How to Prepare a Power System for 12% Wind Energy Penetration: The Portuguese Case Study

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***Abstract* — The 2001/77/CE Renewable Energies European Directive together with Kyoto Protocol ratification supported by a Government vision and strong objective on the reduction of external oil dependence put Portugal in the front line to achieve one of the highest wind energy penetrations within ten years time.**

This paper gives a summarized overview of the Portuguese technical approaches and methodologies followed in order to plan and accommodate the ambitious wind power goals to 2010/2013, preserving the overall quality of the power system.

***Index Terms* —high wind penetration, power system operation, ride through fault, wind power.**

I. Introduction

One may say that, 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 in some European power systems or grid areas introduced a brand new set of technological issues, that recently became one of the more quoted subjects among developers, network planners and system operators [1]. These concerns are not anymore a negligible distribution grid integration issue (e.g. voltage regulation problem, poor quality of the energy injected in grid) that 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 being a real power system operation and planning issue [2]: is the system 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 TSOs planners and regulators together with the experts in this technology grid integration behaviour.

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 a very positive issue and also a clear sign of the wind technology maturity, although that brought a few obligations related to this technology "adult age":

- wind park models have to exist and to allow the TSOs 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;
- adaptation of part of the already planned/existing wind capacity to remain in parallel after the occurrence of identified perturbations that produce serious voltage dips (or at least the most common ones);
- development of "tools" to address and enable to cope with both the spatial and the time variability of the wind production. That includes the necessity of accurate wind forecast models together with spatial correlation assessment;
- "wind power plant" as a contributor to the power system regulation (e.g. frequency by request of the TSO, …).

In Portugal, the wind power goal foreseen for 2010 was established as 3750 MW (RCM 63/2003) and that will constitute 25% of the total installed capacity by 2010. This value was recently raised to 5100 MW (year 2013), by the Government most recent goals for this sector (RCM 169/2005). That power will constitute a ratio of about 33% of the total installed capacity by 2013. The wind energy ratio of production after 2015 - with all the wind capacity working at industrial "*pace*" - is expected to surpass 12%, thus being among the three/four countries in the world with a higher wind energy penetration in the mix.

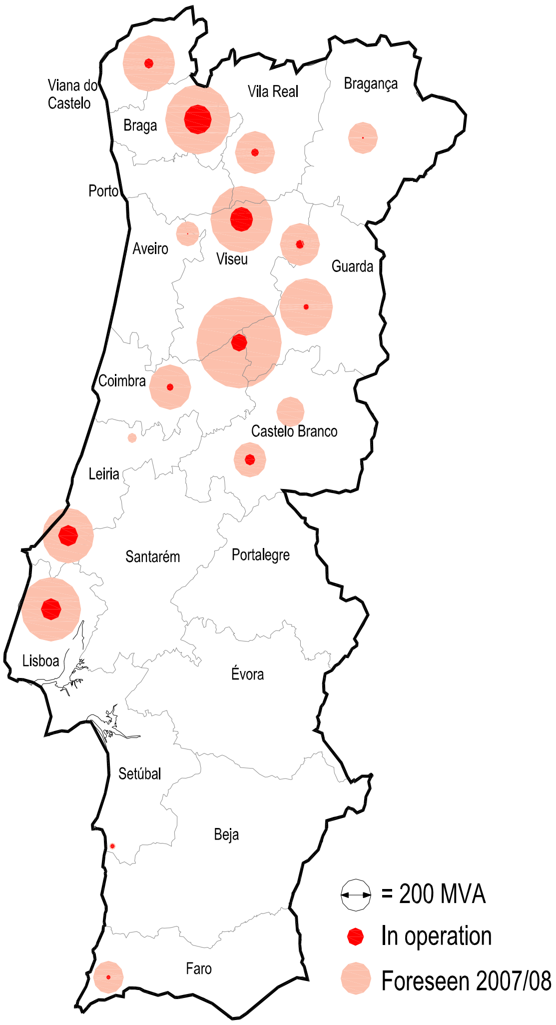

Fig. 1 - Wind power installed in 2005 and permits given 2007/2008

II. Review of Generation Administrative and Technical Access Rules

Preparing the Transmission Network (TN) and the Distribution Network (DN) for the connection of such a large amount of wind power raised a number of important challenges to the TSO, Rede Eléctrica Nacional SA (REN, SA) and also to the DSO, EDP Distribuição Energia, S.A. (an important part of the wind farms will be connected to the DN). This process had to be managed in close cooperation with the Ministry of Economy and Innovation (MEI) and its General Directorate for Geology and Energy (DGGE).

As a consequence of the previous liberalization of the power sector, even before Directive 2001/77/CE, a limited number of promoters had already presented applications for the connection of wind farms, mainly to the DN.

By 2001, with the perspective of a fast and important increase in the number of wind projects, it became clear that the previous paradigm of TN planning based on a small number of well known large new power stations was no longer applicable because it was not possible any more to give individual connection solutions for each project coherent with all the others and assure the future secure and adequate operation of the TN.

The new rules and procedures to manage and process the application for TN and DN connection of new power projects were reviewed and redefined in 2001 in the Decree-Law 312 of Dec. 2001. The main guidelines are as follows:

- The TSO calculates and announces the values of future simultaneous capacities at the different areas/substations in the TN networks according to TN development plans, which must consider and be coherent with the national global RES objectives;
- Developers present their applications for new generation projects to DGGE.
- DGGE sends the applications to the TSO (if above 50 MVA) and DSO (if below 50 MVA) who will prepare the “preliminary information” (PI). At this level, each application is seen independently from the other applications received but considering the capacity already reserved before. For large power stations, the TSO usually studies the possibility of specific not yet planned network reinforcements, if necessary;
- The PIs issued by the TSO and DSO are sent to the promoters by DGGE. Should the promoters want to proceed, they will contact again DGGE asking for capacity reserve. At this stage promoters have to present preliminary technical projects and first environmental viability studies;
- DGGE will then attribute a reserve of capacity for the project. Should there be an excess of demand capacity for a certain network area, DGGE will rank the projects according to the specific criteria defined in DL 312/2001 and/or attribute capacity on a proportional (“prorata”) basis in order to respect maximum network capacities;
- From 2005 on, MEI and DGGE can also promote auctions of network capacity.

Most of the wind generation capacity reserved so far (around 3500 MVA) has been attributed on a proportional basis, due to the large excess of demand for new projects in all the TN areas with significant wind resources. In the second half of 2005, DGGE made a call for proposals of two blocks of 800 and 400 MW of wind power. Tenders will have to fulfil a set of minimal technical requirements and will be evaluated by their economic performance criteria - including the creation of a wind industry *cluster* in Portugal – but also by the offer of technical specifications of the equipments that will enable the power system to cope with the high penetration forecasted for the near future.

III. Power System Studies

A. *Transient Stability*

In order to ensure that the foreseen wind power capacity in 2010/2013 can be safely connected to the Portuguese Transmission and Distribution networks, REN, the concession holder of the Portuguese Transmission Network (PTN) has developed a study concerning the impact of the committed wind capacity on the transient stability of the PTN [3].

The main objective of this study was to evaluate the amount of disconnected wind generation due to voltage dips produced by three-phase short-circuits in the network, for different scenarios of conventional generation / demand, wind power production and geographical distribution of the wind speed.

As far as wind generation is concerned, two scenarios were considered: (i) Uniformly distributed wind generation, meaning that all wind generators were injecting the same percentage of their rated power (80%); (ii) Correlated distribution wind generation, that is, wind power was calculated from wind speed correlation factors – based on time series obtained during two years of measurements.

Three types of wind turbine generators (WTG), currently in use, were modeled: (i) Stall turbine attached through a gearbox to a squirrel cage induction generator, directly connected to the network; (ii) Pitch turbine attached through a gearbox to a double fed induction generator (DFIG), connected to the network, directly, through the stator, and through a rectifier/inverter sys-tem, through the rotor; (iii) Pitch turbine directly attached to a variable speed synchronous generator, connected to the network through a rectifier/inverter system.

The faults were assumed to be cleared both instantaneously (i.e. with inherent operating time – normal operation of the protection system) and time delayed (circuit breaker or communication failure).

The undervoltage protection of the wind generators was, in a first stage of the study, assumed to operate instantaneously, when a limit of 0,9 pu was crossed.

A matter of great concern for the TSOs, confronted with the expansion of wind generation, is the capability of these machines to stay connected to the network, in the event of faults which give rise to voltage dips. Most European TSOs are requiring that the wind turbines connected to their grids are equipped with “RTF - ride through fault capability”, a feature which considerably increases the stability margin of the power system. Most manufacturers nowadays offer this capability, which allows the wind generators to withstand a wider range of voltage variations, for longer periods, without disconnection. This capability has been considered in a second phase of this study.

For the analysis of the results, acceptance criteria – which should not be violated – were established, as follows: (i) Short duration overloads in lines or transformers, not higher than 50% of the rated power (corresponding to the design temperature); (ii) Loss of conventional thermal generation: not higher than 400 MW (rated power of the largest generator) in valley and 600 MW in peak situation – except if the fault clearance results in the tripping of the corresponding line or transformer; unlimited, for hydro generation.

To perform this study the software package Power System Simulator for Engineering (PSS/E) was used. The non-conventional technologies used in wind turbine generators were represented by adapted models resident in the PSS/E library or built upon existing modules.

The large number of simulations coupled with the expected computer time for each simulation, led to the necessity of devising a strategy to diminish the number of simulations to be executed. A three-phase symmetrical short circuit study was performed in all the buses of the interconnected Portuguese and Spanish grids with the aim of establishing the amounts of Portuguese wind turbine generation that would be lost. Three-phase faults in the interconnected network buses that would lead to a loss of more than 400 MW of wind generation were retained for the transient simulation studies.

In the simulations performed, a three phase symmetrical fault was applied to every branch connected to each of the buses selected from the previously performed short circuit study, followed by a trip of the faulted branch. The time of persistence of the fault is conditioned by the behavior of the protection system.

The values of voltage and frequency in the buses, together with the values of active and reactive power in all the branches and generators were registered at the end of each simulation. The occurrence of instability situations in the thermal and large hydro generators connected to the Portuguese grid as well as the occurrence of out of step conditions in all the branches of the Portuguese and Spanish grids were also monitored and registered. The registered values were then analyzed taking into account the acceptance criteria previously established.

As an example of the performed simulations and the corresponding results, Figure 2 shows the variation of the frequency in two 220 kV buses near Lisboa and Porto for one of the circuit breaker failure situation that caused the occurrence of an out-of-step condition.

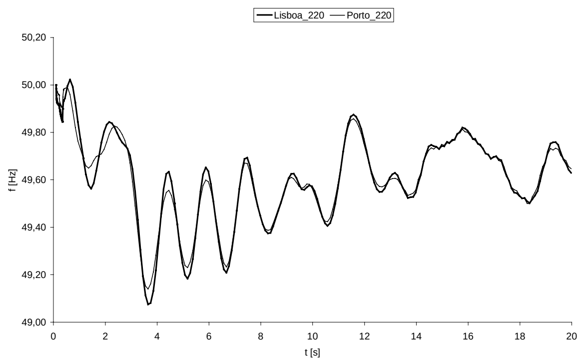

Fig. 2 -Frequency vs time; fault in a 400 kV branch; circuit breaker failure.

The main conclusions achieved at the end of the study could be summarized as follows:

- For some faults in the PTN, with conventional wind turbine protection, the loss of wind power may be above 2500 MW. Furthermore, in some rare situations, loss of synchronism may occur in some parts of the Iberian Power System.
- The loss of wind power in Portugal has an impact on the Spain-France interconnection, which is normally occupied with commercial exchanges from France to Spain. A substantial loss of wind power in Portugal or Spain can give rise to overloads, creating the risk of electrical separation between the Iberian network and the rest of the UCTE grid. This situation can lead to local blackouts in the Iberian Peninsula.

- 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 (up to 1500 MW), thus increasing the stability margin.

B. Security of Supply (Power Reserve)

In a 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. The Portuguese system is no exception. For this purpose, probabilistic nature studies are under development for assessing the performance of the power system regarding this issue.

Chronological Monte Carlo simulation will be used to evaluate the reserve requirements of the future expansion plans of the generation system, to be defined by the Portuguese TSO, considering a large penetration of wind generation. The idea is to investigate the behaviour of 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 [4].

All 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.

IV. PREPARING THE TRANSMISSION NETWORK FOR THE NEW RENEWABLE GENERATION

A. The Existing Network and the Planned Capacity

Based on the wind resource scenarios resulting from previous studies to identify the value and location of wind resources and considering the wind power already in service or reserved, REN, SA defined reasonable wind generation targets (and ranges of uncertainty) for each area of the country.

Adding other renewable objectives such as new large hydro, the Portuguese TSO network planning division initiated a TN development planning study.

The fact that most of the several thousand MW of new wind and of large and small hydro will be located in inner rural areas of the country with very small demand (adding to the previous 4600 MW large hydro power stations already in service) will imply a large increase of the local power surplus to be transported to the large load centres, so dictating the need for an increase in transmission capacity.

Also, it was evident the interest to anticipate the extension of the TN to certain areas of the country where important wind potential had been detected and where a important number and total power of wind farm connection applications already existed or were foreseen.

B. The "Transmission Network Expansion Plan for Renewables"

The result of the 2001 TSO planning division development study, was the first "Transmission Network Expansion Plan for Renewables", which has been updated more than once in the following years in order to adapt it to changes in renewable objectives, to the evolution connection demands by renewable (RES) promoters and to updates in wind resource location studies [5, 6].

The plan also pursues some other investment goals such as the overall system adequacy and security and also the quality of supply for clients and other users of the TN and DN. The plan contains:

- New 400 and 220 kV substations in areas not previously covered by the TN but with strong wind potential and significant number of wind connection demands;
- Some new 400 and 220 kV lines, new 400/200 kV, 400/60 kV and 220/60 kV transformers and also the reinforcement of existing equipment, namely the uprating of a considerable number of 220 kV existing lines.

Fig. 3 highlights (in orange colour, including existing lines to be up rated) the main investment projects in the TN until 2010, which are totally or in part induced by the RES generation program.

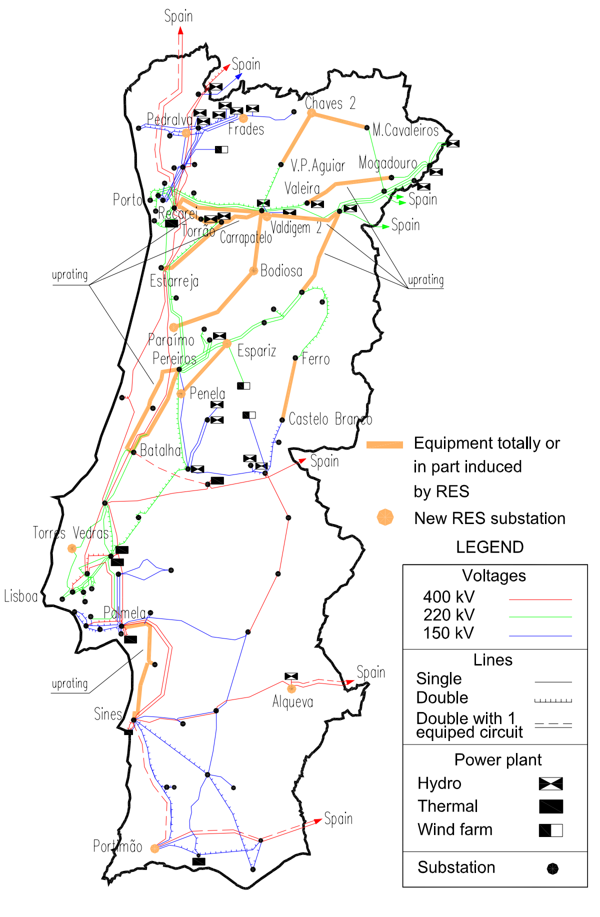

Fig. 3 - Projects induced by RES program, up to 2010 for a target of 4500 MW of wind power

Throughout the 6 year period 2006-2011, 190 million € are foreseen for the investment directly related to the reception and transmission of RES generation for a target of up to 4500 MW of wind power by 2010. This value represents one fifth of the total REN, SA investment in the TN (see fig. 4). These investment values do not cover the costs of the VHV/MV main substation of each wind farm nor does it cover the costs of the VHV dedicated line connecting it to the TN reception point. They do not include, either, the MV inner network inside the wind farms: all these costs are supported by the wind parks developers.

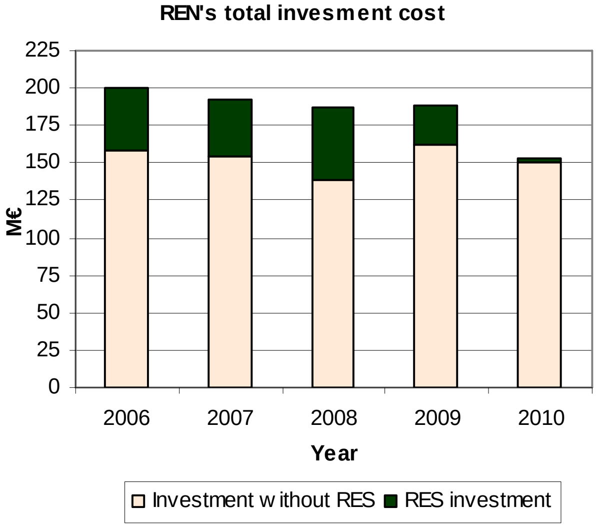

Fig. 4 - REN´s total investment costs and RES associated share.

V. Design and Management of a Power System with Large Amounts of Wind Power

A. *Innovative Characteristics of the Wind Systems*

The new network/system capacity to be attributed to wind power must, according to the terms of the Portuguese official board (DGGE) call for proposals, fulfill the following minimum technical requirements [7]:

- To assure that wind systems to be installed have the capacity to remain in operation in the presence of voltage dips that may result from short circuits or other system occurrences. The wind system must not be disconnected if the value of the effective voltage at its terminals remains above the curve depicted in Fig. 5 during the grid perturbation the originated the voltage dip and after its clearance, for the time limits also defined by Fig. 5;
- To assure the capacity to deliver reactive power during voltage dips that provides support for the network voltage, according to Fig. 6;
- To assure capacity of the wind systems to adjust, by request of the TSO, the reactive power injected in the network for tangent (phi) in the range [0; + 0,2].

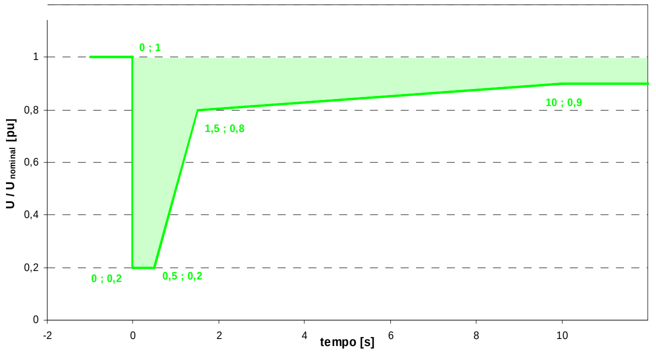

Fig. 5 - Time voltage characteristic curve required to the wind systems (“ride through fault”).

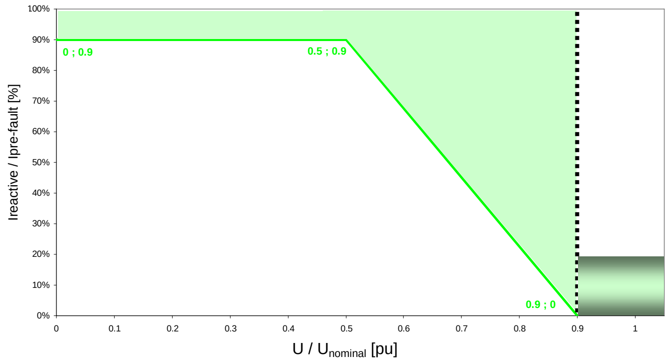

Fig. 6 – Characteristic curve of reactive power delivery by wind power plants during/after voltage dips.

The following added technical capabilities will be positively valued in the call for new wind capacity, if available:

1. Management of wind parks by clusters (“local wind power dispatch”);
2. Additional reactive power control;
3. Interruption of production (disconnection);
4. “Wind energy storage” solutions;
5. Participation in the primary frequency control.

B. *Innovative Characteristics of the Power System*

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 market procedures.

Some innovative strategies and equipments are already in operation in Portugal. Following the Portuguese planning effort carried out by the TSO, included the introduction of a new TN element in Portugal; the phase-shift autotransformer. The “Transmission Network Development Plan for Renewables” showed, for the first time, that such a machine could “force” wind power injected in the 150 or 220 kV levels (or 60 kV DN) of specific geographic areas to enter the 400 kV grid, using available 400 kV capacity and avoiding the construction of new 150 and 220 kV lines.

This idea was further developed in more detail, both from the point of view of the concept of the machine itself and the simulation of the machine operation in the network. Part of this work was done with CESI (Italy) and as a result it was possible to set the specifications for a 450 MVA phase shift machine which was constructed by the Portuguese company EFACEC and is currently in operation at the REN, SA substation of Falagueira.

Posuing the same objective, it is intended to install Wind Generation Dispatch Centres (acting as Generation Aggregation Agents) adopting an hierarchical control architecture, as described in Fig.7.

Having in mind wind generation can inject power either in the transmission network or in the distribution grids, a dialogue with the TSO and the DSO operators is required, as well as with the market operator, assuming therefore that in this case the wind generation can participate also in the market. Spain is presently already promoting the development of a similar architecture for wind generation dispatch control centres.

The capacity of a wind park is usually limited by the capacity of the grid to accept the total power the wind park can inject into the grid. However, in wind generation most of the time wind turbines are operated far from their nominal ratings. So, some over capacity installation in wind parks will be allowed provided that a control of production is performed to avoid an 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.

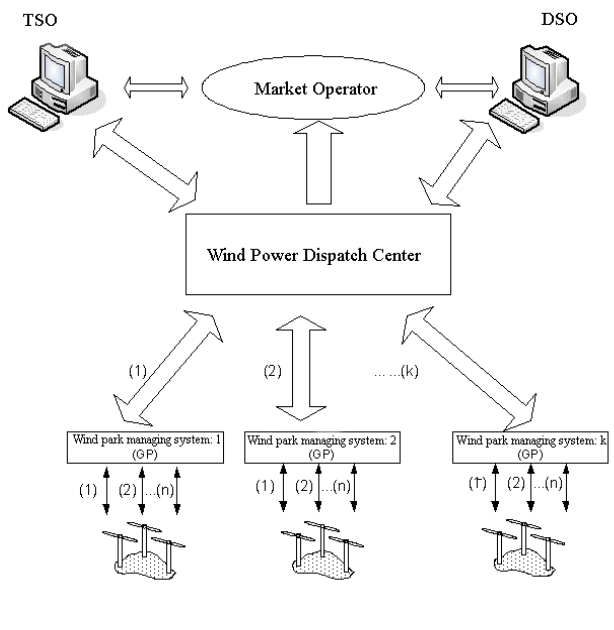

Fig. 7 – Architecture for the management of the system.

Regarding wind parks, the specific nature of the installed energy conversion systems requires specific applications, to be installed at the wind park managing system level. Such applications should be able to “dispatch” some active and reactive generation, when grid operator set points are sent to the wind park.

The operation of these dispatching centres requires also the availability of new managing tools. Generation forecast is the most relevant one. These forecasting tools should be able to foresee the generation of wind parks with time horizons of at least 48 hours ahead. The approach presently under development to produce wind power forecasts exploits Global Numerical Weather Prediction (NWP) results that are afterwards combined with online data, using mesoscale and physical models together with statistical adaptive tools.

When hydro pumping storage is available, new functionalities able to identify the best combined wind - hydro pumping storage strategies should be used. For that purpose wind power forecasts for the hours ahead are needed together with the electricity price behaviour forecasts. The identification of the optimised daily operation strategy can be determined by solving a linear hourly-discretized optimisation problem where the economic benefits of such strategy are driving an objective function. Hydro pumping storage is also expected to be used in the Portuguese system to provide compensation energy whenever necessary. An identification of the operational rules to be adopted is still needed.

C. *Improving 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 turning into a mandatory requirement in the Portuguese Grid Codes. However the already installed wind generators are not capable of withstanding such grid disturbances, which requires the adoption of external measures like the installation of Flexible AC Transmission Systems (FACTS) devices. Such devices are capable of providing a support to voltage profiles, limiting the voltage dip during the short-circuit duration time.

For the Portuguese grid a good solution would then be the introduction of SVC/STATCOMs with a capacity of 10% of the injected generation in each wind generation bus with wind parks that do not have ride through fault capability [8].

Fig. 8 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 for the cases without and with FACTS installed.

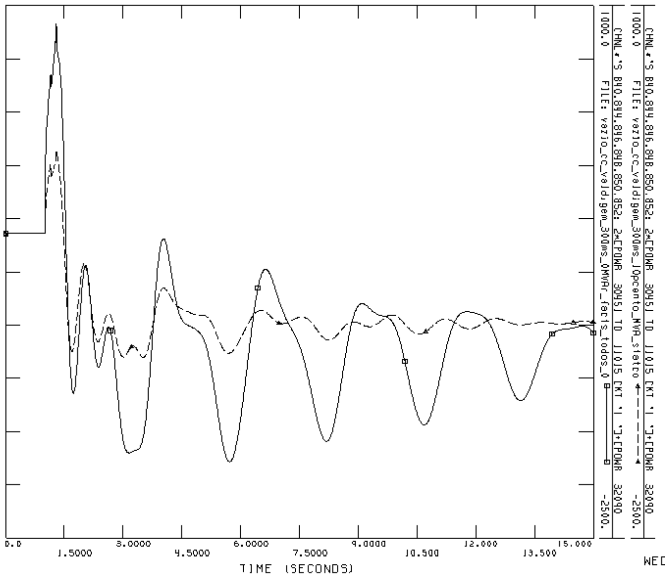

Fig. 8 – Active power flow in the interconnections, following a short circuit in an important transmission bus (300ms) – without STATCOM and with STATCOM (10%).

From these results, one can conclude that it will be beneficial to install FACTS in strategic buses of the Portuguese 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 generators due the tripping of their under voltage protection relays. Apart from avoiding the tripping of some generation units, a good damping of the oscillations can be obtained.

VI. Conclusion

The studies and projects underway and briefly described in this paper show that the design and planning of the integration of large amounts of wind power in the system is a real and effective possibility that may, and should, be widely used, in order to guarantee the overall power quality and security of supply, still enabling to maximize the Wind and other Renewable Energy Sources (RES) embedded capacity.

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