"WIND POWER IN THE UCTE INTERCONNECTED SYSTEM"

NetWork of Experts on Wind Power

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1.- OBJECT.

UCTE (Union for the Co-ordination of Transmission of Electricity) is a TSO organisation, whose main role is to maintain the security of supply and the quality of the energy delivered. In this context UCTE and its member TSOs support the goal to promote renewable energies and reduce CO2 emissions according to EU and national targets.

As a result of the political efforts for a sustainable development, renewable power has increased its penetration in the electricity world. The integration of renewable energy sources especially of wind energy generation changes the power system conditions which must not lead to negative changes of supply quality. Wind power plants are nowadays an earnest field for producing energy and their contribution in some EU countries such as Denmark, Germany or Spain is very significant.

This document presents the level of integration of wind power in the UCTE interconnected network, the state of the art on wind power converters and, after a review of the more frequent problems associated to this type of energy, suggests some recommendations for system planning and operating planning and the requirements for connection of wind farms.system planning and operating planning and the requirements for connection of wind farms.

2.- INTRODUCTION.

With the Council Decision 2002/358/EC of 25 April 2002 the European Union signed the Kyoto Protocol and agreed on an overall 8% reduction of greenhouse gas emissions compared to 1990 levels by the year 2012. This target has at the same time been fixed for every Member State of the European Union.

In the White Paper "Energy for the Future: Renewable Sources of Energy" the European Commission laid down the target to increase the share of renewable energies from 6% to 12% of gross domestic energy consumption by 2010. The White Paper also set a target for the installed wind power, which should be increased to 40.000 MW also by 2010.

The 2001/77/EC Directive of the European Parliament and Council on the Promotion of Electricity Production from Renewable Energy Sources (RES) in the Internal Electricity Market establishes the member quotas to achieve the global target (from 14% in 1997 to 22% in 2010) as well as periodic reporting of the adopted issues and their success. Chapter 3 of this document shows the different RES participation nowadays in the European countries and particularly in UCTE members.

The 2001/77/EC Directive aims to identify and guarantee the proper functioning of national carried support mechanisms for renewable energy (green certificates, investment aids, etc.). Some stated issues are the required guarantee of origin (GoO) of electricity produced from renewable energy sources; the establishment of adequate administrative framework to reduce barriers to the production of renewable energy: clear designation and coordination of authorities, guidelines. The Directive also states the priority access to the grid system of electricity produced from renewable energy source, and points to standard rules for sharing of costs of possible grid reinforcements. Special reference is done to forecasted documents (oct-2005) that will collect national experiences and propose a Community framework with regard to support schemes for electricity produced from renewable energy sources.

Globally, wind energy is the relevant energy renewable source, particularly developed and installed in Europe and naturally linked to industrial technology development and export and to employment creation.

In the aim of accomplishing the potentialities and maximum profitability of this energy while maintaining security and quality criteria in electrical systems, particularities of wind power plants should be taking into account.

Next chapters of the present paper identify the effect of wind power plants on the transmission system operation. The different wind generators technologies are analysed (chapter 4) as well as their interaction with the electrical system (chapter 5): the highly fluctuant energy associated and their behaviour in case of grid disturbance, as well as their capacity of participating in reactive power or voltage control, and also the consequences on quality of energy.

The adequate integration of WPP in the electrical system entrains technical requirements to be accomplished in order to assure its security and performance. TSOs being the ultimate responsible for assuring the continuity and quality of electricity, they suggest in chapters 6 of this paper the required conditions for the connection. Vice versa, their inclusion implies the adaptation of methodological and technical aspects in the TSOs' network planning tasks, so some suggestions to these aspects are given in chapters 7 and 8. Finally, chapter 9 provides some operational solutions and some necessities on the real time operation introduces by those TSOs which have integrated large quantities of wind power.

3.- DEVELOPMENT OF WIND POWER ON THE UCTE NETWORKS.

The participation of RES, and more specifically of wind power, in the energy production is far for being uniform among European countries either UCTE members.

German, Spanish and Danish power systems are exceptional cases in which penetration of windy energy has reached representative values (figure 3a).

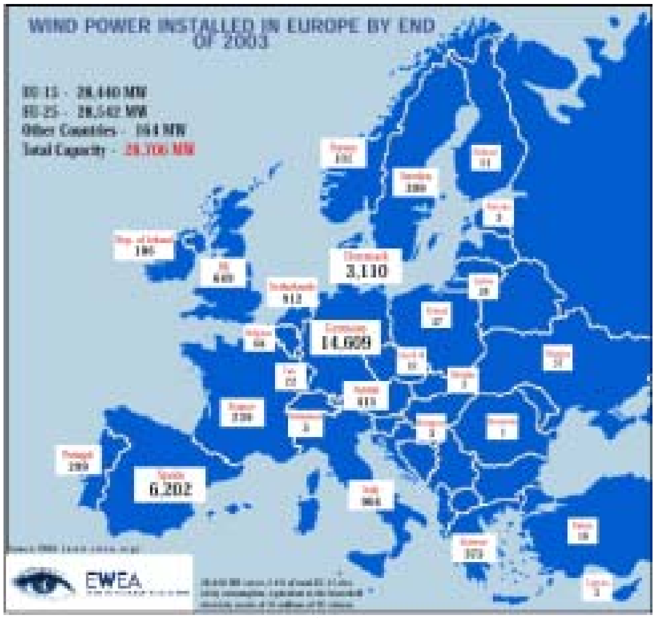

*Figure 3.a.- **Wind power installed in Europe by the end of 2003**.*

Forecasted installed wind power capacities in the UCTE network, plus, Denmark (Western Part) system till the year 2010 is shown in figure 3.b.

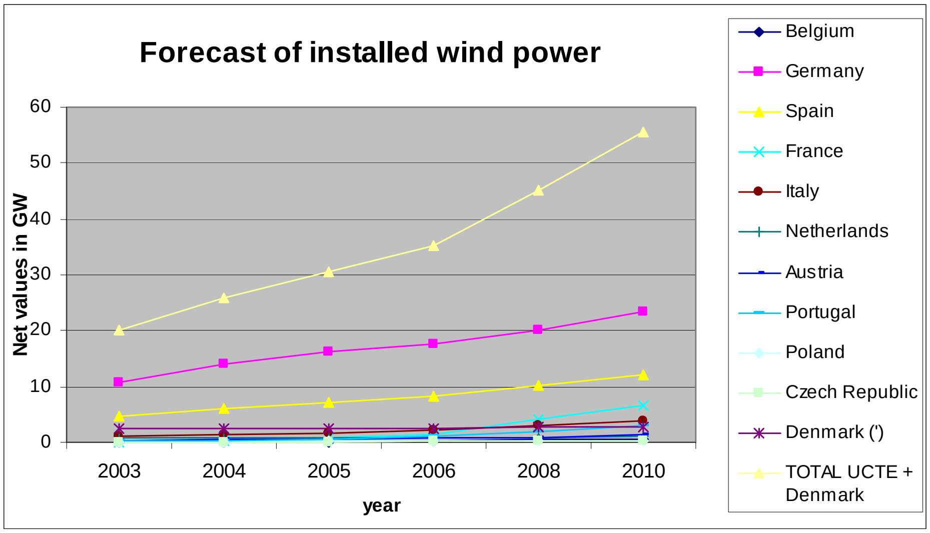

*Figure 3.b[1].- **Forecasted capacities in UCTE network countries + Denmark (WP)**.*

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[1] Figure has been drafted following a methodology that only considers those future plants whose commissioning is "reasonably" sure, and including only UCTE synchronous system (i.e. islands are not taken into account) + Denmark WP).

Regarding to the different technologies already installed in the UCTE network, table 3.a shows, for Germany, Denmark (WP) and Spain, estimated percentages of installed wind power by type of technology referred to national wind power capacity by the end of the year 2003.

Type of generator	Germany	Denmark (WP)	Spain
Squirrel cage	46	77	40.5
Wound rotor IM	-	12	-
Doubly fed IM	19	11	58
Synchronous Generator	34	-	1.5

Table 3.a.- ***Estimated percentages of installed wind power by type of technology referred to national wind power capacity by the end of the year 2003.***

The integration into the networks and the way of connecting wind farms to the evacuation networks shows different practices on the national power systems. While Denmark, the 93% of the wind generation is evacuated by the distribution networks, the Spanish case is quite different (figure 3.c).

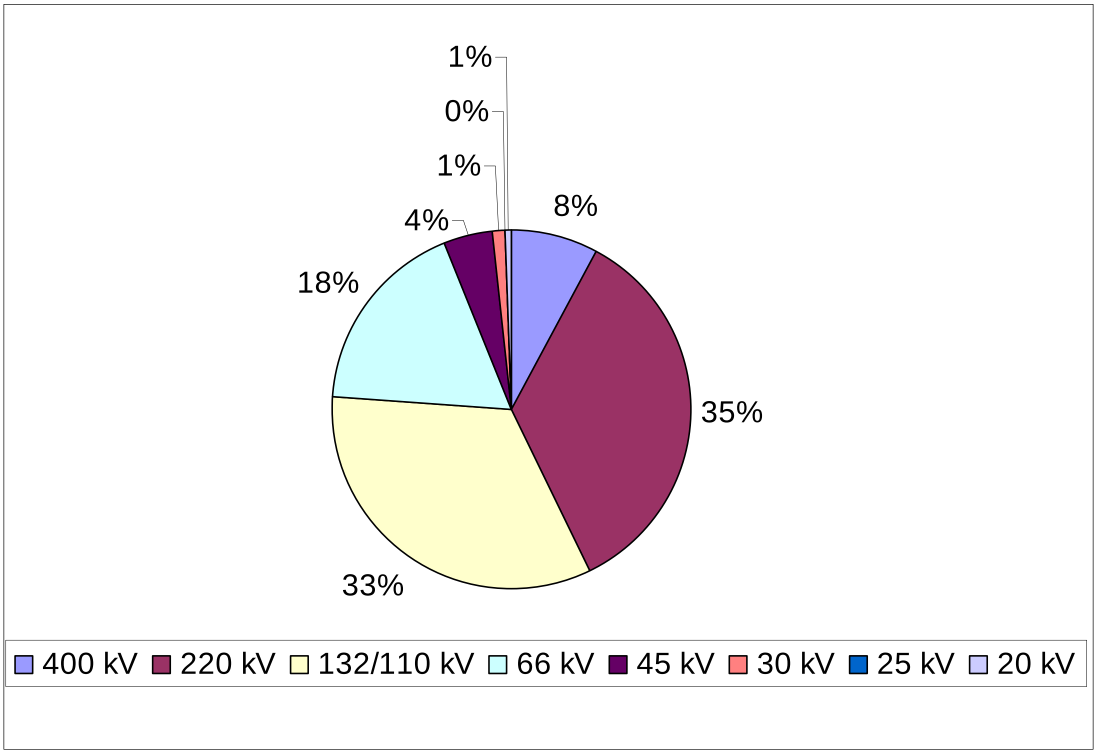


Figure 3.c.- ***Wind capacity by network voltage (Spain).***

4.- CHARECTERISTICS OF WIND SYSTEMS.

As the use of wind power plants increases worldwide, it is important to understand the effect these power sources have on the operation of the grid.

Transmission System Operators (TSOs) focus their attention on the system interaction of the various wind turbine types and the differences compared to conventional power plants as power plants have to provide system services to enable the steady operation of a grid.

4.1.- MAIN GENERATING SYSTEMS.

Wind Energy Converters (WECs) are technical systems used to convert the energy contained in flowing air into electricity. There are several types of these systems and during recent years technology has substantially improved them. Two aspects of WECs are mainly being changed: wind turbine sizes and electronic converters.

Wind turbine sizes are being developed in order to increase electrical generation, in particular at market introduction. The development of grid connections due to new power electronics technologies was introduced to reduce the wind speed variation impact on the electrical frequency and the power generation.

There are different wind power technologies. In this document, the three more commonly used area presented:

- Constant speed turbine with:
  - Squirrel cage induction generator
- Variable speed turbines with:
  - Doubly fed (wound rotor) induction generator,
  - Direct drive synchronous generator.

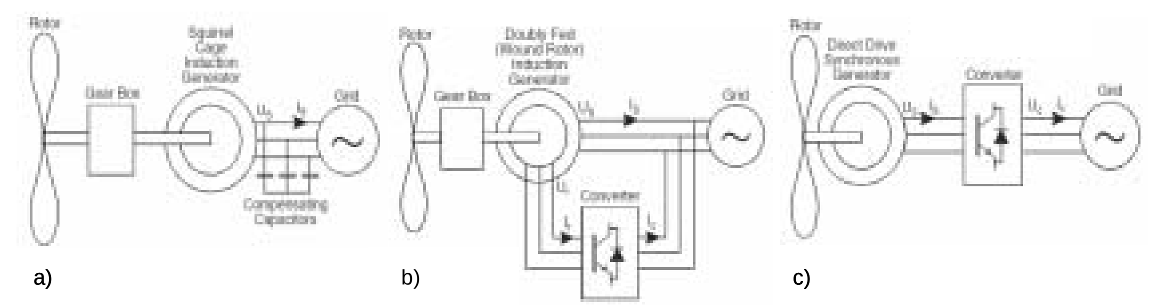


Figure 4.1.a: ***Most important generating systems used in wind turbines: a) squirrel-cage induction generator, b) doubly fed induction generator, c) direct drive synchronous generator***.

4.1.1.- Squirrel cage induction generators.

A squirrel cage induction generator is an asynchronous machine, composed by a squirrel cage rotor and a stator with three distributed windings which are directly coupled to the grid. The wind turbine rotor is coupled to the generator through a gearbox. Substantially this is a constant speed wind turbine because the power converted from the wind is limited by designing the turbine rotor in such a way that its efficiency decreases in high wind speed.

This kind of generators always consumes reactive power and is not able to control and regulate the voltage level. Hence capacitors close to these generators are necessary to avoid a voltage decrease.

4.1.2.- Doubly fed (wound rotor) induction generators.

A doubly fed induction generator has a wound rotor that is connected to the grid through a back-to-back voltage source converter. This converter controls the excitation system in order to decouple the mechanical and electrical rotor frequency and to match the grid and rotor frequency. The wind turbine rotor is coupled to the generator through a gearbox in the same way as the constant speed generator.

4.1.3.- Direct drive synchronous generators.

The most important characteristic of this wind generator is that it is completely decoupled from the grid by a power electronics converter connected to the stator winding. The converter is composed by a voltage source converter on the grid side and a diode rectifier (or a voltage source converter) on the generator side. The direct drive generator is excited by an excitation winding or permanent magnets.

4.2.- POWER-SYSTEM INTERACTION.

4.2.1.- Reactive Power Generation and Voltage control.

The squirrel cage induction generator has a fixed relation between rotor speed, active power, reactive power and terminal voltage. Therefore this type of turbine is not able to control the reactive power output respective the terminal voltage. In order to control the voltage additional equipment for generating controllable amounts of reactive power is needed. As the prime mover wind is rapidly fluctuating, constant speed turbines, when connected to a weak grid, can cause flicker (grid voltage fluctuations due to output power fluctuations).

Variable speed turbines have the ability to control the terminal voltage by adjusting the output of reactive power. The extent is limited by the rating of the converter and the controller.

Generally can be said that the voltage aspect of wind power generation has to be taken into account, especially if wind turbines are connected to a weak grid (at distant locations) and are replacing conventional power plants.

4.2.2.- Behaviour in case of disturbances on the grid

When a short circuit occurs in the transmission grid a voltage dip propagates through it and reaches the wind farms. The voltage dip that reaches one particular wind farm is more or less deep depending on the type of short circuit, the point where the short circuit has occurred and the number and size of synchronous generators that are located near the fault and react increasing their reactive power output. In regions with important wind energy penetration and little synchronous generation, voltage dips can be quite deep.

Traditionally wind generators are disconnected quickly (within seconds) when the voltage drops. This is due to the protection of electronic converters and former connection rules (disconnection at voltage drops higher than 10-20% in order to prevent the system of possible voltage fluctuations caused by generator oscillations and large consumption of reactive power by the generators).

When a voltage dip reaches a wind generator with a squirrel cage machine, the mechanical active power remains constant, the generated active power falls, the wind generator accelerates, the current and the reactive power consumption increase largely, the reactive power produced by the capacitors that compensate the consumption of the induction generator falls sharply and the reactive power losses in transmission and distribution lines increase. The acceleration of the machine can be very quick if the inertia is small. When the short circuit is cleared, as the speed has increased, the active power tends to be higher than before the fault. But this also requires higher current, higher voltage drops in the lines and transformers and the voltage at the induction generator does not recover the pre fault value. As a consequence, it may happen that the machine trips because of overcurrent protection.

Summarized can be said that the contribution of turbines with squirrel cage induction generators to the fault current in the first 100 ms is quite similar to the contribution of a synchronous generator, but the behaviour of these wind turbines changes after the fault clearance when it consumes a large quantity of reactive power causing an eventual voltage instability. The risk of voltage instability (and rotor speed instability) increases when the fault duration is long and when the wind generators are connected to a weak grid. Normally the overcurrent protection activates before a voltage or rotor speed instability occurs.

Turbines with doubly fed induction generators contribute to the fault current. As power electronics converters are very sensible to overcurrents they are presently quickly disconnected from the grid during a fault. A possibility for protecting the rotor side converter against high rotor currents is to bypass the rotor during grid faults. This is known as “crowbar protection”. For limiting the rotor current and for influencing the speed-torque characteristic of the machine, the rotor can preferably be bypassed through an impedance. The machine will now speed up and start absorbing large amounts of reactive power. Unless there is a fast return of the voltage this will typically lead to tripping of the machine.

Turbines with direct-drive generators are able to contribute to the fault current, depending on the rating of the electronic converter. Due to the costs, traditionally most converters are not dimensioned for a higher current than the nominal. Therefore these converters (plus controlling system) limit the fault current to the nominal value. Presently turbines with direct drive generators are quickly disconnected in case of disturbances on the grid.

If the wind power penetration in a region is high a fault (voltage drop) followed by the disconnection of the wind turbines can cause a large generation deficit. Therefore new grid connection requirements demand the ability to withstand voltage drops of certain magnitudes and durations (chapter 6).

4.2.3.- Frequency control

The prime mover of wind power is uncontrollable and therefore wind generators hardly ever contribute to primary frequency regulation.

Normally, WECs do not contribute to frequency control (if they operate in so called frequency independent mode). Technically WECs with blade control could provide frequency control if they operate at a reduced output level.

Conventional power plants have to balance the power fluctuations caused by the wind turbines. Also adequate reserve capacities are needed to cover unexpected losses of wind power, caused by shutdowns due to high wind velocities or to a grid fault. This again emphasises the tendency towards a less than optimal part-load operation, which can cause an increase of the specific fuel consumption in conventional power plants. The higher the penetration of wind turbines is the higher are the requirements for the remaining conventional power plants to keep the fluctuations of the frequency within the limits.

New connection requirements demand at least the reduction of power output in case of overfrequency.

4.2.4.- Summary of WECs capabilities.

Table 4.2.a summaries the capabilities of the different technologies:

	Constant speed wind turbine	**Variable speed wind turbine with doubly fed induction generator**	**Variable speed wind turbine with direct drive synchronous generator**
Output power control and frequency control/short term balancing	Switching wind turbines on and off / Control of blades	Switching wind turbines on and off Control of pitch angle and power electronic converter	Switching wind turbines on and off Control of pitch angle and power electronic converter
Output power availability and long term balancing	Problematic due to dependence on wind as primary energy source	Problematic due to dependence on wind as primary energy source	Problematic due to dependence on wind as primary energy source
Voltage control	Not possible without extra equipment	Possible when converter rating is sufficient and when controlled appropriately	Possible when converter rating is sufficient and when controlled appropriately
Supply of fault current	Inherent to working principle	Difficult due to limited overloading capability of power electronic converter	Difficult due to limited overloading capability of power electronic converter
Fault-ride-through capability	Risk of voltage instability, dependent on actual wind speed, fault duration and grid strength	Problematic due to substantial difficulties in controlling power electronic converter	Theoretically possible, but only with appropriate control of the power electronic converter

*Table 4.2.a.- **Summary of the capabilities of the different wind power technologies**.*

5.- INTEGRATION OF WIND POWER.

Actually wind generators have two different locations of resources, in-shore and off-shore, and two different kinds of impacts, local impacts and wide-system impacts.

5.1.- LOCATION OF RESOURCES (IN-SHORE AND OFF-SHORE)

Wind resources are often located in remote areas (*in-shore* or *off-shore*) far from transmission network facilities. For integrating large scale wind power plants (WPP) therefore often grid reinforcements and new transmission lines are needed to transport the produced energy to the load centres.

The advantages of offshore wind power plants, compared to inshore, are the reduction of visibility and noise problems and steadier winds with higher average speeds, resulting in a higher energy yield. The disadvantage is the cost increase caused by the additional cost of constructing offshore and the longer distance that must be covered for connecting to the grid and the consequently reinforcements in the present grid.

5.2.- IMPACTS ON POWER-SYSTEM.

Due to the fact that the prime mover of wind power plants is highly fluctuating and that generating systems, different from conventional power plants (synchronous generators) are used the effects of WPP on the power system has to be analysed. In general it can be said that the impact of wind power becomes more severe the higher the wind power penetration level is.

The wind power characteristics are reflected in a different interaction with the power system:

- Local impacts of wind power are impacts that occur in the (electrical) vicinity of a wind turbine or wind farm and can be attributed to a specific turbine or farm. Local impacts occur at each turbine or farm and are largely independent of the overall wind power penetration level in the system as a whole.
- System-wide impacts, on the other hand, are impacts that affect the behaviour of the system as a whole. They are an inherent consequence from the application of wind power but cannot be attributed to individual turbines or farms

5.2.1.- Local impacts:

Wind power locally has an impact on the following aspects of power system:

- branch flows and node voltages
- protection schemes, fault currents, and switchgear ratings
- Power Quality:
  - harmonic distortion
  - flicker.

The first two topics must always be investigated when connecting new generation capacity. This applies independently of the prime mover of the generator and the grid coupling, and these issues are therefore not specific for wind power. The way in which wind turbines locally affect the power quality depends on whether constant-speed or variable-speed turbines are used (4.2.1.-).

The contribution of wind turbines to the fault current also differs between the three main wind turbine types (4.2.2.-).

The third topic, power quality is divided into two subtopics:

> Harmonic distortion is mainly an issue in the case of variable-speed turbines because these contain power electronics, an important source of harmonics. However, in the case of modern power electronics converters with their high switching frequencies and advanced control algorithms and filtering techniques, harmonic distortion should not be a principal problem.
>
> Flicker is a specific property of wind turbines. Wind is a quite rapidly fluctuating prime mover. In constant-speed turbines, prime mover fluctuations are directly translated into output power fluctuations because there is no buffer between mechanical input and electrical output. Depending on the strength of the grid connection, the resulting power fluctuations can result in grid voltage fluctuations, which can cause unwanted and annoying fluctuations in bulb brightness. This problem is referred to as *flicke*r. In general, no flicker problems occur with variable-speed turbines, because in these turbines wind speed fluctuations are not directly translated to output power fluctuations. The rotor inertia acts as an energy buffer.

5.2.2.- System-wide impacts

Apart from the local impacts, wind power also has a number of system-wide impacts because it affects:

- power system dynamics and stability
- reactive power and voltage control
- frequency control and load following/dispatch of conventional units.

The impact on the **dynamics and stability** of a power system is mainly caused by the fact that:

- in wind turbines, generating systems different from synchronous generators are applied. The specific characteristics of these generating systems are reflected in their response to changes in terminal voltage and frequency, which therefore differs from that of a grid-coupled synchronous generator (4.2.-);
- with variable-speed turbines, the sensitivity of the power electronics to overcurrents, caused by voltage drops, can have problematic consequences for the stability of the power system; as a relatively small voltage drop can lead to the disconnection of a large amount of wind generators and therefore to a large generation deficit (Figure 5.2.2.a)

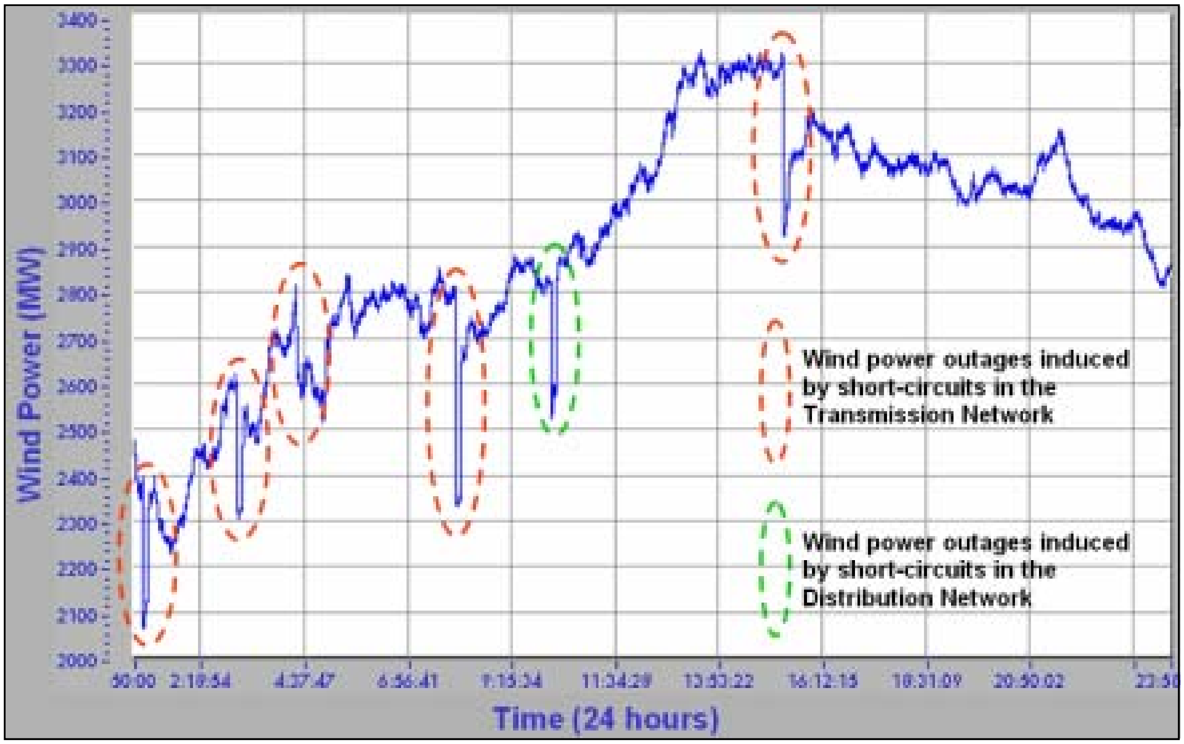


*Figure 5.2.2.a.- **Wind power trips induced by faults on the Network**.*

The impact of wind power on **reactive power generation** and **voltage control** depends on:

- the capability of wind turbines of varying their reactive power output. Not all wind turbines can vary their reactive output power (4.2.1.-);
- the locations of wind farms (5.1.-). When choosing a location for a conventional power plant, the voltage control aspect is often easier to consider because of the better location flexibility of a conventional plant;
- the coupling to the grid. Wind turbines are relatively weakly coupled to the grid because their output voltage is rather low and because they are often erected at distant locations. This reduces their contribution toward voltage control.

When the output of conventional synchronous generators is replaced by wind turbines at remote locations on a large scale, the voltage control aspect must be taken into account explicitly. For these regions it has to be analysed how the control of voltage can be managed. There are different possibilities – for example: 'must run conventional power plants' for reactive power generation, the installation of FACTS, the requirement for every wind turbine to be capable of active voltage control.

The impact of wind power on **frequency control** and **load following** is caused by the fact that:

- the prime mover of wind power is highly fluctuating and uncontrollable (4.2.3.-). This leads to the difficulty of making a precise forecast of the wind power production in the long term (12-72 hours ahead) and to the necessity of conventional power plants to balance the (forecasted and not forecasted) power fluctuations to meet the load curve. The higher the wind power penetration level, the larger is the impact of wind power on the demand curve faced by the remaining conventional units, resulting in and fewer remaining units. Thus, the requirements on the ramping capabilities of these units must be stricter in order to match the remaining demand curve and to keep the fluctuations of the system's frequency, caused by unbalances between generation and load, within acceptable limits.

In general it can be said that the impact of wind power becomes more severe the higher the wind power penetration level is.

6.- SUGGESTION FOR GRID CODE REQUIREMENTS.

Grid code presents the technical requirements to establish the compatibility between the running of the equipment (generators, devices,..) connected to the power system and the power system itself.

Hereafter the requirements are split in two topics: technical requirements and system services.

6.1.- TECHNICAL REQUIREMENTS FOR GRID CONNECTION

The technical requirements for connection to the transmission network are defined at the delivery point and they are a set values concerning to frequency, voltage, short-circuit power and stability.

6.1.1.- Requirements for abnormal frequencies and voltages

In principle these are the same requirements as for normal power plants. An example of E.ON Netz, Grid code for high and extra high voltage (August 2003), but more or less general valid is given in figure 6.1.1.a:

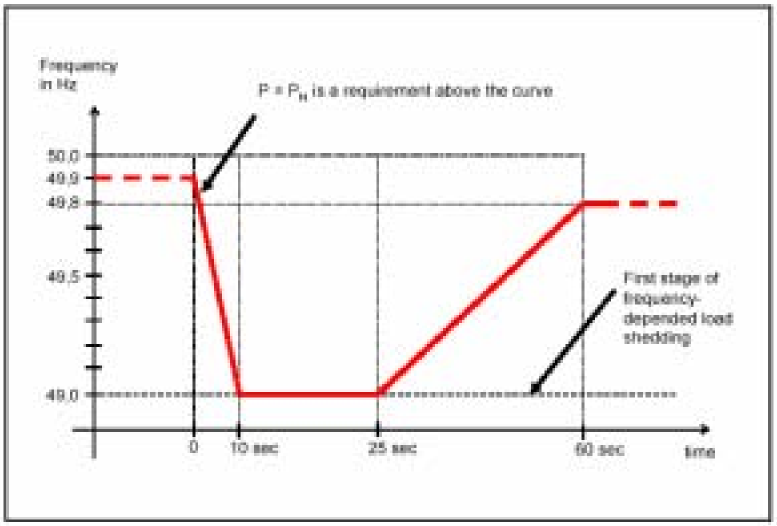


Fig. 2 Frequency envelope where no restriction of the active power output is allowed

Figure 6.1.1.a.- ***Requirements for abnormal frequency****.*

With frequencies above the bold line in this figure it is not permitted to reduce active power output.

Larger frequency deviations may lead to a reduction of production, but normally not more than 15 or 15% of the actual output before the frequency drop. The time limitations are given in the figure 6.1.1.b.

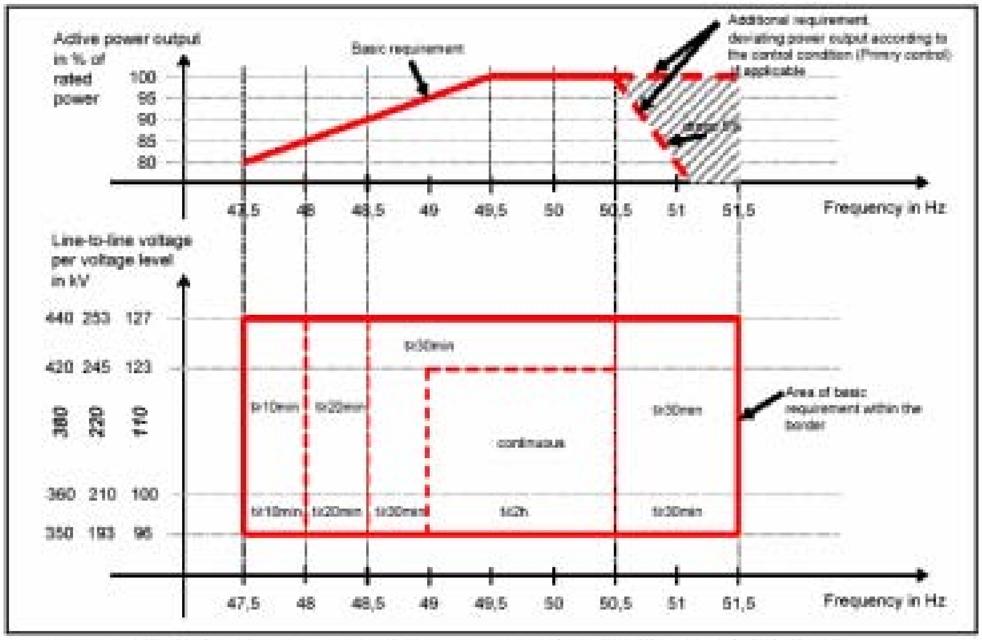


Fig.3 Requirements on the output power of the generating units to the network for certain periods as a function of network frequency and network voltage (quasi-static consideration, i.e. frequency gradient ≤ 0,5 %/min; voltage gradient 5 %/min)

Figure 6.1.1.b.- ***Requirements for abnormal voltages and frequency.***

The basic requirements presented in the figure above, must be met. Additional requirements may be agreed upon separately.

Renewables are mostly exempted from the requirement of island operating after disconnection.

6.1.2.- Quality of supply:

In order to ensure good-quality supply, disturbances caused by wind farms must not exceed some limit values for the following phenomena:

- Rapid voltage variations,
- Flicker,
- Umbalance,
- Harmonics,

In general, the limit values are associated to the short circuit power, so the maximum evacuation capacity (in MVA) in a connection node would not be higher than a percentage (i.e. 5%) of the minimum Short Circuit power before the new installation.

~~TSOs calculate this maximum evacuation capacity, as the minimum short circuit power in the 50% percentile.~~

6.1.3.- Stability requirements

In all operational conditions wind farms shall be able to withstand certain fault sequences without being disconnected, for instance a three-phase fault with a certain clearing time or a two-phase fault with an unsuccessful reclosing after a certain time.

Each system should decide on the necessary requirements in order to keep the stability taken into account local circumstances.

In the following the requirements of E.ON are taken as an example. Figure 6.1.4. shows the voltage limit curve at the network connection point with a near-to-generator short circuit, above which generating units with a large symmetrical short-circuit current component, must not be disconnected from the network.

Active power must resume immediately following fault clearing, with for instance a gradient of 20% of the rated power per second.

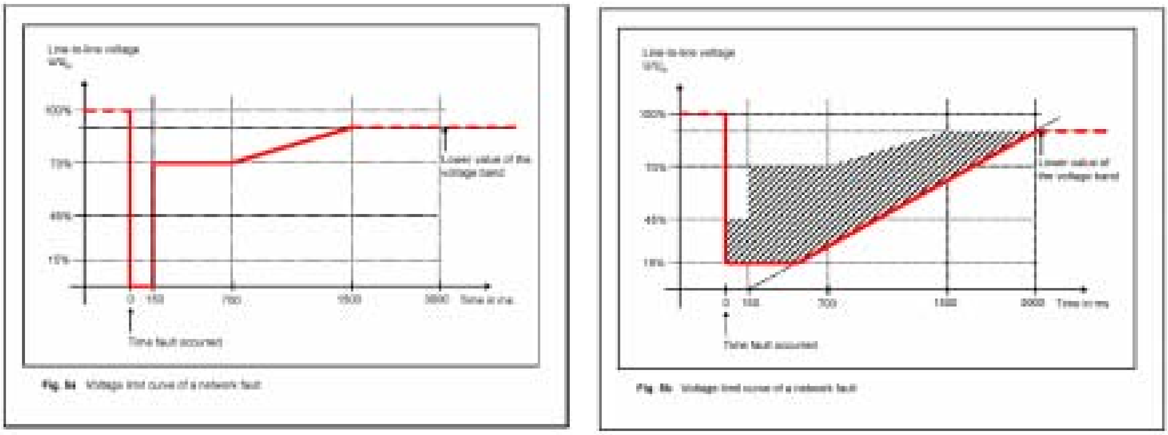


*Figure 6.1.4.- **Fault ride through requirements**.*

In case of generating units with a low symmetrical short-circuit current component, it is generally allowed to disconnect for a short period after a fault has occurred (because of fault ride-through problems) but the wind farms should reconnect after fault clearance and must start producing power again with a certain gradient. The active power increase can take place with a lower power increase if the restoration of voltage is delayed (shaded area).

When a network is disturbed and the voltages do not recover sufficiently, the generating units must support the voltage. If a voltage drop of more than 10% occurs the generators must be switched over to voltage support. This support must be provided within a short time after identification and must last several seconds.

6.1.4.- Protection.

Protection of plant shall be selective with the network protection.

Disconnection if frequency is too high or too low, or voltage deviations are out of the defined range.

6.2.- SYSTEM SERVICES.

6.2.1.- Primary frequency control.

Renewables normally are exempted of providing primary control. So then operate in the frequency independent mode.

But, fast reduction of power might also be obliged, for instance if the frequency is above 50,5 Hz. Then a rate of decrease of 5 to 10% per second may be required (figure 6.2.1).

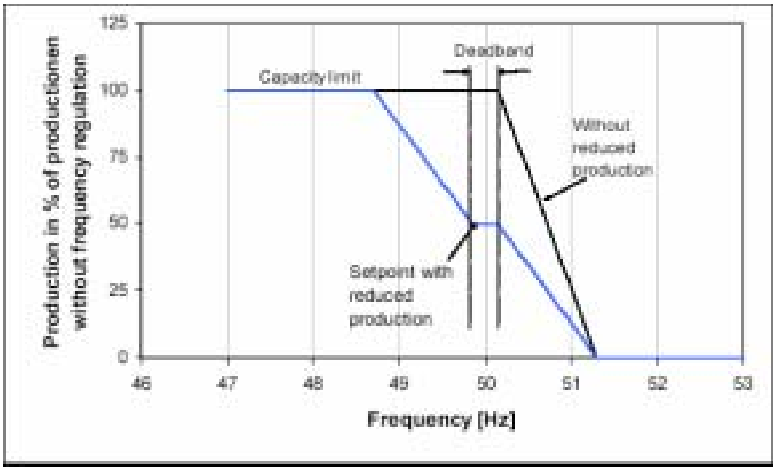


*Figure 6.2.1***.- *Fast reduction of power requirement (ELTRA).***

6.2.2.- Production control

Production limitation: it must be possible to reduce the power output in any operating condition and from any operating point (for instance in the range of 20-100% of the rated power) to a maximum power value (set point value) specified by the TSO. The associated accuracy may be specified, for instance ± 5% of installed power.

Reduction of power output may have a minimum rate per minute (for instance 10%) and on the other hand the increase of power may also be limited to a certain rate (for instance also 10% per minute).

6.2.3.- Reactive power exchange

Mostly at the connection point the exchange of reactive power should be more or less zero (within a defined margin, depending on the actual output). In some countries, by agreement between wind power owner and the grid company, the compensation task can also be assigned to the grid owner.

But the generators should be designed to be able to meet a certain range of reactive power exchange (for instance between a power factor of 0,9 leading and 0,9 lagging at full active power output).

The switching and control of reactive power is mostly limited to a certain percentage of the maximum connection capacity (for instance 2,5 to 10%).

In general the rapid voltage change because of switching should be limited to a maximum of 2 or 3%.

6.2.4.- Solution of technical constraints.

Once all operation proceedings have been carried out, especially those concerning conventional generation facilities, and no other possibilities for the solution of this kind of constraint can be considered, the TSO is able to order the production rate reduction of wind power generator facilities and other power sources which are considered legally similar.

It is important to remark that the generation capacity assignment of the network in these conditions shall be studied with objective, transparent and fair criteria, laying upon the free market principles.

7.- MODELLING WIND FARMS FOR SYSTEM STUDIES.

To be able to study the impacts of introducing wind power into the power system, special models are needed. The following section briefly discusses the basic model requirements for operating and planning a transmission system with a significant infeed from wind power.

Only the three most important applications as seen from an electro-technical point of view are described. Model requirements for wind power forecasting, determination of reserves, etc. are not described.

7.1.- LOADFLOW

Normally, the WECs are represented as a PQ machine for steady-state analysis. Attention must be paid to the power factor of the installation. In special applications a particular wind power plant may be operated in voltage control and should then be modelled as a PV machine. In this case a PQ-diagram at the connection point is required.

For steady-state voltage stability studies both the machine and any reactive compensation must be represented individually.

7.2.- SHORT CIRCUIT

Due to the very different applications of short-circuit analysis it is impossible to give a general guideline for representing WECs. The fault current delivered by a WEC is very dependent on the duration of the fault and the voltage drop. Especially, the protection system of the WEC plays an important role for the behaviour.

For instance in case of switching of shunts the voltage change is relatively small. The WECs will therefore continue normal operation.

In case of fault studies a squirrel cage induction machine will provide a transient fault current for typically 100 ms. After that, the machines will start absorbing reactive power since it relies on excitation from the grid. Depending on the protection design, some doubly fed induction machines will behave like a squirrel cage until the voltage recovers, while others will simply trip during the fault clearing.

The table 7.2.a describes the typical fault currents delivered by the different WEC types.

	Squirrel cage induction machine	Doubly fed induction machine	Direct drive synchronous machine
Switching	Transient	Transient	Rated current
Short circuit 0-100 ms	Transient	Depending on the design	None or up to rated current
Short circuit >100 ms	Negative	Depending on the design	None or up to rated current

*Table 7.2.a.- **Fault currents delivered by the different WEC types**.*

The short-circuit power is an important measure of the system strength and the value is often referred to in connection rules and used for other applications such as harmonic and transient studies. Ideally, the modelling of the short-circuit power provided by a WEC should be checked in dynamic studies. More work is needed in order to harmonise the representation for different applications.

7.3.- DYNAMIC STABILITY. (TRANSIENT STABILITY)

For large power systems it is necessary to aggregate the WEC so that the number of machines in the model is kept at a reasonable level. The WEC can usually be lumped into a generic machine representing all WECs with the same technology in the same substation.

Besides the electrical parameters of the machines, it is vital to represent the most important protection systems such as undervoltage and overcurrent protection. In case of temporary tripping during a fault the resynchronisation has to be modelled at a general level.

In case of power electronic converters a description of the control system in terms of fundamental frequency RMS values is required. Since converters might block on transients which are not represented in dynamic analysis, it is useful to have an electromagnetic transient model for verification and adjustment of protection settings.

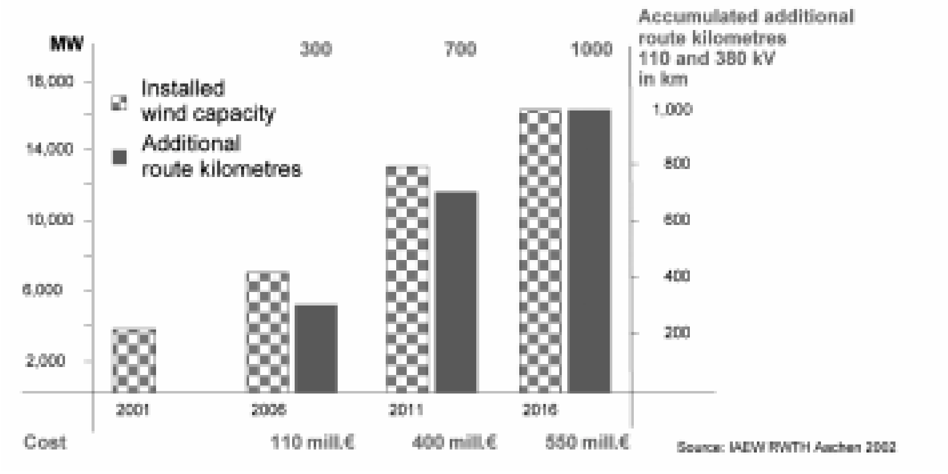
For applications involving gear boxes it is often necessary to represent the shaft as a two-mass model in order to take the torsional swings and the design of the necessary controller into account.

If the blade angle is adjusted to reduce the mechanical power during the disturbance of interest, it is necessary to represent the pitching system and the aerodynamic characteristics of the blades. Usually, a constant wind input can be assumed for system studies.

8.- SYSTEM PLANNING AND NETWORK DEVELOPMENTS.

One decisive factor for the further expansion of wind energy use will be the capacities of the electricity grids. Up to now, electricity supplies have largely been decentralized, with power stations having been built across the country as close to the points of consumption as possible. This has made it possible to avoid transporting electricity across long distances. The power grids were built to bring the energy from these power stations to the consumers, which has meant that, expressed in simple terms, energy has always flown in one direction and only across relatively short distances. This has changed with the boom in wind energy. An increasing number of wind parks have been and are being built primarily in coastal and relatively sparsely populated areas of low consumption, which in periods of strong wind generate more energy than the area in question consumes at the same time. Consequently, this surplus energy must be transported over long distances. The line grids in the coastal regions can no longer do this in their current state without limits. If offshore wind parks will also be built on a greater scale in the future, additional grid expansion measures would also be necessary in the extra-high voltage grid.

Today, the grids in some regions e.g. of Germany are already approaching their capacity limits. When the wind is strong, they are unable to take any additional wind power. Wind power does not only cause regional grid congestion in the north German Federal States. In the North Sea and in the Baltic Sea area, far more wind power is generated under conditions of high wind and low load than is consumed in these states. Since in the coming years the expansion of wind power is set to progress on the basis of political will, by the end of the decade at the latest, e.g. the North Sea and Baltic Sea area will be wind power export states across long distances. This will drastically change the current principle of decentralized electricity generation close to the point of consumption. Cross-border electricity trading will also be significantly hindered by increased grid congestion. New transport lines will be necessary on a large scale in order to bring wind power generated on the coast and at sea to the consumer centres. In its expert assessment relating to this, the Institute for Electrical Plant and Energy Management of the RWTH Aachen assumes that by 2016, up to 1,500 km of new high-voltage and extra-high voltage power lines will be required for this in Germany.



Source: IAEW RWTH Aachen 2002

Figure 8.a.- ***Wind power development and grid upgrading****.*

The grid operators require planning and investment security for expanding the wind power grid. Politicians, wind park planners and grid operators must therefore develop realistic scenarios for the further expansion of wind power – including offshore – that can serve the grid operators as a planning basis for the additional capacity requirement. Due to the often lengthy approvals procedures that are involved, comparatively long realization times must be expected for the construction of new high-voltage and extra-high voltage power lines. It is therefore necessary to speed up the approvals procedures for the construction of required new lines for wind power and to in future link the approvals procedures for new wind parks to the approvals procedures for the required grid expansion. There is a risk of bad investments being made if this is not successful: Wind parks without a sufficient grid connection, or lines set up for wind power but for which there is no supply.

9.- OPERATIONAL ASPECTS.

Large quantities of electricity energy cannot be directly stored. This means that every second, exactly the amount of energy must be fed into the grid that is taken out at the same time. If the amount fed in differs from the amount tapped, this can cause faults or even failure of the supply. The transmission system operators must therefore at all times ensure a balance in their control areas between generation and tapping (power-frequency control).

The prime mover of wind turbines (i.e., the wind) is hardly controllable and fluctuates randomly. There are to be considered two factors:

- Wind generation prediction for load coverage.
- Imbalances produced by turbulence, high wind speed.

To be able to predict the wind generation accurately is of course the most important objective of a wind generation forecast. Different weather conditions are associated with different uncertainties. This information could influence the day-ahead needs of regulating capacity in the system.

The best way of estimating the uncertainty of a forecast is to base the evaluation on several forecasts. These rules out the most common of today's meteorological forecasting methods, the deterministic forecast.

Power fluctuations are induced by turbulence, which is a stochastic quantity that evens out when many turbines are considered. An exception, however, is formed by storm-induced outages that occur when the wind speed exceeds the cut-out value. These are not induced by stochastic turbulence but by storm fronts and can therefore affect a large number of turbines simultaneously. Online measurements could warn the forecasting system and the operator before the deviation suddenly shows up.

9.1.- FORECAST OF WIND GENERATION

To forecast wind power, the TSOs of the UCTE network with greater installed wind power, namely E.ON, ELTRA and REE, use complex forecasting systems.

A flowchart of a typical wind forecasting tool is given in Figure 9.1.a.a. It can be seen that there are four inputs to the system. These inputs feed the prediction algorithms, which are the core of the tool. Then, several outputs are generated (in this case two are presented): the reports containing the predictions to be used by the TSO, and some feedback to be used for the prediction algorithms to adapt to the new data.

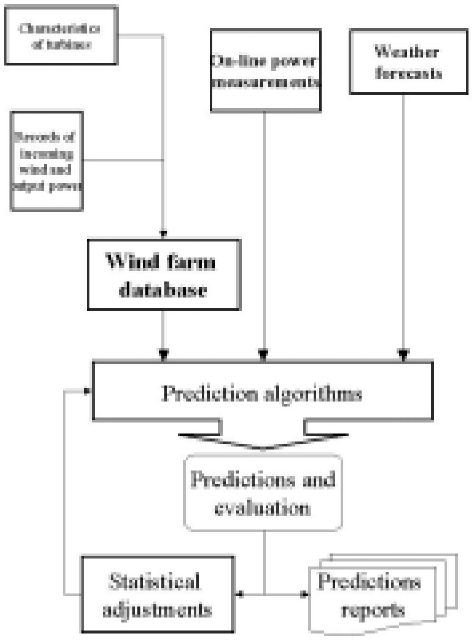


Figure 9.1.a.- ***Flowchart of a typical wind forecast tool.***

For a given wind farm, a wind forecast tool needs four types of inputs. Namely, (a) the characteristics of the wind farm, (b) historical records of simultaneous incoming wind and output power, (c) on line measurements of power output, and (d) meteorological predictions. The algorithms depend on the types of input available. These inputs are as follows:

Data from wind farms include number and kind of turbines, with their standard power curve, latitude and longitude of farm placement, point of connection to the grid, etc.

The second type of input, only available for some wind farms, is the historical records of simultaneous incoming wind (actual wind) and output power. These historical records are then used to build "real" power curves to be used instead of those "ideal" ones, formed from standard power curves of wind turbines.

The third input is the wind speed and direction forecasts for every wind farm. These forecasts come from a numerical weather prediction tool. In general, they are provided by the National Meteorological Services.

The quality of wind power forecasting is to great extent limited by the quality of the wind forecasting. Like all weather forecasting, this is only partly reliable. Too, the spatial resolution of these meteorological predictions is very low and does not take into account local topography. So, the accuracy of the predictions decreases.

The fourth type of input is the **on line information of the wind farm providing energy production**. Different time intervals can be used (hourly, quarter,…)

The forecasting horizon can (from Eltra's practices) be separated into 3 sections:

1) 0 to 6 hours ahead, used as basis for trading in the regulating market.
2) 6 to 42 hours ahead, used as basis for the contingency analysis. Also used for estimating system imbalance.

3) 42 to 120 hours ahead, used as secondary input for outage planning and for estimating system balance.

Forecasting within horizon 2 and 3 which are the most common planning horizons for most TSOs, is totally dependent on quality of the meteorological forecast.

The accuracy of the predictions will depend on the amount of available information and the prediction horizon, a shorter prediction horizon means higher accuracy. The availability of on line measurements allows the analysis a statistical time series which provides more accuracy predictions.

9.2.- POWER FLUCTUATIONS AND REGULATING POWER

To maintain a reliable supply of electricity, provisions must be made to ensure a reasonable level of backup generation and operating reserves that can quickly be tapped to respond to a system emergency.

Due to the wind intermittency the operating reserve allocation should be more accurate and is much more interesting in electricity markets that should define how to assess the charges for ancillary services.

The TSO's experience of the past years has shown that whenever electricity consumption was comparatively high because of the weather, namely during cold wintry or hot summer periods, wind power plants could make only a minor contribution towards covering consumption.

In order to also guarantee reliable electricity supplies when wind power plants produce little or no electricity – for example during periods of calm or storm-related shutdowns – traditional power station capacities must be available as a reserve. The characteristics of wind make it necessary for these **"shadow power stations"** to be available to an extent sufficient to cover over a percentage of the installed wind energy capacity (80% in the case of E.ON). This means that due to their limited availability, wind power plants cannot replace the usual power station capacities to a significant degree, but can basically only save on fuel.

Of crucial importance to the wind-related demand for reserve capacity is the expected maximum forecast deviation and not, for example, the mean forecast error. This is because even if the actual infeed deviates from the forecast level only on a few days in the year, the transmission system operator must also be prepared for this eventuality and have sufficient capacity available so that a reliable supply is still guaranteed. The "shadow power stations" have to be there to react in case of shortage.

9.3.- OPERATIONAL PLANNING, GENERATION AND CONGESTION MANAGEMENT.

Operational planning is related to those activities carried out by a TSO in order to prepare the Operation of the system in the short term, i.e. less than 1 year. So, the TSO basically carries out load flow calculations and, if required, transient stability analysis.

Previously, the TSO should create scenarios, credible scenarios, considering the load forecast and the coverage of the demand and the more probable network availability, programmed maintenance of generators and transmission assets. So the first question arrives: what will be the wind power generation if the wind power forecast is too difficult?

In several countries, wind power has priority of dispatching, and the network developments, to evacuate and transmit this energy to the consumption centres, do not follow the wind power developments due to, among other reasons, the long approval process. So congestions and bottlenecks can appear and the TSO has to solve. The temporary solution is the limitation of the injection of wind power applied by the TSO.

Due to the weak "fault ride through capability" of present wind farms, transient stability studies are needed in order to calculate the maximum wind power infeed, compatible with the system security, considering system operation point and in particularly, periods of low load. The result of this grid analysis can be other limitation of the wind power.

Both possible limitations to wind power applied by the TSO has to be authorised by the national regulation.

In 2003 E.ON Netz introduced what is called "generation management ", in the north-east part of its network. Every impermissible load on equipment is automatically forwarded to the grid management centre of E.ON Netz in Lübeck. Following identification of the affected region, a signal is sent to the wind parks feeding in electricity in this region.

The signal defines the maximum active power at which the region's wind energy plants can feed electricity into the grid in view of the current grid situation. The wind park operators are responsible for the demanded reduction in the infeed power. They therefore make an essential contribution towards maintaining a safe supply.

Other type of solution, with very similar aim to the E.ON's one, is proposed by REE. In the case of wind farms, the average size is smaller than conventional plants, and thus the number of agents could be bigger. There is also another difficulty, the possibility of several producers connected to the same network bus. In this case any order or limitation of production issued by the TSO, at bus level or at national level, has to be executed by a coordinator. So REE proposes the called "Delegate Dispatching". This Delegate Dispatching is similar to the already existing generation dispatching and will act as executor of the instructions given by the TSO.

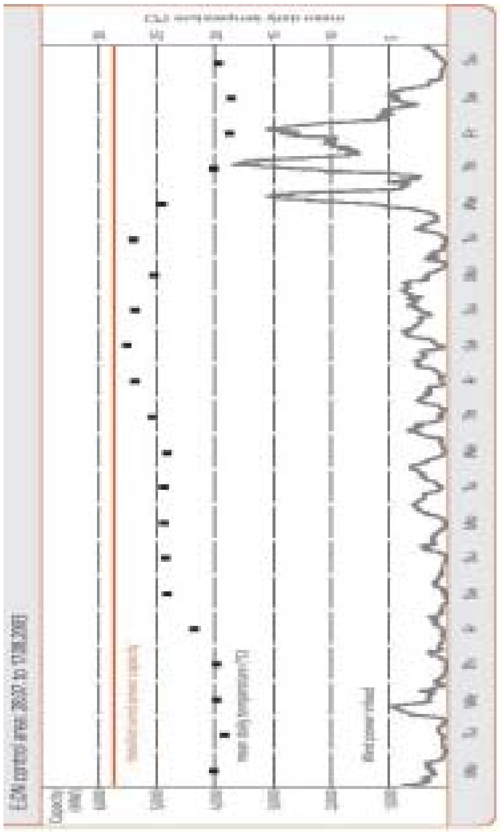


Figure 9.3.a.- ***Minor contribution of wind power during extremely weather conditions (E.ON).***

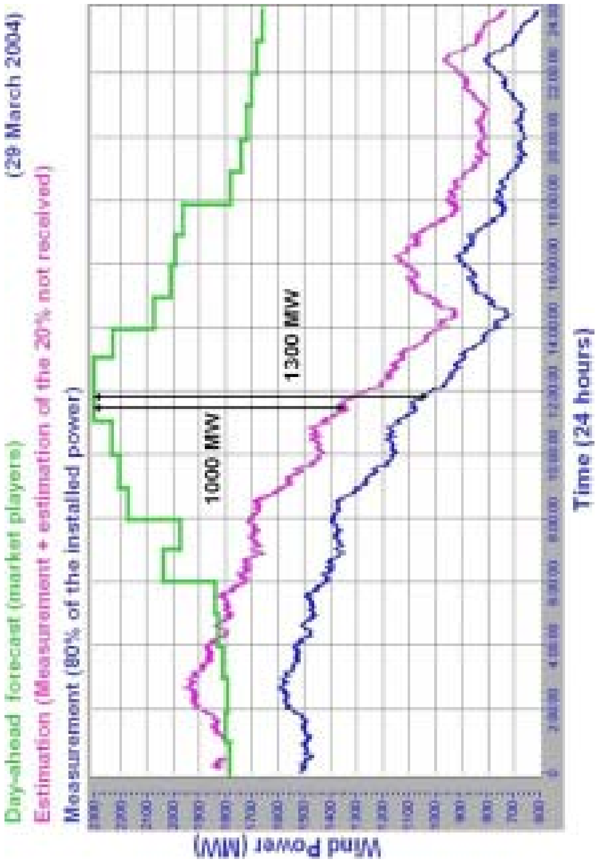


Figure 9.3.b.- ***Great use of reserves due to bad wind power forecast (REE).***

10.- CONCLUSIONS.

More than 24000 MW in wind mills are already connected to the UCTE networks, this enormous figure is not uniformly distributed over UCTE. Three countries, Germany, Spain and Denmark (WP) contribute with, approximately, the 98% of the total.

These examples of successful were based on very ambitious national plans accompanied by interesting retribution schemes, which are not the purpose of this report.

Wind power is different from conventional sources of energy due to three main reasons: prime mover, the wind, location of resources and the electrical machines. Controllability and availability of wind power significantly differs from thermal or hydro generation because the primary energy source can not be stored and is uncontrollable. Wind power does not very much complicate short term balancing and all wind turbine types can be used for it, although variable speed wind turbines have better capabilities. Long term balancing is problematic. The power generated by wind turbines depends on the actual value of the wind speed. When there is no wind, no power from wind turbines is available. Wind turbines even complicate the long term balancing task, particularly at high wind power penetrations.

High penetration of wind power requires advanced solutions in order to keep the actual level of power quality, those solutions can be expensive, as the shadow power stations, development of dispatching centres (under the ownership of the TSO or others) which transmit the accuracy orders given by the TSO to the wind farms.

The integration of wind power is possible, but requiring the development of adequate procedures which harmonised and made compatible the technical requirements and the market rules.

Great efforts has put on the development of wind forecasting tools, but the improvements needed for more accurate forecast need the improvement of the weather forecast. The availability of wind power real time measurements lessens that important lack.

Considering the reduced contribution of wind generators to short circuit power and the high meshed level of the UCTE network, a short-circuit on the transmission network can lead to widespread voltage dips to neighbouring TSOs. Therefor, the “fault ride through capability” of wind generators is an useful requirement to prevent large outages of windpower dependent on the given regional potential gradient area. Additional requirements must guarantee the necessary voltage recovery behaviour after fault clearing. So the integration of wind power needs the collaboration among TSOs and UCTE is an adequate plattform for that.

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