in a three –bladed rotor type of wind turbines. In the frequency of 8.4HZ, corresponding to 12p,a small amount of energy is also presented that has been related to the flexible aero-elastic part of the wind turbine in addition to the induction generator.PSD of power measurements from different three-bladed wind turbines show similar pattern ,i.e. the power variations reduce significantly above the frequency of 3P. Although one could expect high power variations in a board frequency range, a three bladed rotor cancels the multiples harmonics different from the 3np and in addition, the dynamic components of the wind turbines damp the high frequency power oscillations.

The power variations are consequence of the wind field on the rotor area and the wind turbine dynamics. The turbulence and tower shadow influence the wind field on the rotor area and the three blades crossing the wind field transfer the power variation to the main shaft. The power on the main shaft will dynamically interact with the wind turbine components, e.g. drive train tensional moments, and finally the generator will convert the power to the network.

The flicker defined in the previous works is related to the continuous operation of the wind turbines. In addition, wind turbines also generate flicker due to switching operation and start –up. The flicker during continuous operation is caused by the power fluctuation from the turbulence added to the wind turbine dynamics. The flicker due to switching operations is caused by startup or switching of generators of wind turbines because the high inrush currents cause voltage dips. Associated to the flicker emissions during switching operations, the voltage dip is relevant because the voltage will drop instantaneously due to the inrush current.

This report focus on the analysis of the continuous operation of wind turbines, therefore it is restricted to the flicker and voltage dips from switching operations are not treated in this report.

The flicker emission is short term and long term can be estimated from the power quality tests. The power quality tests of wind turbine for different network phase angle condition and different annual mean wind speeds for a wind farm. The short term flicker emission (Pst) and long term flicker emission (Plt) to a wind farm can be estimated [7].

$$Pst = PLt = \frac{1}{Sk}\sqrt{\sum_{i=1}^{Nwt}(Ci(\Psi\kappa, \nu a), Sn, i)^2} \quad (3.3)$$

Where Sk the short circuit capacity ,Cis the flicker coefficient of wind turbine I to specific network impedance phase angle Ψκ and annual average wind speed ν**a**from the site Sn,istartedpowerof wind turbine i andNwtis the number of windturbine in the wind farm. The PstandPLtare assumed the same because it is assumed that the mean wind speed and turbulence will be maintained in 10 minutes average as well as in 120 minutes.

Equation (3.3) takes into account the cancellation effects, which comes from the wind dynamics in the wind farm that is not correlated, so the flicker is not a linear sum of all flicker produce from each wind turbine. Because the 3P is a main flicker contribution and these relatively high frequencies are approximately uncorrelated this is a reasonable assumption.

3-3 Large – Scale Integration of wind power

As introduced before, here the large scale integration problems are based on the small scale ones. The large- scale integration means a relatively high wind power compared to the local power system. The large integration can occur in two main conditions:

- Large wind farms connected to the transmission system
- Several small wind farms connected to the distribution systems in one area of the power system.

In conditions, the power quality and system stability assessment become more complex and depending on the sizes, they demand special investigations of voltage and frequency variations.

In small scale integration, the frequency was assumed constant. With high wind power capacity installed, the large active power variation can interact with frequency controllers in conventional power stations, so frequency variations can happen. In addition, large active power demanded by the wind farms can reduce the reactive power supply; hence the voltage stability limits can be reduced and must be analyzed too.

There are several issues arising from large scale wind power integration, but here the focus is on the voltage stability and the dynamic power oscillations during normal operation of the power system. In order to introduce the main issues of the power system and wind turbines,

Figure3.5 presents a simple single line with the basic structure of the power system, where it is possible to distinguish the main system components [6].

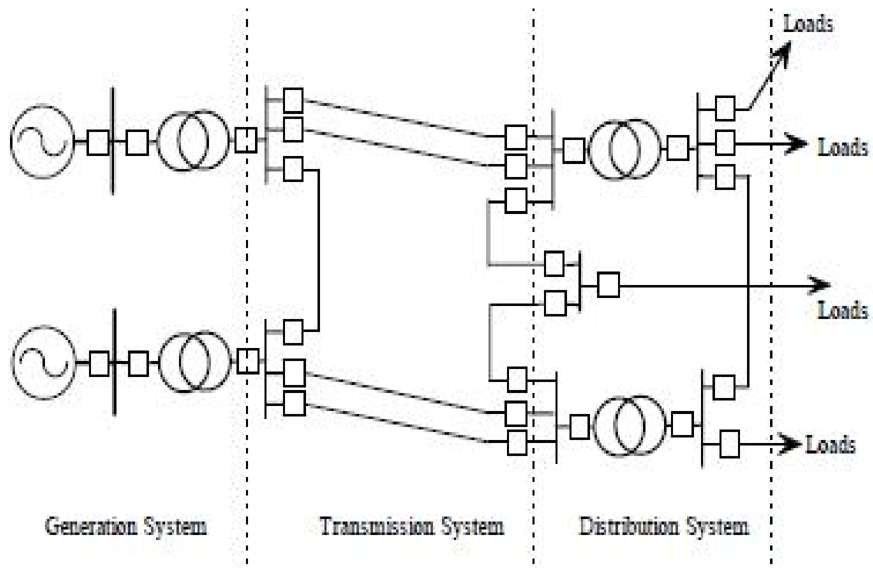


Figure3.5 Basic power system structures

The generation system is mainly composed by synchronous machines that are usually large. The transmission system is composed by transmission lines that extend for large distances and interconnect different generation units. The transmission line demand special consideration in controlling the voltage at the terminals due to reactive power flow (In AC type lines). Distribution systems deliver power to the loads where the voltage level is lower. The distribution lines require special attention to control the voltage at the loads.

The power system must supply a reliable and quality electrical power to the loads. In order to achieve reliability, the power system must have reserves and controller that can deliver the power when it is demanded, task mainly supplied by conventional generators and controllers installed throughout the power system. On the other hand, active controllers compensate the voltage and frequency variations keeping the power quality within limits.

The power system quality and stability depends mainly on the power system controllability, assuming that the power is available. Figure3.6 presents a simple equivalent of the entire power system including the main controllers where only conventional equipments are included [6].

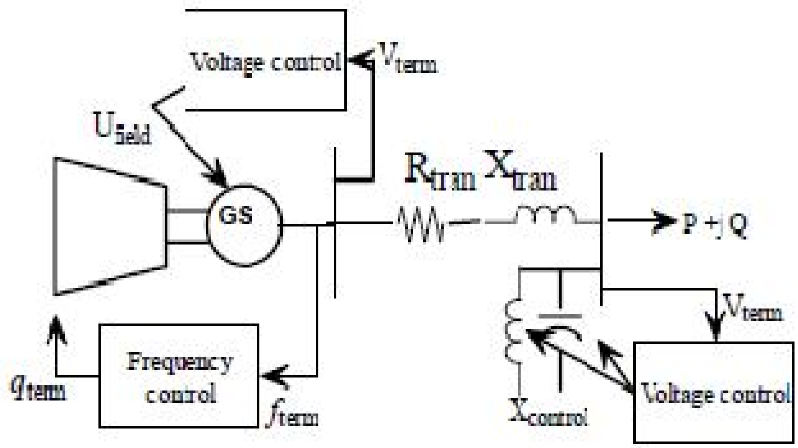


Figure 3.6 Single line Equivalent of power system

In Figure 3.6, the apparent power supplied to the load (P+jQ) Flows through the transmission and distribution system from the generators GS. The power flux result in voltage variations compensated near to the loads with decentralized voltage controllers- by adding or reducing reactive power and in the generation stations with voltage controllers that change the excitation level of the synchronous machines. Variations on the governors act to keep the balance on consumption and production increasing or decreasing the prime mover power. The voltages controllers are mainly related to the reactive power while the frequency controllers to the active power.

Wind turbines are special kind of generators, which has none or little voltage and frequency control capability and they supply an intermittent power. In addition, wind turbines in general use asynchronous generator that demand reactive power from the network to its excitation. The reactive power demanded to the wind farms is partially compensated by capacitor banks and the network supplies rest of the reactive power.

The active power produced from wind farm varies all the time and leads to continuous power flux variations. On the generation stations, it leads to continuous action of the frequency controllers to keep the balance on production and consumption (and frequency constant)

3-3-1 Voltage Stability Problem

A definition to the voltage stability phenomenon has not been widely accepted yet. Nevertheless, several task forces have worked on basic definitions of voltage stability. For instance, the IEEE task force report , defines the voltage stability in terms of the ability of maintain voltage so that when load is increased , load power will increase hence voltage and power are controlled.

Although voltage stability definition is not widely accepted, the voltage collapse is well recognized. Here, the voltage collapse occurs if after on an increase in load or power injection, the voltage is below acceptable levels followed by a progressive and un- controllable decline in voltage.

The voltage stable operation means that the voltages near to loads are identical or close to the pre-disturbance values, where disturbances may be a simple load increase or variation in power from wind farm.

The voltage collapse in general results from an incident of voltage instability. The voltage instability phenomenon is defined as having crossed the maximum deliverable power limit; the mechanism of load power restoration becomes un-stable reducing instead of increasing the power consumed. The voltage instability event can grow to voltage collapse leading to entire a large port of the power system with very low voltage profile.

Here, in order to illustrate the voltage collapse a simple formula based on the load flow calculations is introduced. Figure 3.7 presents a single line diagram used to define simple analytical equations to voltage stability (the shunt elements are not included) [1].

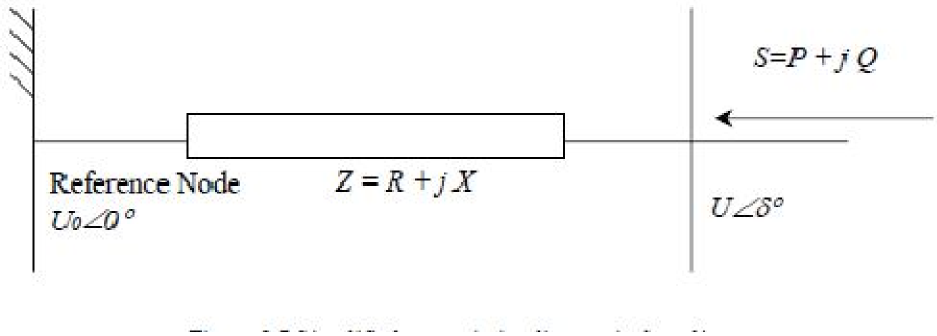


Figure3.7 simplified transmission line equivalent diagram [1]

Above Uo is the infinite node voltage Z is the impedance characteristic to the specific node (also called short circuit impedance). The voltage difference between the two nodes can be defined as [1].

U-Uo = Z. $\frac{S*}{U*}$(3.4)

Assuming Uo real and rewriting equation (3.4) as

U- U* = Uo.U* +Z.S* (3.5)

$UR^2 + UI^2$ = Uo (UC- j UI) + (R+jX). (P-jQ)

And remembering that U* = (UC- j UI) . In addition, a function H is defined as H = Z.S* =HR+jHI . Isolating the imaginary part of the voltage (UI) as:

$UI = \frac{(PX-QR)}{Uo} = \frac{H_1}{Uo}$(3.6)

And inserting in equation (3.5):

$UR^2 + \left[\frac{(PX-QR)}{Uo}\right]^2 - Uo.\ UR - (PX - QR) = 0$ (3.7)

$UR^2 + \left[\frac{H_1}{Uo}\right]^2 - Uo.\ UR - HR = 0$

The real part of the voltage in the node can be defined as:

$UR = \frac{1}{2}\left[Uo \pm \sqrt{Uo^2 - 4\left[\left[\frac{H_1}{Uo}\right]^2 - HR\right]^2}\right]$(3.8)

For the sake of simplicity, it is assumed that the infinite node voltage Uo= p.u, then equation (3.8) becomes very simple as:

$$UR=\frac{1}{2}\sqrt{\left[\pm\sqrt{\frac{1}{4}-(H_1^2-HR)}\right]}(3.9)$$

Adding the real part of the voltage in equation (3.9) and the imaginary in equation (3.6) results in the voltage at the node as follow:

$$U=\frac{1}{2}\sqrt{\left[\pm\sqrt{\frac{1}{4}-(H_1^2-HR)}\right]}+jH_1(3.10)$$

Now it is possible to state that:

- If $HR-H_1^2<\frac{1}{4}$there is no physical solution
- If $HR-H_1^2=\frac{1}{4}$both solutions coalesce and the point of voltage collapse is reached
- If $HR-H_1^2>\frac{1}{4}$the solution is double one physical onespurious (unstable).

The voltage stability is complex and, even to a very simple case, includes the load, network characteristics, and the voltage at the sending node.

Using the diagram in Figure 3.7, it is possible to illustrate the maximum power transferred to specific node as a relation of the voltage at that node (Figure 3.8) to different load factor conditions.

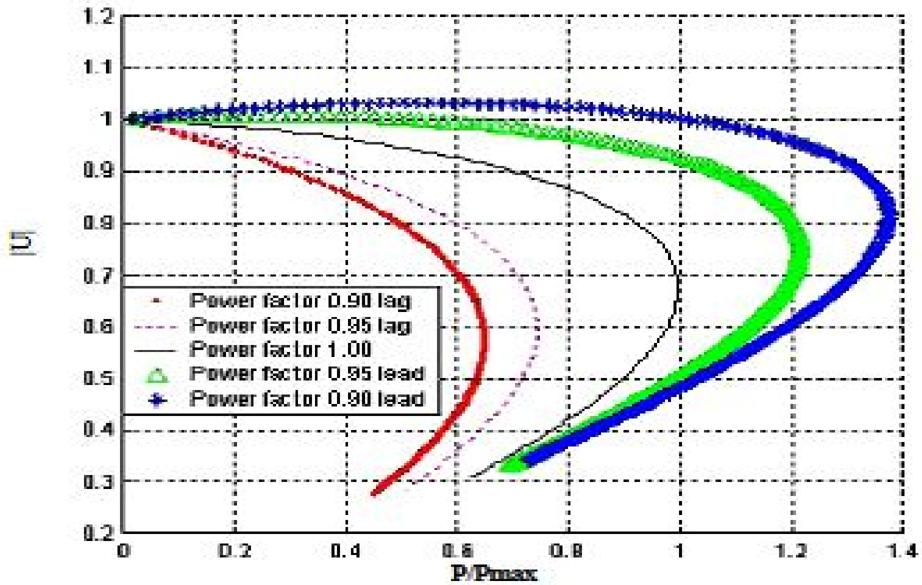


Figure3.8 Power Transfer to a node as function of the voltage

(Nose curve)

Figure 3.8[5]is a simple illustration of the relation between the power transmitted to a node and its voltage. This curve is the voltage Vs. Power characteristic of the node also called “nose- curve”. Using Figure 3.8, the voltage stability limit is characterized by the vertical tangent at the nose point that is in fact the maximum power transmitted to the node in agreement with definitions above.

When transferring the problem to the complex power system, the relevant factors that lead to voltage instability are: the transmission lines and power transfer strength of the power system; generator reactive power/ voltage control limits; load characteristics; characteristic of reactive power compensation; and the action of voltage control device such as under load tap transformers.

The dispersed voltage controllers acting on the distribution grid also influence the voltage stability. Distribution grid uses under load tap changer transformer, which under voltage instability events, tends to increase the problem by increasing the current flow in order to reestablish the set voltage level.

In addition, the characteristics of the reactive power compensation devices with the voltage contribute to the voltage instability. Usually, shunt capacitor banks compensate the reactive power in the power system. The reactive power supplied from shunt capacitors is related to the squared of the voltage. Hence, when started a voltage decline it will reduce the local reactive power production stressing even further the transmission lines and reducing further the voltage level. Similarly, the load response to voltage changes influences the voltage stability.

Finally, large number of wind farms on power systems (high penetration) demands reactive power and in addition some synchronous generators (generation station) are shut down in order to achieve cheaper energy production. Under this condition, the excessive demand for reactive power can be a problem.

3-3-1-1 Analysis of voltage Stability

The analysis of voltage stability for a given power system involves examination of several aspects, e.g. distance to voltage collapse among others.

The voltage stability here includes period’s from1.5 minutes to hours, being a dynamic problem rather than static. However, as the dynamics involved in the voltage instability is analyzed by static models.

The load flow problem is very closely associated with voltage stability analysis. The load flow programs determine the operation characteristics of the power system based on the load schedule and voltage reference in the generation units.

In load flow problems, the Jacobin (Newton Raphson algorithm) represents a linear relation between the power and voltage specific operational point. When the voltage collapses, the maximum power transferred was reached and the Jacobin becomes singular. At that point, there is no solution to the load flow problem and that is the maximum transmissible load. The use of the Jacobin properties has been pointed by several authors where model analysis and voltage collapse proximity indicators have been proposed.

3-3-2 Frequency Control Problem

The power system has a nominal frequency for which all generators are synchronized. In a synchronized system, the power is naturally shared between different generators based on the rate of the rating of the generators or as defined by the system operators.

The frequency control in 10 minutes can be classified in primary and secondary. The primary control is fast control actions to keep the instantaneous balance between production and consumption. Secondary control is slow control action to re-establish nominal system frequency and scheduled power interchanges. This thesis focus on the primary control of frequency because it's controller acting instantaneously to avoid frequency deviation related to stochastic variation from wind turbines.

The primary frequency control is done by speed governors; with automatically adjust the prime movers driving the generator to keep the balance on consumption and generation. The speed governor act based on speed deviation where" most automatic controls use high gain negative feedback, which , by its active nature can cause oscillations to grow in amplitude with time".

Originally, the interconnected generator was fairly close to one another, and oscillations were at frequencies of the order of 1 to 2 Hz. Dampers windings on the generators were used to prevent the oscillations to grow. Increasing the demands for reliability makes the rapid automatic voltage controllers that are used to prevent the generator loosing synchronism following a system fault. This fast action tends to reduce the damping of the system oscillations hence special power system stabilizers – PSS – were designed to damp those oscillations. The power system is very complex and specific components can interact with other causing oscillations.

From operating point of view, oscillations are acceptable as long as they decay. Oscillations are a characteristic of the power system, which are initiated by the normal small changes in the system load and, in this report, from wind farms power variations. The wind farm power produced can be viewed as a continuous negative load variation that demands the speed governors to act all the time to keep the balance on the system.

The power oscillations can be sustained due to the controller natural characteristic. Although the oscillations are not expected to increase in time, the sustained variations can become a problem.

3-3-2-1 Analysis of Power system Oscillation

The power system oscillations analysis may be done by modal analysis complemented by dynamic simulations. The modal analysis uses a linear representation to the entire power system being suitable to analyze small disturbances in the power system (it is also called small signal stability however must be used with caution because it does not include the non linear behavior of equipment on the electrical power system. Hence, it is also important to include dynamic simulations to analyze the power system oscillations during normal operation.

The modal analysis has been recognized as one of the most reliable tools to analyze power system. With the modal analysis it is possible to define the Eigen values of the power system hence it is possible to identify the electromechanical oscillation modes.

The power system can be described by equation that includes: all electromechanical characteristic, the network equations and the controllers. These equations can be linearised on an operational point. Where, the linear model put on the form of a set of first order differential equation with constant coefficients (state equations) have the form [2].

$[\dot{X}]=[A].[X]+[B].[u]$ (3.11)

$[Y]=[C].[X]+[d].[u]$

Where X is a vector of the dynamic state variable, A is the state matrix, B is the input matrix of coefficients describing the direct connection between the input and output variable: the vector **u**.

The Eigen value of A represents the roots of the state equations defined as the values of S that satisfies [2].

det$[A - SiI]$=0 (3.12)

Where each solution of Si defines a time function$\boldsymbol{e^{Sit}}$ **,** that satisfies the state equations. The function is called a mode of oscillation of the system.

If all Eigen values have a negative real part all modes decay with time and the system is said to be stable. If one Eigen value has positive real part, the corresponding mode will grow exponentially in time being unstable.

The modal analysis characterizes the modes of oscillation of the power system and the less damped oscillation modes, i.e the modes that the respective Eigen value are close to the positive plane. Hence, the possible problems in frequency control in the power system are characterized.

However, the modal analysis must be accompanied with dynamic simulations in order to include the non-linear characteristic of the power system. Hence, dynamic models to large scale wind power must be applied to the power system dynamic simulations to analyze the interaction between the wind power and frequency controllers during normal operation of the power system, in addition to the modal analysis.

Table 3.2 [1]The main integrations problem

		Problems	**Causes**
Large scale	Small Scale	Steady state voltage rise	Wind speed variation
		Over current	Peak of wind speed
		Protection error action	Dynamic operation of wind turbines
		Flicker emission during continuous operation	Switching/ startup operation of generators
		Voltage drop	Inrush current due to switching operation of generators
		Harmonics	Power electronic convertors
		Power system oscillation	Inability of the power system controllers to cope with the power variations from the wind farm and load
		Voltage stability	Reactive power limitations and excessive reactive power demand from the power system

Dynamic simulations including the entire power system are very expensive. In order to analyze the main characteristics of the power system, dynamic reduced models are used. The dynamic reduction is an aggregation of machines and loads with similar dynamic performance that reduces the number of equations to describe the power system and does not lose important information. In this thesis, dynamic reduced models are used to analyze the power system performance with wind power.

3-4 Remark on Wind Energy Integration

The Integration problems caused by wind power have been discussed in this chapter. The problems were classified in small scale and large scale integration. Table3.2 presents the main integrations problem from wind power

The main conclusions are:

- Small scale integration of wind energy deals mainly of voltage quality and reliability;
- Large scale integration of wind turbines include small scale problems and overall stability problem;
- The analysis of large scale demands suitable modes to represent wind power;
- Network characteristics play an important role on the power system stability and quality;
- Wind turbines characteristics play also an important role on the power system stability and quality;
- In order to investigate the wind power influences on the power system quality and stability it is imperative to use of appropriate models to represent the wind farm and power system. The wind turbine models must have the following characteristics:
- Dynamic models for the wind speed acting on each wind turbine;
- The special wind coherence in large scale;
- Detailed model to the wind turbine dynamic;
- Proper representation of the power flux of the wind turbine generator;
- Time feasible in order to analyze large power system

Moreover, the power system models must have the following characteristic:

- Include proper models to the electrical component;
- Include model of the loads;

- Be flexible to allow implementation of wind turbine/farm models and interact with other simulation tools;
- Input/output capabilities in order to analyze the data;
- Allow the implementation of large power system;
- In large integration, represent properly the electro- mechanical modes in the power system.

Chapter Four

Case Studies and Discussions

4-1 Introduction

In this chapter we describe the test systems used in the appended articles. Our general goal is to investigate the effect of a wind farm on a general power system. It is known that a number of generators which are close together and which behave similarly can be represented by a single generator.

In the same way, an aggregate of DFIGs such as a wind farm, can be represented by a single DFIG, and that power system, typically made up of synchronous generators, can be represented by a single synchronous generator.

4-2 Voltage Stability in Modern Power System

Large amount of wind energy can modify the voltage stability of a power system as introduced previously. Here, the impacts of wind power to the voltage stability characteristics are illustrated.

4-2-1 Power system characteristics

The power system studied is a small part of an existing power system. Figure 4.1 shows a single line diagram of the modeled power system where the rated voltage is 33 KV .which includes the total impedance of the lines and load s installed on the network.

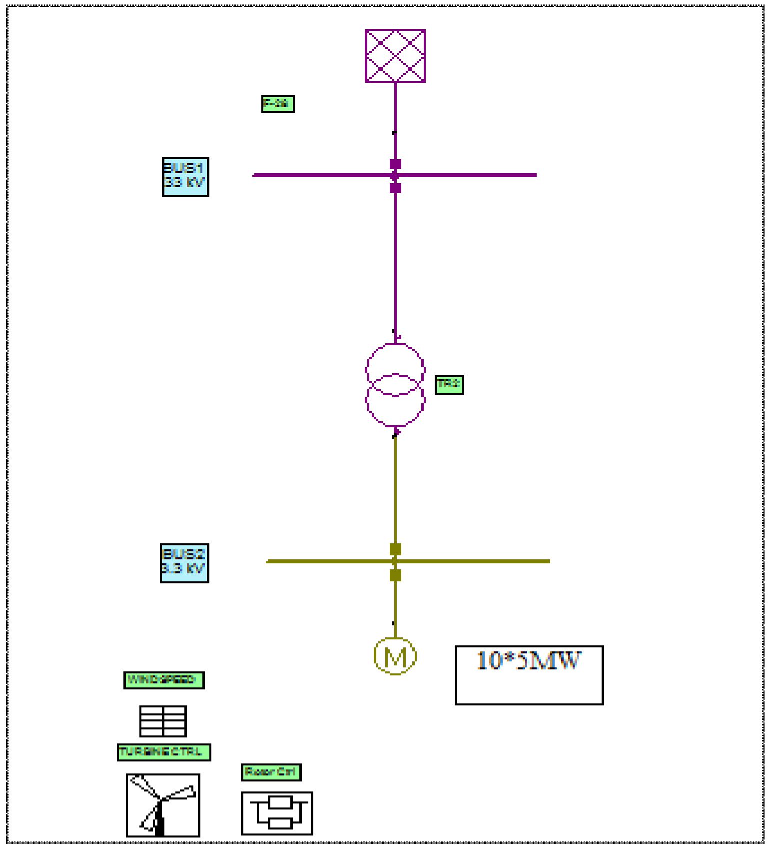


Figure 4.1 Single Line Diagram for Wind Farm Connected to a Grid at 33KV

Buses is supplying reactive power to the network as indicated in the diagram and in addition, a capacitor bank with rated power is installed on busies to reduce the reactive power flux on the network.

The loads dependency on the voltage is complex and constant power related to the voltage is a neutral assumption. An inverse dependency on the reactive i.e. increase of power demanded as the voltage decrease, reduces the limit of maximum load that can be installed to bus. On the other hand, a direct power relation can increase the voltage stability limits because the loads (on the power system) reduce with voltage reduction. In addition, the reactive power compensation with shunt capacitor bank is relevant to the voltage stability because of the high sensitivity to the voltage (i.e. reactive power proportional to V^2). In this power system, the load ability to bus is influenced by shunt capacitors banks, which heavily compensate the reactive power. The voltage reduction leads to an increase in the flow of reactive power through the lines that reduce further the voltage.

4-2-2 Wind power presentation

In this section, a static model simulates the wind farm power production because the voltage stability problem is slow. The wind farm static model must simulate the reactive power demanded based on the active power and the voltage at the wind turbine bus.

In this thesis the active is (P) and the reactive is (Q) powers are specified to the load flow program. The P component is the rated power of the wind farm to be installed on a specific sit and Q is computed based on the voltage terminals with a polynomial function. Because of, the wind turbines have no active control on the voltage.

The polynomial function used here was fitted based on three different sizes of induction machines. Assuming the rated active power, the reactive power consumption depends on the voltage. An increase in the voltage lead to an increase in the reactive power because the induction machine excitation (i.e. the reactive power consumption) is related to V^2 on the other hand the voltage decrease leads to an increase in the reactive losses that is related to V^2 increasing the total reactive power consumption.

The polynomial function to the reactive power for induction machines does not include the no load capacitor bank installed at the wind turbines and the normalization factor is the nominal reactive power at rated voltage. The reactive power compensation of the entire wind farm is modeled as shunt capacitor banks in the load flow program.

4-2-3 Wind power Impacts on the voltage stability

In order to investigate the wind power impacts on the voltage stability, all the wind power in power system is concentrated on it. Connecting large wind power to the weakest bus is expected to be worst case scenario to the voltage stability because this bus already faces limited power transfer capabilities. Figure 4.2 shows the behavior of the voltage of the entire power system

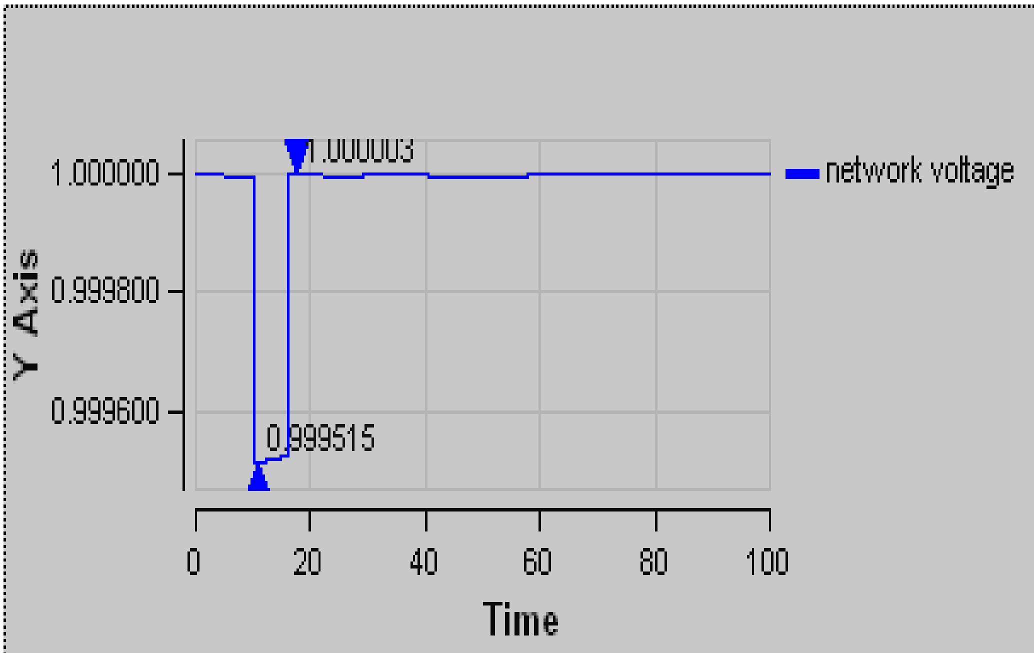


Figure 4.2 Voltage behaviors during and after the fault

In order to investigate 50 Mw wind farm in the network and their impact. The size of this wind power represents about 20 % of power penetration in the power system.

The demand of reactive power is the key factor on voltage stability from wind farm, hence wind turbines with power electronics, which can actively control the reactive power, can be used to regulate the voltage and improve the voltage stability.

Another important feature using power electronics as cited before is that they can be used to regulate the voltage by injecting or draining reactive power. However, the maximum apparent power of the power convertor must be respected.

The active power produced from the wind farm is reduced to respect the thermal limits of the power electronics. In particular example, the controllers were not implemented and the reactive power from the wind far was increased linearly until it reaches the maximum of 30 MVAR(corresponding to a power factor of 0.8 capacitive) and the active power is reduced to 40 Mw in order to respect the 50 MVA limit.

4-3 Case Study Two, Voltage Stability and Quality in a Sudanese Power System

Large amount of wind power has been proposed to Sudan. The Sudanese power system is mainly composed by hydropower station. However, in some region, it is not possible to install more hydropower stations. In addition, during the last few years along dry season leaded the entire power system to a critical minimum water level on the reservoirs resulting in a national energy crisis.

The Sudanese government has introduced new regulation to diversity the power matrix. The wind power is one of them, which is expected to contribute to the energy in a large extend in years to come. The east of Sudan presents good wind conditions and complementary wind characteristic to the Nile River. Therefore, to this region alone, more than 280MW of wind power have been proposed.

4-3-1 Power System Characteristics

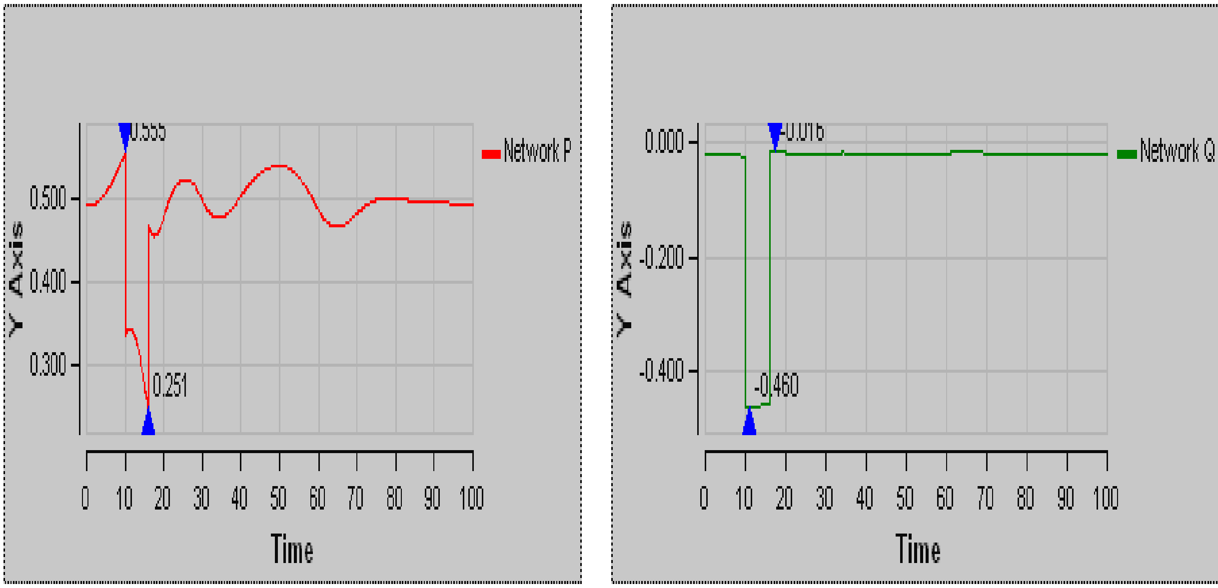
The interconnected Sudanese electrical power system is divided in four regional systems: North (N); Northeast (NE); Southeast (SE) and South(S). There are connections between all four regional systems. The connections between the NE system and the N are strong with a transfer capacity of few hundred mega walls, however to the other region there is a single link in 220KV and 110KV with limited power transformer.

The installation of 50MW to a part of the system is investigated with respect to the voltage stability and voltage quality during continuous operation. The 50MW is divided in 10 wind turbines where all of them are installed to Dongla or Toker bus. Figure 4.1 presents a schematic representation of the network to which the wind farms are installed.

4-3-2 Wind Power Representation

The total wind power has 280 MW of convention wind turbines, i.e. directly connected to the network that uses induction machines and partial reactive power compensation with shunt capacitor banks. The total power is divided in two wind farms with 40 identical wind turbines, all of them installed to bus on high voltage level.

The voltage stability analyses are similar to section 4.1 case studies one: voltage stability in modern power system, where fixed active power and voltage dependent reactive power (see Figure 4.3 A, B) model the wind power. The reactive power dependency on the voltage is modeled with a polynomial function of voltage.



A B

Figure 4.3Active And Reactive Power with response of stability

4-3-3 Wind Power Impacts on the voltage stability

The Load ability curve characterizes the voltage stability in the study cases similar to the previous section.

The impacts of 100 MW (Dongla) wind farm on the voltage quality are analyzed by means of dynamic simulations using NEPLAN and WASP software programs. The "NEPLAN" is applied to a conventional fixed speed wind turbine connected to the transmission level at 33 KV with dedicated lines and transformers.

The voltage is analyzed under different wind speeds with two load conditions, heavy load and light load. The wind speed are simulated from 0-14 m/s all of them with 20% turbulence intensity. Those wind speeds represent the wind speed range with most relevant power variations from wind turbines. Above 14 m/s the power conversation of the wind turbine limits the active power and the wind speed variations lead to relative small power variations and blow 8 m/s the level of the power is small and the power variations are also reduced.

Figure 4.4 shows the few minute's average values of the active power produced by the wind farms and its influences on the average voltages on Dongla under heavy and light load conditions. It also includes the maximum and minimum values to each load condition as envelop curves.

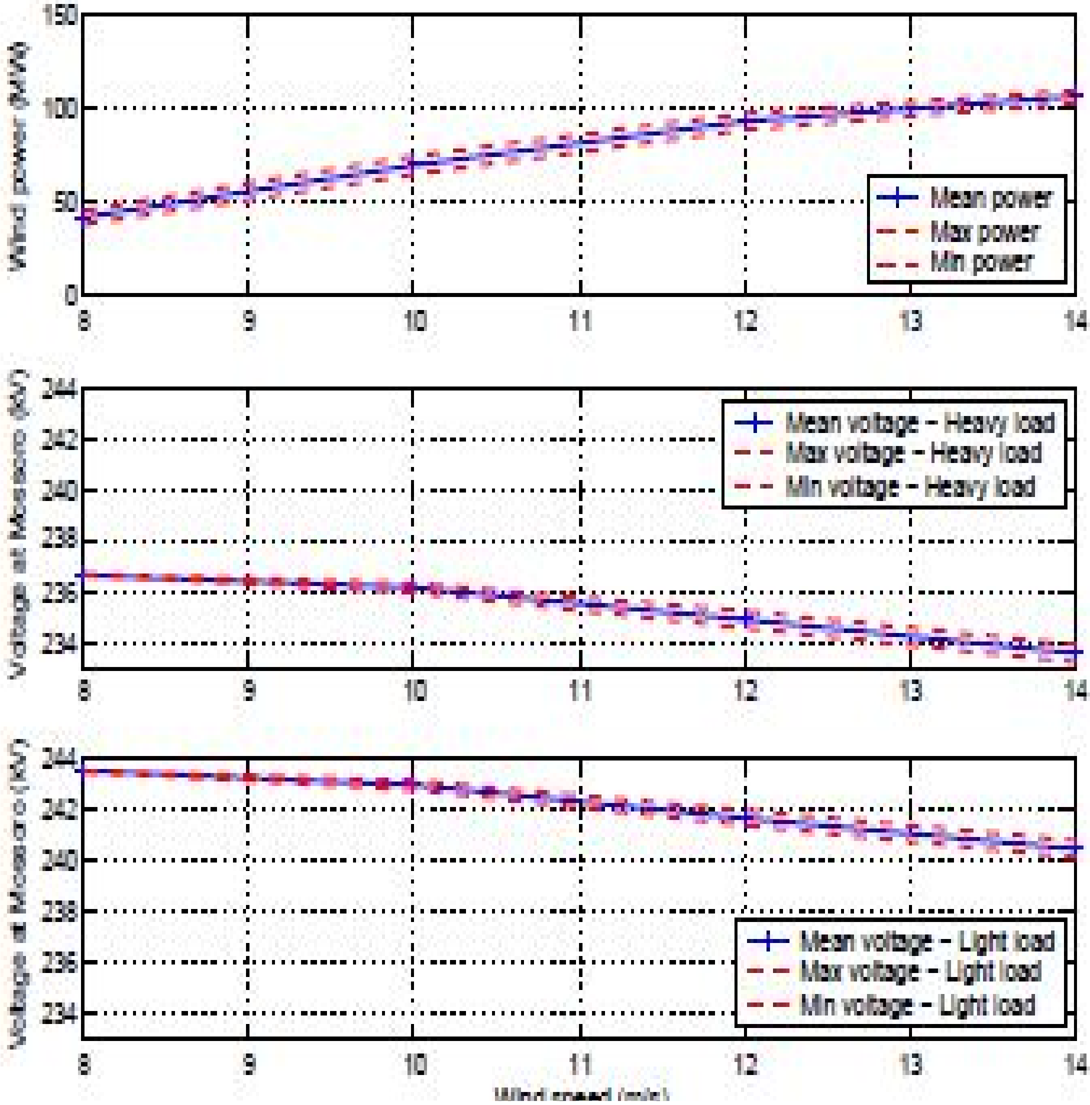


Figure 4.4 wind power influences on the voltage to different wind speed

The power production by the wind power increases with the wind speed and the voltage on both load conditions reduce with the increases wind speed. As the mean wind speed increases, the wind power produced and the reactive power demands increases that causes voltage drop due to losses in the network. The main voltage differences between the heavy and light load are caused because of the reactive power compensation schemes to each load condition (i.e. large shunt capacitors installed under heavy load condition).

The main differences between the heavy and light load conditions are on high wind speeds where the voltage reduction influences the reactive power produced by the capacitor banks installed in the power system. Hence, the heavy load condition, which has more capacitors installed, presents the high standard deviation of voltage and reactive power.

Table (4.1) below presents the main characteristics of the 5 MW wind turbine used in the simulation [5].

Table (4.1) Basic characteristics of the 5 MW wind turbine

Nominal power	5MW
Rotor Diameter	64m
Generator Speed	1500rpm
Rotor Speed	21rpm
Capacitor Bank	2000KVAr
Electrical Frequency	50 Hz
Tower Height	75m
Gearbox Ratio	71.43
First Torsional Frequency	1 Hz
Estimated logarithmic Damping to drive train	5%
Number of blades	3
3P frequency	1.05Hz

4-4 Case Analysis Remarks

Power quality and stability problems from large wind farms to the network have been investigated here. Three case where analyzed to illustrate the problem on the power quality and stability when integrating large amount of wind power, namely the voltage stability, voltage quality and the frequency control were investigated.

The voltage stability was illustrated by means of load ability curves drawn to the power system. The studied case shows that the wind power can contribute to improve the voltage stability and the reactive power is an important issue from large wind power concerning the voltage stability.

The conventional wind turbines reduce the reactive power availability in power system; fact is deeply related to the voltage stability. In this power system studied, the voltage stability was in general reduced with wind power because of the reactive power demanded by the wind turbine generators. However, new wind turbine technologies using electronic power convertors, which can regulate the reactive power from the wind turbine, improved the voltage stability and it can actively contribute to regulate the voltage.

The voltage stability depends also on the network characteristics. The case represents the integration to the transmission level 33 kV where the reactance's inductive of the lines and the reactive power compensation schemes played an important role.

The voltage stability was addressed in heavy and light load condition where the voltage on the network was modified in each condition due to reactive power compensation schemes. The wind power had small impact of the voltage stability, where it increased the load- ability limits of the local power system, fact that is different from the previous case. In case tow, a relative low reactive power is flowing in the network when compared to case one that explains the improvements on the voltage stability.

The wind farms will be installed to the transmission level hence the voltage variations on the low voltage levels area can be influenced .When distribution grid data is available , the model must be extended to include the distribution grids and the voltage quality on the consumer must be assessed.

Chapter Five
Conclusion and Recommendations

5-1 Conclusion

A methodology to investigate the wind power influences on the power system was presented in this thesis. It includes analysis of the wind power influences on the voltage stability, power system stability and power quality characteristics.

The voltage stability was analyzed with load-ability curves to the power system. The voltage stability was influenced by the wind power integration, where the reactive power was the main factor. Load-ability commutation tool was developed in this thesis and a static model to the wind power on the voltage stability was presented. Modification of the wind turbine characteristics, i.e. application of power electronics, was simulated improving the voltage stability.

The main conclusions for the voltage stability are that although the wind power alleviates the active power fluxes in the network, the reactive power flux to the wind farms will reduce the voltage stability limits. Wind turbine technologies with power convertors that can actively control the reactive power consumption increased the voltage stability (i.e. extended the power limit of the voltage collapse) of the power system.

The power system stability and power quality were investigated with the dynamic simulations. Dynamic models to large scale wind power that can assess the power system stability and quality were presented. The dynamic models are based on aggregation produces of wind turbines.

In addition, the problems for the power systems stability that are mainly related to power oscillations were studied with model analysis to identify the most relevant characteristics. The applications of the model analysis with the dynamic simulations are recommended in order to assess possible power system stability problems.

5-2 Recommendations

A nonlinear controller has been used in DFIGs, and it has been shown that the controller can perform well under a range of contingencies, but this has only been shown empirically. The theoretical analysis of the stability of the generator has yet to be investigated .It would be beneficial to find a nonlinear controller for which the region of stability could be determined.

The voltage behavior of DFIGs under large voltage disturbances has been examined. A deeper analysis of the voltage support capabilities of DFIGs, including the possibility producing reactive power from the grid-side converter, would give a better understanding of the voltage limitations of DFIGs.

There are very many aspects of DFIGs which have not been fully explored, but the author hopes that this list of suggestions for future work will inspire someone working in this area.

6References

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