Incidence on Power System Dynamics of High Penetration of Fixed Speed and Doubly Fed Wind Energy Systems: Study of the Spanish Case

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***Abstract*—In this paper, a preliminary analysis of the impact of high wind power penetration in the planning and operation of the Spanish power system is presented. The problems studied in the paper are those related to the stability of the power system. This key subject could be deeply influenced by the installation of up to 15,000 MW of wind power generation as it has been planned for the next six years. The analysis presented here is based on the results of dynamic simulations. Dynamic models of the induction generator (squirrel cage and doubly fed) and models of the wind farms have been developed to make possible the simulations. From the simulations results some conclusions and recommendations have been extracted, which would contribute to the appropriate integration of the new wind generation foreseen for the Spanish power system.**

***Index Terms*—Doubly fed induction generator, power generation control, power system stability, wind power generation.**

I. INTRODUCTION

AN important increase of power produced by wind energy is foreseen for the next years in Europe. Many countries have very important plans to install new wind energy farms: Germany has recently become the country in the world with the largest amount of wind power installed, Denmark has a very important plan to install offshore wind energy power plants; in Spain more than 3,000 MW have been installed and very fast growing plans are under consideration. Greece, Portugal and other countries are also involved in the movement toward this renewable energy source. In Spain an amount as high as 15 000 MW of installed wind generation power has to be considered for the next 6 years if all different regional plans are taken into account. As the Spanish power system has presently a power peak of about 35 500 MW, the penetration of Wind Energy Conversion Systems (WECS) in Spain could reach a very important amount especially in off-peak situations and in particular regions. Additionally, the particular situation of the Spanish power system, with weak interconnection ties with the rest of Europe, suggests that those integration studies could be more important for the Spanish power system than for other systems.

WECS can be broadly divided between fixed speed and variable speed devices. Fixed speed devices consist of asynchronous generators directly connected to the grid, while variable speed machines are connected through an electronic interface. The first type is simpler and cheaper, but the second one usually has better performance and allows active and reactive power regulation. Doubly Fed Induction Generator (DFIG) is widely used nowadays in Spain.

Most of the Spanish wind energy comes from fixed speed turbines rated between 500 and 1000 kW, clustered in wind farms of a power comprised between 30 and 250 MW (more than one wind farm connected to the grid at the same high voltage bus). In this paper, a study of the incidence on the Spanish network dynamics of a high level of wind generation is presented. The transient behavior of both fixed speed and DFIG devices are analyzed when a large wind power penetration is expected. This study has been conducted in two electrical regions of the Spanish system that have very important wind energy development plans: Galicia and Aragón-Navarra.

II. DESCRIPTION OF THE WECS

For modeling WECS, a suitable model of wind and mechanical system must be provided. Two wind models have been used for the study of the effect of wind speed fluctuations and the corresponding generated power variations in the system. One of them is based on the Kaimal spectrum [1], while the second one uses direct wind speed measurements provided to the authors by CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecno-lógicas). The mechanical drive train is modeled as a second order system. The use of more complex models that allow the representation of pulsating torque does not seem to make any difference in the results [2]. However, the values of stiffness and damping coefficients may have an appreciable influence on simulation results [3].

Power given by a wind turbine, under smooth wind flow conditions is given by (1)

$$P = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \quad (1)$$

ρ is the density of the air, A the rotor area, v the wind speed, C_p a dimensionless performance coefficient [4] and λ the tip speed ratio, $\lambda = \omega R/v$, R being the radius of the rotor and ω the mechanical angular speed of the blades; β is the pitch angle.

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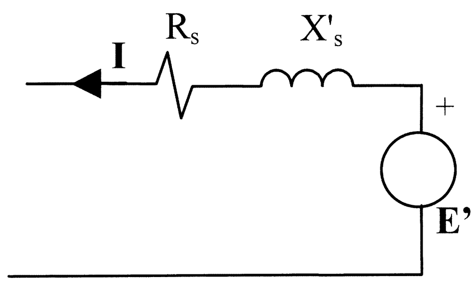

Fig. 1. Equivalent circuit of the induction generator.

The performance coefficient is different for each turbine, and it must be obtained experimentally.

A. Fixed Speed Devices

The widely used squirrel cage induction generator (SCIG) has been considered. Both the stator transients and the subtransient regime can be neglected in this study. Then, the transient model represented in Fig. 1. will be used [5].

The internal voltage, represented by the phasor E', is given by the differential equation:

$$\frac{dE'}{dt} = \frac{-1}{T'}\left[E' + j(X_{ss} - X'_s)I\right] + jE's\omega_0 \tag{2}$$

where X_{ss} is the total stator reactance, X'_s the transient reactance, and T' the rotor transient time constant. The slip is determined from the generator speed, ω_g, and synchronous speed, ω_s, as: $s = (\omega_g - \omega_s)/\omega_s$ (sign is the opposite of usual one, because this device generates energy). The stator current, I, is calculated at each instant by solving the equations of the entire network, which includes the equivalent circuit of Fig. 1 with the actual value of E'.

The operational speed of this machine is in most situations very close to the synchronous speed, and the turbine torque may be obtained by means of the characteristic curve giving the power vs. wind speed, usually provided by the manufacturer for constant speed operation.

B. Doubly Fed Induction Generator

A short description of the DFIG follows. More details can be found in [5]. A justification of performed simplifications is given in [6]. A scheme of the system is shown in Fig. 2. In this system, power can be delivered to the grid both by the stator and the rotor.

Delivered rotor and stator power are:

$$P_R = sP_s \quad P_m = (1+s)\cdot P_s \tag{3}$$

where P_m is the mechanical power delivered to the generator, P_s is the power delivered by the stator, P_R is the power delivered by the rotor. When this device works below the synchronous speed the rotor takes power from the stator. When it works above the synchronous speed, the rotor gives power, and power is delivered to grid through stator and rotor. The range of variation of slip s determines the size of converters C_1 and C_2, whose size is a fraction of the rated power. Because of mechanical restrictions, a practical speed range could be between 0.7 and 1.1 p.u.

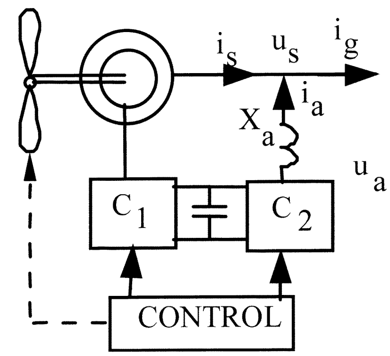

Fig. 2. Scheme of the doubly fed induction generator.

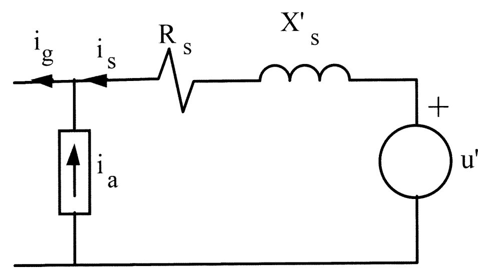

Fig. 3. Generators and converters, as seen from the grid.

Converters C_1 and C_2 provide the control of this device. Converter C_1 controls rotor voltage, and therefore electromagnetic torque. Converter C_2 maintains the grid voltage and the exchange of reactive power with the grid. In the model, the converters are supposed ideal, and the DC link between them has constant voltage. A simple electrical model of the whole system is given in Fig. 3.

In this figure, i_a is a current source that represents the stator converter C_2, and u' is a voltage source that represents the rotor control, performed by the converter C_1. The values of the source u' and the inductance X'_s are given by the equations:

$$u'_d = \frac{\omega_s L_m}{L_{rr}}\psi_{rq}$$

$$u'_q = -\frac{\omega_s L_m}{L_{rr}}\psi_{rd} \tag{4}$$

$$X'_s = \omega_s\left(L_{ss} - \frac{L_m^2}{L_{rr}}\right) \tag{5}$$

where L_{rr}, L_{ss} are the self inductances of rotor and stator windings, L_m is the is the mutual inductance between rotor and stator windings, ψ_{rd}, ψ_{rq} are the components d, q of rotor flux linkages and ω_s is the stator flux linkages frequency.

Converter C_2 controls the voltage u_a in order to regulate the current through reactance X_a, and therefore to give the value of I_a. This inductance is added as a harmonic filter and to facilitate the control of the current.

The generator dynamic model has two state equations plus the swing equation. It is similar to the squirrel cage model, but rotor voltage is not zero. Stator transients have been neglected, as usual in Power Systems Dynamic Studies [5], even with complex control systems such as the one described here.

1) Control System: Torque Control: This control acts on the rotor side converter C_1. The expression of electromagnetic

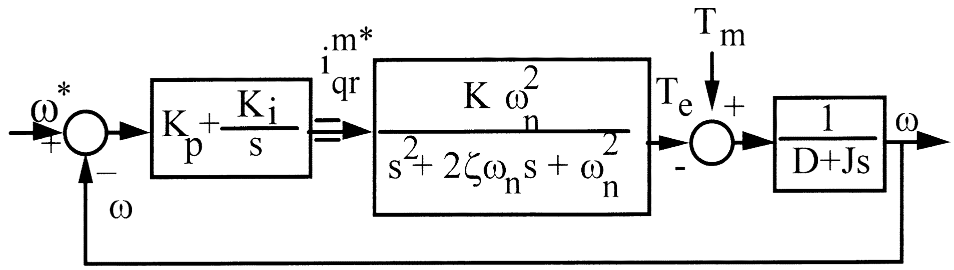

Fig. 4. Speed control.

torque, in Park variables in a reference frame where direct axis coincides with stator flux linkages ψ_s, is,

$$T_e = -\frac{L_m}{L_{ss}}\psi_{sd}^m i_{rq}^m. \tag{6}$$

Current i_{rq} is the q component of rotor current. Superscript m means that a new reference frame has been chosen to arrive at the more simple (6). The control loop is shown in Fig. 4. The aim of the loop is to modify the electromagnetic torque of the generator according to speed variations through the value of i_{rq}^m. Assuming that ψ_s remains constant, the electromagnetic torque is proportional to i_{rq}^m. The second order system in the loop between i_{rq}^m* and T_e represents the generator (the inner loop of i_{rd}^m is not represented).

As shown in (4), the voltage source u' of figure depends directly on rotor flux, whose expression in the new reference is

$$\psi_{rd}^m = \left(L_{rr} - \frac{L_m^2}{L_{rr}}\right) i_{rd}^m + \frac{L_m}{L_{ss}}\psi_{sd}^m \tag{7}$$

$$\psi_{rq}^m = \left(L_{rr} - \frac{L_m^2}{L_{rr}}\right) i_{rq}^m + \frac{L_m}{L_{ss}}\psi_{sq}^m = \left(L_{rr} - \frac{L_m^2}{L_{rr}}\right) i_{rq}^m. \tag{8}$$

Therefore, any variation in rotor current can be considered as variations in the value of u'.

2) Control System: Reactive Power Control: This control is provided by converter C_2 of Fig. 2. In Park variables, with a reference frame placing the direct axis in coincidence with u_{sd}, the equations that links voltages and currents through X_a are

$$u_{sd}^s = -\frac{X_a}{\omega_{\text{base}}}\frac{di_{ad}^s}{dt} + X_a i_{aq}^s + u_{ad}^s \tag{9}$$

$$0 = -\frac{X_a}{\omega_{\text{base}}}\frac{di_{aq}^s}{dt} - X_a i_{ad}^s + u_{aq}^s. \tag{10}$$

Superscript s is for the new reference frame. The expression of complex power supplied by this converter is $S = u_d^s i_{da}^s + j u_d^s i_{qa}^s$. In this scheme, active power cannot be controlled in C_2, since the power that this converter receives from C_1 must be delivered to the grid. Reactive power, however, can be controlled by means of i_{aq}^s. If the wind turbine has the reference of generating the reactive power Q^* then

$$i_{aq}^{s^*} = -\frac{Q^*}{u_{sd}} - i_{sq}^s \tag{11}$$

3) Control System: Control Strategy: Control systems of DFIG allow a great variety of control strategies. A common one, that has been followed here, is to maximize the obtained power for each wind speed. Fig. 5 shows the relationship between mechanical power and mechanical speed of a 400 kW wind turbine for several wind speed values. The dotted line that links all the maxima shows the optimal operating points (maximum value of performance coefficient C_p). Variable speed devices allow the selection of mechanical speed in order to work under these conditions. This frequency is used as reference in the speed control of Fig. 4. Maximum speed and rated power limit the performance of the device.

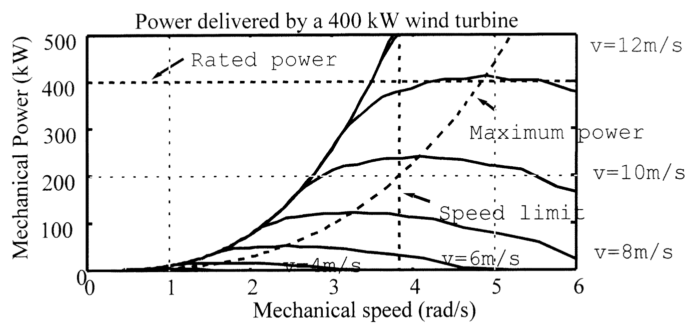

Fig. 5. Maximum power strategy.

C. Wind Farm Model

To model the wind farm, it has been considered that the wind turbines are arranged in line, so that a wind front reaches each wind generator with a small delay between them. This delay is a function of angle between the speed of the wind front and the wind generator line. The mechanical torque is computed for each individual wind generator of the farm and then the torque resulting from the addition of all of them is applied to an equivalent model of the wind farm. The dynamic response of this wind farm model has been compared in a particular case with that of a detailed model in which each wind turbine, generator, capacitor and the associated electrical system were considered separately. It was confirmed that in all simulations of interest in this study the dynamic responses of the detailed and the equivalent models were practically the same.

III. Study of the Spanish Case

A. Framework of the Study

A study of the impact on the Spanish system of the new wind generation planned until the year 2004 is reported here. The basis for the study are the dynamic simulations that have been performed using the PSS/E package, with user developed models of the squirrel cage induction machine, of the doubly fed induction machine and of the mechanical coupling between the wind turbine and the induction generator. A wind farm model that uses the previous components and a model of the fluctuating wind speed input have also been developed. Wind power installed in the considered time horizon (2004) will be 1950 MW in Galicia and 3650 MW in the Aragón-Navarra region. Wind power generation has been connected to the grid in different 220 and 132 kV buses, including the line impedance to reach the main grid bus. 90% of power delivered by wind generation has been considered here. The study cases have been prepared using the forecasted demand data for the whole Spanish system (basically a 10% load increase from 2000 to 2004) and the network developments needed for evacuating the wind power in the Galicia and Aragón-Navarra regions. About conventional generation, two new 450 MW combined cycle plants has been considered in peak situation The dynamic model of each wind farm includes an equivalent model of its internal electric network. An equivalent wind generator at 690 V is considered. In the case of squirrel cage generators, an equivalent shunt capacitor to compensate the reactive power up to a 0.99 inductive power factor is also included at this voltage level. The wind farm models also includes a step-up transfromer 690/20 kV, a short 20 kV line and another transformer from 20 kV to 132 kV or 220 kV.

The electrical data and the curve of generated power vs. wind speed are included in Appendix A. Data of the mechanical coupling between the wind turbine and the induction generator are difficult to obtain, and typical values have been chosen. Undervoltage and overspeed protections have also been included. The effect of overcurrent protections would not provide different results because, with the actual settings, they are much slower than undervoltage protections and in all the cases that they would act, overspeed protections would do it also. A reduced map of the studied zone is given in Appendix B.

B. Simulation Results

It has been studied the analysis of the dynamic response of the system to network faults: short circuits, line trips, generator trips. These are typically 20 seconds simulations. From the analysis performed, it has been concluded that the effect of fluctuations of wind power generation is negligible compared with the effect of short circuits in the power grid. As a consequence, during the 20 seconds that last the dynamic simulations, wind power input has been considered constant.

C. Short Circuits in the Transmission Grid

1) Squirrel Cage Induction Generators: When a short circuit occurs in the transmission grid a voltage dip propagates through it and reaches the wind farms. The voltage dip that reaches one particular wind farm is more or less deep depending on the type of short circuit, the point where the short circuit has occurred and the number and size of synchronous generators that are located near the fault, that react increasing their reactive power output. In regions with important wind energy penetration and little synchronous generation, voltage dips can be quite deep. When a voltage dip reaches a wind generator (squirrel cage machine), the generated active power falls, while the mechanical power does not change; so the wind generator accelerates. The acceleration of the machine can be large if the inertia is relatively small.

TABLE I
STUDIED CASES

SHORT CIRCUIT IN		CLEARING	SITUATION	
VOLTAGE (kV)	BUS BAR	TIME (ms)	PEAK	OFF PEAK
400	MAGALLON	100	CASE 1	---
400	LA SERNA	300	CASE 2	CASE 3
220	MAGALLON	500	CASE 4	CASE 5

TABLE II
TRIPPING TIME IN DIFFERENT CASES

WIND FARM	TRIPPING TIME				
	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
ONCALA	1,41	1,36	1,37	1,47	1,45
VOZ MEDIA		1,39	1,4	1,59	1,48
REMOLINO		1,45	1,44	2,95	1,54
TARAZONA		1,46	1,45		1,55
RUEDA		1,52	1,48	2,94	1,55
MUELA			1,53	2,91	1,55
MONCAYO			1,49		
BELCHITE			2,94	2,91	1,56
JAULIN			2,94	2,92	1,57
MARIA					1,58
LOS VIENTOS					1,58
TERUEL					1,59
CALAMOCHA					1,60
SANGUESA					1,67
CORDOVILLA					1,65
TUDELA					1,61
QUEL					1,67
TOTAL MW	450	890	1487	1182	2110

When the short circuit is cleared, as the speed has increased, the active power tends to be higher than before the fault. But this also requires higher current, which produces higher voltage drops in the lines and transformers, and therefore the voltage at the induction generator does not recover immediately the pre-fault value, but a transient period follows. As a consequence, it may happen that the machine continues accelerating until the overspeed protection trips. In fact, the wind farms nearest to the fault will trip first. Other wind farms might also trip if they would reach its over speed protection threshold. When some wind farms trip, the voltage tends to recover. In this way, a transmission system normally cleared fault could induce a large number of wind generators tripping in the nearby area. In areas such as the Aragón-Navarra with the present wind generation plans, more than 1000 MW of wind power could be tripped in a single, normally cleared, transmission line fault. Five short circuit simulations have been selected for this analysis as shown in Table I. The results of five short circuit simulations are summarized in Table II, where it is shown that as the wind generation penetration increases, the system becomes weaker in the sense that a larger number of wind generators will trip by their over speed protection when a transmission line fault occurs.

2) Undervoltage Protection: In Spain, all wind generation farms must have an instantaneous undervoltage protection system adjusted to the 85% of the rated voltage [7]. It has been found in all simulations performed that if this protection operated instantaneously, all 3650 MW wind generation in the

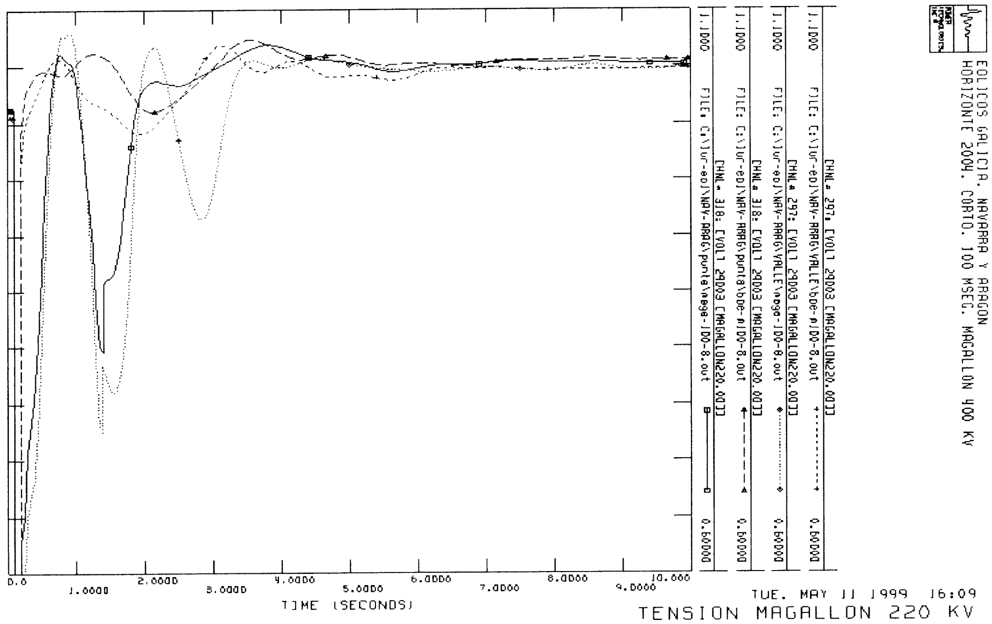

Fig. 6. Voltage at MAGALLON 220 kV bus. The more oscillating curves have been obtained without undervoltage protections (continuous line, peak load situation; dotted line, valley situation). Of the other two, the peak load situation is the one with a higher oscillation.

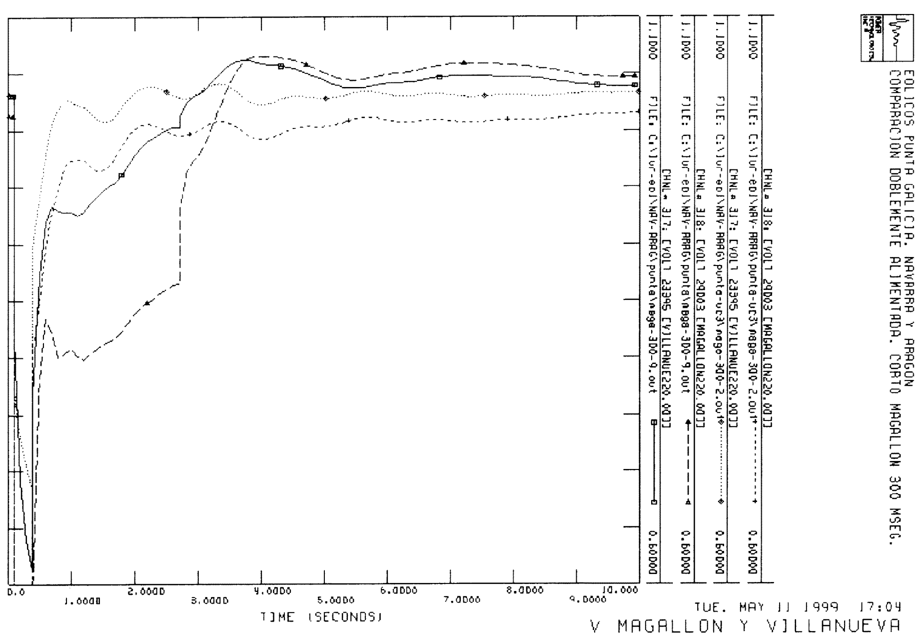

Fig. 7. Comparison between responses produced by SCIG and DFIG in substations of Magallón and Villanueva. The continuous line is voltage in Villanueva with SCIG. Above it, in the two first seconds of simulation, are voltage in Magallón with DFIG, and, higher, voltage in Villanueva with DFIG. In the bottom in the first 2 s, voltage at Magallón with SCIG.

area would have tripped. Even in a short duration fault correctly cleared in the 400 kV system (not so near the wind farms) a large amount of wind generation could be tripped. Of course, this would be unacceptable for system security reasons and the simulations presented in the Section II have been continued without these protections tripping (see Table III).

In Fig. 6, the evolution of the voltage at one 220 kV bus after a 400 kV bus bar fault cleared in 0.1 seconds is shown in two different base cases (peak and off-peak situation) with and without undervoltage instantaneous tripping in all wind farms.

TABLE III
CURVE P–V

Curve P-v									
M/s	4 2	5	7	9	11	12	14	21	25
P (kW)	0	20	114	254	407	490	600	600	trip

In the two cases with undervoltage relays all wind generation (3650 MW) have tripped instantaneously, and the voltage is restored quickly, but the power lost is compensated through the interconnection lines with France, which become overloaded and will trip later. In the other two cases where no instantaneous tripping has been applied, wind generators produce large oscillations lasting 3 or 4 seconds until some of them are tripped by their overspeed protection and the rest remain stable. It can be seen that there are two aspects of the problem. One the one hand, it is better to trip as soon as possible all wind farms that will trip anyway. It has been found in the simulations that many wind generators if left untripped, would oscillate and produce a disturbance that could last up to 4 seconds until the over speed protection trips them. This long disturbance would provoke the tripping of other wind generators of the area that would not have tripped otherwise. For this reason, the instantaneous tripping would be good. But, on the other hand, if it were installed in all wind generators then as said before, all wind generators in the affected area would trip after some single transmission line fault.

Then the problem is to trip as quickly as possible those wind generators that are more affected by the transmission system fault without tripping the rest. This objective could be achieved using either an instantaneous voltage threshold much lower than 85% or, perhaps better, a time delay. In fact a well-studied scheme of perhaps two voltage thresholds with two-associated time delays could be a good solution.

If the transmission system fault is quickly cleared and the most affected wind farms are tripped successfully in a short time, then the disturbance will probably be harmless from the power system viewpoint. However, this objective is not easily achievable since the compromise between an excess of wind farm fast tripping and the lack of it, that would lead to a late over speed tripping of more wind farms, is a difficult task.

3) Doubly Fed Induction Generators: The simulations performed show that only between a half and one third of the wind generation tripped in the case of squirrel cage generators would be tripped with this type of generator. That is, of course, while all other conditions remain equal. The instantaneous undervoltage tripping would be even more inappropriate for these machines. The much more favorable response of this kind of generator (from the power system viewpoint) can be seen in Fig. 7 where the voltages of two 220 kV buses in two particular simulations, one with each kind of induction machines have been represented.

The two voltages that are more quickly recovered correspond to the simulation with doubly fed induction machines. It is seen that in the simulation with the squirrel cage machines one of the voltages (that of the faulted bus) remain under 0.85 p.u. during almost 5 seconds. In the doubly fed machine case both voltages almost recover the 0.85 p.u. value shortly after the fault clearing (0.4 seconds) and even the bus with the fault recovers to about 0.98 p.u. after only 1 s.

IV. Conclusions

The performed simulations seem to show that:

1) A large amount of not-controlled wind generation connected in small areas could have negative consequences on system dynamics. Two possible alternatives are, either to use variable speed devices in the wind farms or to install carefully designed dynamic voltage support systems in the area.
2) It is recommended that the adjustments of the voltage protection be carefully studied. Instantaneous tripping at 85% of nominal voltage seems prone to cause unexpected problems. A suggestion for the change could be voltage protective systems with two voltage thresholds and two different time delays.
3) In the performed tests, variable speed devices seems to have a much better dynamic performance than fixed speed. In the proposed example, they do not need capacitors.

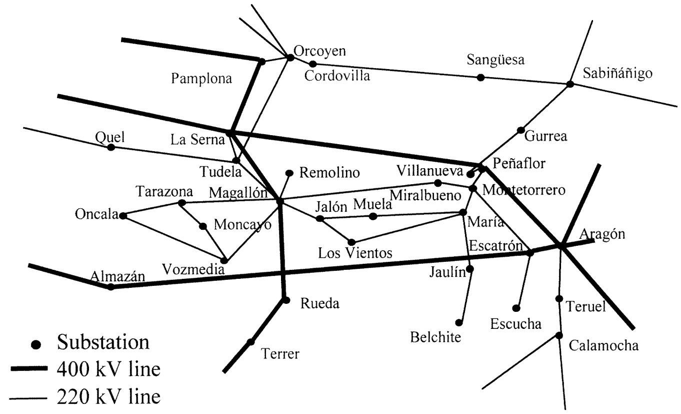

Fig. 8. Spanish transmission grid (fragment).

Appendix A
Data of Wind Generators

Induction Generators (Machine Base):

Stator Resistance 0.0059 p.u.
Stator Reactance: 0.0087 p.u.
Magnetizing Reactance: 4.76 p.u.
Rotor Resistance: 0.019 p.u.
Rotor Reactance: 0.143 p.u.
Generator Inertia: 0.45 s
Generator Damping: 0.005 p.u.

Wind Turbine—Induction Generator Coupling:

Coupling stiffness: 50 p.u.
Coupling damping: 1 p.u.

Wind Turbine Model:

Inertia constant: 5 s
Damping: 0.005 p.u.

Modeled Protections:

Over speed (each wind generator): 1.15 p.u.
Undervoltage (wind farm): 0.85 p.u.

Transformer $T1$:

Rated Power: 1.1.P
Impedance: 6%
X/R ratio: 12

Transformer $T2$:

Rated Power: 1.1.P
Impedance: 11%
X/R ratio: 28

Line (100 MVA Base):

R: 0.008 p.u. (100 MVA base) $X = 0.017$ p.u.

APPENDIX B
PART OF SPANISH 2004 PLANNED TRANSMISSION GRID (ARAGÓN-NAVARRA GRID)

See Fig. 8.

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