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Wind Energy Technology

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1. Introduction

Electricity is regarded as one of the indispensable means to growth of any country's economy. This source of power is the heartbeat of everything from the huge metropolitans, industries, worldwide computer networks and our global communication systems down to our homes. Electrical energy is the lifeline for any economic and societal development of a region or country. It is central to develop countries for maintaining acquired life styles and essential to developing countries for industrialisation and escaping poverty.

Electrical energy is a high quality form of energy which is not found in nature. Instead it has to be obtained from the conversion in power plants of other types of energy supplies.

These energy supplies can broadly be divided into two classes:

- Renewable energy which is obtained from continuous or repetitive currents of energy occurring in the natural environment
- Non-renewable energy which is obtained from static stores of energy that remain boundless released by human interaction

Until the end of last century the industrialised world has mainly satisfied the demand for electrical energy by developing technologies for the generation of electricity which use mainly non-renewable energy supplies such as coal, fuel or nuclear. These environmentally hazardous generation technologies continue to be the backbone of the electricity generation system. The need for harnessing renewable energy supplies is apparent as world population increases and as each individual presses for a higher standard of living in terms of material goods especially in rural and developing regions.

Renewable Energy Systems (RES) and Distributed Generation (DG) have the potential to become the foundation of a future more sustainable energy supply system. Their scale deployment will transform the energy landscape from a system dominated by the centralized combustion of fossil fuels to a new one in which new technologies, environmentally friendly, contribute to a substantial development.

From an investment view point, it is generally easier to find sites for RES and DG than for large central power plants and, in addition, such units can be installed in a short time, near to the end consumer. The widespread integration of RES and DG together with energy efficiency, covering supply and demand, has provided support to achieve the major EU policy objectives:

- Sustainable energy development, combating climate changes and reducing air pollutants is the paradigm of the future power systems. The shift from the large scale combustion of fossil fuels to a more decentralized energy supply based on RES has contributed for meeting the Kyoto commitments, regarding the emission of greenhouse gases, particularly CO2: 8% reduction of emissions from 1990 levels by 2008-2010 and 20% by 2020 compared to 1990;
- Security and diversity of energy supply. Reducing the external energy dependence is crucial for the development of a dynamic and sustainable economy for Europe;
- Increasing the penetration of RES, doubling their share in energy supply quota from 6% to 12% of gross Energy consumption and raising their part in electricity production from 14% in 2001 to 22% is an objective to be attained by 2010.
- Energy marked liberalization, increasing opportunities for smaller scale generators.

The main objective of any generation and distribution utility is to satisfy the demand of customers with a high quality product. This product namely electricity must be supplied continuously round the clock.

Wind generation, photovoltaic's panels, fuel cells and microturbines – just to mention a few- are new forms of electricity under development. They define the so called RES (**R**enewable **E**nergy **S**ystems) and involve the exploitation off distribution sources through the concept of DG (**D**istributed **G**eneration). Today, wind power and CHP (**C**ombined **H**eat and **P**ower) are entering into a competitive level with traditional forms of energy generation. Tomorrow it is expected that one speaks also about microgeneration (microturbines, micro-CHP, photovoltaic systems and fuel cells).

Wind energy is the renewable energy source that had a higher growing in the last decades and can be considered a hope in future based on clean and sustainable energy.
The idea that wind power is going to play a significant role in our energy future has begun to take hold. Clean, emissions free, wind power is now correctly regarded as an increasingly important part of the answer to the twin global crisis of energy security and climate change.
We are in the midst of a period of fundamental change as to how we produce and consume energy, and nowhere is this clearer than in the explosive growth in investment in the clean energy sector, with wind power taking by far the largest share of that investment, some 50 billion USdollars in 2007 alone. More wind power was installed in Europe in 2007 than any other technology, some 40% of all new power generation capacity, and it also accounted for 30% of all new generation capacity installed in the United States during that same period. Of equal significance is the fact that for the first time in decades, the majority of the 2007 market was outside Europe, concentrated primarily in the United States and China.
However, the integration of both RES and DG into the overall power systems operation requires that energy generation in both transmission and distribution systems can no longer be considered as passive appendage. Reliability, safety and quality of power are the main issues linked to the large-scale deployment of DER (**D**istributed **E**nergy **R**esources) so that their effect on the European transmission and distribution networks cannot be neglected. Rather, it must be addressed with a comprehensive system approach.
Figure 1 shows global wind power capacity, 1991–2008 (in MW).

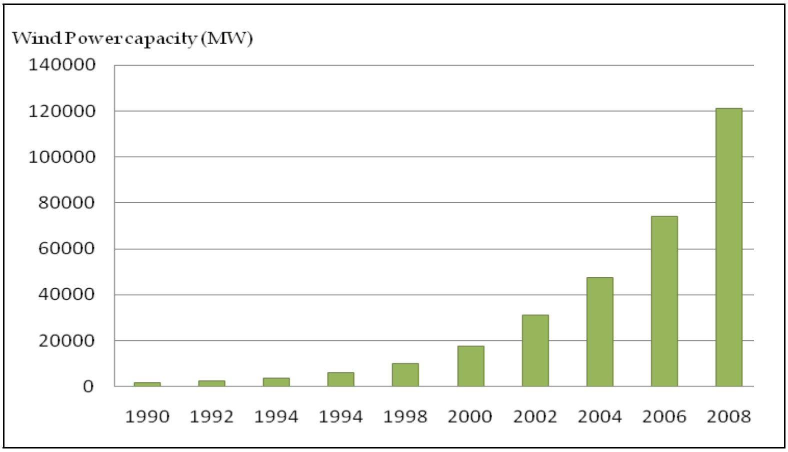

Fig.1. Wind Power, existing World Capacity, 1995-2008 (in MW) (Source: Global Wind Energy Council, Global Wind 2008 Report)

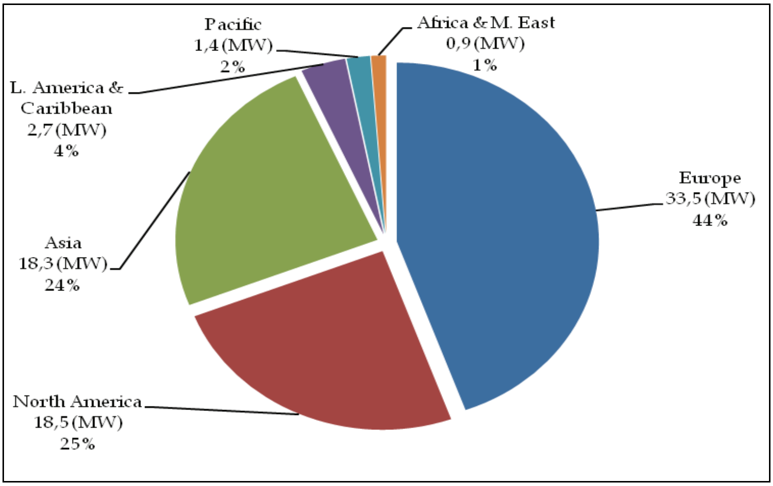

Fig. 2. Targets of wind capacity to be installed by 2010 (Source: Global Wind Energy Council, Global Wind 2008 Report)

2. Europe Wind Power Overview

The two oil crises that occurred in the seventies of the last century led Europe thinking in new ways of energy production based in renewable resources. The wind resource was already very used to produce mechanical work for many years. The presence of windmills is one of the most characteristic features of the Europe landscape, so developments to use this resource to produce electrical energy become to be interesting. National wind power programmes were started in almost all Europe member countries in decade of 1970 and have been continued since then, but it's usual to consider that the modern wind energy

industry had started in the 80's of the last century. Till the early 1980s, Europe possessed only nearly 5% of the worlds installed capacity in wind power. Nowadays Europe is leading in terms of installed capacity and in terms of technology developments.
Taking use of the existence of European programmes and funds, governments of almost European countries have launched programmes aimed to developing the wind energy sector. Using as reference the decade of 1990, because before that wind power installed capacity and the growth per year was almost insignificant, Europe growth from nearly 500 MW in wind power installed in 1990 to 65.933 MW in the end of 2008. In the beginning, countries like Denmark, the Netherlands, Germany, Spain and United Kingdom had the highest degree of development; nowadays Germany and Spain are the countries with the most wind power installed. The power installed in these two countries is more than 60% of the power installed in all Europe.

The wind power potential varies enormously across Europe, as we can see in the figure below. Europe is divides into two wind zones, the north zone where the wind speed is higher, result from the cyclones-anticyclones running in an East-West direction over the North Atlantic Ocean. In the South zone, with more mountainous terrains and where Mediterranean Sea and North Africa creates local wind systems, the wind may have very high speeds.

In addition to the areas of strong potential figured in the map, Figure 3, and in order to make a correct estimate of the potential at a particular site, is necessary to put an anemometer for a minimum period of one year, to collect data of wind speed, frequency and direction, density of air, etc.

Associated to the increase of installed wind power is the development of technologies. In the 90's of last century, wind turbines usually used Europe come in the 100-500 kW range of unit power. Since then, the unit power of the generator, the diameter of rotor blades and the tower height never stop and were always increasing. The evolution of modern turbines is a remarkable story of engineering. In the last 20 years turbines have increase in power by a factor of 100 and coefficient of performance had evolution from 0.4 to 0.5, which is near of the maximum coefficient of performance, determined by Betz limit. During the years seems that there is no limit for the growing of towers height and rotor diameters. In the beginning, small systems had rotor diameters of 12 meters or less, installed in towers of a little more than 20 meters of height and power of 50 kW, nowadays towers can be higher than 120 meters, with rotor diameter of 120 meters and power of more than 5 MW (Figure 4).

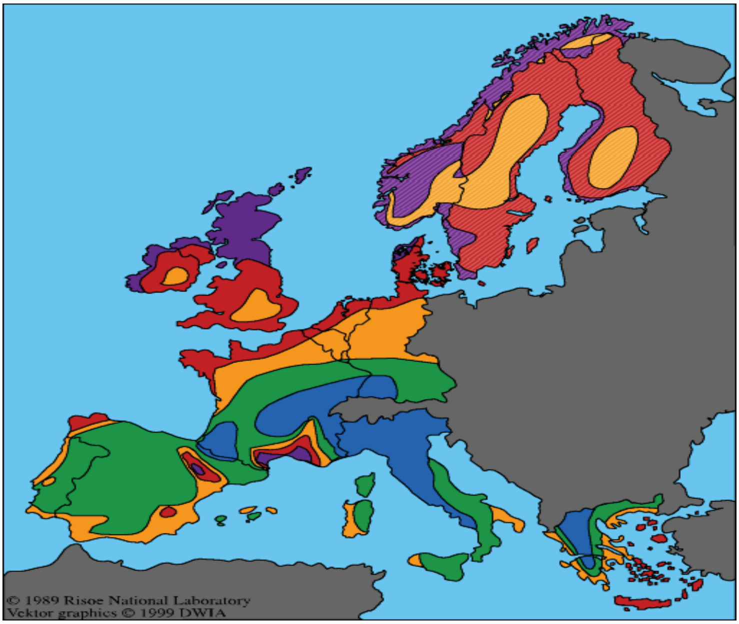

Fig.3. European Wind Atlas (Source: Danish Wind Industry Association)

	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400
			>7.5							
			5.5-7.5							
			<5.5							

Table 1. Wind Speed at 50 m above ground level. (Source: Danish Wind Industry Association)

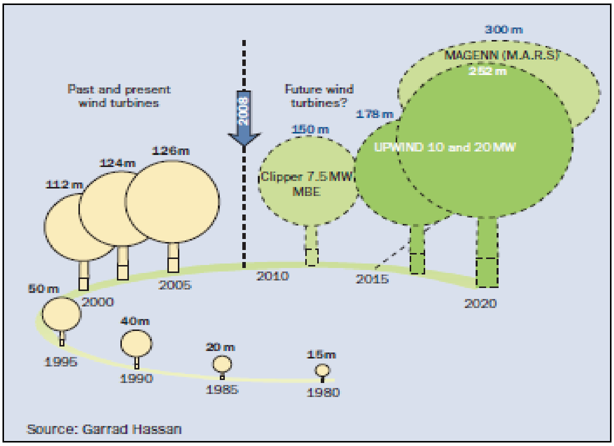

Fig. 4. Growth in size of commercial wind turbine designs (Source: Danish Wind Industry Association)

Figure 4 shows the perspective of growth in size of commercial wind turbine designs from 1980 to 2020.

3. Wind Energy Conversion Systems

The production of electricity from wind energy presents an increased growth and sustained since 1985. Currently, there are wind generators located throughout the world whose power already reaches values exceeding 3000 MW.
The main technologies used in electromechanical conversion of wind energy into electric energy are based primarily on three types of electric machines:

- The direct current (DC) machine
- The synchronous machine
- The induction machine

These machines work on the principles of the electromagnetic actions and reactions. The resulting electromechanical energy conversion is reversible. The same machine can be used as the motor for converting the electrical power into mechanical power, or as the generator converting the mechanical power into electrical power.
Typically, there is an outer stationary member (stator) and an inner rotating member (rotor). The rotor is mounted on bearings fixed to the stator. Both the stator and the rotor carry cylindrical iron cores, which are separated by an air gap. The cores are made of magnetic iron of high permeability, and have conductors embedded in slots distributed on the core surface. Other way, the conductors are wrapped in the coil form around salient magnetic poles. In the Figure 5 is possible to see a cross-sectional view of the rotating electrical machine with the stator with salient poles and the rotor with distributed conductors (Mukund, 1999). The magnetic flux, created by the excitation current in one of the two members, passes from one core to the other in the combined circuit always forming a closed loop. The electromechanical energy conversion is accomplished by interaction of the magnetic flux produced by one member with electric current in the other member. The latter may be externally supplied or electromagnetically induced. The induced current is proportional to the rate of change in the flux linkage due to rotation.

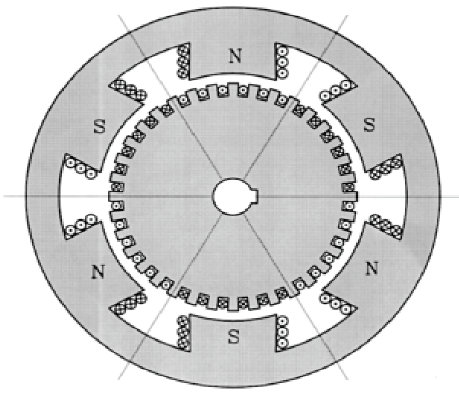

Fig. 5. Cross section of the electrical machine stator and rotor

DC Machine

The conventional DC machine is either self-excited by shunt or series coils carrying DC current to produce a magnetic field. Actually, the DC machine is often designed with permanent magnets to eliminate the field current requirement, hence, the commutator. It is designed in the "inside-out" configuration. The rotor carries the permanent magnet poles and the stator carries the wound armature which produces AC current. This current is then rectified using the solid state rectifiers. Such machines do not need the commutator and the brushes; hence, the reliability is greatly improved. The permanent magnet DC machine is used with small wind turbines, however, due to limitation of the permanent magnet capacity and strength. The brushless DC machine is expected to be limited to ratings below one hundred kW (Mukund, 1999).

Synchronous Machine

Most of the electrical power consumed in the world is generated by the synchronous generator. For this reason, the synchronous machine is a well established machine. The synchronous machine works at a constant speed related to the fixed frequency. Therefore, it is not suitable for variable-speed operation in the wind plants. Moreover, the synchronous machine requires DC current to excite the rotor field, which needs sliding carbon brushes on slip rings on the rotor shaft. This poses a limitation on its use. The need of DC field current and the brushes can be eliminated by the reluctance torque. The reliability is greatly improved while reducing the cost. The machine rating, however, is limited to tens of kW. The reluctance synchronous generator is actually used for small wind generators (Mukund, 1999). In the Figure 6 is possible to see the diagram of connections of wind generators equipped with variable speed synchronous machines.

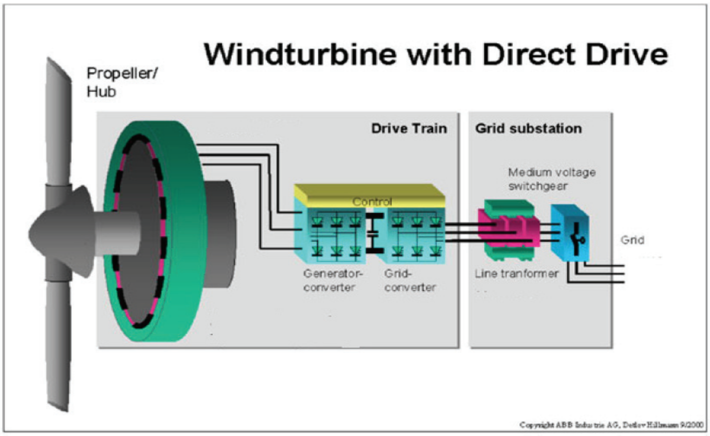

Fig. 6. Connections diagram of a synchronous generator operating the variable speed (Source: ABB Industries).

The systems represented in Figure 6, the synchronous machine is connected through a system of converting ac/dc/ac, as the frequency of stators voltage and currents is different in the frequency of the electrical network.

Such generators typically do not have the gearbox, and the mechanical speed of rotation of the rotor is identical to the speed of rotation of the turbine. Typically the speed of rotation of the turbine (and the rotor of synchronous machine) varies between 17 rpm and 36 rpm, so the machine has a high number of poles.

The stator of the synchronous machine has six phases and is connected to two independent converting systems ac/dc/ac. The parallel between the two conversion systems is made at the outlet of converters dc/ac (grid converters) that is connected to the elevator transformer. Each of the converters ac/dc connected to the generator (the generator converters) consists of one to six pulse bridge converter equipped with thyristors. These thyristors operate with a constant firing angle.

The DC voltage at capacitor terminals, placed in parallel in connection at direct current, must be set to a constant value. However, for low values of the speed of the rotor, the excitation system of synchronous machine is unable to ensure that value, being necessary to use a "chopper" (converter dc/dc) converter installed between the generator and capacitor, which is disconnected when the rotor speed exceeds a certain value.

The grid converter is a six pulse converter bridge equipped with IGBTs, with a control system based in pulse width modulation (PWM). This converter controls the active power injected into the grid and the power factor. The control of active power in the grid converter allows the imposition of electromagnetic torque into generator, thus making it possible to control the rotational speed of the wind turbine-generator group in order to obtain the specific speed of the tip of the blade optimal (λ) for each value of wind speed (Akhmatov, 2002).

Figure 7 illustrates the active and reactive power supplied by the grid converter of such a wind generator according to the rotational speed of the rotor.

Unlike the induction machine, the synchronous machine, when used in the grid-connected system, has some advantages. It does not require the reactive power from the grid. This results in better quality of power at the grid interface. This advantage is more important when the wind farm is connected to a small capacity grid using long low voltage lines. Actually, wind plants generally connect to larger grids using shorter lines, and almost universally use the induction generator (Cigrè, 2001).

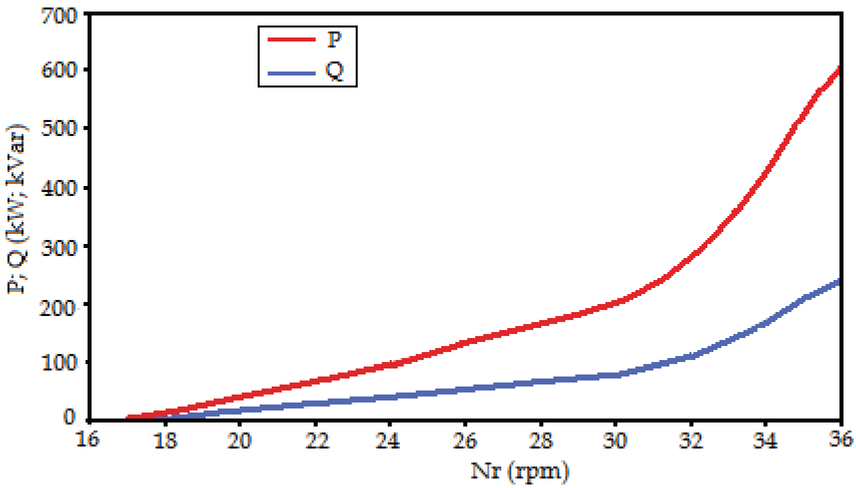

Fig. 7. Active and reactive power supplied by a wind generator equipped with synchronous generator operates the variable speed depending on the speed of the rotor.

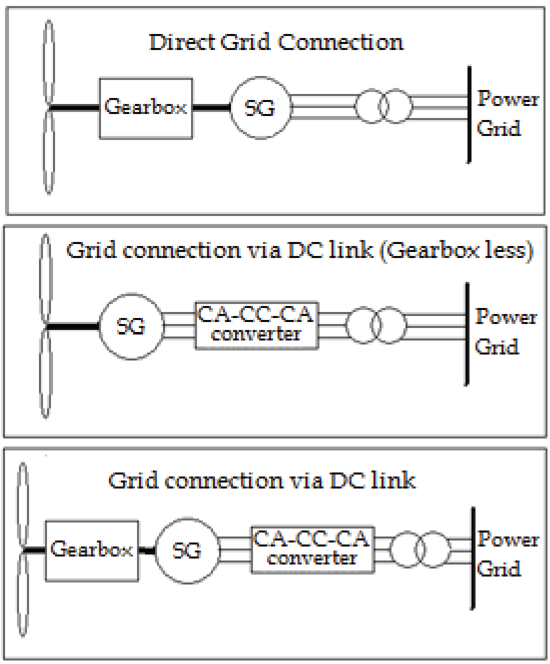

Fig. 8. Settings of synchronous machine used as a wind generator

Induction Machine

The primary advantage of the induction machine is the rugged brushless construction and no need for separate DC filed power. The disadvantages of both the DC machine and the synchronous machine are eliminated in the induction machine, resulting in low capital cost, low maintenance, and better transient performance. For these reasons, the induction generator is extensively used in small and large wind farms and small hydroelectric power plants. The machine is available in numerous power ratings up to several megawatts capacity, and even larger.

The induction machine needs AC excitation current. The machine is either self-excited or externally excited. Since the excitation current is mainly reactive, a stand-alone system is self-excited by shunt capacitors. The induction generator connected to the grid draws the excitation power from the network. The synchronous generators connected to the network must be capable of supplying this reactive power. For economy and reliability, many wind power systems use induction machines as the electrical generator.

Operation of the Induction Generator in Autonomous Mode

The induction machine to function as a generator must be operated at a speed above the synchronous speed and to be provided with a reactive power to produce and keep the machine's magnetic field. This reactive power can be produced by capacitors connected to the machine, as described in Figure 9. Thus, it is possible to achieve self-excitation of the machine in order to feed a load alone.

The capacitors are usually connected in delta because they have the advantage of lower capacity to get the same effect as with capacitors connected in star. Thus, the voltage V1 and the frequency f1 of the generators of induction in empty and laden depend primarily on parameters of the machine, the capacity of condensers and speed n> f1/p, where "p" is the even number of poles.

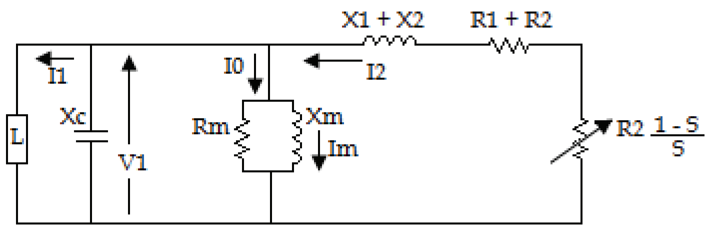

Fig. 9. Approximate equivalent scheme of an induction generator for autonomous load

The existence of residual magnetism in the machine, with the machine to turn, will result in the emergence of power swing in the machine between the stator coils and condensers. Indeed, the coils of inductance L and the capacity C of the capacitors are an oscillating circuit and therefore fluctuations of energy may be damped or amplified.

If the rotor rotates with angular velocity w_r whose frequency is higher than the frequency of own oscillations (given by 1 / √ LC) then the power of the rotor copper losses in the oscillating circuit and the machine turns on. If however there is no residual magnetism or if this is not enough, the oscillations do not occur or cushion quickly and the machine not exciting.

The operating voltage and frequency are determined in terms of the approximate equivalent circuit of Figure 9. On no load, the capacitor current Ic= V1/Xc must be equal to the magnetizing current Im=V1/Xm. The voltage V1 is a function of Im, linearly rising until the saturation point of the magnetic core is reached (Figure 9). The stable operation requires the line ImXc to intersect the V1 versus Im curve. The operating point is fixed where V1/Xc equal V1/Xm, that is when 1/Xc=1/Xm, where Xc=1/wC. This settles the operating frequency in hertz. With the capacitor value C, the output frequency of the self-excited generator is therefore:

$$f = \frac{1}{2\pi X_m} = \frac{1}{2\pi\sqrt{C.L_m}} \quad (1)$$

Under load conditions, the generated power $V1I2\cos\varphi_2$ provides for the power in the load resistance R and the iron loss in Rm. The reactive currents must sum to zero:

$$\frac{V_1}{X} + \frac{V_1}{X_m} + I_2.\sin\varphi_2 = \frac{V_1}{X_c} \quad (2)$$

This equation determines the output voltage of the machine under load (Mukund, 1999).

As it possible to see in Figure 10, the process of self-excitation requires the presence of a residual magnetism and magnetic saturation of the magnetization curve of the machine to be successful, or to have a clear intersection between the two characteristics (of magnetization and strain in capacitors).

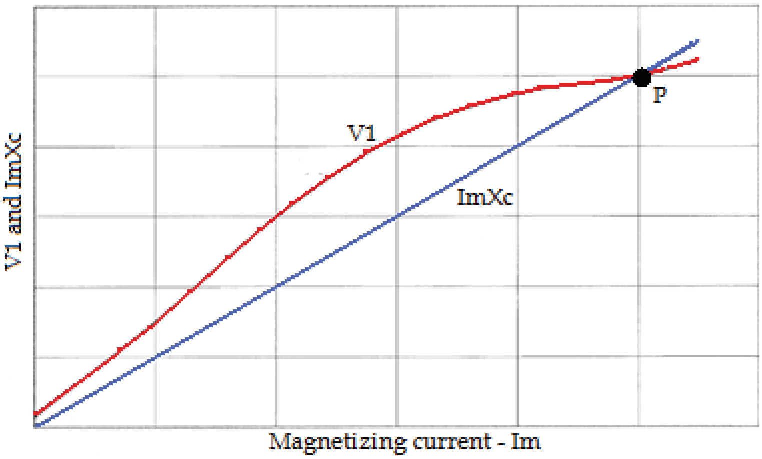

Fig. 10. Operating characteristics of the induction generator with capacitive self-excitation

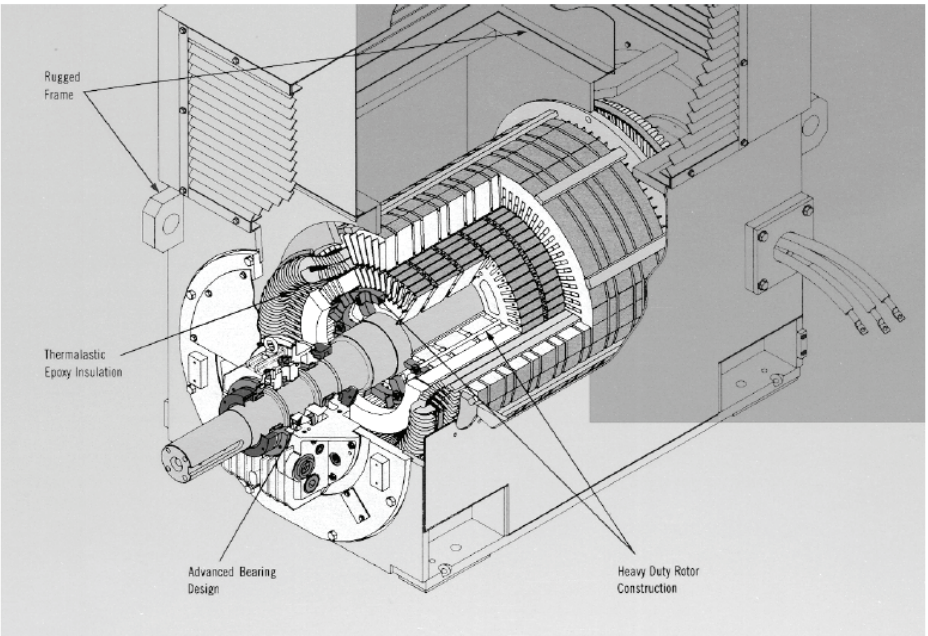

Fig. 11. Two MW induction machine (Source: Teco Westinghouse Motor Company)

Operation of the induction generator connected to the network
The electromagnetic power through the air gap is given by:

$$P_{em} = 3.I_2{}^2.\frac{R_2}{s} \quad (3)$$

that is positive for s> 0 and negative for s <0, where "s" is the slip of the machine. That is, for s <0 the electromagnetic power flow at rotor to the stator. Part of this power is dissipated (by Joule effect) in the copper winding of the stator and the remainder is supplied to the network. This corresponds to the operation of the machine as a generator (Figure 12). In this case, the machine must be operated at a speed n> f1/p and both the power and the electromagnetic torque are negative.

When assessing the performance of induction generator we can use the approximate equivalent diagram of Figure 9 with s <0. The resistance that ((1-s) / s) R2, which reflects the electromagnetic power, depends on the slip, but the reactance X does not depend on the slip, or are always positive. Consequently, the induction machine always absorbs reactive power in whatever condition of operation.

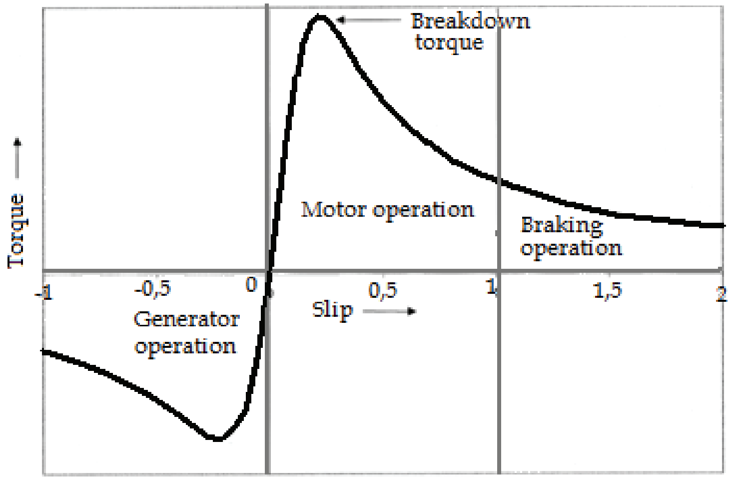

Fig. 12. Torque versus speed characteristic of the induction machine in three operating modes

How is possible to see in Figure 13, if the generator is loaded at constant torque T_L, it has two possible points of operation, P_1 and P_2. Only one of these two points, P_1 is stable. Any perturbation in speed around point P_1 will produce stabilizing torque to bring it back to P_1. The figure also shows the limit to which the generator can be loaded. The maximum torque it can support is called the breakdown torque, which is shown as T_{max}. If the generator is loaded under a constant torque above T_{max}, it will become unstable and stall, draw excessive current, and destroy itself thermally if not properly protected (Manwell et al., 2002).

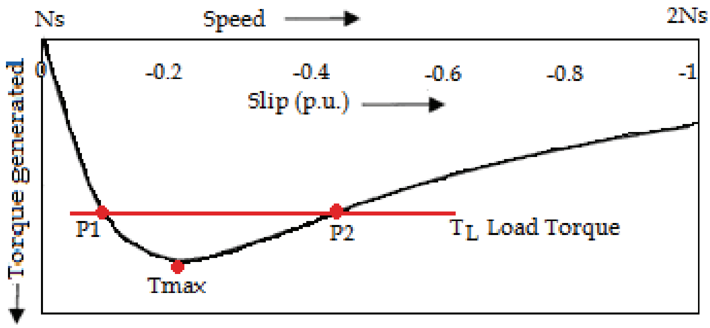

Fig. 13. Torque versus speed characteristic of the induction generator under load

Usual Configuration of the Induction Generator

The induction generators connected to the network or in autonomous mode are mainly used, for constant or variable speeds and a link voltage/constant or variable frequency, in mini-hydro and wind energy systems. Possibilities for the use of double fed induction generators and the squirrel cage rotor are summarized in Table 2.

Induction generator	speed		Network connection	Isolated	Frequency		Voltage	
	Constant	Variable			Constant	Variable	Constant	Variable
Double Fed		X	X		X		X	
Squirrel Cage	X	X	X	X	X	X	X	X

Table 2. Configuration of the Induction Generators.

The principle of operation of the double fed induction machine is based on the ability to control its speed by variation of the resistance of the rotor. Figure 14 illustrates the change curves of torque/slip of the induction machine due to the variation of resistance connected in series with the winding rotor.

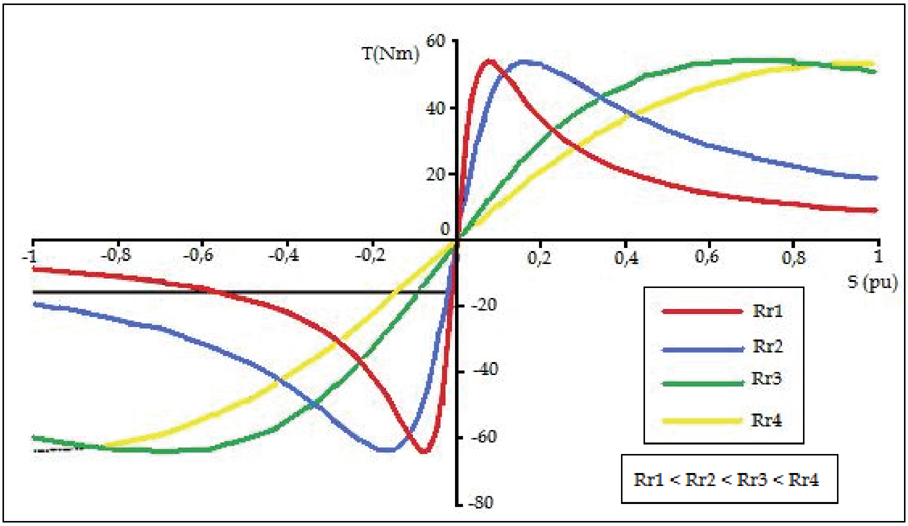

Fig. 14. Curves of torque-speed characteristics for different values of the resistance of the rotor

As shown in the Figure 14, for a given mechanical torque T, can vary the speed of induction machine by varying the rotor resistance. If instead of a variable resistance, if we install a system for converting ac/dc/ac connected to the rotor, it is possible to extract the active power by the rotor of the machine and thus control the speed. This is the principle of energy away from the winding rotor induction machine.
The mode of operation of double fed induction generators based on the principle described above: to negative slips, until it reaches the intensity of the stator rated current of the machine, the power extracted by the rotor of the machine is controlled so as to optimize the speed specified the tip of the blade of the rotor and thereby maximize the value of the coefficient of the power turbine.

For negative slips, higher (in modulus) for which the intensity of the stator current reaches the nominal value, the active power in the stator and the rotor remains constant, like showed for the line in black, on Figure 14 (Manwell et al., 2002).

This principle of speed control by use the slip energy means that this machine can function as a generator for positive slip. To ensure this mode of operation, it is necessary to provide active power to the rotor. In Figure 15 we can see different ways to use the induction machine as wind generator (Cigrè, 2001).

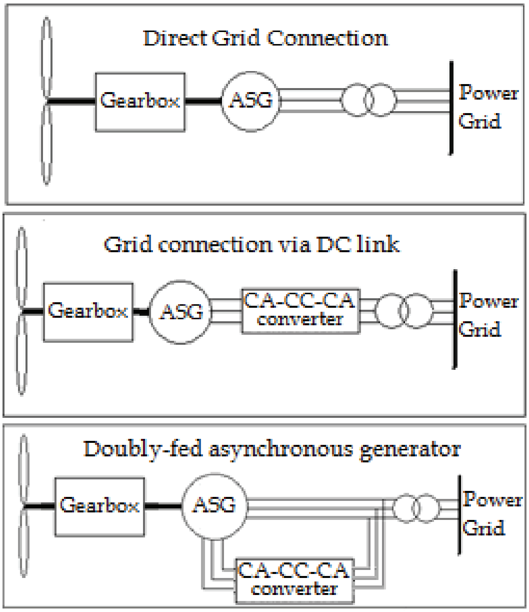

Fig. 15. Settings of induction machine used as a wind generator

The connections of double fed induction machine are shown in Figure 16.

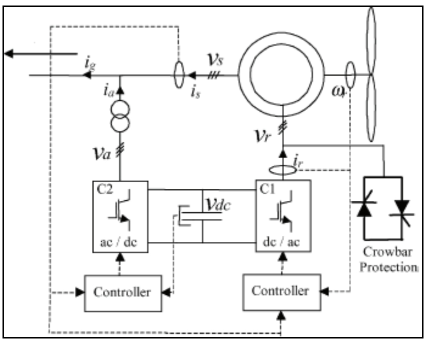

Fig. 16. Scheme of connections of double fed induction machine (Almeida et al., 2004)

The stator of the induction machine is directly connected to electric power. The rotor is connected to the network through a system of converting ac/dc/ac and a transformer.
The converters ac/dc/ac that interconnect the rotor of the machine to the network via the transformer, are bridge-type converters PD3 to six pulses equipped with isolated gate bipolar transistors (IGBTs) controlled by the pulse width modulation. Typically, in double fed induction machine, converter connected to transformer controls the voltage into the terminals of the capacitor in DC current system, and controls the power factor at the point common to the circuits of the rotor and stator. The converter directly connected to the rotor of the induction machine control module and the argument of the intensity of current injected or extracted through the rotor (Ekanayake et al, 2003).

The principle of operation of the control system with pulse width modulation can impose a form of wave approximately sinusoidal with frequency, amplitude and phase adjustable to the AC terminals of the converters.

In Figure 16, the converter ac/cc/ac connected to the rotor of the induction machine, allows the control of the frequency of the wave form applied to the rotor, which is equal to the slip frequency of the machine in a given point. Simultaneously, it also controls the module and argument of the intensity of current in the rotor. Converter ac/cc connected to the terminals of the transformer controls the magnitude of the voltage into the terminals of the capacitor. The frequency of the alternating current frequency is equal to the network frequency with which the converter is interconnected, and the control of the phase impose the power factor of the machine. This feature of the control system of pulse width modulation to adjust the phase of the wave of voltage and intensity of current wave can dispense the use of batteries of capacitors in most cases. Typically, manufacturers provide a control of power factor between 0.9 inductive and 0.9 capacitive to the terminals of the machine (Akhmatov, 2002).

The purpose of the control system of converters ac/cc/ac is to ensure the maximization of the coefficient of the turbine power, especially in the region characteristic of the power depending on the wind and where the power is not controlled. Additionally, the control systems of converters maintain a given value of power factor at the point of interconnection of the doubly fed induction machine with the electric power grid. In region of characteristic where the turbine power is controlled, the control system of converters ac/cc/ac keeps constant the total power, extracted by the stator and rotor of the machine, complemented by the control system of step angle of the rotor blades. It is therefore concluded that the control system of wind generators equipped with double fed induction machine can maximize the electrical power delivered to the network in the range of variation of wind speed (Ekanayake et al, 2003).

4. Grid Integration of Wind Farms

For small penetration levels of wind power in a system, grid operation will not be affected to any significant extent. Presently in European Union (EU), wind energy supplies only about 4% of overall electricity, but with the perspectives of achieving 12-15% of electricity from wind power by the year of 2020, the problem of grid integration must be analysed. For scenery of larger penetration levels, changes in power systems and in the methods of operations to accommodate the further integration of wind energy are needed. In spite of total percentage of wind power in EU being lower, only 4%, in some countries that percentage is higher. Countries as Denmark with 25% or Portugal with 11% are examples of that. Based on data from the WindPower Monthly magazine, March of 2009, the percentage of energy supplied by wind in the year 2020 in each of 27 EU member countries is depicted in Figure 17.

Analysing the data is possible to see that some countries have high targets to reach in terms of wind power. Countries like Ireland, Denmark, Portugal, Germany, Greece, UK and Spain, with more than 20% of power being generated by wind plants, grid integration is an issue that must be ensured. The already established control methods and backup available for dealing with variable demand and supply are more than adequate for dealing with the additional variable supply such as wind power at penetration levels up to around 20% of gross demand (Windpower, 2009).

When power obtained by wind is connected to the distribution network, situation of some countries, Portugal is an example, there is no big problem with the integration of wind in the power system because the network is very meshed and can be very quickly reconfigured.
With the actual penetration of wind power in the Portuguese distribution network, the grid is operated and designed to operate even if there is a partial blackout of wind power. The restrictions to the connection of more wind power to the system are caused by the capacity of power lines.

If the distribution network has weak lines, in terms of capacity of power transmission, making the connection between substations with wind parks and the loads, when there is a lot of wind, is necessary to limit the power produced by the park because of no capacity of energy distribution by the interconnection line. This problem can be solved with more investments in the improvement of power lines.

When energy produced by wind is connected to the transmission level, the problem of network operation is higher. At that level power must be dispatch by the control centre, which means that must be more confidence on the forecast, because power produced must not be off-line instantaneously, causing loss of power. On the other hand, there are few large power stations in a power system, so the shutdown of one of the traditional large power stations, by accident or planned, is a problem to the system operator. In a power system the number of wind generator can be very large, so the system will not notice the shut-down of a 2 MW wind turbine. The problem is when a coal fired plant or a nuclear plant shuts-down instantly. Even in terms of power reserve needs, this issue only is relevant when the magnitude of wind power variations becomes comparable to the load variations. Reserve requirements for wind power can be obtained from the existing conventional power plants, but the allocation and the use of reserves lead to extra system costs.

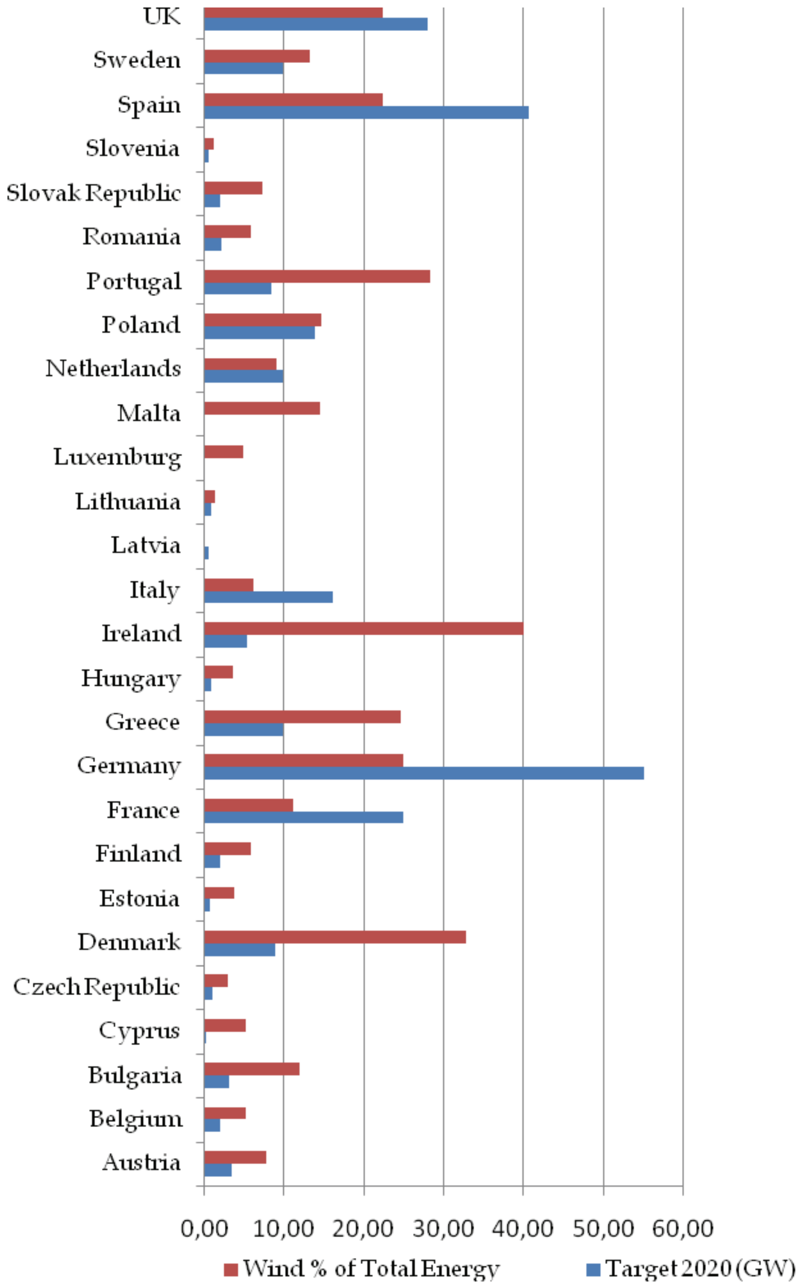

Fig. 17. EU 27 wind development to 2020

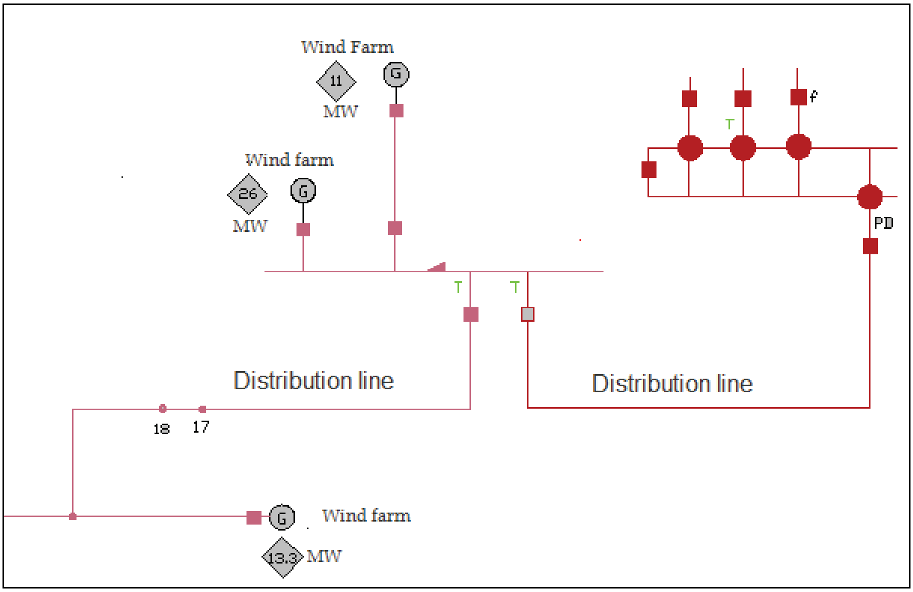

Fig. 18. Part of a distribution grid with integration of wind power generation

The most important principles of operation of any power system is the safety and efficiency. For that reason all the actors, consumers or producers, must comply with technical requirements. Because of that, clear rules are needed to ensure the well, safety and efficient operation of the system. These rules are normally called by "grid codes", and reflect the true technical needs for system operation. The problem is that these technical requirements are not adjusted for all European countries where the level of penetration of wind power is not the same. Normally, grid codes contain high costly requirements sometimes with no technical justification for some actual grids. It is not feasible that grid codes only reflects the technical needs for system operation, based on experience of countries with large penetration of wind energy, in countries with small wind power penetration requirements such as fault-ride trough or primary control are inappropriate. Because of that is important to harmonised grid codes for wind energy at a European level. That seems not to be an easy task, because of the national specificities of each European country in terms of wind penetration level, network robustness, geographical size of the system, etc. Expanding the rules adopted by more developed countries in terms of wind energy, to others where wind energy levels are not so high, is not a good practice.

5. Grid Codes

With the integration of large amounts of energy produced by using the wind resource, in the utility grids, additional requirements in terms of grid codes are needed to integrate wind power with other conventional generation forms. The way as wind farms react to power system disturbances and the way how they contribute to the disturbances, must be a target of regulation. High short-circuit currents, big unbalances on frequency or over- and under-voltages during a fault occurrence can damage wind generators. The relay protection of the

wind farm is designed with the objective of complying with requirements for normal operation and support the grid when a fault occurs and in the system restoration after a fault occurrence. The system relay protection has to secure wind farms against damage from the impacts occurring at faults in the power network. National grid codes, which are from the responsibility of governments and system operators, have the responsibility of imposing rules to maintain power system stability and power quality.
Normally, wind turbines were disconnected from grid when voltage goes below 80 or 90% of nominal value. But a timeless shut-down of wind turbines can have a reverse action, and contribute to system disturbance. To prevent bad actions, the way as wind farms react to voltage dips or frequency deviations, must be regulated.
A voltage dip can be described by a sudden reduction of the voltage, between 10 and 99%, in a point of the network, followed by the restoration of voltage after a short time. Normally time duration is lower than 1 second and amplitude is lower than 60%.

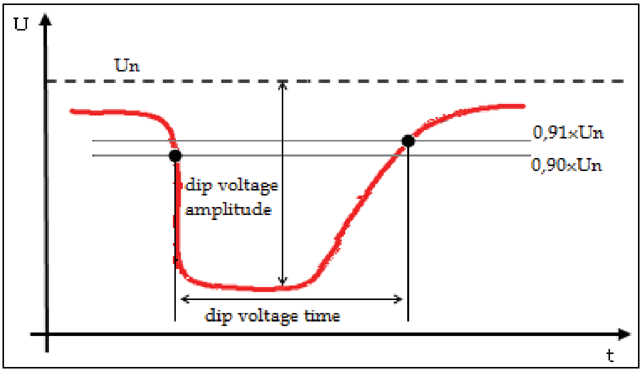

Fig. 19. Dip voltage representation

Most of European countries impose rules to the wind farms grid connection similarly to the existing rules for conventional power plants grid connection. These rules normally contain minimum technical requirements, defined by the system operators to the wind farms owner, as a way to ensure security of supply, reliability and power quality. Next an overview of requirements in the national grid codes for wind turbines is presented. Some countries have different grid codes for transmission and distribution networks (Denmark) while others have focus only on transmission level (Germany and Spain). Some other European countries, even with some considerable penetration of wind generation, doesn't have any specific grid code for wind turbines, using the same rules imposed for conventional power plants connection (Portugal).

For wind farms connected to grids under 100 kV, the Danish system operator impose that they must be maintained connected to the network if a 3-phase short-circuit occurs for 0.1 seconds. In the presence of a 2-phase short-circuit with a duration of 0.1 seconds followed by another one with the same duration occurring 0.3-0.5 seconds after the first one, the wind farm should remain connected. Wind turbines must fulfil these requirements when these situations occur for two times in 2 minutes or six times in 5 minutes (Energinet, 2004a; Iov et al., 2007). For connections to grids with voltages above 100 kV, the same requirements are needed adding the situation for 1-phase short-circuit were wind farm shall not be disconnected in the same conditions described for a 2-phase short-circuit in the distribution network. In the transmission system wind turbine must hold with at least two situations of 1, 2 and 3-phase short-circuit within 2 minutes interval (Energinet, 2004b; Iov et al., 2007).

In Germany the grid code, applied to networks with voltage levels 380, 220 and 110 kV, impose that wind farm shall fed short-circuit current into the grid during the fault period when the fault occurs in the grid, outside the protection range of the generating plant. However wind farms must be disconnected in special situations such as when voltage falls below 85% from the rated voltage. In that situation disconnection should happen with a time delay of 500 msec. If the voltage at the wind turbine terminal is equal, or less, than 80% of minimum permanently voltage permitted, 25% of the generators must be disconnected from the grid after 1.5 sec, 1.8 sec, 2.1 sec and 2.4 sec respectively, if the voltage doesn't increase to the minimum permitted level in the meantime. In a situation of overvoltage, 120% of the maximum permitted voltage value, the affected generator must be disconnected from the grid with a time delay of 0.1 seconds. In a situation of voltage dip wind generators must provide a reactive current to support the grid voltage. This action must take place within 20 msec after fault detection and shall be maintained for more 500 msec after voltage returns to normal (E.ON, 2006; Iov et al., 2007; Tsili et al., 2008).

Spanish requirements related to voltage dips specify that wind farms must support voltage dips without tripping. During the faults and in the recovery period wind farms can't absorb reactive power, must not absorb active power and must provide to the network the maximum reactive current. Consumption of active and reactive power is admitted during a period of 150 msec after the beginning and 150 msec after the clearance of the fault, in specific conditions. This wind farm behaviour is required for balanced three-phase faults and unbalanced two-phase and single-phase faults (REE, 2005; Tsili et al., 2008).

In Portugal wind farms with power installed over 5 MW must remain connected to the grid when voltage in wind farm terminal is over the limit curve illustrated in the Figure 20, for a 3, 2 or single-phase fault. The fault ride through requirements for wind turbines of the three mentioned countries are shown in Figure 20.

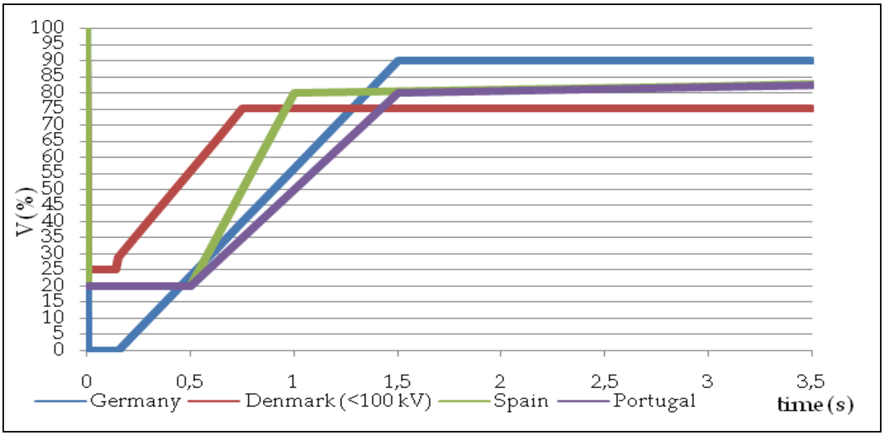

Fig. 20. Fault ride through capability of wind farms in National Grid Codes of Germany, Denmark, Spain and Portugal

During the faults and in the recovery period, wind farms can't absorb active or reactive power. Wind farms must provide reactive power during the voltage dip period as showed in Figure 21, the maximum permitted delay for the beginning of production of reactive power is 40 msec after fault detection. Zone (1) represents the reactive power contribution during the period of fault and restoration, and zone (2) represents the normal operating period.

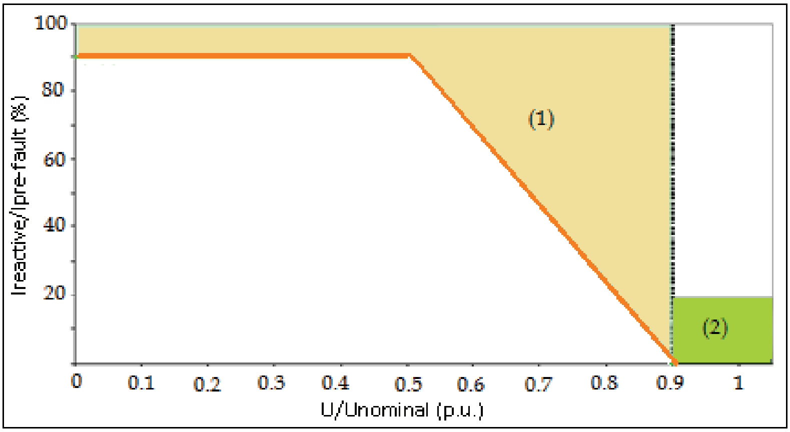

Fig. 21. Reactive power contribution.

Frequency is an indicator of balance between production and consumption. In the European power network frequency is very stable, varies in a range of 50±0.1 Hz.
In terms of frequency, Danish grid code allows a variation between 47Hz and 52Hz, for a short limit of time. Outside these limits disconnection must occur after 0.2 seconds. A continuous variation is permitted between 48,5Hz and 51Hz.
In Germany the frequency range allowed for variation is between 47.5Hz and 51.5Hz, for a short limit of time. Outside the limits the unit must be automatically isolated from the network without delay. Continuous variation is allowed between 49Hz and 50.5Hz (Iov et al., 2007; Tsili et al., 2008).
In Portugal wind farms must support frequency deviations between 47.5 Hz and 51.5Hz without necessity of disconnection from the grid.

6. Typical Faults

Operational costs and an efficient maintenance of wind generators are very important aspects in modern wind farms. Wind generators can't be dispatched efficiently, normally due to the wind characteristics, but worst than don't have wind to generate energy is to have the machine stopped due to a fault. Associated to a fault is a time to repair it and equipment to do that. Because of the wind generators dimension, if is required, for instance, a crane to make the repair, that can be a bigger problem than the original one because of the unavailability of this kind of machines and the high costs associated. Fault detection techniques are becoming indispensable in modern wind parks. Fault detection techniques offer some important benefits, like the prevention of major components failures, the reduction of maintenance costs, detailed information on wind generators performance and vibration characteristics and allow for condition based maintenance schemes to increase maintenance intervals (Caselitz et al., 1996).

There are three typical kinds of faults that can occur in a wind generator, electrical faults, electronic faults and mechanical faults. The electrical faults occur with some frequency but are the most unexpected because all used equipment (electrical machines) is very developed and is well known. Induction generators or transformers are electrical machines used for decades. So, it is not expected to have faults in these equipments but, the reality shows that electrical problems exist. Most common failures are bearing related, due to short circuit currents, and insulation problems. These kinds of problems can be explained by the necessity to reduce the machines dimension and the need to work with new construction materials that aren't well tested. When an electrical fault occurs, the costs involved to solve the problem are very high and normally the problem is solved by the substitution of the fault component.

Electronic faults have a higher occurrence frequency than the electrical faults. These kinds of problems occur frequently in sensors and in electronic cards. The anemometer measurement is one example of a component that has a very high fault rate. Electronic components faults can be provoked by lightning effects or other weather phenomena. Normally electronic components breakdowns occur after storms with lightning hitting the towers. When these problems occur, the solution is to substitute the electronic component by a new one. It isn't necessary any specific and high costly machine to solve the problem, a crane for instance, but is necessary to remember that an electronic component failure can lead to the offline of the turbine and to the costs of not production energy associated to that. There are a lot of sensors installed in a wind generator, for instance, wind generator can give information about errors in yawing, in hydraulics, in ambient surroundings, in rotation, in generators, in pitch system, etc. A wind generator of 2MW can have a list of about 20 errors in generator only. So, a very large number of sensors are present in each wind tower and because of that the probability of bad functioning of the sensors is very high.

The third types of faults, the mechanical, are associated to the gearboxes and to the blades. With the increase of size of wind towers, the rotors velocity must be slowed. So, the gearbox must reduce the velocity applied to the rotor. Because of that, forces applied to the cog-wheel of the gearboxes are very high which can lead to the tooth break. Other problem is when a lightning hits the blades. The blade has a thin metallic layer connected to the mass copper conductor. When a lightning hits the blade, the metallic layer or the copper conductor can be destroyed or the tip of the blade can be damaged. Some of these problems can be solved with no necessity of bring down the blade but others needs that. With the increase of size of the towers and blades, stronger winds are catch. So, the continuous vibrations and centrifugal forces that turbine blades are submitted make this component the weakest mechanical link in the system.

Due to the dimension and to the costs involved, three components of a wind turbine must be monitored. They are the blade system, the gearbox and the generator. Not only are the replacement components expensive, but major expense is also associated with obtaining and mobilizing the large crane needed to repair these components. A fault in any of these systems can cost a lot of money, time and the necessity of specific equipment to make the reparation. Figure 22 depicts the mean time to repair of wind turbines and is clear that the blade system, the gearbox and the generator are the three components that needs more time to repair.

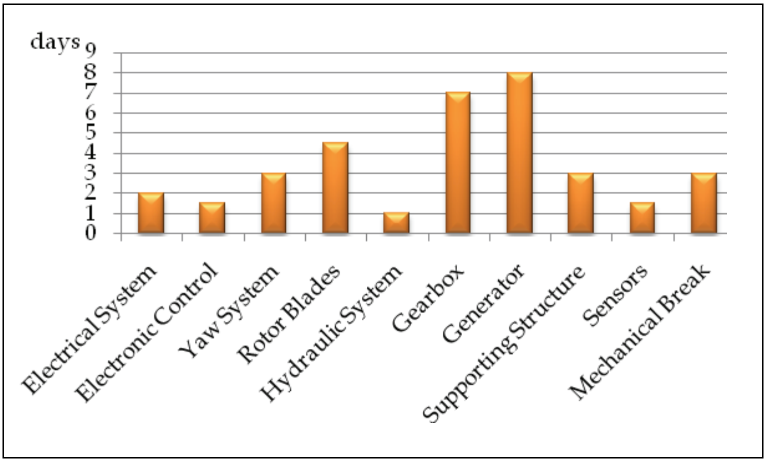

Fig. 22. Typical Downtime per failure

Based on one year data obtained from a real wind farm, equipped with 10 wind generators of 2 MW each, is possible to get some conclusions. With all the data arrived to the control centre was possible to make a graphic with the downtime of each machine and the out of service time of the totality of the wind farm during one year. Figure 23 shows the results.

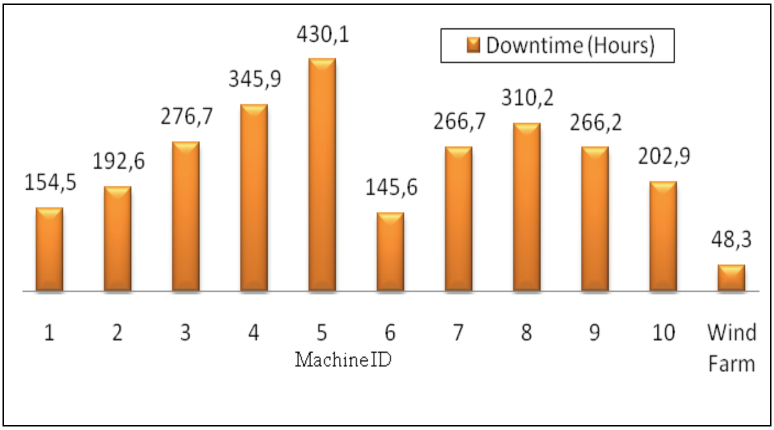

Fig. 23. Wind generators and wind farm downtime, during one year

Making some statistical calculus is possible to see that the average time stopped by each machine was 264 hours/year, approximately. But the totality of the wind farm only was out of service 48.3 hours, in a year. This reinforce what was said before that the probability of blackout of a wind farm is very low and decreases if instead of a wind farm, the analysis is enlarged to a region or to a country.

Looking deeper for the causes of faults that led to the machine stopping and dividing the causes into five groups: not planned (NP), planned (PL), network fault (NF), short time planned (SP) and other causes (OT), some conclusions can be made. The not planned stop

covers all the causes that were not planned, as examples of causes are the substitution of damage equipments; out of communications; stop caused by high temperature of generator, etc. In the planned stop (PL) group are represented the time used for planned maintenance of the wind turbines. In the network fault group (NF) will be grouped all the stops caused by the network, like actuation of protections of maximum or minimum voltage in the substation, high currents in the rotor caused by network problems, etc. In the short time planned stops (SP) is represented the time used for upload software or to make some adjust in parameters. All causes that led to wind turbine stop due to weather conditions, like ice phenomena, strong winds, etc are grouped in the OT group.
Making this analysis is possible to conclude that almost 80% of the stopped time of a wind turbine is due to not planned actions. All the other groups have a small influence in the out of service of the machine. Figure 24 shows the influence of each group in the out of service time of the wind turbines.

As we can see most of the causes that led to a stop of a wind turbine have unexpected causes. An early detection of possible faults in wind turbines assumes a great importance because it allows better maintenance and repair strategies and can prevent major problems in other components. The installation of control centers designed specifically for monitoring, dispatch and control wind farms is a good solution for reduce the downtime of wind turbines or wind farms because the system operator see online what is happening in the installation and can quickly alert the maintenance team when a problem occurs in a machine or in all wind farm.

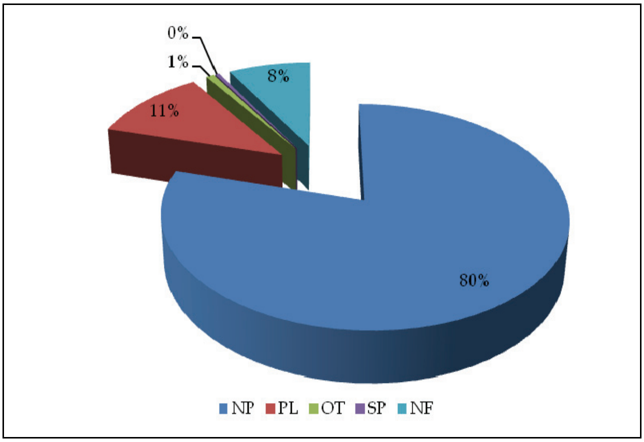

Fig. 24. Percentage of each group of faults

Computer tools that analyzes data with the objective of detect and prevent possible faults are interesting. Techniques of current signature analysis, or vibration analysis, or temperature analysis, are techniques that are taken into account by wind turbine manufacturers. In the control centre it is possible to see information of the temperature of the nacelle, temperature of generator and bearings, transformer temperature, gear oil temperature, and more. It is possible to access to the generators speed, wind speed, power produced, voltage and currents. All this available information can also be used to give some hints of developing failures in a wind turbine.

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