Modeling of Squirrel Cage Turbine for Voltage Dips Studies

M.P. Comech, S. Martín, J. Mur, I. Franco, M. García-Gracia

***Abstract*— European Grid Codes has been reviewed due to the increasing levels of wind-turbine generation in modern power systems. The main requirements concern the fault ride through capabilities. Since simultaneous loss of several thousand MW wind generation in system fault would lead to stability problems.**

The wind turbine fault ride-through capabilities can be analyzed by means of dynamic simulation.

The aim of this paper is to investigate the modeling requirements of wind turbine for power system studies. The study is applied to a squirrel cage wind turbine.

***Index Terms*-- Wind power generation, wind park modeling, grid code, power system dynamics.**

I. Introduction

THE number of wind energy installations is rapidly growing worldwide. With increasing wind power production, it is important to predict the grid interaction of wind turbines.

In the past, wind turbine generators were allowed to disconnect from the system during faults [1]. Nowadays, there is an increasing requirement for wind farms to remain connected to the power system during faults, since the wind power lost might affect the system stability.

When a fault happens, the system voltage at that point is essentially brought to zero volts. The flow of current into the fault results in voltage drops throughout the network. This effect is commonly named voltage dip. Loss of generation during voltage dips can affect system stability. Due to this fact, Wind farms shall be able to withstand voltage dips with the depth and the duration described on Grid Code.

The behavior of wind farms during voltage dips is analyzed by means of dynamic simulation. PSS/E [2] is a widely recognized tool of power system operators and its results tie closely with what is measured in real life. To allow the investigation of the behavior of wind generators and their impact on the electric power system, wind farms have to be modeled.

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Modeling wind farms requires careful analysis of the equipment and controls to determine the characteristics that are important in the timeframe and bandwidth of such studies [3].

The aim of this paper is to investigate the modeling requirements of wind turbine for power system studies. The study is applied to a squirrel cage wind turbine.

II. The Fault Ride Through

The increasing interest in wind generation has brought a number of areas of Grid Code into focus, which means severe difficulties for wind farms. Therefore, a review of the connection conditions was necessary for wind turbines to become an integrated power source on the transmission system.

The area of fault ride through capability is one with serious implications for system security and thus has implication for the level of penetration of wind generation allowed on the network. When a fault happens, the voltage drops throughout the network, with the consequential tripping of any generation without sufficient fault ride through capability. Following fault clearance, the system would need sufficient spinning reserve to cover the loss of the generations disconnected during the dip. During system perturbances the system stability depends on the generators connected to the system to restore the system to normal operation. Disconnection of generation in the event of system faults would lead to local voltage problems and power quality issues and, in extreme, system collapses.

European system operators have come to a different ride through capabilities. In general, there are two different groups of requirements being put on wind turbines:

- *First group*: Turbines must remain connected to the HV system, for a specified minimum duration, for a fault resulting in zero volts at the point of common coupling. This group includes England [4], Wales, Scotland, France and Denmark [5].
- *Second group*: Turbines must remain connected to the HV system, for a specified minimum duration, for a fault resulting in a minimum stated voltage at the point of common coupling. This group includes Germany (E.ON Netz Grid Code) with a stated voltage of 15 % [6], Spain 20 % (draft) [7,8] and Ireland 5 % [5].

The difference between the two groups is primarily the magnitude of voltage dip. The first group requires operation for 100 % dip; the requirements of the second group are not so hard.

Fig. 1 shows the voltage vs Time profile at point of common coupling of the E.ON Netz Grid Code as an example. A wind farm must remain connected to the system for voltage dips, where the voltage measured at the HV terminal of the grid-connected transformer remains above the heavy black line.

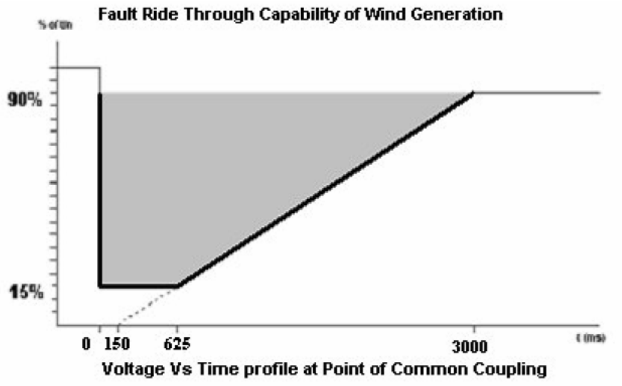

Fig. 1. E.ON Netz voltage dip curve.

Simulation models must be developed to analyze the wind farm behavior before voltage dips. Verification procedures are being developed in order to verify simulation models from de results obtained on field test in the wind farm. These models must be suitable for investigating the voltage dip behavior of wind farm connected to large systems.

III. Model Requirements

Dynamic simulation allows to verify that the wind farm fulfill the requirements imposed by new grid code. Wind turbine models and wind farm models must be suitable for investigating voltage dip behavior.

The behavior of a very detailed model can be closest to the real wind turbine performance, but the computational cost may be excessive. Therefore, there must be agreement between the detail level and the computational cost.

When the response to grid disturbances is of interest, it is mainly the generator description that affects the response of the turbine. However, simulation models must incorporate the description of the aerodynamics and drive train in order to predict their impact.

In this paper the different modeling options are analyzed in order to obtain the requirements that must fulfill the model used for the simulation of fault ride-through.

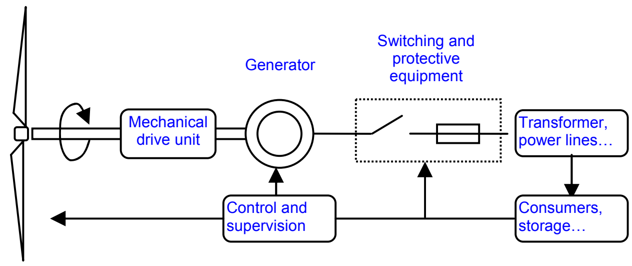

Fig. 2. Fixed speed wind turbine scheme.

A. Rotor model

The wind turbine rotor extracts the energy from the wind and converts it into mechanical power. The rotor is a complex aerodynamic system that can be modeled with different detail levels. There are models that consider the rotor geometry and the distribution of the wind in the rotor [9]. These models have a drawback: the computation time become complicated and lengthy.

To solve this problem, a simplified rotor model is normally used when the electrical behavior of the system is the main point of interest. An algebraic relation between wind speed and mechanical power extracted is assumed, which is described by the following equation [10,11]:

$$P = 1/2 \cdot \rho \cdot A \cdot Cp(\lambda) \cdot V_w^{\,3} \qquad (1)$$

Where P is the power extracted from the wind [W], ρ the air density [kg/m^3]; A the swept area and V_w the wind speed [m/s]. Cp is the performance coefficient that depends on λ, the tip speed ratio:

$$\lambda = \frac{\omega_{tur} R}{V_w} \qquad (2)$$

B. Shaft system model.

Sometimes, representation of the shaft system in the dynamic wind turbine model used in investigation of transient voltage stability was neglected, and the mechanical construction of the wind turbines was simply modeled as a lumped-mass system with the lumped inertia constant of the turbine rotor and the generator rotor [12]:

$$H_L = H_M + H_G \qquad (3)$$

Where H_L denoted lumped inertia constant, H_G and H_M the inertia constant of the generator and the rotor respectively.

[12] shows a demonstration of electromechanical interaction between the shaft systems of the fixed speed wind turbines and the electrical grid. This electromechanical interaction is seen as torsional oscillations in the shaft systems equipped with gearboxes. The shaft oscillations results in fluctuations of the voltage, machine current, rotor speed and other electrical and mechanical parameters.

There are different representations of the shaft system in the literature [13], but the two mass model shown in Fig. 3is the most used in investigation of transient voltage stability. The behavior of this model is described by means of the following equations [11, 12, 9]:

$$\begin{aligned} 2H_M \frac{d\omega_M}{dt} &= T_M - K \cdot \Delta\theta - D \cdot \Delta\omega \\ 2H_G \frac{d\omega_G}{dt} &= K \cdot \Delta\theta - T_E + D \cdot \Delta\omega \end{aligned} \qquad (4)$$

Where K is the shaft stiffness, D the damping coefficients, T_M the mechanical torque coming from the rotor, and T_E is the electromagnetic torque from the generator. $\Delta\omega$ is the difference between the angular speed of the turbine and the generator, and $\Delta\theta$ the difference between the angles:

$$\Delta\theta = \theta_T - \theta_G$$
$$\Delta\omega = \omega_T - \omega_G \quad (5)$$

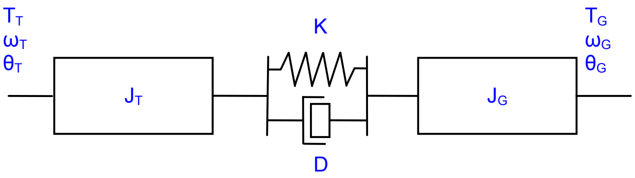

Fig. 3. Drive train model.

C. Generator model.

The basic mathematical equations to represent induction motors and generators were developed many years ago. In these equations the three-phase stator and rotor windings of an induction machine can be represented by two sets of orthogonal fictitious coils. The next equations have been developed by considering the following assumptions:

- The stator current was assumed positive when flowing from the machine.
- The equations were derived on the synchronous reference.
- The q-axis was assumed to be 90 º ahead of the d-axis with respect to the direction of rotation.
- The q component of the stator voltage was selected as the real part of the busbar voltage and d component was selected as the imaginary part.

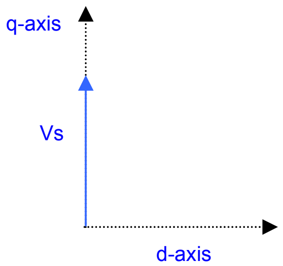

Fig. 4. Generator equation reference frame.

The per unit equations in the reference frame described are [14]:

$$v_{ds} = R_s i_{ds} - \omega_s \psi_{qs} + \frac{d}{dt}\psi_{ds}$$
$$v_{qs} = R_s i_{qs} + \omega_s \psi_{ds} + \frac{d}{dt}\psi_{qs} \quad (6)$$

$$v_{dr} = R_r i_{dr} - \left(\frac{\omega_s - \omega_r}{\omega_s}\right)\psi_{qr} + \frac{d}{dt}\psi_{dr}$$
$$v_{qr} = R_r i_{qr} + \left(\frac{\omega_s - \omega_r}{\omega_s}\right)\psi_{dr} + \frac{d}{dt}\psi_{qr} \quad (7)$$

where

$$\psi_{ds} = L_{ss} \cdot i_{ds} + L_m \cdot i_{dr}$$
$$\psi_{qs} = L_{ss} \cdot i_{qs} + L_m \cdot i_{qr} \quad (8)$$

$$\psi_{dr} = L_m \cdot i_{ds} + L_{rr} \cdot i_{dr}$$
$$\psi_{qr} = L_m \cdot i_{qs} + L_{rr} \cdot i_{qr} \quad (9)$$

and:

$$L_{ss} = L_s + L_m$$
$$L_{rr} = L_r + L_m \quad (10)$$

The equations described above and the movement equation describes the induction generator behavior:

$$\frac{d\omega_r}{dt} = \frac{1}{2H}\left(T_e - T_m\right) \quad (11)$$

As can be seen, the induction generator behavior can be described by means of five differential equations. This is the fifth order model.

There has been an on-going discussion on the level of detail needed to simulate electrical machines for stability studies. It has been generally accepted that, accounting for the respective bandwidth, the dynamics associated with the stator winding can be ignored ($d\Psi_{ds}/dt = 0$, $d\Psi_{qs}/dt = 0$) [14], and only flux linkage dynamics and mechanical movement (inertial dynamics) need to be accounted for. It is evident that, even in case of full-order models, the accuracy of the results is undermined by the fact that these software packages represent the transmission network by algebraic and not differential equations.

First order model for DFIG and variable speed wind turbine can be found in the literature. In these models the dynamic associated with the rotor winding are neglected ($d\Psi_{dr}/dt = 0$, $d\Psi_{qr}/dt = 0$) [15].

D. Wind farm model.

The model of the wind farm can be considered to have two potential levels of representation (Fig. 5):

- A *detailed* model, representing individual units and the connections between these units and the system. A large wind farm may need a hundred of buses and branches. This detailed model can be used to study the voltage and flows within the wind farm.
- An *equivalent* wind farm, modeled as seen from the system. The individual generators are lumped into equivalent machines represented at the collector buses. The size of the system representation is reduced to a few buses and the data requirements are reduced. The equivalent model enables the model order and the computation time to be reduced. This level of modeling is often used in system studies where the effects of the injection into the system on system flows and voltages are the concern, and the internal wind farm conditions do not need to be determined.

There are different equivalent models in the literature. In [16,17] two equivalent models are described, one for wind turbines with similar winds, and another for wind turbines with any incoming wind.

Stability studies can have up to hundreds of wind farms composed of a large number of wind turbines; therefore it is difficult to know the distribution of the wind inside each park. Due to the lack of data, the equivalent used in this study does not take into account the wind speed distribution.

The equivalent model can be calculated in the following form:

- MV/LV transformer: Is calculated as the parallel of the MV/LV transformer of each wind turbine.
- The apparent and real power are generated by the equivalent generator are:

$$S_{WF} = \sum_{i=1}^{n} S_i$$
$$P_{WF} = \sum_{i=1}^{n} P_i \qquad (12)$$

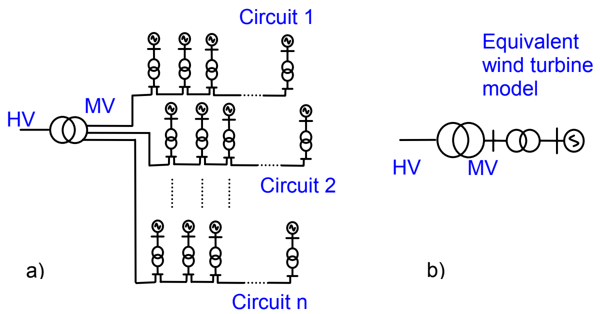

Fig. 5. Wind farm models: a) Detailed model, b) Equivalent model.

IV. Studies

In this paper the influence of each part of the model is analyzed. The study shows the simulation results obtained with the different models of generator, shaft system, and wind farm described above.

A. *Shaft system model influence.*

To investigate the modeling requirements the double circuit power network shown in Fig. 6 has been modeled in PSS/E. A 600 kW wind turbine is connected to Bus 1. The external network is modeled by means of an equivalent connected to Bus 3. The fault is applied at the mid point of one of the double circuit lines (Bus 2) at t = 4 s and is cleared after 500 ms.

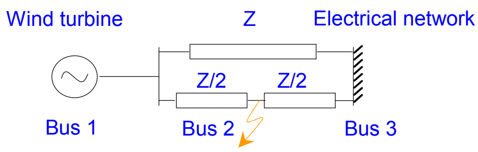

Fig. 6. Simulated network.

As it is explained above, the literature [11, 12, 9] says that the lumped-mass model is not valid to simulate the wind turbine behavior.

The influence of the shaft system model has been analyzed by means of the simulation of the electrical network shown in Fig. 6.

The next figure shows a comparison of the generated power obtained with the lumped-mass model and the two-mass model. When the fault is cleared, power calculated by the two-mass model has a ripple that does not appear in the curve calculated by the lumped model.

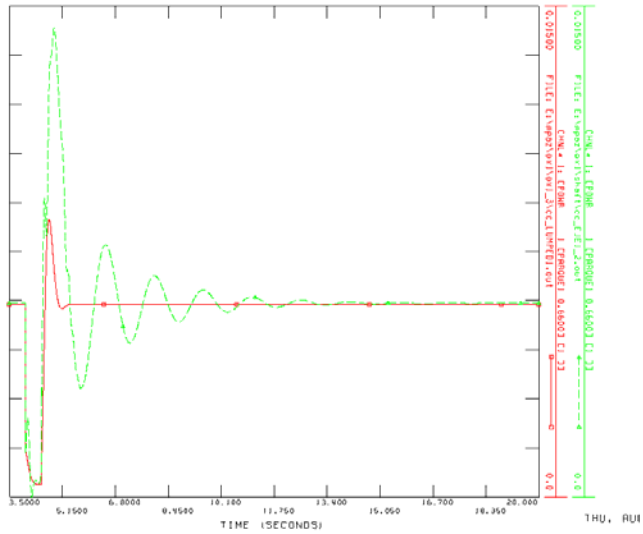

Fig. 7. Wind turbine generated power. Red solid line: lumped-mass model. Green dashed line: two mass model.

B. *Generator order model influence.*

In order to analyze the generator order model influence, the shaft system model has been simplified to a lumped-mass model. So that, shaft model behavior does not influence in this comparison.

Fig. 8 shows the bus voltage obtained by simulation of the first, third and fifth order model at Bus 1.

When the fault is applied, the voltage obtained by the three different models is similar, but the first order model voltage presents an over voltage when the fault is cleared.

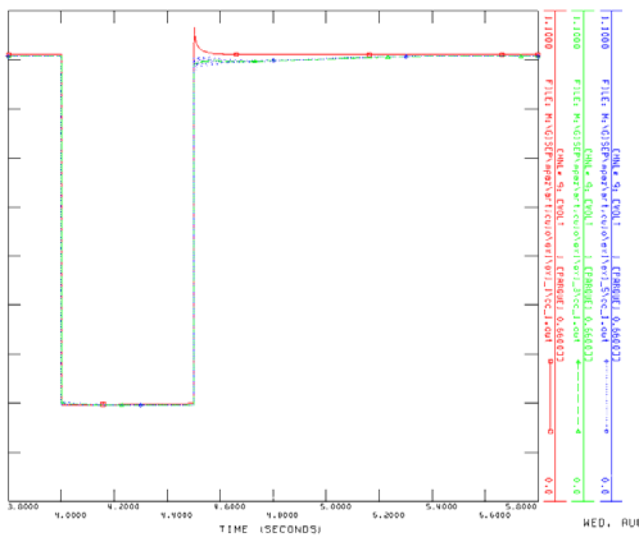

Fig. 8. Voltage at Bus 1. Red solid line: first order model. Green dashed line: third order model. Blue dotted line: fifth order model.

Fig. 9 shows the power generated by the wind turbine generator. As can be seen third and fifth order model shows a similar behavior, but the power obtained by means of the first order model shows a different behavior during the fault and it has an over oscillation when the fault is cleared that does not appears with the other models.

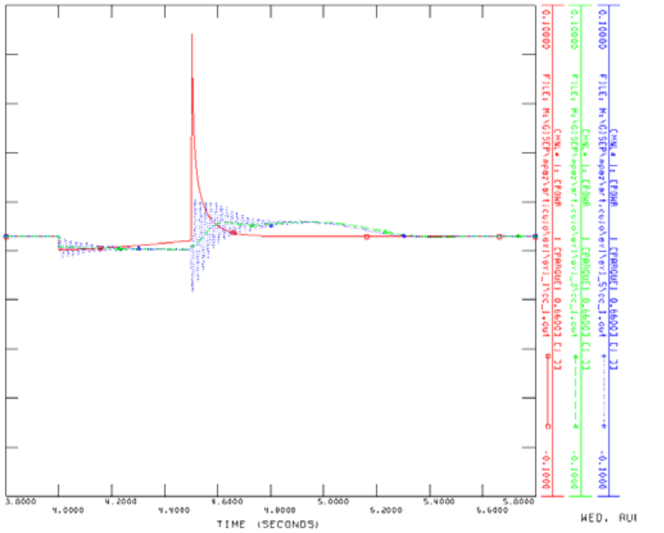

Fig. 9. Wind turbine generated power. Red solid line: first order model. Green dashed line: third order model. Blue dotted line: fifth order model.

In Fig. 10, the red curve represents the response of the third order model and the green one the response of the fifth order model.

The power obtained by means of the third order model is, approximately, the surrounding curve of the obtained by the fifth order model.

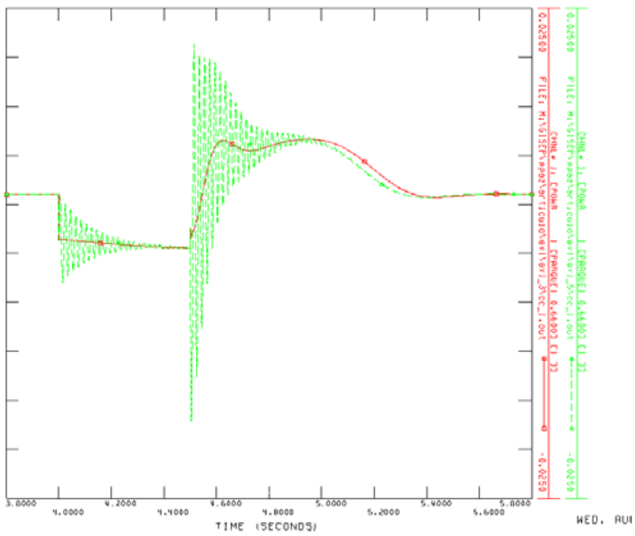

Fig. 10. Wind turbine generated power. Red solid line: third order model. Green dashed line: fifth order model.

The simulation of large power systems with wind turbines modeled by the fifth order model can last hours, because of the integration step needed in this model. For that reason the third order model is more useful than the fifth order model, when large power system is studied. Nevertheless, the influence of this assumption has to be analyzed.

To investigate the influence of the generator model the power system shown in Fig. 11 has been simulated. A wind farm with 13 wind turbines of 600 kW is connected to a large network with hundreds of branches, buses, generators…

The Point of common coupling (PCC) of the wind farm is Bus 1. Bus 1 is connected to the system through Line1.

To study the influence of the generator order model a three phase fault at Bus 3 has been simulated. Fig. 12 shows the voltage evolution at Bus 6 (220 kV). Fig. 13 shows the power flow at Line 6. The curves obtained with both models are equal when the point of interest is distant from the wind farm PCC.

Third and fifth order model can achieve identical results when the zones analysed are distant to wind turbines. Fifth order model needs a smaller integration step, and simulation time increases. For this reasons, third order models are preferred for dynamic simulation of large power systems.

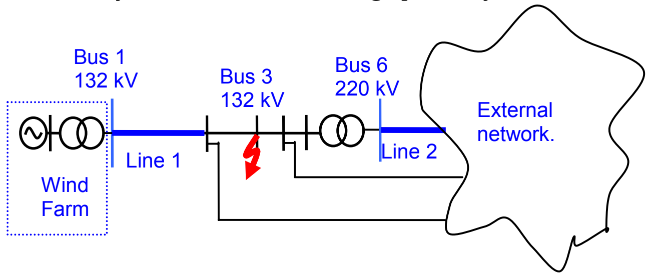

Fig. 11. Simulated network.

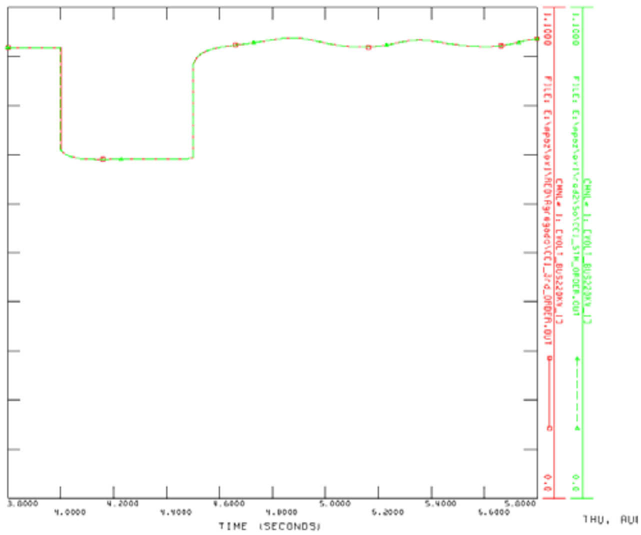

Fig. 12. Voltage at Bus 6 (220 kV). Red solid line: third order model. Green dashed line: fifth order model.

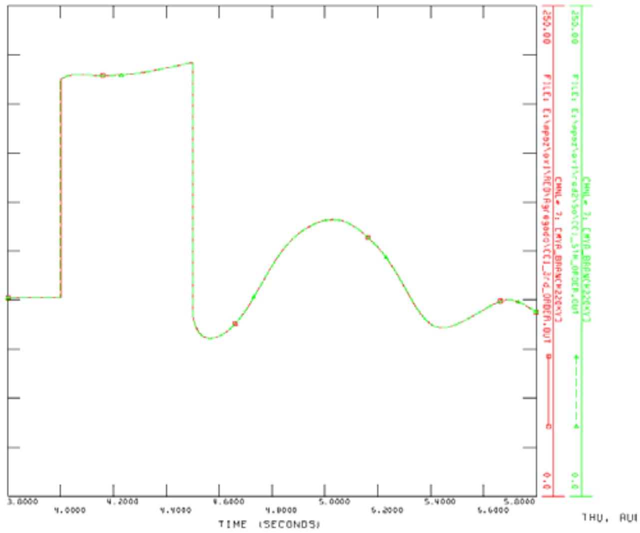

Fig. 13. MVA flow in Line 2. Red solid line: third order model. Green dashed line: fifth order model..

C. *Wind farm model influence.*

The wind farm model influence has been investigated by simulating the network shown in Fig. 11.

The next figures show the comparison between the detailed and the equivalent model. Voltage evolution at Bus 1 (wind farm PCC) is shown in Fig. 14. The curve obtained by the equivalent model is slightly different when the fault is cleared. Fig. 15 shows voltage at a bus distant from the wind farm (Bus 6, 220 kV). The results obtained with both models in this bus are similar.

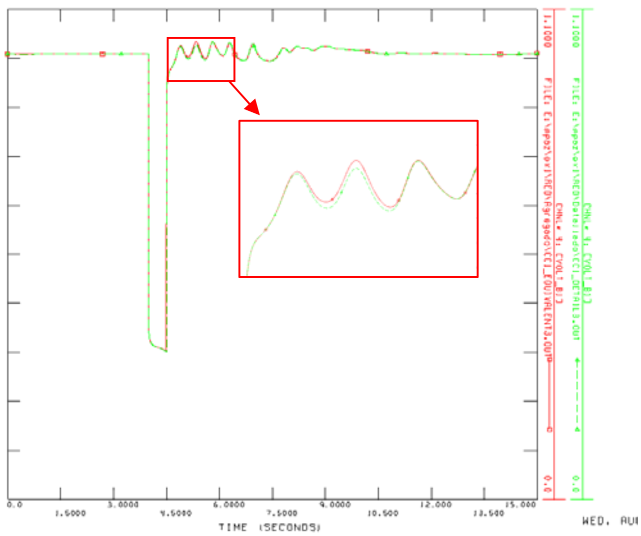

Fig. 14. Voltage at Bus 1 (132kV). Red solid line: equivalent model. Green dashed line: detailed model.

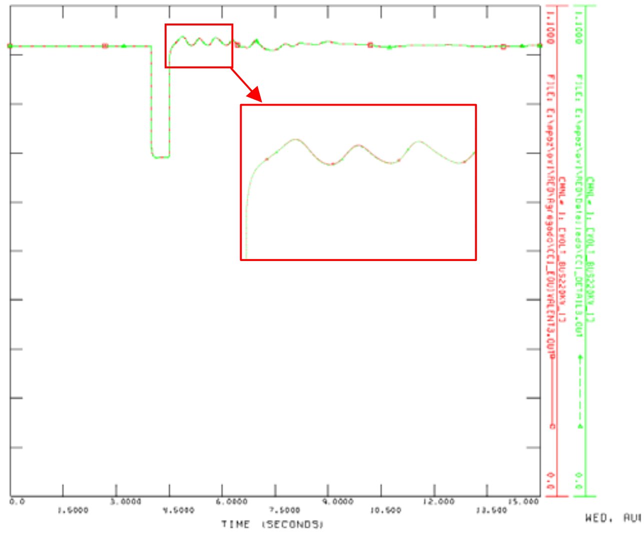

Fig. 15. Voltage at Bus 6 (220 kV). Red solid line: equivalent model. Green dashed line: detailed model.

Fig. 16 and Fig. 17 show the MVA flow in Line 1 and Line 2 respectively. Line 1 is the evacuation line of the wind farm. In this case the results obtained by the detailed and the equivalent model are different. Line 2 is a distant line, and the results obtained by the two models are alike.

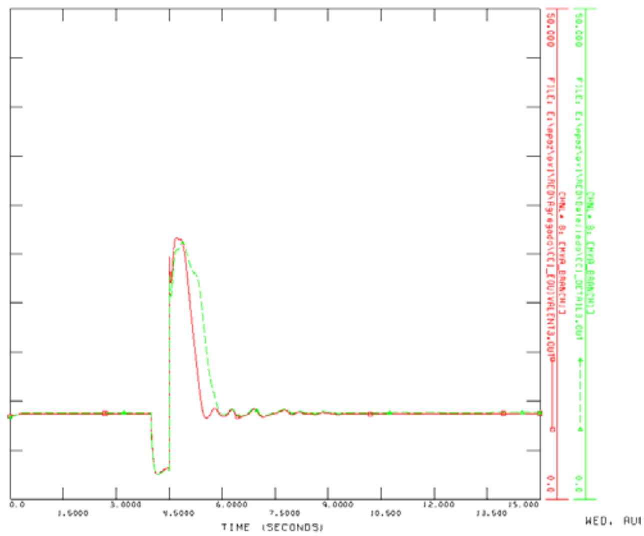

Fig. 16. MVA flow at Line 1. Red solid line: equivalent model. Green dashed line: detailed model.

The detailed model is necessary when the internal network of the wind farm is analyzed.

When the aspects of interest are the behavior of the entire wind farm to a voltage dip, the equivalent model is appropriated.

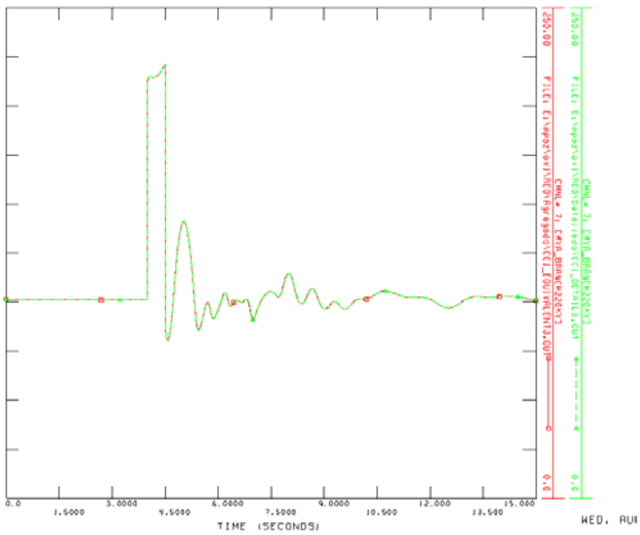

Fig. 17. MVA flow at Line 2. Red solid line: equivalent model. Green dashed line: detailed model.

V. Conclusions

In this paper, wind turbine modeling requirements have been analyzed.

Simulation of large power systems can need long simulation times. The use of detailed models need smaller integration time, and increase the simulation time.

Models must be suitable for investigating the impact of large power systems. Therefore, the developed model shows a behavior closest to the real wind turbine behavior with a not excessive computational cost. The precision obtained is enough to have a good estimation of the wind farm behavior.

VI. Biographies

M. P. Comech received her M.S. degree from the University of Zaragoza in 2003. She is working for towards her Ph.D. at the Zaragoza University. Her research interests are in the field of renewable energy, power system modeling and integration of wind generation into electric grids.

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Since 1990 he has been teaching and researching in the Department of Electrical Engineering, University of Zaragoza. His main research interests are in the field of power system protection, renewable energy, electrical transients, high voltage, lightning protections and dielectrics. He is an IEEE member and a member of national committee of CIGRÉ.

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