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The Future Energy Mix Paradigm: How to Embed Large Amounts of Wind Generation While Preserving the Robustness and Quality of the Power Systems?

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1. Introduction

The 2001/77/CE Renewable Energies European Directive together with Kyoto Protocol ratification by many countries, supported by some Governments vision and strong objectives on the reduction of external oil dependence, put Europe and other developed economies in the front line to achieve a remarkable wind energy penetration within ten years time. These goals will not be achieved without technical costs and risks, but mainly, without a careful planning and assessment of the power system behaviour with large amounts of wind generation (SRA, 2008; IEAWind, 2008).

These days, one of the most relevant difficulties the wind sector faces was caused by this technology own extreme success. The high capacity installed in the last decade introduced a brand new set of power system technological concerns that recently became one of the more referenced subjects among developers, network planners and system operators.

These concerns are not anymore a negligible distribution grid integration issue that some years ago the experts tended not to give too much relevance since they were easily solved and even more easily avoided through good design and planning, but this is a real power system operation and planning challenge (Holttinen *et al*, 2009): will the power systems be capable to cope with the specificities of the wind power production in large quantities (aka "high penetration") without requiring new wind park models, system operation tools, increased performance of the wind turbines or even a change in the Transmission System Operators (TSOs) conventional mode of operation?

The recent concern of the TSOs is very legitimate, since it is their responsibility to design and manage the power system global production and its adjustment to the consumer loads as well as to assure the technical quality of the overall service, both in steady-state and under transient occurrences.

The wind power capacity reached such a dimension in some European power systems that obliged the TSOs not to neglect the typical behaviour of these spatially distributed renewable power plants, that being a situation that must be addressed by the wind park developers, the wind manufacturers, the TSO planners and regulators together with the experts in this technology grid integration behaviour.

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Notwithstanding these reasonable concerns, the current trend in this R&D area is already that wind generation can be embedded in the system in large amounts and these resources managed through adequate interconnection, holistic transmission planning and system operation adaptation.

The fact that large wind parks started to be seen as “normal power plants” that have to behave as any other generating unit in the system is also a very positive sign of the wind technology maturity. This recent maturity brought a few obligations related to this technology “adult age”:

- Wind park models have to be developed and to allow the TSO to simulate, at least, the large wind parks connected to the transmission network in order to study their grid integration, address their behaviour and assess their stability under transient perturbations of the system.
- Part of the already planned/existing wind capacity has to be selected or adapted to remain in parallel after the occurrence of identified perturbations that produce serious voltage dips (or at least the most common ones).
- The “tools” to address and enable to cope with both the spatial and the time variability of the wind production need to be developed. That includes the necessity of accurate wind forecast models together with spatial correlation assessment.
- In extreme cases the “Wind Power Plant” must act as a contributor to the power system regulation (e.g. frequency control by request of the TSO …).

This chapter presents the new existing technological capabilities that should equip any wind turbine and wind power plant installed in a modern power system facing high to very high wind penetration, as well as it identifies the new wind power plants aggregation and clustering principles that are already being implemented in countries as Spain and Portugal. Moreover, the changes in strategies and methodologies of planning and operation of power systems required to implement (with minimal investments and risks) the paradigm of the future energy mix with a high amount of time-dependent renewable generation are also addressed.

2. Technical barriers to high wind penetration

A fact that should be acknowledged is that several countries and regions in Europe already have a very high penetration[1] of wind generation. Among others, one should mention Denmark, whose wind capacity provides typically 20% of the annual consumption, but also Spain, Portugal and Ireland, these later all above 10% and growing steadily every year (IEAWind, 2009).

There has always been some general concerns associated with the particularities of the wind generation in the power sector. Among others, the fact that wind power is highly variable in time and space and it doesn’t offer guarantee of power. Another concern is that high (>10%) penetration requires added reserves and costs. Recently, IEA Wind Implementing Agreement R&D Task 25 report (Holttinen al, 2009) compared the costs computed for the additional reserves motivated by wind power concluding that, in the worst case scenario,

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[1] several definitions of wind penetration exist, being the most common the percentage of the yearly consumption provided by the wind and used in this text. It is also used, but less common the definition based on the ratio between the wind capacity and the peak load of the power system.

these costs are always bellow 4 cent.Euro/MWh what constitutes less than 10% of the wind energy value.

Another preoccupation within the power sector is that the operation strategies to cope with wind generation and its characteristic fluctuations under very high penetration scenarios are still being developed: there are solutions being identified and some already in use for the most common grid and system transient constraints, but neither all the possible probable occurrences are addressed nor detailed adequate tools to characterize them are already fully available.

2.1 Transmission limited capacity

The first historical reason normally invoked to limit the amount of wind generation embedded in the grid is the grid limited capacity. That limitation of capacity usually refers only to the transmission capacity, once in most countries the developers of a new wind park are asked to invest themselves on the distribution grid reinforcement and even pay the totality of the cost to build the interconnection lines to the already existing network. In European countries this limitation is being addressed in different ways, but the vast majority of countries are dealing with this classic barrier and nowadays are starting to include renewable energy in general and wind energy in particular in their transmission system development plans (DENA study, 2005; REN 2008).

But constructing new transmission lines is a long and difficult path for all developed countries where environmental and social impacts prevent and delay the installation of new electric lines. In realistic terms, with the existing constraints to reinforce the transmission network, and on a “business as usual” scenario, it could take several decades to reach 20% distributed renewable penetration on a European scale.

2.2 Security of supply. Power unit scheduling

a. Balancing Power.

Being a time depended and highly variable energy source, wind power gives no guarantee of firm power generation at all or, in the limit, gives a quite reduced one at a very short production forecasting time scale. It is a commonly accepted fact that there is a threshold, above which, increasing the wind power penetration also increases the power reserve requirements of a system (Holttinen *et al*, 2009). This has been addressed in detail for some power systems or control areas, e.g. Nordpool (Holttinen, 2004) and the results are quite encouraging: the associated costs are much lower than expected up to a certain upper limit (typically 10%) and are only representative for very high penetrations above 20%. The increase level is strongly depending, as expected, on the system generation mix.

b. Wind Power Time and Space Variability

It was back in the early 1980’ that some R&D groups started to address the problematic issue of the excessive “wind variability” and typical fluctuations (Lipman *et al*, 1980) and, at that time, the almost impossible task of forecasting the wind production within time intervals useful for power system operation (Troen & Landberg, 1990).

Another issue strongly related to the wind generation used to be the high frequency content of the power delivered to the system, mainly in the range of flicker emission (from 0.1 to 20 Hz). Those fluctuations could degrade the quality of the service in the surroundings of wind parks (Sorensen, 2007; IEA, 2005; Estanqueiro, 2007) and limits were successfully defined through international standards in order to guarantee an acceptable level of quality (e.g. IEC 61400-21, 2001).

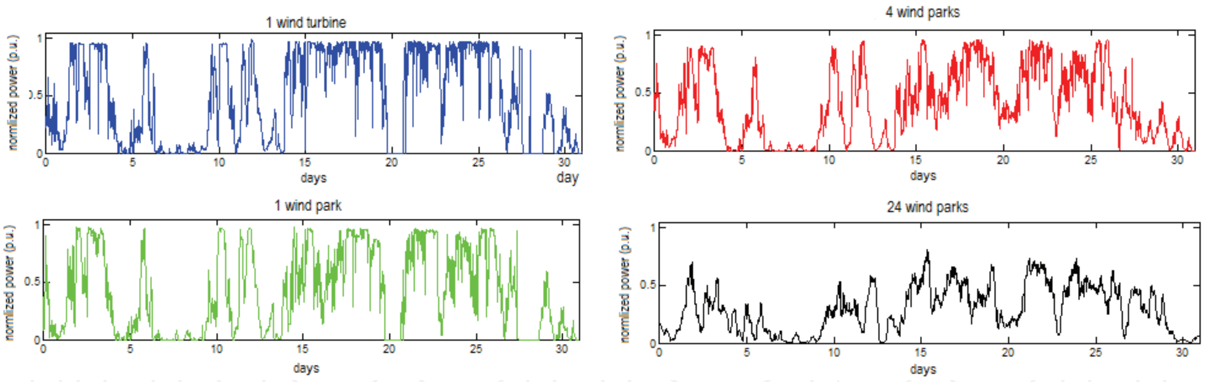

Fig. 1. Wind Power variability and aggregation smoothing effect

c. Wind Generation Technical Reliability

The main concern of every TSO with a large wind capacity in the grid is the sudden disconnection from the grid of all or most of the wind generation as a response to a fast grid perturbation, normally referred as a "voltage dip". Low voltages or dips are usually originated by short circuits and may lead to the islanding of some parts of the network including some conventional generating units. For the wind generation capacity to remain connected to the grid under such circumstances, it is necessary that the wind turbine generators can withstand these voltage dips, a characteristic known as the "ride through fault -RTF" capability (or LVRTF – low voltage ride through fault) which is nowadays requested by most grid codes and national or local regulations.

2.3 Operational energy congestion. Surplus management

In power systems where the energy mix is flexible in terms of regulation (e.g. high penetration of hydro plants with storage capacity) and has a "portfolio approach" with complementary regulation capabilities, the cost with added reserves associated with the large integration of wind in the system is normally lower than in rigid, inflexible power systems.

An issue that is commonly raised when the integration of large amounts of wind power is addressed is: what if the situation of excess of renewable penetration (e.g. wind + hydro) occurs? Should the wind parks be disconnected? would the hydro be reduced?... what is the most important value to preserve, the volatile energy that, if nor extracted from wind will be lost, or the sensible "business as usual" approach "if the hydro is historically in the system, it is a reliable and a unexpensive renewable source", therefore it should never be disconnected...

This situation, commonly referred as surplus of renewable generation raises the uncomfortable issue of either disconnecting wind generators or spilling water which would be turbined in the absence of wind. This issue is again more economical than technical, but a regulated market approach recognizing the benefit of all renewable generation has the ability to overcome these difficulties.

More straightforward approaches – although not necessarily simpler to deploy - consist on having added interconnection with neighbor power systems and use the available ancillary services on larger scales as a contribution to overcome this problem.

These barriers will be addressed in the subsequent sections, together with the possible solutions to overcome the wind integration limitation imposed by them.

3. Technical solutions for large integration: wind power plants innovative concepts

3.1 Innovative characteristics of the wind systems

a. Low Voltage Ride Through Fault

A matter of great concern for the TSO, confronted with the large expansion of wind generation, is the reduced capability of some wind turbines to stay connected to the grid, in the event of faults which give rise to voltage dips.

Therefore, and recognizing the large potential of wind energy, but also revealing an extreme concern towards its growth and future development and in a very acceptable form, almost all TSOs with an already representative wind energy penetration have issued grid codes requiring the wind turbines and power plants to contribute with some basic – but slightly "anti-natural" for the wind technology - power system operation functionalities, a feature which considerably increases the stability margin of the power system under transient perturbations. The more publicized one is the LVRTF – low voltage ride through fault capability, whose characteristics for several grid codes (e.g. the German, the Spanish and the US) are depicted in Fig. 2.

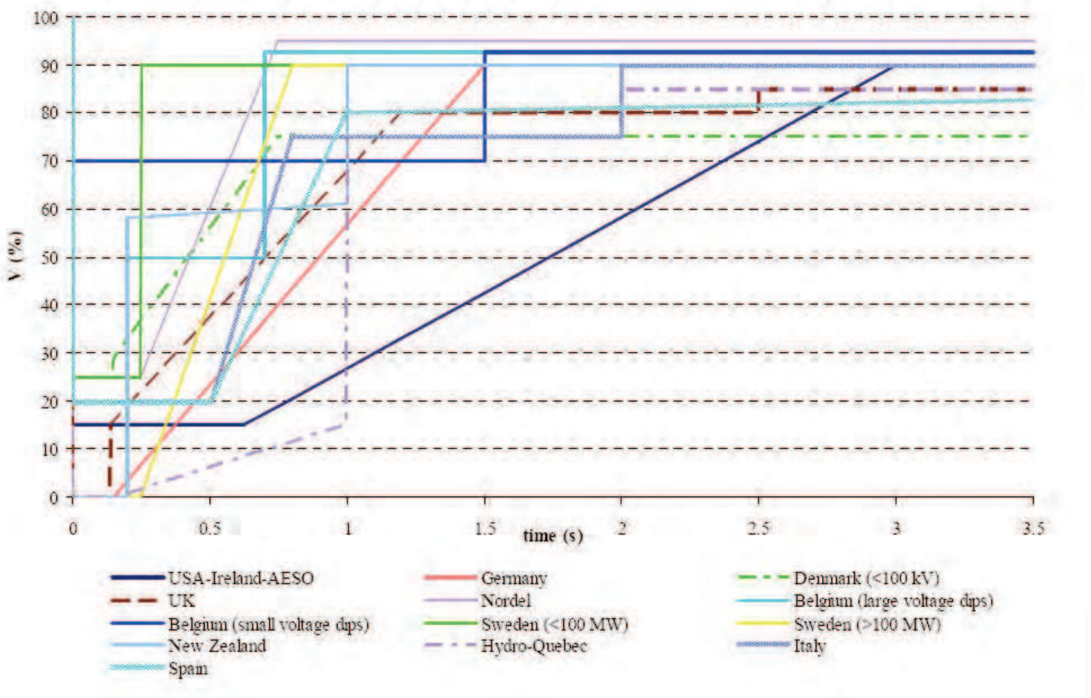

Fig. 2. LVRTF requirements for various grid codes (Tsiliet *al*, 2009)

Most wind turbine manufacturers nowadays offer this capability at an additional cost (usually 5% approx.), which allows the wind generators to withstand a wider range of voltage variations, for longer periods, without disconnection. It should be noted that a power system equipped with less modern wind technology (e.g. without RTF capability) does not have an intrinsic limitation regarding the behavior of the older wind parks under the occurrence of voltage dips. The large electrical industry has already developed RTF systems specifically for the wind industry that, when installed on a wind park without this capability are able to control its response under faults and emulate this new capability of modern wind turbines.

The wind technology RTF capability was one of the most relevant steps this industry has taken once it enabled to put it at a response level similar to the conventional generation in the occurrence of transient events and thus, enabling the TSOs to maintain or in some areas of the network even increase the power quality offered to the consumers.

b. **Participation in the primary frequency control. Low Frequency Ride through Fault**

Large scale recent events (e.g. 4th November 2006) that were propagated to almost all the European Network (1st UCTE synchronous area) and affected even some North-African countries raised the issue of wind turbine response to extreme low frequency occurrences as the one depicted in Fig.3.

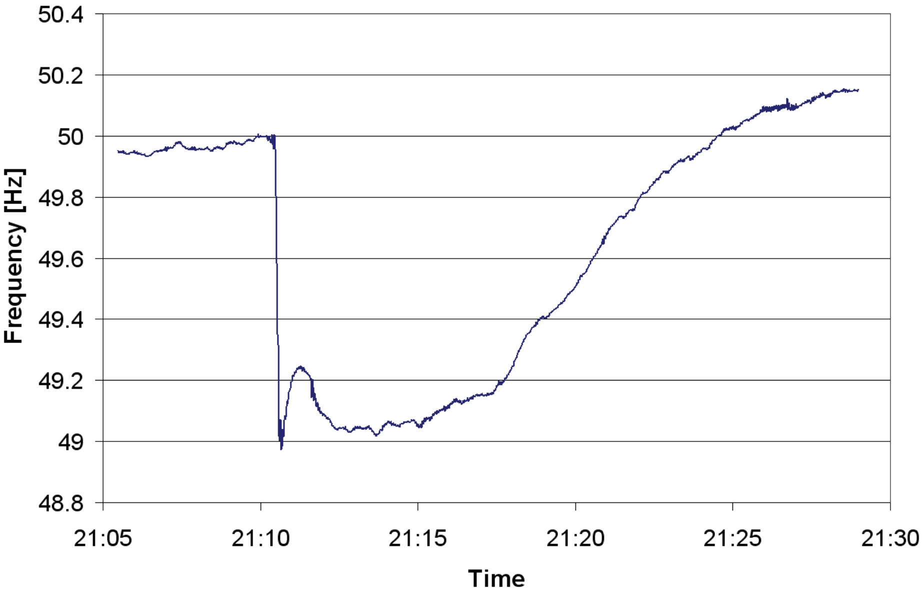

Fig. 3. Frequency dip in the European network on the 4th November 2006

If wind generators with primary frequency regulation capabilities are used, which means adopting a specific primary frequency control and a deload operation strategy - below the maximum extraction power curve (95% for example) a considerable contribution can be obtained from these units to reduce the impact of this frequency dip (Almeida & Peças Lopes, 2005). Such control strategy may provide a considerable contribution for the frequency regulation, especially in windy regions and power systems with reduced flexibility, e.g. without hydro power or reduced regulation capability.

The use of "frequency flexible" power electronics will definitely provide a relevant contribution for the power system robustness, by avoiding grid electronic interfaced wind generators disconnection from the grid when these system disturbances take place: the 2006 event shown in Fig. 3 was extremely useful to show that different wind turbine manufacturers show completely different capabilities, and moreover, that technical solutions for this concern already exist in some wind turbine manufacturers.

Isolated windy power systems with traditional frequency control problems are the typical example for the privileged application of this recent functionality of the wind turbines.

3.2 Wind power control, curtailment and overcapacity

The replacement of large conventional power plants by hundreds of wind generation units spread over the transmission and distribution system requires the development of new concepts for monitoring, controlling and managing these generation resources having in mind network operational restrictions and also market procedures.

Innovative strategies and equipments are already in operation in some European countries. The capacity of a wind park is usually limited by the capacity of the interconnecting grid. However, in wind generation most of the time wind turbines are operated far from their nominal ratings (see Fig. 4). Therefore, in order to optimise the grid connection costs, some agencies authorize the so-called "over capacity" installation in wind parks provided that a control of production is performed to avoid the injection of power larger than the initially defined by grid technical constraints. Since monitoring and control of this generation can be performed using the wind power dispatch centres, this limit can be adapted to the network operating conditions without compromising network security operational levels.

An economically effective tool is to draw wind power purchase agreements that safeguard the possibility to interrupt (curtail) the wind generation in cases technically documented and justified. This possibility is already being used in some countries together with overcapacity. This is a legal innovative approach in Europe where the permanent access of renewable sources to the system was normally widely accepted.

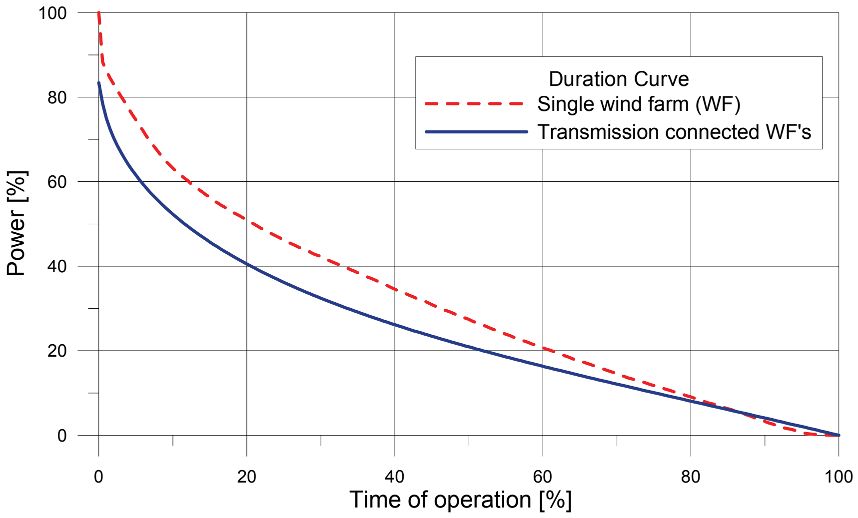

Fig. 4. Comparison of wind power duration curves for a single wind park and the all the wind farms connected to the transmission network

Fig. 4 also highlights the fact that it may be economically interesting and very relevant for low wind regions where the wind park nameplate power is never or very seldom achieved (areas with a wind Weibull distribution with almost "no tail") to reduce the nominal power of the local transformers and the dedicated interconnection line to values around 80 to 90% of the nominal capacity of the wind power plant. This is due to the fact that the investment costs associated with the remaining 10 to 20% of the grid capacity (and equipments) are high, but the value of the energy generated in these maximum operation conditions of a wind power plant is rather low, typically below 5% of the annual profits. This approach should be handled with care in turbulent windy areas where the high resource regimes may bring added control problems for the wind power plant.

The uncorrelated fluctuations of the power output of an aggregate of wind power plants allow to take that effect into the design of the electric infrastructure and sub-sizing both the transmission line and the transformer. On a power system/control area scale this has a huge impact (~10% connected capacity)

3.3 Wind generation aggregation. Virtual wind power plants

Wind power has developed in varied forms in different countries: while in some regions remains an essentially distributed electrical energy source (e.g. Denmark, Netherlands and some areas of Germany) connected to the medium voltage distribution grid, and sometimes even to the low voltage; in others as Spain, Portugal and also the United States this topology is being overcome by the installation of extremely large wind parks (with several hundreds of MW) connected to high (or even very high) voltage transmission lines.

This recent and innovative tendency of the wind industry required the operation of these power plants to be adapted to the new configuration and dimension of the wind plants. In Spain the generation of large transmission connected wind parks is already being aggregated and centrally managed by clusters that constituted a "local wind power dispatch center" and adopt an hierarchical control architecture as depicted in Fig. 5. A similar approach is already defined for the Portuguese power system for the latest generation of wind parks and will be the technical basis for the future development of the remaining sustainable wind energy potential (Estanqueiro, 2007).

This aggregation of the wind generation has several positive side effects as it enables to take advantage of one of the most basic characteristics of the wind resource: its spatial lack of correlation in what concerns the fast wind fluctuations (Estanqueiro, 2008). Other wider studies (Holttinen *et al*, 2009) have shown that a part of this smoothing effect may extend to the spatial scale of one control area, but a deep knowledge of the frequency of the fluctuations involved in the cancellation effects is still not available. Nevertheless, what could be, at a first glance, a negative characteristic may turn, in fact, to be extremely beneficial for the power system operation, since the most hazardous oscillations induced by wind tend naturally to cancel themselves. In order to profit from that effect, it is required the share of common grid interconnection, otherwise large power fluctuation may not be felt by central dispatches, while they are affecting local or regional parts of the transmission network. The smoothing effect is also not present when a whole country (or power system) is immersed in high (or low) pressure atmospheric circulations or passed by large frontal areas.

The need to monitor remotely the state and level of generation of wind power plants was recognized both by the manufacturers of wind turbines and the International Electrotechnical Commission (IEC) several years ago. The IEC Technical Committee 88 – Wind Turbines started the development of a new international set of standards on communications (see IEC 61400-25-1, 2006) and is currently updating the power quality Standard IEC 61400-21 (2001).

But the possibilities offered by the aggregation of hundreds of wind generation units spread over the transmission and distribution system largely exceed the static information contained in the simple monitoring of the wind power plant production with dispatching purposes. After implementing this type of tools, and benefiting from the natural behaviour of wind turbines (cancellation of fluctuations, modular generation, high inertia, among others) it is possible to operate these large clusters of generating groups as a Virtual Wind Power Plant and thus managing these generation sources having in mind network operational restrictions and market procedures.

Regarding wind parks, the characteristic nature of the installed energy conversion systems usually requires specific applications to be installed at the wind park managing system level. Under the typical architecture proposed in Fig. 5, such applications should be able to "dispatch" some active and reactive generation, when the system/grid operator set points are sent to the wind park, thus contributing (till a certain extent) to the frequency and voltage regulation, what reinforces their perception effectively as VWPP - Virtual Wind Power Plants.

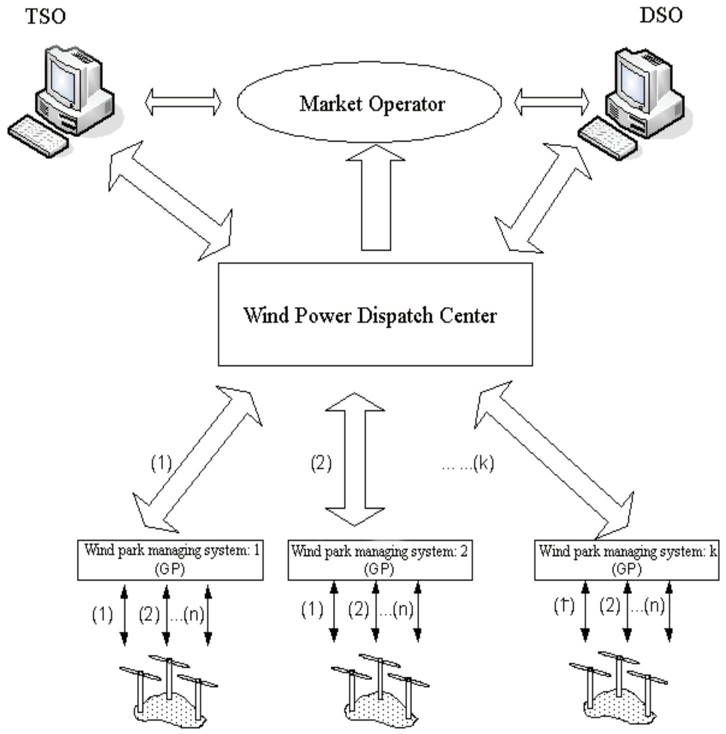

Fig. 5. A possible architecture for the management of the power system with wind aggregation agents (Estanqueiro et al, 2007).

The operation of these local dispatching centres at distribution level requires also the availability of new managing tools, one of the most relevant being the wind generation forecast. Wind forecasts are improving every day, being used by all TSOs in Europe with acceptable deviations within the useful time ranges for power system operation. These forecasting tools provide information about the wind generation within acceptable error margins with time horizons of, at least, 48 hours ahead and the larger the control system, the lower the wind correlation and the smoother the wind power output and the forecast quality.

The best existing tools use Global Numerical Weather Prediction (NWP) models results that are afterwards combined with online data through assimilation techniques, using mesoscale climatic models together with physical or statistical adaptive tools (Tambke *et al*, 2006).

The installation of wind power control at a distribution system operator level and the introduction of wind generation aggregation agents is already enabling to develop and implement the concept of Virtual Wind Power Plants. It should be noted, however, this concept is much more powerful than just the aggregation of wind generation, this later almost a logical procedure having into consideration its spatial distribution and the cancellation of the fluctuation produced at large geographic scales. Therefore a new wider concept is emerging and deals with Virtual Renewable Power Plants (VRPP) that may benefit from the generation aggregation of the natural complementary of several renewable resources as generation of electricity in PV solar power plants, that may be associated to wind power plants with generation profiles where the night periods are dominant but also with biomass or thermo solar power plants, both having some capacity of production regulation. These new concepts enable to the:

a. Clustering of wind generation (onshore and offshore) for power output smoothing, power control and partial curtailment in large wind power plants.
b. Enhancement of distributed generation systems (DGS) use by regional/local treatment of biomass for electricity generation integrated with wind and PV applications.
c. Correlation of renewable distributed resources, assessment of the excess of renewable energy generation and need for added large/local energy storage capacity (e.g. pumped hydro, FC/H2, VRB batteries and plug-in vehicles)

3.4 Additional remote reactive power control

In order to assure the wind power plants have the capability to deliver reactive power during voltage dips, thus providing support for the network voltage, some TSOs are requiring reactive voltage support similar to the one presented in Fig. 6.

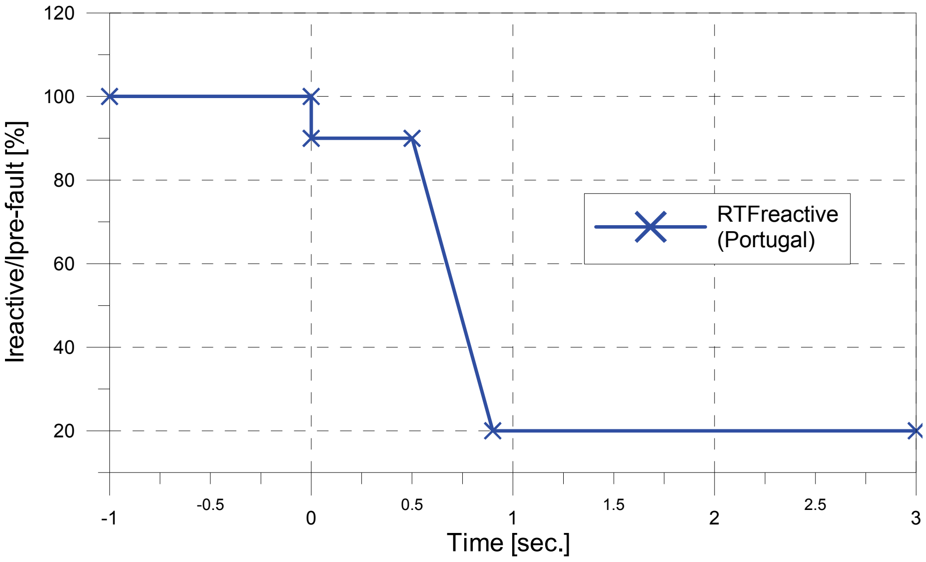

Fig. 6. Characteristic curve of reactive power delivery by wind power plants during/after voltage dips (at t=0).

This capability is also required to enable the adjustment, by request of the TSO, of the reactive power injected in the network in predefined ranges, that in some countries assume values within the interval $tg\varphi \in [0,0.2]$.

3.5 Wind power security of supply

One of the main negative characteristics related to the wind generation usually pointed out by the power systems planners and operators is its non contribution for the security of supply, due to its intrinsic time dependency and variability. Although the wind power variability and the reduced contribution to the capacity credit of a power system is a well know characteristic of the wind generation, one should be also aware of its trustful contribution for the system security of supply in time scales larger than a few days. In Fig. 7 the energy generation contribution of several renewable sources is compared in terms of annual equivalent number of rated hours, being the wind energy surprisingly more reliable than hydro power on a yearly basis.

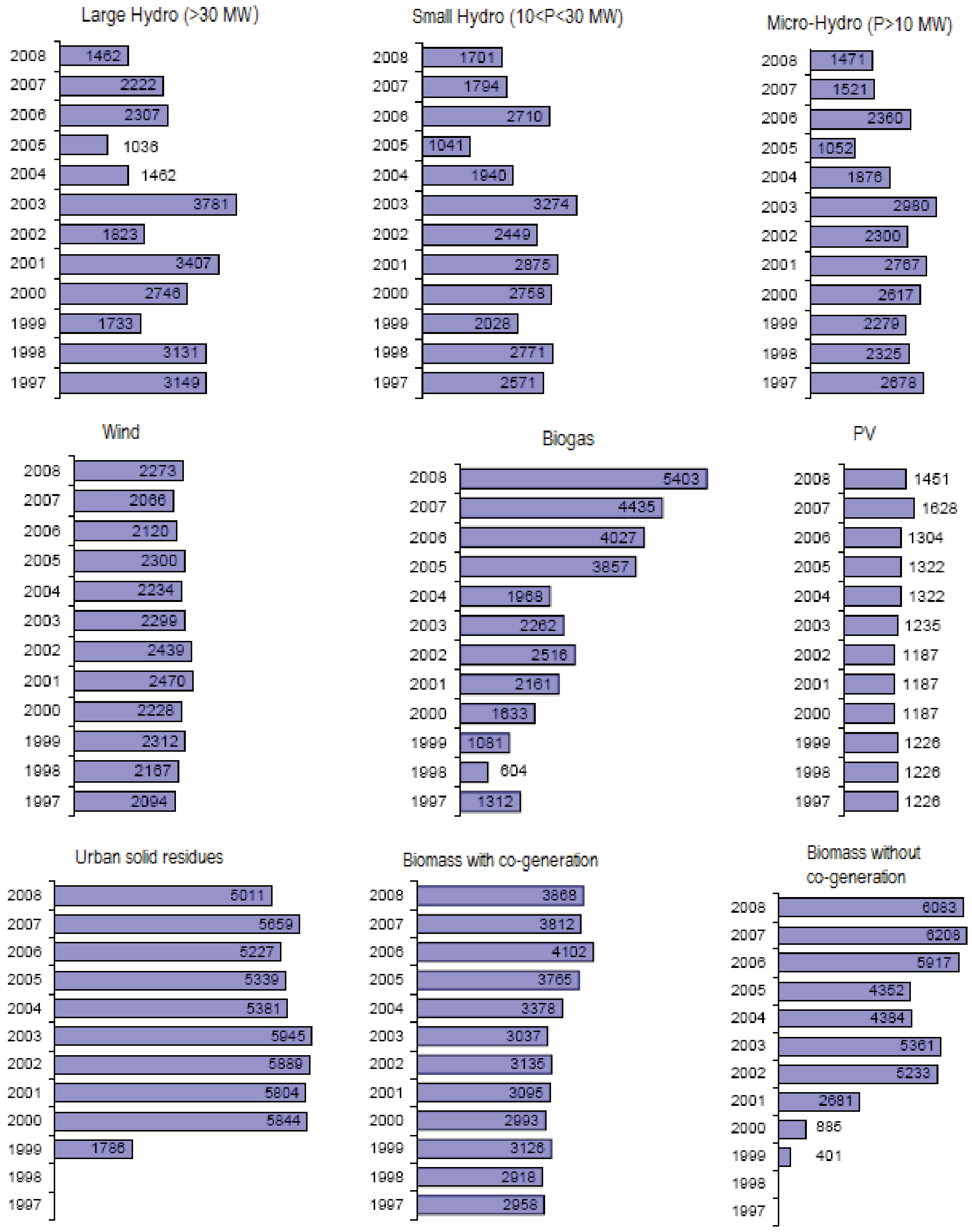

Fig. 7. Comparison of annual equivalent production hours of different renewable sources (source: DGEG, 2009)

4. Large integration of wind generation: the power system challenges

The imposing question for the large integration of wind generation in power system is then: what are the real challenges and how to address them?

Mainly, the characteristics of the wind generation that clearly differentiate it from the conventional generation and have a higher impact on its large integration in the power system are within the list below:

- Wind is regarded has not offering security of supply, may require significant added reserves and also impacts on conventional power unit scheduling;
- There is a limited capacity on the grid to embed this spatial distributed generation;

- Wind is (totally) time dependent and gives (almost) no guarantee of firm power… there are added costs for wind integration in some power systems, specially for penetration >10%;
- There are also operation and management great “challenges”: in power systems with significant amounts of rigid generation (either non-dispatchable renewable or nuclear, for example), to foresee large integration of wind may produce Energy Congestion and a difficult Surplus Management;
- Large wind integration affects the robustness of the system operation.

The only possible answer being “one by one...” and using the scientific and technical tools already available, when that is the case, and develop new ones, in the areas still unaddressed...

It is commonly accept in the field that the key to overcome these issues are to add flexibility to the power system, and to study/simulate all possible occurrences using comprehensive, inclusive models.

4.1 A new holistic approach for the transmission power system

The most classical “technical” barrier for the large penetration of wind energy is the limited capacity of the transmission grid. One should clarify this is really an economic, environmental and social barrier, not a technical limitation that, is common to all new power plants, based on spatially distributed renewable energy system (RES) or not. Moreover, large power plants currently being interconnected to the power systems usually benefit from no (physical) grid integration costs at all.

The common approach with large conventional power plants is for the Transmission System Operator (TSO) or the Government of the control zone where a new conventional power plant will be interconnected to provide direct access to the transmission network, being the reinforced costs taken by the operator of the transmission network and distributed by the final consumers. Some associations of wind power developers tried, in the recent past to adopt a similar approach for the grid connection of the wind power plants, but few countries have pursued this path with the relevant exception of Germany.

More relevant for the wind sector large deployment than the distribution grid costs is the non inclusion of the wind energy and other renewable capacity goals in the transmission network development plans. One of the few countries where a holistic approach to the power system planning was implemented was Portugal. There, all forecasted power plants and power sources have been systematically included in the TSO recent development plans (REN, 2005; REN, 2008), having as direct result the fact that Portugal presents the lowest grid integration costs reported by the IEA Wind Task 25. Fig. 8 highlights (with dashed lines, including existing transmission lines to be upgraded) the main investment projects in the Portuguese transmission network until 2010 that are totally or in part induced by the Governmental renewable goals.

In Portugal the methodology followed by the TSO was based on wind resource scenarios that identified the value and location of wind resources and took into consideration the wind power already in service. With those inputs, the TSO was able to define reasonable targets for the wind generation (and ranges of uncertainty) for the different areas of the country. Adding other renewable objectives such as new large hydro, the network planning division performed a transmission network development plan. This task should not be overlooked, since most of the several thousand MW of new wind and hydro power plants

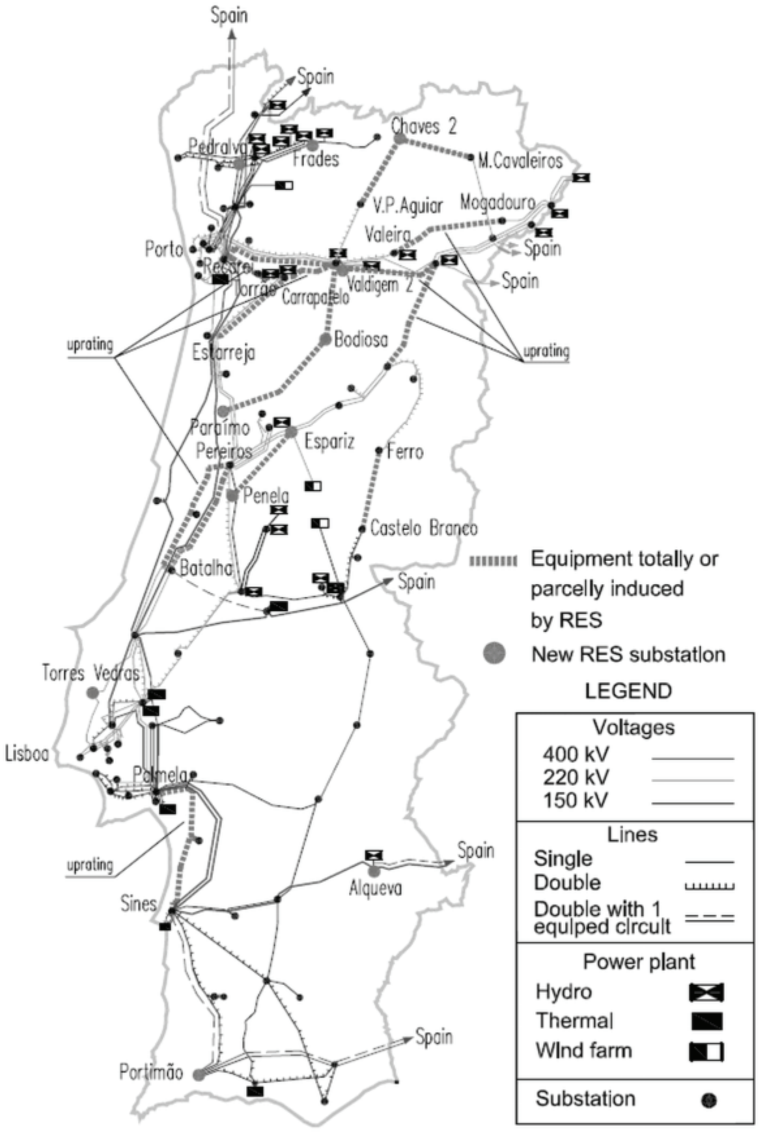

Fig. 8. Example of the Portuguese new transmission lines induced by renewable energy sources (source: REN, 2008)

will, in the future, be located in inner rural areas of the country with very small demand, that implied a large increase of the regional power surplus to be transported to the large load centers, so dictating the need for a non-negligible increase in transmission capacity.

The Portuguese plan also pursued some other investment goals such as the overall system adequacy and security as well as the quality of supply for clients and other users of the transmission and distribution network.

Throughout a 6 year period 2006-2011, 190 million Euro were allocated by this TSO for the investment directly related to the integration and transmission of renewable generation, including 4500 MW of wind power (Fig. 9). This value represents one fifth of the total TSO investment in the transmission network. The investment costs on new lines induced by the renewable generation were allocated according to their relative use of transmission capacity. It should be referred these investment values do not include the costs of wind power plant interconnection to the existing grid in form of dedicated lines, once these are not supported by the TSO in Portugal, but rather by each wind park developer.

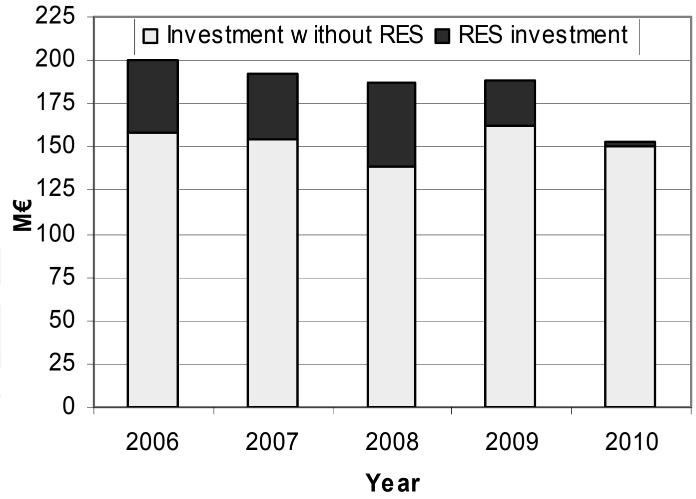

Fig. 9. TSO’s total investment costs (MEuro) and reweable energy sources (RES) associated share (source: REM, 2008).

4.2 The power system contribution for large wind integration

Taking into consideration the enormous difficulties felt by all TSOs for the construction of new transmission lines, it is rather surprising to conclude that little has been done to improve the existing network efficiency and utilization, for the benefit of the smooth grid integration of wind power and other distributed renewable, but also to lighten the pressure from the difficult construction of new transmission lines. Nowadays, the environmental and social impacts of new electrical lines turns into “mandatory” measures as:

- online monitoring of transmission lines (temperature, wind, loads, etc);
- introduction of new network components (e.g. phase shift transformers);
- use of Flexible AC Transmission Systems (FACTS) devices;
- upgrading degraded components as cables, lines, protections and transformers.

All of these urgent measures to be implemented by the transmission grid operators. Notwithstanding the measures just presented that enable to operate existing lines with higher efficiency levels, with the existing steady increase in consumption, the construction of new transmission lines and the reinforcement of the existing ones will be needed. In order to optimize the integration costs of the wind power, it would be desirable that the wind deployment official national objectives would be included in the medium to long term development plans of the power systems. However this situation has seldom been reported.

Some innovative strategies and equipments are already in operation in some countries where wind penetration is growing very fast: a new not very common transmission network element was recently included and is being suggested for many power systems; the phase-shifter (transformer). These electrical machines can “force” the wind power flow, injected in the high voltage levels of 60, 150 or 220 kV in some specific geographic areas to enter the 400 kV grid, using the available higher voltage lines capacity and thus avoiding the construction of new high voltage lines.

4.3 Improving the power system dynamic behaviour with FACTS

The loss of large amounts of wind generation may lead to system instability problems or to overload of interconnection lines. The capability of survival of these generation units to voltage dips that follow a short circuit in the grid is thus becoming a mandatory requirement in several Grid Codes. However, some of the already installed wind turbines are not capable of withstanding such grid disturbances, which may require the adoption of external measures like the installation of Flexible AC Transmission Systems (FACTS) devices. These devices are capable of providing a support to voltage profiles, limiting the voltage dip during the short-circuit duration time. Some studies (Franco Marques & Peças Lopes, 2006) strongly suggest that it would be beneficial to install FACTS in strategic buses of the transmission network in order to mitigate the impact of short circuits that may occur in the grid and that may lead to the disconnection of large amounts of wind generation due the tripping of their under voltage protection relays.

Apart from avoiding the tripping of some generation units, also a good damping of the oscillations can be obtained as depicted in Fig. 10 that describes the behaviour of the sum of the power flow in all the interconnection lines between Portugal and Spain following a short-circuit in an important transmission bus in the scenarios without and with FACTS installed.

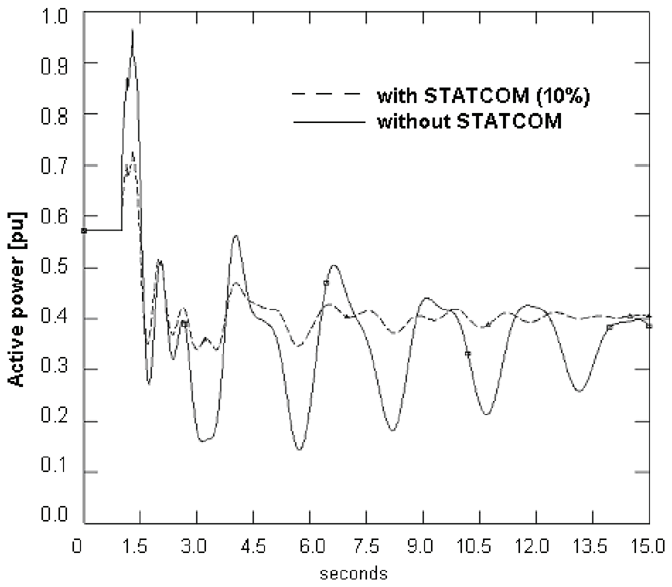

Fig. 10. Active power flow in the interconnections, following a short circuit in a relevant transmission bus – with and without STATCOM (Franco Marques & Peças Lopes, 2006).

4.4 Adding flexibility to the power system: storage and transmission reinforcement

Different generation mixes face different challenges when integrating large amounts of wind power. However, it is commonly acknowledged in the area of wind grid integration that adding flexibility to the power system easies its operation under high penetration of fluctuating renewable sources as the energy (Chandler, 2008; Holttinen *et al*, 2009). There are several ways to add flexibility to the system, being the simplest to handle to add storage hydro capacity in the geographical areas where this resource exist and is possible to deploy in a sustainable way. Another possibility is the added flexibility obtained through the interconnection with neighbouring countries and the reinforcement of the transmission network (Ackermman (Ed.), 2005).

The example of the Portuguese hydrologic plan (PNBEPH, 2007) presented below and currently underway was not only to increase the renewable generation penetration, but also to promote a smoother operation of the power system with the forecasted very high wind penetration (above 20% after 2015).

In some generation mixes the main power system constraint may end up being excess of renewable generation (e.g. wind + run-of-river hydro) during the no-load hours. Due to this fact it was recently introduced in some countries the concept of *wind energy storage* - and other highly variable time-dependent renewable primary sources – through the establishment of bilateral contracts between the wind park owners and the operators of reversible hydro power stations.

The identification of the optimised daily operation strategy for the mix of renewables can be determined by solving a linear hourly-discretized optimisation problem where the economic benefits of such strategy are driving an objective function (Leite da Silva *et al*, 2007).

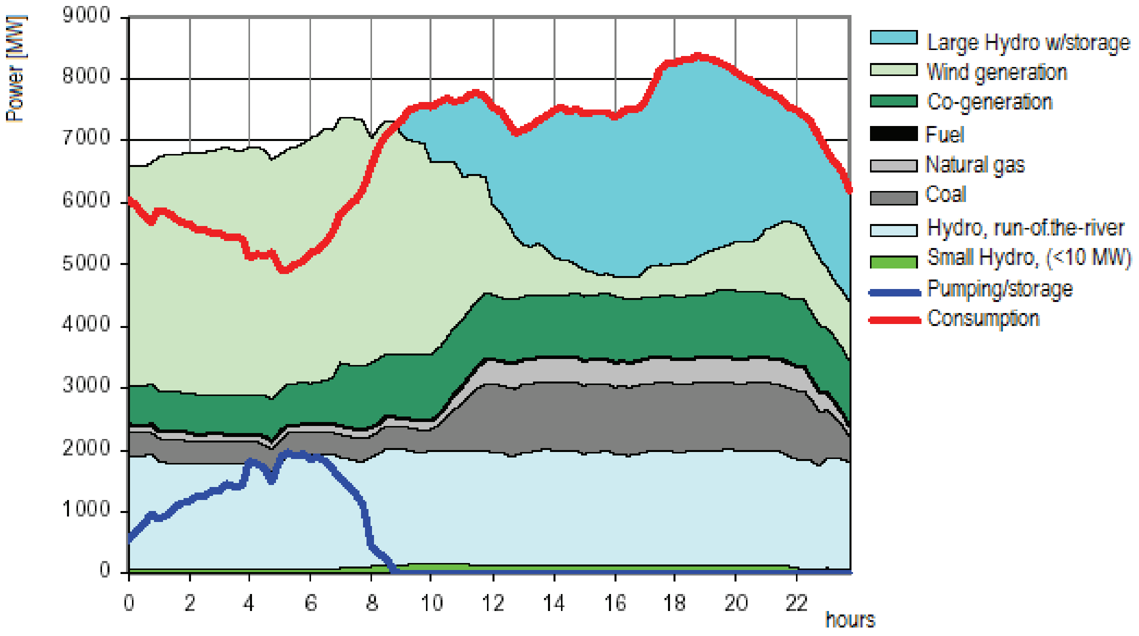

Fig. 11. Scenario of a power system generation profile for a wet windy day in 2011 (PNBEPH, 2007).

This form of *wind energy storage* enables to optimise the daily operation strategy of the power system and allows to:

- Minimize deviations to participate in structured markets;
- Contribute to the secondary and tertiary power reserves;
- Increase of wind contribution for the regulation capacity

When hydro pumping storage is available, the existing methodologies able to identify the best combined wind/hydro pumping storage strategies should be used. In the absence of hydro energy resources, other storage techniques may also be helpful and should be investigated (e.g. H2/Fuel Cells, compressed air/gas, flywheels, etc).

5. Power system studies for wind generation safe integration

5.1 Transient stability assessment

In order to ensure that planned wind generation for the near future will be managed within safety ranges, TSOs are assessing the response of their control area and the impact of the committed wind capacity on the transient stability of the transmission network (e.g. Sucena Paiva *et al*, 2005; GE Energy, 2005).

The main objective of these transient stability studies is to evaluate the percentage of the wind generation that will be disconnected due to voltage dips produced by drastic events as three-phase short-circuits in the network, for different scenarios of conventional generation / demand, and wind power penetration, as well as the spatial distribution of the wind power.

As far as wind generation is concerned, several scenarios may be considered: (i) Uniformly distributed wind generation, with all wind generators injecting a similar percentage of their rated power (80%); and (ii) the most realistic situation where the wind generation is uncorrelated and distributed, in a form that reproduces the passage of the large air masses that pass through control zone several hundreds or thousands of kilometres wide.

In the transient stability studies the most disseminated wind turbine technologies should be modelled: (i) Classical wind turbines equipped with induction generators; (ii) Wind turbines with double fed induction generator (DFIG); (iii) Wind turbines equipped with variable speed synchronous generator, connected to the grid through a rectifier/inverter system.

The main conclusions that may be achieved at the end of such transient studies normally address the following subjects:

- For some faults in the transmission grid, when wind turbines are equipped with conventional technologies (non-ride through fault), it may occur an almost complete loss of wind power. This, in some rare situations, may also originate a loss of synchronism in some parts of the power systems.
- The loss of wind power in a country or control zone has an impact on their neighbours through existing interconnections. Substantial loss of wind power in some areas can give rise to overloads, creating the risk of electrical separation of some power systems, a situation that can lead to local blackouts.
- The addition of control equipment to ensure that the wind turbines remain connected during most short-circuit situations (ride through fault capability) results in a significant reduction in the loss of wind power under faults and transient events, thus largely increasing the stability margin of a power system.

It should be referred that, the relative immature phase of grid codes development specifically to cope with the large and increasing penetration of wind energy have generated a wide range of requirements, typically one by each TSO, without any concern about the need to standardize the industrial production of wind turbines (see Fig. 2).

The need to standardize the fault ride through requirements has recently been a subject of concern of the European Wind Energy Association (EWEA) which currently runs a working group on harmonization of grid codes (EWEA, 2008).

5.2 Power reserves and security of supply.

In a near future scenario characterized by such large amount of wind power integration, system planners are under a huge pressure to come out with solutions for the determination of the required amount of system capacity to guarantee an adequate supply.

Traditionally the power reserve requirements have been based on criteria that protect against the loss of the largest power group delivering to the system. These deterministic criteria do not take into account neither the accuracy of the demand and wind power forecasts, nor the probability of the largest generator or interconnection outages, and the consequences of such contingencies.

For this purpose, probabilistic nature studies started to be used for assessing the performance of the power system regarding this issue and are still being further developed to address the wind generation forecast errors (Ortega-Vazquez & Kirschen, 2009). The objective is to investigate the behaviour of the common reliability indices, like LOLP = loss of load probability; LOLE = loss of load expectation; EPNS = expected power not supplied; EENS = expected energy not supplied; LOLF = loss of load frequency; LOLD = loss of load duration; LOLC = loss of load cost, as well as well-being indices.

Chronological Monte Carlo simulation may be used to evaluate the reserve requirements of the future expansion plans of the generation system, to be defined by a TSO considering a large penetration of wind generation (Leite da Silva *et al*, 2007).

This analysis requires a proper modelling of system components regarding their reliability, which involves the treatment of the primary energy resource availability (hydro, wind, cogeneration, etc.), maintenance policies and specific forced outage rates.

6. Wind power plant models for the 21st century power system

One of the difficulties faced by power system planners and operators is there are not enough accurate off-the shelf tools to describe the dynamic, non-linear behavior of Wind Power Plants and, by doing that, increasing the degree of confidence of the TSOs in this form of power generation. To allow for a smooth and safe integration of large amounts of wind generation the power system needs:

a. Simulation platforms with distributed Renewable Energy Sources (RES) and non-linear system devices;
b. To model the behavior of the power system/grid with large scale integration of renewable generation on large/European scale using the classical power system approaches.

Although several models were published in the latest years (e.g. Estanqueiro, 2007; Perdana, 2007 among others) and a few European projects as Tradewind (2009) and EWIS (2008) have given excellent 1st steps in the recent past, new wind power dynamic models for power system stability studies including aggregation and clustering of wind turbines are still requested.

The relevant role of wind turbine dynamic and transient models in the large integration of wind generation planned for the next decade is due to:

- the 20% renewable penetration (mainly wind) forecasted for 2020 in Europe, may reveal itself a too risky task in technical terms if the European TSOs do not possess the requested tools to simulate the power system under extreme occurrences and carefully plan for secure operation under those circumstances.
- It should not be asked to the system operators to (apparently) reduce the robustness of their systems without providing them with the simulation models that enable to characterize the wind power plants response to every possible occurrence in the system.
- It is questionable if the European Power Systems will be manageable with a 20% penetration of variable generation (on an yearly basis) without more sophisticated simulation tools and a more detailed knowledge of the renewable power plants transient behavior.

In the future it is expectable that the network areas are classified in terms of transient response capability of wind turbines to survive low voltage ride through faults; the voltage and frequency regulation will, most probably, be asked for some pre-identified grid areas. Wide wind power control and, in certain conditions, curtailment of wind generation will be a reality. This allows to conclude that the better the available dynamic wind power plant models are in the future - and the larger their capacity to perform under transient behavior of the network - and the more effective is the wind power control capability, the more reduced will be the need to curtail this renewable electrical energy source.

7. Conclusions

Increasing the penetration of wind energy for high levels, typically near 20% on an annual basis, requires an articulated common effort of the TSOs, regulatory official agencies and wind park developers to use and require the most recent and high performing wind and power system technologies in order to guarantee the overall power quality and security of supply, and thus enabling to maximize the wind and other renewables embedded capacity. The main concepts that need to be addressed in the near future are:

- real-time assessment of transmission capacity.
- use of DGS as grid active voltage controllers;
- coordination of ancillary services on a European scale;
- integration of balancing markets and coordination of reserves within EU grids/control areas;
- implementation of solutions to allow for efficient and robust system operation with significant amounts of highly variable generation and storage;
- full deployment of the VRPP – Virtual Renewable Power Plants Concept;
- use of DSM – Demand side management for system added flexibility;
- Fuel Cells/hydrogen generation for regulation of highly variable renewable sources;
- Inclusion of plug-in vehicles as distribution storage units in the distribution network planning;

so as to become feasible the management of the power systems while preserving the global quality characteristics and security of operation under a 20% penetration of sources of electrical energy as variable as the wind.

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This book is the result of inspirations and contributions from many researchers of different fields. A wide verity of research results are merged together to make this book useful for students and researchers who will take contribution for further development of the existing technology. I hope you will enjoy the book, so that my effort to bringing it together for you will be successful. In my capacity, as the Editor of this book, I would like to thanks and appreciate the chapter authors, who ensured the quality of the material as well as submitting their best works. Most of the results presented in to the book have already been published on international journals and appreciated in many international conferences.

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