Participation of wind parks in voltage control of power system networks

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I. SUMMARY

In Spain, voltage regulation in transmission networks is mainly done by controlling the reactive power in conventional generators. In wind energy, an incentive payment related to the reactive power compensation is applied. The maximum value of incentive payment and the objective power factor depend on the period of the day: peak, valley or flat.

In this paper, a different behaviour is proposed, thus the influence of including wind parks in the voltage regulation is analyzed. The behaviour of generators, lines, and voltages are taken into account in order to compare the proposed situation with the current one.

II. INTRODUCTION

The wind power installed in Spanish parks is more than 16500MW, where fixed speed wind turbines with asynchronous generators represent approximately the 40% of the installed power. In wind parks with asynchronous machines, reactive power compensation is typically done by means of capacitors banks, which are divided into steps, installed in the LV side of wind turbines and in the MV side of substation. The total reactive power installed in Spain with these machines could be higher than 1000 MVAr; they are distributed in multiple nodes and with a large number of steps in each one. Some wind parks have increased the number of capacitors banks and their power so as to obtain the best incentive payment. In this way, the number of nodes with a possible participation in voltage control could be highly increased if the wind parks reactive energy is controlled. The range of regulation of reactive power with the capacitors banks of a wind park is constant.

In addition, the rest of special regime (biomass, photovoltaic and cogeneration) is governed by the same legislation as wind farms with regard to the reactive power. In recent months, it has been generating half of the special regime, excluding wind power, it is between 6000 and 8000 MW. Thus, it can reach values of wind generation and other special arrangements up to 15000 MW.

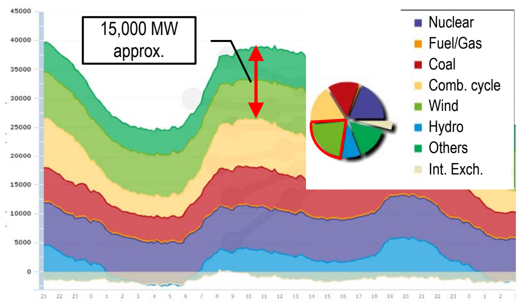

Fig. 1. Generation share (www.ree.es)

Transmission system operators (TSOs) must adapt their grid codes for enabling wind generation to connect to the transmission ensuring the security of supply. Active power control, frequency control, voltage control, reactive power compensation, or voltage sag immunity are aspects that have been regulated in different grid codes around the world. The focus of this study is the reactive power compensation, which is a common aspect regulated by the TSO's of Spain (REE), Germany, Denmark, Scotland, etc. TSO

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grid codes impose different reactive compensation strategies. Next, there are examples of reactive requirements in the European countries with most wind power installed.

1) In E.ON network (Germany), each wind park with a rated power of <100MW must be able to operate with a power factor from 0.95 inductive to 0.95 capacitive (see Fig. 2). The operating point for the reactive exchange is determined by the TSO and the new working point must be reached within a minute time [7].

2) In REE network (Spain), wind parks specifications for the reactive power ranges are not obligatory, but an incentive or penalty complement depending on the achievement of specified PF is applied [3].

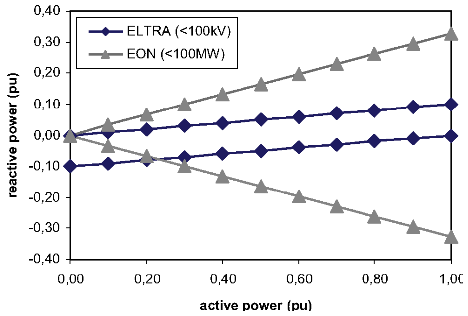

Fig. 2. Reactive compensation limits in ELTRA and EON grid codes.

III. Objectives

The main objective of this paper is to demonstrate that participation of wind farms in voltage regulation has a better impact in transmission and distribution network operation than the actual scheme, used in Spain, which is based on a bonus/penalty payment related to power factor. Fig. 3 presents the Spanish transmission network. Colour of the circles represents the type of generation and colour of the lines represents the percentage of charge related to its rated power.

IV. Methodology

The method is based on the implementation of an Optimal Power Flow (OPF). The OPF takes into account the next constraints:

- Thermal constraints of lines and transformers.
- Technical constraints of generators.
- The regulation of transformers is fixed.
- Nodal voltage is limited to the levels, established in Spanish grid code [5] (see Table 1).

Finally, the OPF objective function includes minimum energy losses and reactive power of generators.

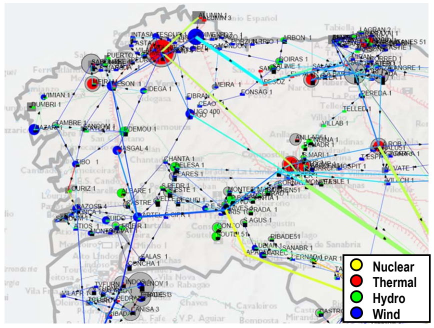

Fig. 3. Part of Spanish transmission network (northwest)

Table 1. Voltage limits of Spanish transmission network

Voltage level (kV)	Voltage limits (kV)	
	Mín.	Máx.
400 kV	390	420
220 kV	205	245

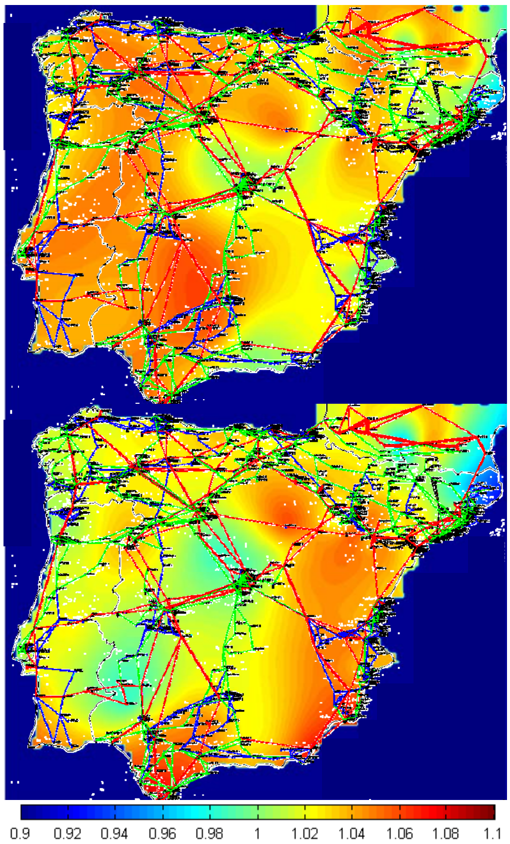

Fig. 4. Network voltage for different geographical distributions of wind energy generation

The data used in OPF was obtained from the Spanish TSO; real situations with high and low wind power generation as well as different geographical distributions of generation have been analyzed. In Fig. 4, two examples associated with high wind energy generation in the west (upper figure) and in the east (lower figure) are presented. The wind generation is directly related to weather; i.e. when the storms sweep across the Spanish peninsula it causes a marked increase and decrease in the wind in each region, at different times of the day. In these cases, the injection of wind power varies between locations over time, and as a consequence, its influence in the transmission network also varies.

In order to analyze the impact of wind generation behaviour on network voltages, the following scenarios have been considered:

- **A**: Fixed power factor during the different periods of the day (peak, valley or flat).
- **B**: Transition behaviour between periods in scenario A.
- **C**: Voltage regulation control is implemented in all wind parks. Reactive generation is limited to a PF between 0,95 inductive and 0,95 capacitive.

In Fig. 5 reactive power and nodal voltage are shown in three scenarios: (A) using fixed PF=1; (B) during the transition from PF=1 to PF=0,95 cap and (C) with voltage regulation implemented in wind generation. Zones with excessive reactive injection (biggest circles) or voltage deviation (red circles) are marked in scenarios (A) and (B). This behaviour is corrected in the scenario (C).

1. Fixed PF (Scenario A)

Spanish legislation (R.D. 661/2007 [3]) establishes that wind farms will receive incentives according to the power factor generated at different times of the day (flat peak, valley), as shown in Table 1. Periods of day can be seen in Table 2 [4].

Participation of wind turbines on reactive compensation depends on their technology, consequently:

- Asynchronous generators cannot generate reactive power, so, most wind farms have installed capacitor banks in wind turbines and in the substation of wind farm.
- Doubly-fed generators can control their reactive power injection by controlling their power electronic converter connected at the rotor side. However, in certain machines, low power factors cannot be achieved due to design limits.
- Synchronous generators can control its reactive power injection through their full-size AC/AC converter.

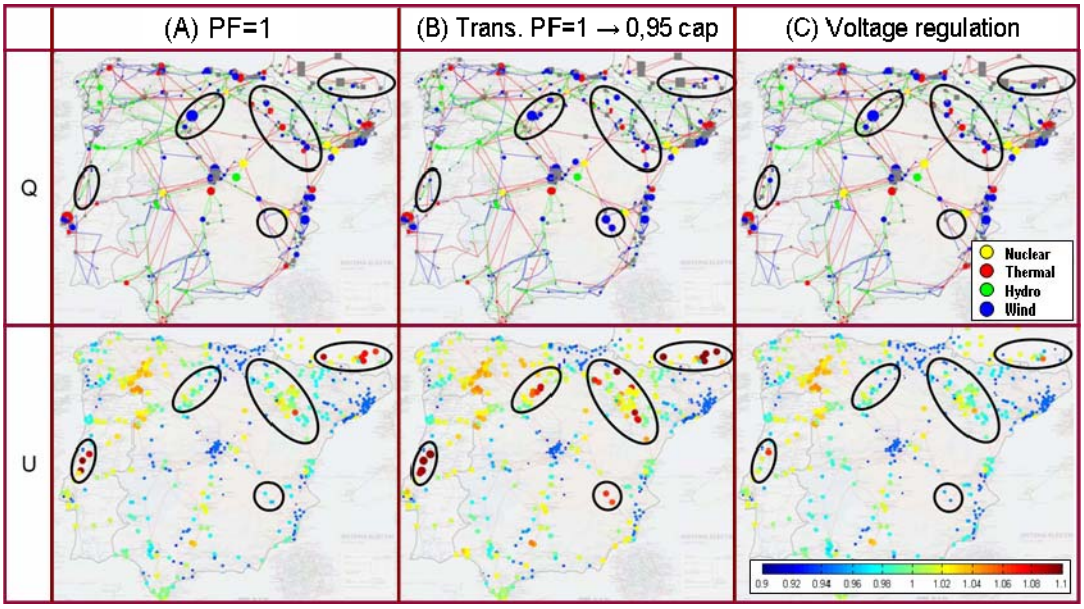

Fig. 5. Reactive power and nodal voltages in transmission network in three scenarios.

Table 1: Incentive payment for reactive compensation in Spanish wind parks

	cos φ	Incentive (%)		
		Peak	Flat	Valley
Inductive	<0,95	-4	-4	8
	<0,96 and 0,95	-3	0	6
	<0,97 and 0,96	-2	0	4
	<0,98 and 0,97	-1	0	2
	<1,00 and 0,98	0	2	0
	1,00	0	4	0
Capacitive	<1,00 and 0,98	0	2	0
	<0,98 and 0,97	2	0	-1
	<0,97 and 0,96	4	0	-2
	<0,96 and 0,95	6	0	-3
	<0,95	8	-4	-4

Table 2. Periods of day

	Period	Time
Winter	Peak	18:00 to 22:00
	Flat	8:00 to 18:00 22:00 to 24:00
	Valley	0:00 to 8:00
Summer	Peak	9:00 to 13:00
	Flat	8:00 to 9:00 13:00 to 24:00
	Valley	0:00 to 8:00

All wind turbines (fixed and variable speed ones) and capacitor banks in substation can be coordinated to achieve certain PF values by means of a central controller [1].

Nowadays, many of the parks are not designed to vary their PF objective. This is because before the adoption of the RD 661/2007, they were designed to achieve a PF equals to 1 all the time, which is only valid for the flat hours. However, many of these parks can achieve PF less than 0.95 inductive during valley hours by disconnecting the batteries of condensers. Thus, high bonuses can be achieved 20 hours a day.

2. Transition between objective PF (Scenario B)

During the transition between periods of day, abrupt changes in the reactive power generated by wind parks can be produced due to the change in objective PF. For example, in a high wind situation, wind parks would change their PF objective from 0.95 inductive to 1; so, in a short period, all wind parks will inject to the network a significant amount of reactive power. Therefore, conventional generators (thermal, hydro, nuclear) will compensate all the reactive power injected by wind generators to maintain nodal voltage. This will provoke a change in the transmission network voltage due to the abrupt changes of reactive power injection.

In some cases, voltage variations are not significant (if there is conventional generation near wind farms) but in other situations they really can be.

The most remarkable situations are usually those produced in distribution networks where the wind farms are. The worst situations take place in distribution networks with voltage levels of 45 and 66 kV and in 132 kV radials networks.

This situation can occur in all transitions throughout the day. In Spain, there are four transitions each day: valley to flat, flat to peak, peak to flat and flat to valley. However, the first and last transitions are the most important, because they imply more reactive variation than the other ones.

The Spanish TSO has established in certain areas of the network different PF objectives than those established in Table 1. This is to avoid the problems caused in areas with high wind energy generation, where there is not enough conventional generation to control the voltage.

3. Implementation of voltage regulation in wind parks (Scenario C).

The participation of wind farms in the voltage regulation has the following advantages:

- It provides high-capacity generation / consumption of reactive power from wind farms.
- Avoid abrupt changes in generation/consumption of reactive power thanks to transition periods (flat, peak and valley).
- Although there are wind farms distributed throughout the national territory, there are areas with higher concentration, so voltage regulation enables a best voltage control.
- There is less variation in the voltage of distribution networks with high wind power.

In short, you can reduce variations of nodal voltage throughout the entire network and all over the day.

If the trend of installing wind farms continues to grow at current rates (the objective of the European Community is to achieve a 20% of renewable generation in 2020), there will be higher penetration of wind energy. In Spain, a 40% of wind energy penetration has been achieved in windy days. In these situations, the conventional generation penetration will have reduced their ability to manage reactive power. This implies why wind generation should be involved in controlling stress.

The Spanish legislation establishes in grid code P.O. 7.3 [5] the requirements for voltage regulation of the conventional generation. Conventional generation must participate in voltage regulation with a reactive power equivalent of 15% of the maximum rated power. This participation is not remunerated. They can also take part with greater reactive power margins; in this case, participation is remunerated.

Nowadays, all Spanish wind farms over 10 MW are associated to control centres and they can receive instructions of TSO from CECRE (control centre for renewable energy). The wind park participation in voltage regulation could be achieved if PF objective values were sent to these control centres by TSO. PF values could be calculated as function of nodal voltage.

4. Spanish network characteristics

The regulation of tension in the Spanish network is conditioned by two facts:

- There are few international interconnections.
- A big amount of wind farms are connected to the distribution network.

1) Interconnections of the Spanish transmission network

Spain´s interconnections with neighbouring countries mainly affect the management of wind energy. The Spanish system has interconnections only with France, Portugal and Morocco.

The number of connections with France is very low, which implies an exchange capacity around 1,000 MW. Therefore, the connection of the transmission network with other networks of the UCTE is very weak.

The ability to trade with Portugal is reasonably high (Spain and Portugal have created a unified market called MIBEL), but it is a country that has no neighbours. Furthermore, high wind generation occurs simultaneously in Spain and Portugal due to their geographical location.

Interconnections with Morocco will not increase the network reliability in Spain, due to the absence of a robust transmission network in Africa.

Consequently, an adequate network management in the Peninsula (Spain & Portugal) is essential to avoid situations where the connection with another UCTE could be lost.

2) Wind farms connected with distribution network

Many of the wind farms are connected to distribution networks in the voltage levels of 132 kV and 66 kV. Energy generated by these parks is injected to the transmission grid through the substation boundary. In these areas, the distribution system meets not only the distribution function, but it is also responsible for transmitting the power of the parks to the transmission network.

When winds are high, there is a large amount of wind energy in these areas; it is injected from the distribution network to the transmission network. The first consequence is an increase of tension in these distribution networks.

Data published by the system operator (REE) is only related to the transmission network and, therefore, does not include most of the 132 kV networks. Accordingly, within those areas where wind generation is located, most of the calculations are made with aggregate data.

V. EXAMPLE

The map in Fig. 6 shows the distribution of generation and consumption of nodal active power in the Spanish transmission network, with high wind power in the east of the country during a flat period.

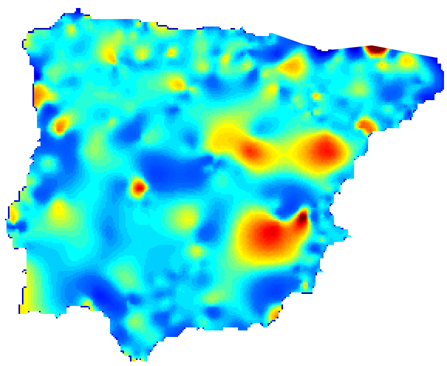

Fig. 6. Distribution of nodal active power

The curves in Fig. 7 and Fig. 8 present the results of the distribution of reactive power in the following three situations:

- Flat period: wind and special regime generation have unitary PF.
- Peak period: wind and special regime generation have changed from unitary PF to 0.95 capacitive.
- Wind and special regime generation have implemented voltage regulation.

There are two big areas, located in the east, where the reactive power injected increases when changing from PF=1 to PF=0.95 capacitive. Within these areas there are a great number of wind parks. When compared with the implementation of voltage regulation, it can be seen that the parks in those regions decrease their PF, hence reducing the reactive energy injected to the transmission network.

The Fig.9 represents the histograms of the previous three cases for four different voltage levels. It is shown that with PF=1 the reactive power is lower than with PF=0.95 capacitive in all the voltage levels of the network. It is also noticeable that allowing the wind parks and the rest of the special regime to participate in the voltage control, the reactive power doesn't reach extreme levels, next to the limits. This results in a more concentrated histogram, with less standard deviation than for any of the other two situations.

From Fig. 10 to Fig. 13 results of the three scenarios at different hours is presented.

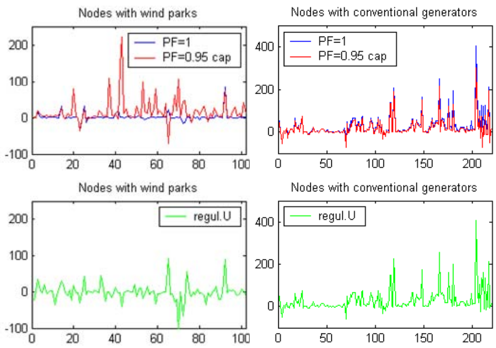

Fig. 7. Nodal reactive power

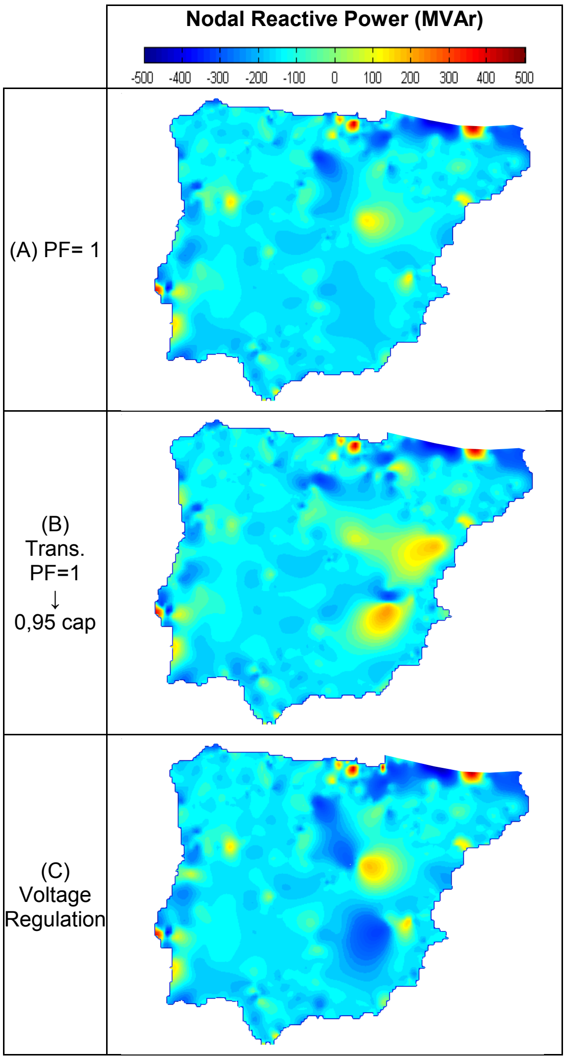

Fig. 8. Distribution of nodal reactive power in different scenarios

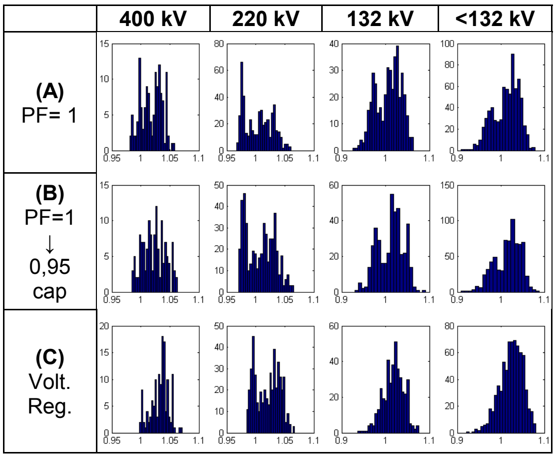

Fig. 9. Voltage histograms

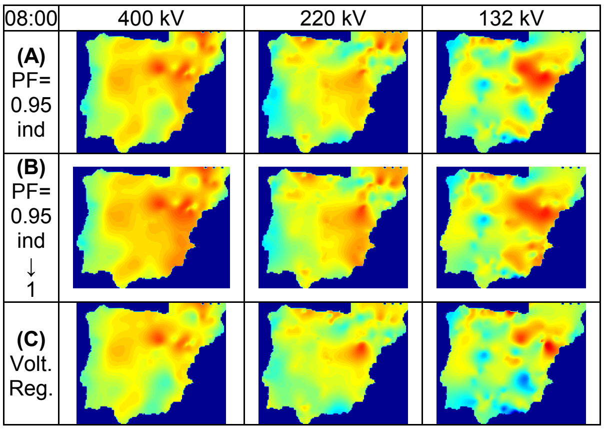

Fig. 10. Nodal voltage at 8:00 hours

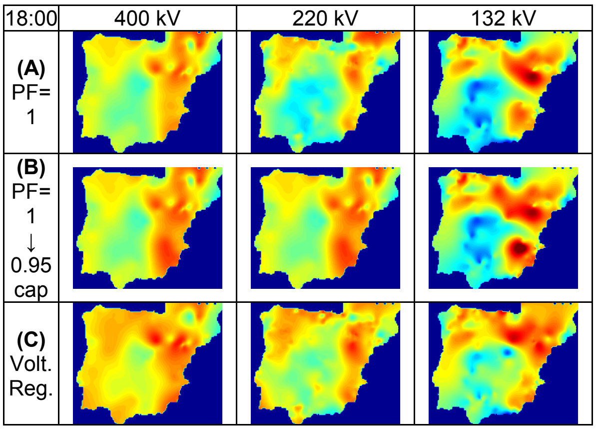

Fig. 11. Nodal voltage at 18:00 hours

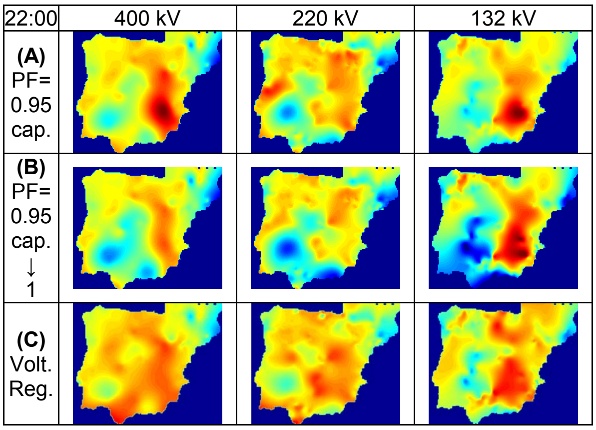

Fig. 12. Nodal voltage at 22:00 hours

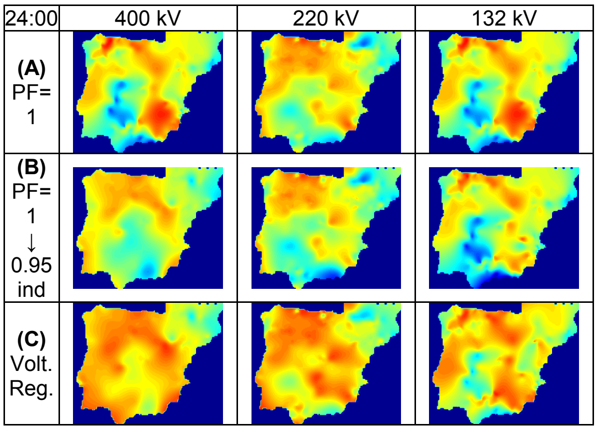

Fig. 13. Nodal voltage at 24:00 hours

VI. Conclusions

This paper deals with the impact of including wind parks in the network voltage control. For the sake of this study, an optimal power flow approach has been developed, and the obtained results under different situations have been analyzed. The main conclusions are:

1. The increase in wind energy penetration implies a reduction in the capacity of conventional generation to regulate nodal voltage. Participation of wind generation in voltage regulation would improve the operating conditions of the network, hence reducing the margin of voltage variation and the reactive power to be generated.
2. Problems related to voltage variations in power network, caused by abrupt PF variation during transition of periods (peak, valley and flat) are reduced thanks to the participation of wind farm in voltage regulation. Nodal voltage deviation and margin of reactive injection are reduced too.
3. Reactive control in wind parks provides regulation capacity distributed throughout the entire network. A voltage regulation scenario would contribute to a higher stability in transmission and voltage distribution.

VII. Acknowledgment

The authors would like to thank the personnel of Sotavento Experimental Wind Park for their contribution and help with field experience and for their accessibility to the measurement data.

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