Participation of Wind Power Plants in the Spanish Power System during Events

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***Abstract*—The ever increasing level of wind power penetration in Spain has a remarkable impact on power system operation and costs. Furthermore, the Iberian Peninsula Power System is considered to be a weak systems.With a weak interconnections, wind power fluctuations could affect the security, reliability and stability of power system. There are times when a combination of several events or several actions taken (coincidence or coordinated) may lead to the worst condition of power system. An evolution of procedures and regulations related to power system have been performed and developed by Spanish Transmission System Operator (TSO) to tackle these extreme events; thus, improving the overall wind power integration.**

This paper analyzes the wind power events and the evolution of procedures during past several years implemented by Spanish TSO. Events are analyzed from TSO perspective as well as from the wind farm and wind turbines point aspects. Operational decisions and techniques developed and performed by Spanish TSO to resolve these events are also described in this paper.

***Index Terms*—Power system, wind power plants, events.**

I. INTRODUCTION

Wind resources can be managed through proper plant interconnection, integration, transmission planning, and system and market operations, [1]–[3]. With its total installed wind power capacity of more than 20GW, Spain is an example a good coordination of wind system integration. During 2010, 16% of the energy consumption in Spain was generated by wind power. The minimum and maximum wind power production levels in 2010 were 191 MW and 14 901 MW, i.e., 0.99% and 76.14% of the installed capacity, respectively. Spanish system has been operated some days with more than half of its demand covered by wind generation (the last time was on the 6th November, 2011 with 59.6 percent of the consumption fed by wind). Wind power supplied 20.73% of the demand during the month of March, 2011, making it the technology with the highest energy produced during that month. On the other hand, the main weakness in the Spanish power system is the interconnection capacity to neighboring countries —1 300 MW with Portugal, 1 400 MW (import) or 400 MW (export) with France and 900 MW with Morocco—.

Two key aspects about system operation with large amounts of wind power in Spain are the grid codes or operational procedures —PO— required by Red Eléctrica de España —REE [4], the Spanish transmission system operator (TSO)— and a Control Centre of Renewable Energy —CECRE—. CECRE has been in operation since 2006, and it is considered a worldwide pioneering initiative to monitor and control renewable power plants, specifically wind farms.

PO are approved by the Ministry with consultation to the regulatory body for energy systems, National Energy Commission —CNE—.

Taking into account the penetration of renewable energy in the Spanish power system, some PO apply to wind power, [5]:

- PO that apply in part to wind power and other renewable units:
  - PO 3.2. Technical constraint management (D-1, real-time...).
  - PO 8.2. System operation of generation and transmission.
  - PO 9. Information exchanged with the System Operator (observability).
- PO that apply specifically to wind power or other renewable units:
  - RD 661/2007. Voltage control aspects.
  - PO 3.7. Controllability of non-manageable renewable power plants.
  - PO 12.3. Voltage dip ride-through capabilities of wind generation.
- In the process of approval:
  - PO 12.2. Requirements for new power plants.
  - PO 7.5. Voltage control by renewable generation.
  - ENTSO-e. European network of transmission system operators for electricity have studied "Requirements for Generators" which will be proposed to the European Commission. It will establish maximum requirements for TSO and minimum ones for power plants.

About the CECRE, all wind power data are collected by the TSO. Data are measured for peninsular area (excluding Canary Islands and Balearic Islands) wind farms connected to CECRE. CECRE is an operating unit within the Power Control Center

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—CECOEL— connected to the 98.6% of installed wind power capacity, while the rest wind power, 1.4%, is estimated.

To ensure the security of the system, REE requires real-time communication with the wind power plants, enabling it to monitor at all times their conditions and their state of operation and to issue the necessary commands remotely in order for them to fully coordinate these stations.

The telecommunication deployment of almost 800 wind farms spread all around Spain has been accomplished by aggregating above 10 MW all the distributed resources with power rating. The information is collected from the production units, which in turn is needed for real time operations. Measurements, such as active and reactive power, voltage, connectivity, temperature and wind speed and wind direction, are taken from wind farms every 12 seconds and sent to a Renewable Energy Source Control Centre —RESCC—. Power plants above 10 MW must be controllable thorough a RESCC, and in the case of wind generation, set-points are sent via Inter-Control Center Communications Protocol —ICCP— links and wind power generation must be adapted every 15 minutes.

This paper analyzes wind power events occurred in the past several years in Spain, emphasizing the response of wind farms and wind turbines to these events. In section II, a description wind farms and data acquisition are presented. A description and classification of events based on their characteristics will be described in section III. Furthermore, examples of main events are described in the following subsections. Finally, conclusions are given in section IV.

II. Wind farm data

This study relies on wind farm data obtained using the SCADA system at the wind farms, together with recorder devices monitoring currents and voltages at selected wind farms and wind turbines.

Power quality (PQ) analyzers, based on IEC 61000-4-30 class A accuracy, frequency synchronization, and absolute time requirements, have been installed at some Spanish wind farms. These analyzers, with a maximum sample rate per channel of 10 MHz, are able to capture detailed voltage and current waveforms during transient events such as voltage sags, including the clearance of the fault, by using the trigger options to obtain the entire transient. The transient data is collected only during transient events (i.e., event triggered) when there is a sudden change of voltage due to transient events.

Figure 1 shows schematically the PQ analyzer installation, being connected between the DFIG and the 0.69/20 kV power transformer. This analyzer measures the three stator voltages and currents, the rotor line current and the DC bus voltage, of the power converter. The other PQ analyzer is used to measure the line voltages and currents at the wind farm electrical substation (20 kV). Both analyzers are linked via WiFi to a UMTS/GPRS modem, allowing a remote access to their configuration and recorded data. In this way, this solution can be extended to more PQ analyzers, located in other DFIGs or in different points of the power system.

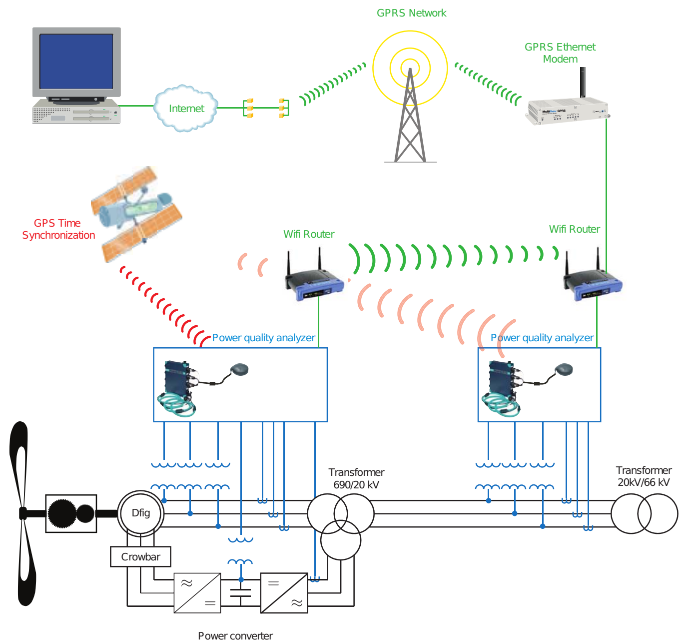


Fig. 1: Wind farm and data acquisition arrangement

III. Considered singular events

As wind generation exhibits variable and somewhat random behavior, there are times due to coincidence or coordinated weather systems when extreme events take place. Advanced forecasting techniques may help alleviate some of the effects of rapid coordinated changes in wind generation, but in systems where wind generation accounts for the majority of electric energy generated, extreme events can ocurr and they may affect the security of these systems.

Based on their ramping characteristics, wind power fluctuations events can be classified in, [6]:

- Wind power die-out. A wind power die-out refers to a persistent drop in the wind power.
- Wind power rise. A wind power rise consists in a sustained rise in wind power that can create a persistent ramp up.
- Wind power lull. Wind die-outs are inevitably followed by wind rises. When both events happen in short succession, they form a wind lull.
- Wind power gust. A wind gust is opposite of a wind lull, it starts with a ramp up and ends with a ramp down.

Another classification is based on different events. The main causes are:

- Meteorological phenomena. Events caused by meteorological phenomena are usually formed by a wind power rise later followed by a wind power die-out. In short areas these events can be formed by persistent wind gusts. In Spanish system, ramps down are especially harmful because a ramp down of wind power will be followed by a ramp up in the rest of the power plants to restore the power balance.
- Technical and operational causes. In this group the main causes are:

- Voltage sags. Voltage sags produce a sudden drop of wind power generation. This drop is usually recovered afterwards.
- Cut-out speed. When wind speed reach wind turbine cut-out speed (usually 25 m/s), wind turbine is disconnected from system. If this phenomenon spreads to several wind turbines, it could cause a major drop in wind power generation.

These events are usually represented by rapid wind lulls or, wind die-outs if generation is not recovered.

A. *Voltage sags*

Wind turbine manufacturers are required by Transmission System Operators to equipped their turbines with fault ride-through (FRT) capability as the penetration of wind energy in the electrical systems grows, [7]. Spain defined a procedure for measuring and evaluating the response of wind turbines and wind farms subjected to voltage sags, [8], —Procedure for verification, validation and certification of the requirements of the PO 12.3 on the response of wind farms in the event of voltage sags (PVVC)—. The result of following this procedure leads to the certification of its conformity with the response requirements specified in the Spanish grid code, [9]. Some aspects related to that grid code are explained with some detail in [10], [11].

On the other hand, the recent rapid expansion of wind generation has given rise to widespread interest in physical testing of wind power plants and wind turbines due to this growing impact on power grid operations. In this area, validation of computer models of wind turbines is not a trivial issue. Validation must ensure that wind turbine models represent with sufficient accuracy the performance of the real turbine, especially during severe transient disturbances, [12]. In [13] different field tests for modeling validation and standards compliance are categorized according to the main input or stimulus in the test —control stimulus and external physical stimulus—. Among these tests, FRT capability of wind turbines can be performed using factory tests, at the individual wind turbine generator terminals and using short-circuit field measurement data on operational wind turbines and wind farms.

Short-circuit field measurement data on operational wind turbines and wind farms, [14] —called opportunistic wind farm testing in [15]—, is performed with measurement equipment installed at the wind farm site. The equipment records naturally occurring power system disturbances, which are then used to validate wind turbine models. Power system modeling during the disturbances must be taken into account in the validation of wind turbine models. Therefore, monitoring of wind farms and wind turbines can be of interest for the turbine manufacturers, the wind farm operators, and for the TSO.

An extreme event recorded in Spain related to voltage sags occurred on March 19^{th} and 20^{th} 2007. Four disconnection of large amounts of wind power due to voltage sags were recorded (refer to figure 2). Those voltage sags were located in areas with high penetration wind power and during high wind speed periods. In figure 2, Spanish wind power is shown during these events.

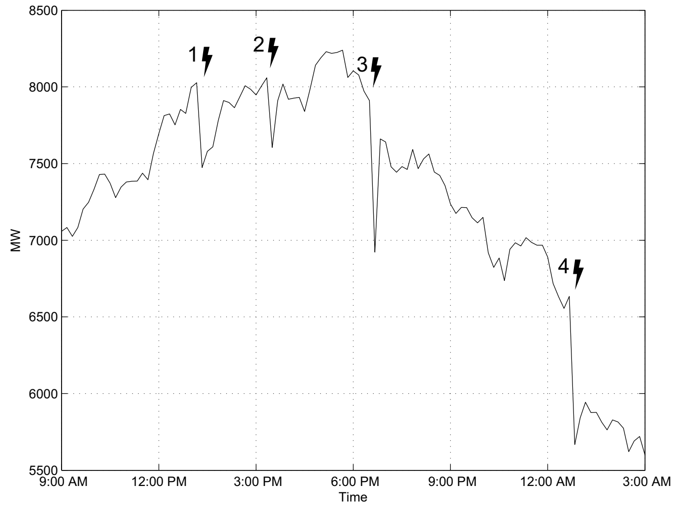


Fig. 2: Spanish wind power during Voltage Sags on March 19^{th} and 20^{th} 2007

TABLE I: Wind Farms analyzed

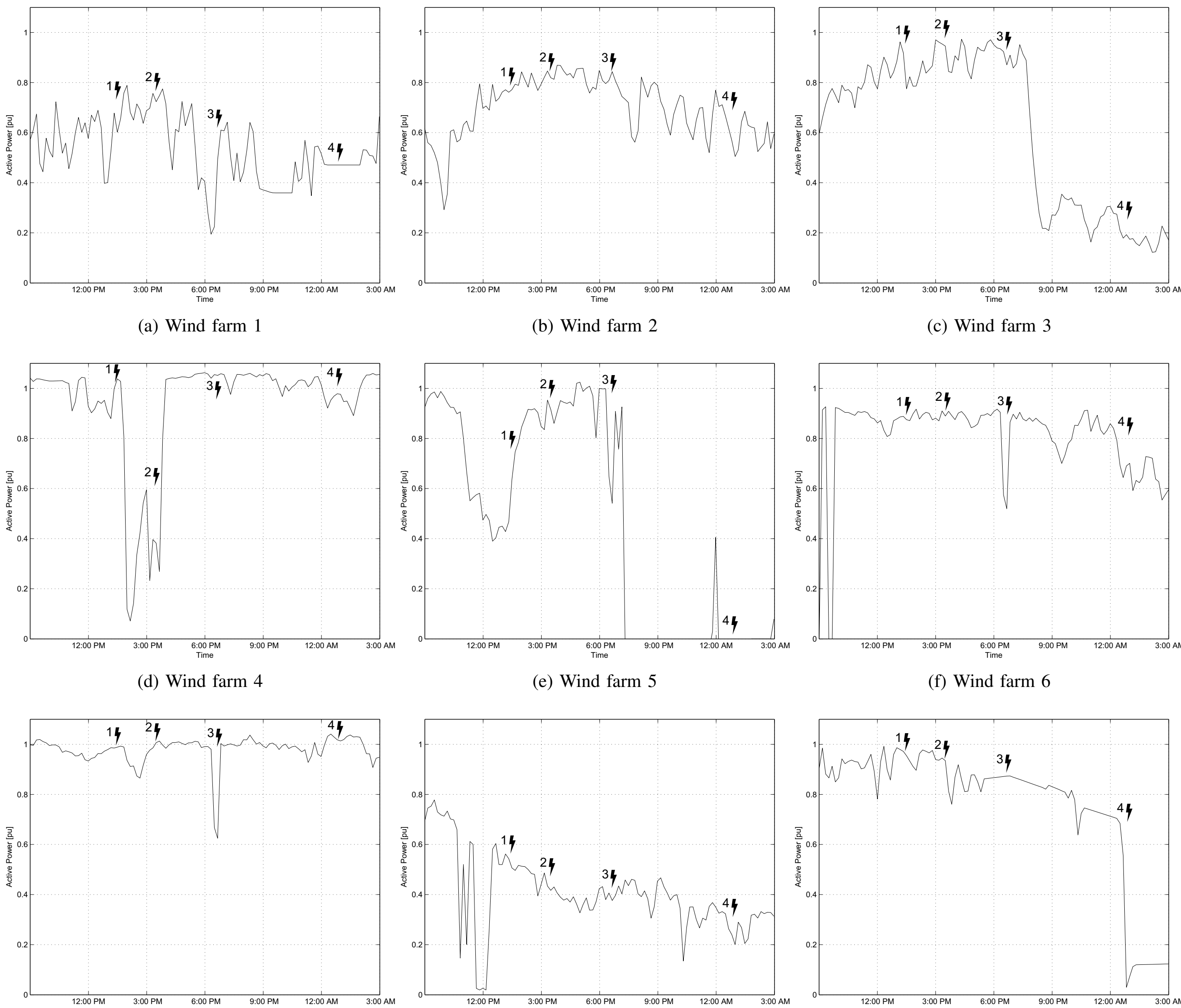
WF	Nom. Power	Wind Turbine model	Number of WT
1	36.5 MW	Gamesa G52	43 (G52)
2	30.4 MW	Gamesa G58/G47	21 (G58) / 19 (G47)
3	27.2 MW	Gamesa G58/G52	19 (G58) / 13 (G52)
4	49.5 MW	Gamesa G47	75 (G47)
5	24.4 MW	Gamesa G47	37 (G47)
6	38.3 MW	Gamesa G52	45 (G52)
7	37.6 MW	Gamesa G47	57 (G47)
8	31.4 MW	Gamesa G52	37 (G52)
9	6.8 MW	Gamesa G58/G52	2 (G58) / 6 (G52)
10	49.5 MW	Neg Micon NM82	30 (NM82)

Wind power generation disconnected during these voltage sags were 553 MW, 454 MW, 989 MW, and 966 MW respectively. Table I lists the size of the wind farms and the number of turbines, and the corresponding wind turbine types.

Additionally, 9 Spanish wind farms located in different areas have been analyzed during these events. In figure 3 wind power from these nine wind farms is presented, being highlighted:

- Wind farms 1, 2 and 3 are located in the same area. They are at high fluctuating partial load. These farms are not affected by voltage sags as they are far away from the faults.
- Voltage sags 1 and 2 only affected wind farm 4.
- Voltage sag 3 affects wind farms 5, 6 and 7. These wind farms are nearby. In the three cases, the response to the sag is similar.
- Only wind farm 9 is affected by voltage sag 4.
- All voltage sags during this day were located in areas with high wind power penetration and during a high generation period.

Operation of power systems under the effect of voltage sags in wind power has led to the TSOs to require FRT capability in wind farms. By the end of 2010, 704 Spanish wind farms have been certified against FRT capability (19.2 GW and around 95% of the installed capacity). A total of 1 GW wind turbines are excluded because of their missed manufacturers,



(a) Wind farm 1

(b) Wind farm 2

(c) Wind farm 3

(d) Wind farm 4

(e) Wind farm 5

(f) Wind farm 6

(g) Wind farm 7

(h) Wind farm 8

(i) Wind farm 9

Fig. 3: Wind power production of 9 WFs during voltage sags on March 19^{th} and 20^{th}, 2007

small size turbines or being prototype turbines. Figure 4 shows the number of power losses greater than 100 MW from 2005 and the percentage of wind power without FRT. As a result of this technical adaptation, the problem of significant wind generation tripping has been solved, and therefore preventive production curtailments for this reason have not been required since 2008.

Supervising SCADA and controlling the wind generation in real time has decreased the number and quantity of curtailments, maintaining the quality and security of the electricity supply, maximizing the renewable energy integration. To enhance the energy integration even more, REE has submitted a proposal of new grid code (P.O 12.2) to the Ministry, with additional technical requirements for FRT among other ones. Its main purpose is to anticipate the expected problems in the Spanish power system between 2016 and 2020, taking into account the incoming plants and new power plant deployed by these years. It is expected that P.O. 12.2 can be applied in 2013.

B. Storms

Meteorological phenomena, e.g. storms or cyclones, are capable of causing large variations in wind power production and very high wind speeds. A storm within this category can affect a large number of wind turbines that have around the same cut-out speed. When cut-out speed is reached, the power generated goes from rated power to zero. If this phenomenon spreads to several wind farms in a particular area, it could cause a major disruption to the stability of the network.

The storm Klaus was named for an extra-tropical mid-latitude cyclone that struck on January 23^{rd}, 24^{th} and 25^{th}

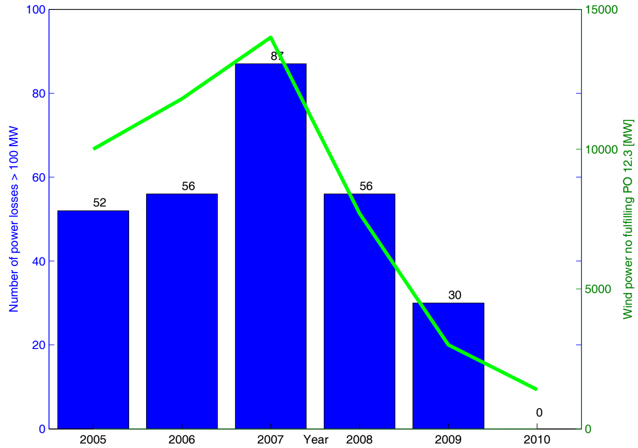


Fig. 4: Evolution of wind power with FRT and number of power losses $\geq$ 100 MW by voltage sags in Spain, [16]

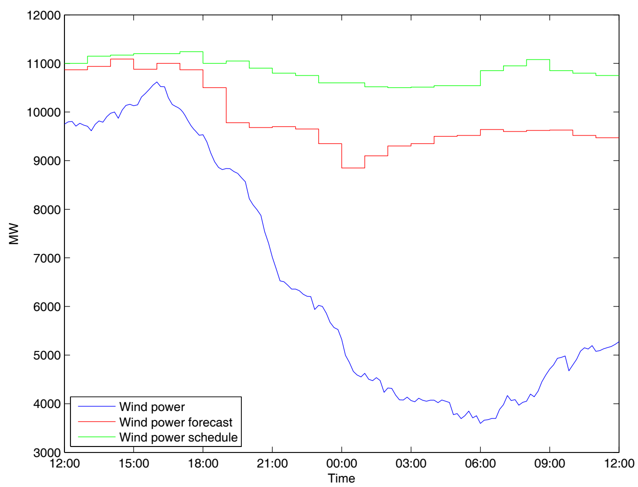


Fig. 5: Wind power, forecasting and schedule during Klaus Storm

2009, being mainly affected Spain —northern— France —southern—. Wind speeds of over 150 km/h were measured in the Spanish and French coastlines. The result was the disconnection of many wind farms in northern areas of Spain, leading to a reduction of about 7 000 MW of wind power in a few hours, (refer to Figure 5). Figure 6 shows the influence of the storm in a Spanish wind farm.

In this emergency situation to operate the power system, the Spanish TSO committed several thermal units to couple in order to increase the volume of reserves to rise. Despite the enormous difference between the forecast and actual wind power production, the operation of the system took place in the required safety conditions.

This example shows the difficulties for forecasting wind power during this type of events. Differences between forecast and real wind power generation reached almost 6 000 MW. Furthermore, wind power ramp down during storm happened during night, matching up with load ramp down, so increased reserves were enough to maintain the system balance.

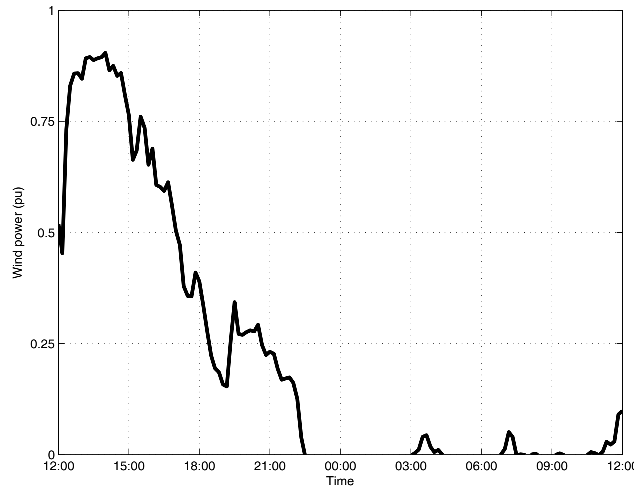


Fig. 6: Wind power in wind farm 10 during Klaus Storm

C. *Wind power curtailments*

Wind energy curtailments due to integration issues in the power system have appeared in the Spanish power system. Until 2009, major curtailments were due to limitations on the distribution networks, but from the end of 2009 cuts have been applied in real time to scheduled energy. However, the renewable nature of this energy, together with economic and environmental issues, have provoked an interest in adding forms of energy storage, specially well-known technologies as pumped hydro storage (PHS). Spain accounts for around 5 000 MW —2.75 GW of pure PHS, with 77 GWh capacity—, technology that is usually exploited due to the limited transmission capacity for exporting to neighbor countries.

As a example of wind power curtailment, table II indexes orders delivered by Spanish TSO during February 28^{th} 2010. Initial and end time for every curtailment period are presented in column 1 and 2. Column 3 represents Spanish wind power at the beginning of the period. In column 4, the Spanish TSO setpoint for this period is listed. In column 5, the real increase or reduction experimented by Spanish wind power in this period is shown. Finally, ratio between real increase or reduction and increase or reduction obtained if wind power would fit setpoint, is presented at column 6. In decrease periods this ratio is equal or higher than 1, while in increase periods is equal or lesser than 1, being 1 the optimum value.

D. *Over-response to wind power curtailments*

On January 1^{st} 2010, the Spanish TSO (REE) gave instructions for several wind power curtailments considering "Non-Integrable Wind Power Excess" defined by REE in the Operational Procedure 3.7, [17]. During these curtailments an over-response in the wind farm power generation was obtained and the reduced power ratio was even more than 4 times the order required [19]. This kind of events may threat the power system operation, and from an economical point of view, as reserves are used for balancing, increasing costs are produced.

Figure 7 shows the sequence of curtailment instructions provided by the CECRE, together with the wind power gener-

TABLE II: Curtailment schedule February 28^{th} 2010

Initial Time	End Time	Wind power (MW)	Wind Power set-point (MW)	Real Increase/Reduction (MW)	Ratio
1:08	2:07	7796	7331	-796	1.71
2:07	3:48	6470	6099	-718	1.93
3:48	6:08	5175	4904	-720	2.66
6:08	8:45	4036	5904	217	0.11
8:45	9:10	3772	6905	420	0.14
9:10	9:43	3807	7905	276	0.07
9:43	–	4209	Installed capacity	–	–

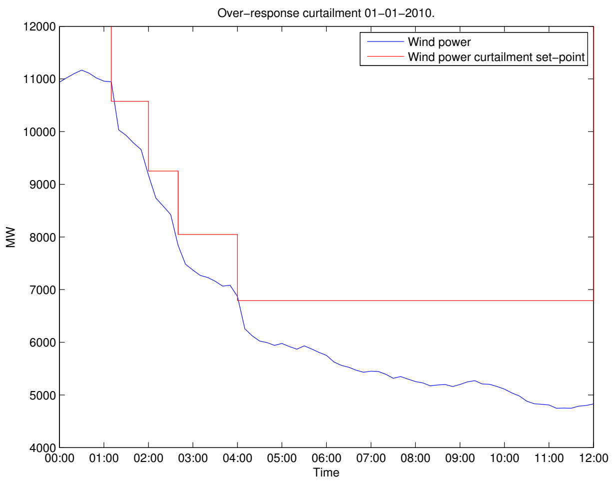


Fig. 7: Over-response to curtailments in the entire Spanish wind power generation

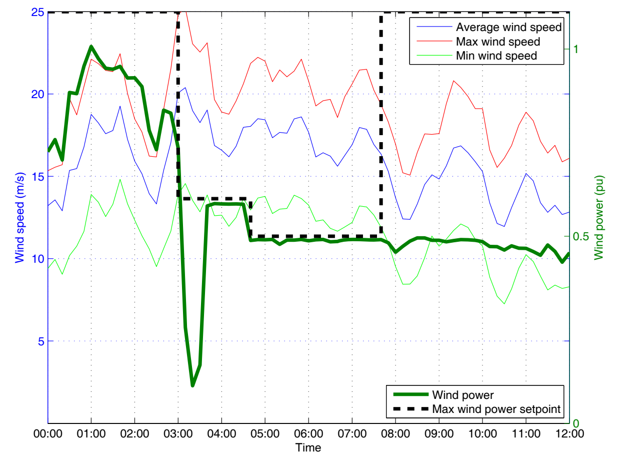


Fig. 8: Example of an over-response in wind farm 10 during January 1^{st} 2010

ation in the power system. There were four orders with over response during these hours, being the effective wind power reduction from 2.42 to 4.02 times the commanded reduction.

The main causes of this over-response were:

- Curtailment is usually performed during low load and high wind penetration periods.
- During these periods, wind farms are often operating under high wind speed and wind power fluctuations are very important. Many wind farms were stopped or under low production by cut-out protection.
- Curtailment is usually applied disconnecting all the wind farm instead of turning off specific wind turbines.

In figure 8, an example of over response to this curtailment is presented for wind farm 10. TSO set point was ordered during early morning (3:00-7:00 pm). When wind speed was over cut-out speed (20 m/s), wind power decreased below set point, reaching half generation and almost no generation. This additional drop must be assumed by reserves up. Sequence of range of production is as follow:

- From 00:00 to 03:00, no curtailment was ordered. Most wind turbines were near or at 1 pu during this period. At 02:10 a slight wind power lull ocurred as wind speed fell.
- From 03:00 to 04:40, a 0.6 pu TSO setpoint was applied. Then wind speed passed 20 m/s and most of WTs were disconnected by cut-out speed protection. Wind farm production fell to 0.1 pu, much less than 0.6 pu. Then wind speed went down, and wind farm production almost reached TSO setpoint. Some WTs were maintained at maximum available power while others were uncoupled resulting the TSO setpoint for the whole wind farm. Some WTs were at maximum available power and the rest remained disconnected. This kind of regulation involves repeated connections and disconnections during curtailment.
- From 04:40 to 07:40, TSO setpoint change from 0.6 pu to 0.5 pu. More WTs were disconnected to achieve this change.
- Finally, at 07:40, TSO released setpoint and wind farm recovered normal control.

Possible solutions to avoid over-response to wind power curtailments, with the actual capacity of energy storage and transmission to other countries, are:

- TSO should dispose of real time wind power generation as well as a wind power forecast during curtailment period. Maintenance schedule and cut-out shut downs must be taken into account.
- It must be studied to perform curtailment orders for control centres level instead of wind farm level. Control centres are connected to CECRE and could improve curtailment management.
- Information about the reasons of curtailment, the application method and wind farms response could help to an overall optimization.

E. Future requirements

The ability of modern multi-megawatt variable-speed wind turbines with power electronic controls to assist in improving the power system performance is now beginning to be explored in some detail. Not only can modern wind plants be added without degrading system performance, they can also contribute to improvements in system performance, [1]. The proposed PO 12.2 takes into account the ability of wind farms to provide voltage control in the system, inertial response, frequency control, oscillation damping, or updated voltage ride-through capabilities.

Some tests have been performed by Spanish utilities together with the Spanish TSO.

1) Voltage control: It is expected that in the Spanish power system, conventional power plants will be progressively replaced by renewable energy based power plants. Even today, voltage control can be easily implemented by the contribution of these power plants. So, nowadays, certain nights and weekends, the Spanish TSO was forced to disconnect up to 50 lines of 220 kV and 400 kV to maintain voltage levels, [16]. REE and some utilities are testing voltage control with wind power plants to gain experience for the future, as voltage control is included in the proposed PO 12.2, for steady-state and transients —overvoltages and undervoltages—.

In [18] a cluster of DFIG based wind farms totalizing 193 MW connected at 220 kV was used to control voltage levels and reach the setpoint demanded by the TSO, through a Dispatch Centre, where the wind farms are connected. Different controllers were used, proving the interaction between different voltage controllers —grid line or node—, being observed promising results.

2) Extreme grid events: A grid disturbance occurred in Europe on November 4th, 2006, when there were significant East-West power flows as a result of international power trade and the obligatory exchange of wind feed-in inside Germany. These flows were interrupted during the event. The tripping of several high-voltage lines, which started in Northern Germany, split the UCTE (union for the co-ordination of transmission of electricity) grid into three separate areas (West, North-East and South-East) with significant power imbalances in each area. The Western Area was composed of Spain, Portugal, France, Italy, Belgium, Luxemburg, The Netherlands, a part of Germany, Switzerland, a part of Austria, Slovenia and a part of Croatia).

Spain was affected by the grid disturbance, being inside the under-frequency area. In Spain, this disturbance provoked:

- The interconnection lines between Morocco and Spain were tripped.
- Tripping of power installation CCGT in Arcos de la Frontera (728 MW).
- Tripping of 2 800 MW in wind power, figure 9. This figure shows the generated active power in tele-measured wind farms coloured in blue, whereas the total estimated wind generated active power is coloured in pink. Around 10:12 p.m., wind power diminished from around 4 000 MW to 1 164 MW.
- 1 500 MW of load shedding.

During that event, frequency relays were installed in wind turbines —maximum frequency (81M) at 51 Hz and minimum frequency (81m) at 49 Hz, complying, in that time, the Spanish requirements, figure 10. After that event, together with other

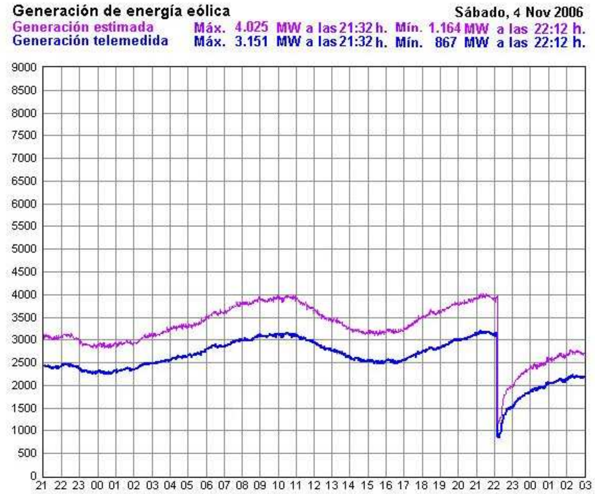


Fig. 9: Wind power generation in Spain on November 4th, 2006. Source: REE

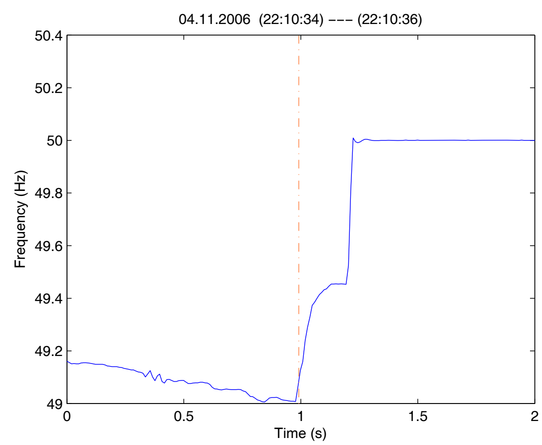


Fig. 10: Measured frequency in a wind turbine

considerations, the protective relaying criteria was modified. Minimum relaying protective devices in wind turbines must be coordinated with the power system, acting when frequency is going down of 48 Hz, at least during 3 seconds.

IV. Conclusion

The high level of wind penetration in the Spanish power system has been possible due to the advanced operational procedures and CECRE. Different events have shown the power system operation during in some cases, extreme circumstances, together with the participation of individual WFs and WTs, linked to CECRE. The nature of these events is diverse, from meteorology —storms—, to faults in the network —voltage dips or other results—, and integration and power system operation issues —wind power curtailments, voltage control, . . .—. In the near future, the Spanish WFs will actively participate in the power system operation, providing voltage control, inertial response, frequency control, oscillation damping, or updated voltage ride-through capabilities.

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