Results using Wind Turbine Models for the Certification Process required by the Grid Codes

E. Gómez-Lázaro, J. A. Fuentes, A. Molina-García, and F. Jiménez

***Abstract*—Operation of power systems is supported by grid codes, which are sets of requirements to comply. One of the key aspects of these grid codes related to wind farms are the ride-trough requirements that impose significant technical issues to the turbine manufacturers which in turn needs precise computer models of their wind turbines to study their fulfillment.**

In this paper two precise and complete models of wind turbines has been implemented in two transient analysis simulators and their results are presented. They take into account the real electrical, mechanical and electronic parameters and the control of the power converter and the active crowbar and with the objective of been used in the required certification process according to the Spanish grid code.

I. Introduction

Power production from wind farms has increased considerably during last years, due to the development of wind turbine technology and the policies and incentives offered in some countries. Therefore, wind farms have a significant influence on the operation of power systems. This impact is obviously important in Europe, where table I, informs about Europe's wind energy generating capacity by December 2007. In Europe, Germany heads the list with 22 247 MW connected to the electrical network, followed by Spain —15 145 MW— and Denmark —3 125 MW—. These three countries alone accounted for 72% of the wind power capacity installed in European Union by end of 2007, Table I.

Operation of power systems is supported by grid codes, which are sets of requirements to comply for all network users. In Europe, some transmission network operators have introduced special grid connection requirements for wind farms. These grid codes are demanding to wind power installations additional requirements to integrate them with the other conventional types of generation. Specifically, national grid codes are requiring uninterrupted generation throughout power system disturbances supporting the network voltage and frequency, and therefore, extending characteristics such as low voltage ride through, or reactive and active power capabilities. In [1], [2], [3], [4] grid connection requirements in Spain, Denmark, Germany, Ireland, Sweden and Scotland are studied.

TABLE I
EUROPE WIND ENERGY GENERATING CAPACITY BY END OF 2007

Country	Capacity(MW)
Germany	22.247
Spain	15.145
Denmark	3.125
Italy	2.726
France	2.454
UK	2.389
Portugal	2.150
Netherlands	1.746
Austria	982
Greece	871
Ireland	805
Sweden	788
Belgium	287
Poland	276
Czech Republic	116
Finland	110
Hungary	65
Estonia	58
Lithuania	50
Luxembourg	35
Latvia	27
Slovakia	5
EU-27 total	56.535
Accesion Countries	163
EFTA Countries	345
Other Countries	93

Source: European Wind Energy Association (EWEA)

Therefore, electrical grid interconnection issues are one of the most significant challenges to the wind energy industry, since wind turbine manufactures tends to be global actors in this market. So, although grid codes are evolving taking into account the technical characteristics of their power systems, this can be in fact a barrier to foreign wind turbine manufactures.

One of the key aspects of these grid codes are the ride-through requirements imposed to wind farms, fixing significant technical issues to the turbine manufacturers, by solving in their products each grid code requirements and by integrating them in one wind turbine model. Obviously, and taking into account the number of grid codes —published or presented as proposals— computer models of the entire wind turbine —integrating the mechanical, electrical, power electronics and control aspects— will play an important role, more than ever.

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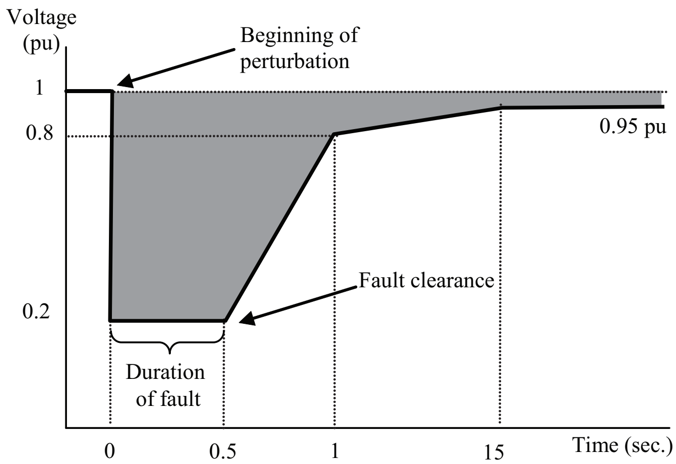

Fig. 1. Voltage-time curve that the generation facility must support. Source: Spanish Grid code P.O. 12.3, [6]

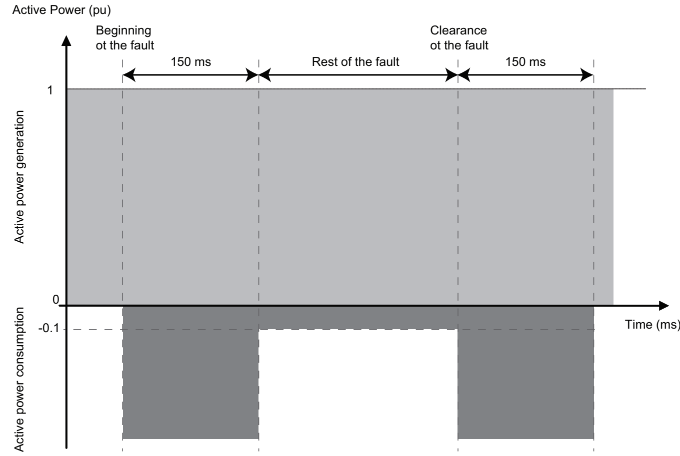

Fig. 2. REE Grid Code requirements for active power (balanced three-phase faults). Source: Spanish Grid code P.O. 12.3, [6]

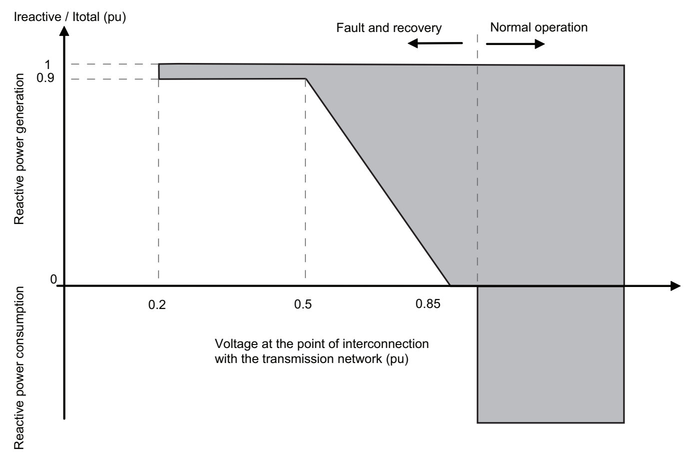

Fig. 3. REE Grid Code requirements for current and reactive power (balanced three-phase faults). Source: Spanish Grid code P.O. 12.3, [6]

II. The Spanish grid code

In Spanish case, REE —the transmission system operator Red Eléctrica de España— grid code, recently approved, specifies that the wind farm must support voltage dips, at the point of interconnection with the transmission network, without tripping. The voltage-time curve that limits the magnitude and duration of the voltage dips, produced by single-phase-to-ground, two-phase-to-ground and three-phase short-circuits, is shown in figure 1. For non-earthed two-phase short-circuits, the voltage limit is chosen at 0.6 p.u. instead of 0.2 p.u.. REE requirements are imposed according to the voltage dip type —balanced three-phase faults and unbalanced two-phase and single-phase faults—. In [5], REE Spanish grid code is commented and justified according to the Spanish electrical power system.

A. Balanced three-phase faults

During balanced three-phase faults, as well as in the voltage recovery period after the clearance of the fault, wind farms will not absorb reactive power.

Nonetheless, reactive power absorptions are admitted during a period of 150 ms after the beginning of the fault, and a period of 150 ms after the clearance of the fault, with the following requirements:

- The net reactive power consumption of the wind farm during the 150 ms interval after the beginning of the fault, in 20 ms cycles, must not exceed 60% of its rated power.
- The net reactive energy consumption of the wind farm after the clearance of the fault must not exceed 60% of its rated power, and the reactive current, in 20 ms cycles, must not exceed 1.5 times the rated current.

In terms of active power, during the fault and later in the voltage recovery period after the clearance of the fault, the wind farm, at the grid connection point, must not absorb active power. However, active power absorptions are admitted during a period of 150 ms after the beginning of the fault, and a period of 150 ms after the clearance of the fault, figure 2. During the rest of the fault, active power consumptions are additionally admitted up to a 10% of the wind farm rated power.

In terms of currents, during the fault and later in the voltage recovery period after the clearance of the fault, the wind farm, at the grid connection point, must provide to the electrical network the maximum generation of reactive current. In any case, this current must be located in the shaded area in figure 3, before 150 ms after the beginning of the fault or after the clearance of the fault. Therefore, the wind farm must generate reactive current with voltages under 0.85 pu, and it must not consume reactive power between 0.85 pu and the minimum admissible voltage for the normal operation of the electrical network.

B. Unbalanced two-phase and single-phase faults

During unbalanced two-phase and single-phase faults, as well as in the voltage recovery period after the clearance of the fault, wind farms must not absorb reactive power at the grid connection point.

Nonetheless, reactive power absorptions are admitted during a period of 150 ms after the beginning of the fault, and a period of 150 ms after the clearance of the fault, with two constraints:

- The net reactive energy consumption of the wind farm will not exceed the 40% of its rated power during a period of 100 ms.
- The net reactive power consumption of the wind farm after the fault clearance, in 20 ms cycles, will not exceed the 40% of its rated power.

Additionally, transitory consumption is permitted during the rest of the fault.

In terms of active power, during the fault and later in the voltage recovery period after the clearance of the fault, the wind farm, at the grid connection point, must not absorb active power. However, active power absorptions are admitted during a period of 150 ms after the beginning of the fault, and a period of 150 ms after the clearance of the fault. Additionally, active power consumptions are admitted during the rest of the fault with two constraints:

- The net active consumption must not exceed the 45% of the equivalent rated active energy of the installation during a period of 100 ms.
- The consumption of active power, in cycles of 20 ms, must not exceed the 30% of its rated active power.

III. Verification of requirements imposed by the Spanish grid code

The Spanish Wind Energy Association has developed a document, [7], about the verification of requirements imposed by the Spanish grid code, [1], [5]. It is focused on:

- Procedure of test of wind turbines and FACTS
- Procedure for model validation
- Procedure for wind farm simulation

The certification process includes the following verifications of specified requirements:

- Verification that the wind farms do not disconnect as a consequence of voltage dips in the grid connection point associated with correctly cleared short circuits according to the voltage time curve indicated in the grid code
- Verification that the power and energy consumption (active and reactive) in the grid connection point, for balanced and unbalanced faults, are less than or equal to the levels marked in the grid code

Basically, it describes the steps being required by the certification process, according to the Spanish grid code:

A. Field Measurements in wind turbine and/or FACTS

This test must be performed with a voltage dip generator at the terminals of the wind turbine and a measurement system, complying IEC 61400-21 and IEC 61000-4-30. The test must me carried out with two operation points in the wind turbine —one test between the 10%-30% of the wind turbine rated power and the other between 80%-100% and, in both cases, the power factor should be between 0.90 inductive and 0.95 capacitive—.

Voltage dips applied to the wind turbine must be must be inside the marked region of figure 1. Specifically, two voltage dips are proposed:

- A three-phase voltage dip with a duration of at least 0.5 s and a remaining voltage of $20\% + 3\%$
- A isolated phase-to-phase voltage dip with a duration of 0.5 s and a remaining voltage of $60\% + 10\%$

Voltage and currents waveforms must be acquired, with at least a frequency of 5 kHz, being registered during at least 10 seconds before the beginning of the voltage dips and 5 seconds after the clearance of the fault. The following magnitudes must be computed:

- Rms Voltages
- Rms fundamental voltages and currents per phase in pu
- Direct, inverse and zero sequences of voltage and current
- Active power in pu
- Reactive power in pu
- Reactive current in pu
- Reactive current divided by the total current
- Active and reactive energy according to the Spanish grid code

In [1], [5] different definitions of reactive power have been applied to voltages and currents obtained in wind turbines submitted to voltage dips, being studied in detail how it affects to the energy calculation using the Spanish Grid Code.

B. Simulation of wind turbine and/or FACTS models

Wind turbine model must be applied to the four tests detailed in the previous section, being recorded the same magnitudes. The model is considered validated when differences up to 10% with the equivalent test field are found in:

- The rms value of the fundamental harmonic voltage in each phase
- The rms value of the fundamental harmonic current in each phase
- The active and reactive three-phase power.

C. Simulation of wind farm response

Wind farm model must include certified wind turbine models, together with the wind farm electrical installation —cables and transformers—, being the rest of the electrical system outside of the wind farm modeled as an ideal programmable voltage source. The source must provide two different Rms voltage profiles —three-phase and phase-to-phase voltage dips—.

Assessment and certification of compliance of wind farm model is obtained when none of the wind turbines in the wind farm is tripped together with the fulfillment of active and reactive power requirements imposed by the Spanish grid code.

IV. Results

Taking into account the wind turbine and wind farm models required by the Spanish grid code, and precision imposed by validation and certification processes involved —sections III-B and III-C—, it is clear that complex models must be developed. Moreover, these models are submitted to severe voltage dips, and power system electromagnetic transient problems must be

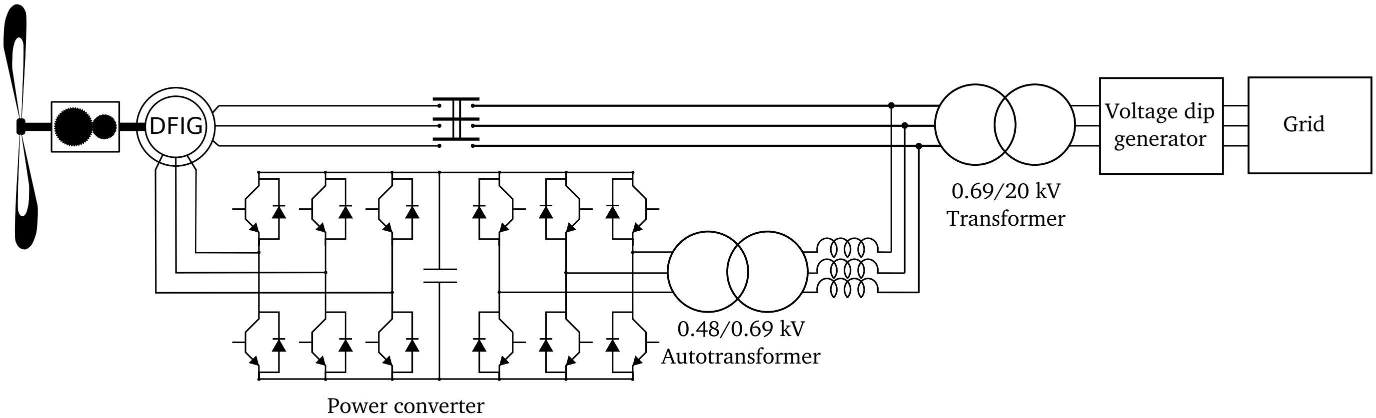

Fig. 4. Simplified diagram of the Dfig and the fault generator

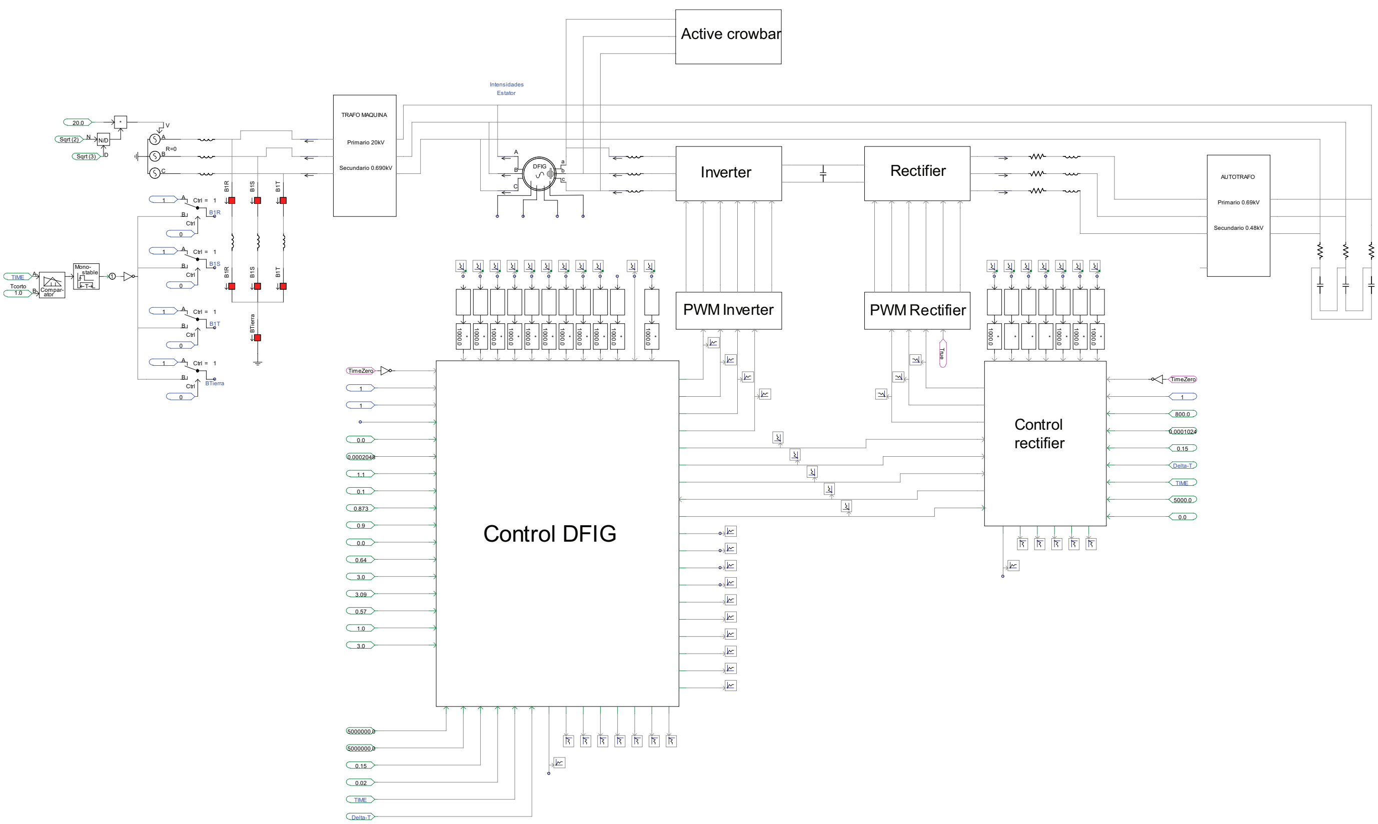

Fig. 5. Block diagram model for the Gamesa wind turbine G5X

solved, involving the activation of protection systems as the active crowbar.

Wind turbine electrical models need, to accomplish the requirements imposed by the Spanish Grid Code, subtransient simulation software, such as ATP, EMTP, PowerFactory-DigSilent, Saber or the MATLAB Power Systems Blockset. These packages contain more detailed and higher order equipment models than power system dynamics simulation software. Two software packages have been used to model the wind turbine: PSCAD/EMTDC and SABER. These software packages contain a library of elements and components for accurate simulation of complex power systems including power electronic converters, HVDC systems, and FACTS. Electrical machines are available as well: synchronous machines —salient poles and round rotor—, squirrel cage and wound-rotor induction machines.

PSCAD (Power Systems CAD) is composed by a graphical user interface and the EMTDC solution engine. PSCAD/EMTDC employs the well know and established nodal analysis together with trapezoidal integration rule with fixed-step algorithms, [8], [9]. PSCAD/EMTDC includes interpolation to remove numerical chatter or spikes. PSCAD/EMTDC invokes the chatter removal algorithm when a switching is detected. This algorithm is also initiated when oscillations in the slope of the voltages and currents for three time steps are detected, [10], [8]. SABER is a simulation tool used in circuit and power electronics design, developed to handle problems involving non-linearity, as present in studies on power systems. Details about the solution methods implemented in SABER are not known to the authors, being the same reported by other researchers, [11]. In [12], a detailed comparison, involving technical aspects related with the software packages, is presented.

Results of PSCAD/EMTDC and SABER models of a real wind turbine —Gamesa G52 with a rated power of 850 kW— are presented. Both models take into account the real G52 mechanical, electrical and electronic parameters, together with the same algorithms implemented in the real wind turbine, such as the power converter —IGBTs control level— or active crowbar algorithms. Figure 4 shows a simplified diagrams with the main components of the wind turbine and the fault generator. In order to compare both models, the same case have been applied to them. Figure 5 shows a detailed block diagram of the PSCAD entire model, being the SABER model quite similar, since PSCAD elements have been modeled according to the elements provided by SABER.

A balanced three-phase fault have been applied to the wind turbine models. Specifically, its characteristics are a remaining voltage of 0.2 pu —from 20 kV to 4 kV— with a duration of 0.5 s —starting at 1.0 s—. Therefore, this voltage dip complies with the specified one in section III-A. Simulations have been performed with the following set points imposed:

- Active power: 850 kW
- Reactive power: 0 VAr
- Stator connection: Delta
- Rotor mechanical speed: 1620 rpm
- Voltage DC bus: 800 V

Therefore, the simulation is done at full power, one of the two operation points specified in section III-A. Different electrical and mechanical magnitudes are compared in both models. Figure 6 shows the stator voltages, being quite similar. Figure 7 shows the DC bus voltage, where major differences can be observed at the beginning of the simulation, due to different initial values.

Electromagnetic torque representation is plotted in figure 8, being both results quite similar, due in part to the dfig model in both simulators. However, at the beginning of the voltage dip, differences in peak values are a bit bigger, due to different initial values as well.

Figure 9 plots the active crowbar voltage, being fired at 1.0s —the beginning of the voltage dip—, and at 1.5s — the clearance of the fault—. As it can be seen, crowbar activation times are similar due to the same control algorithms implemented in both simulators. On the other hand, differences in voltage levels —around 100V— are observed between them when the crowbar remains unfired. The difference could be explained because of the different algorithms that both simulators used in the simulation of the model. While it can be said that the PSCAD uses the Dommel algorithm for transient simulations of electrical networks, [9], [8], and inside it the trapezoidal integration method, SABER uses an HSPICE algorithm.

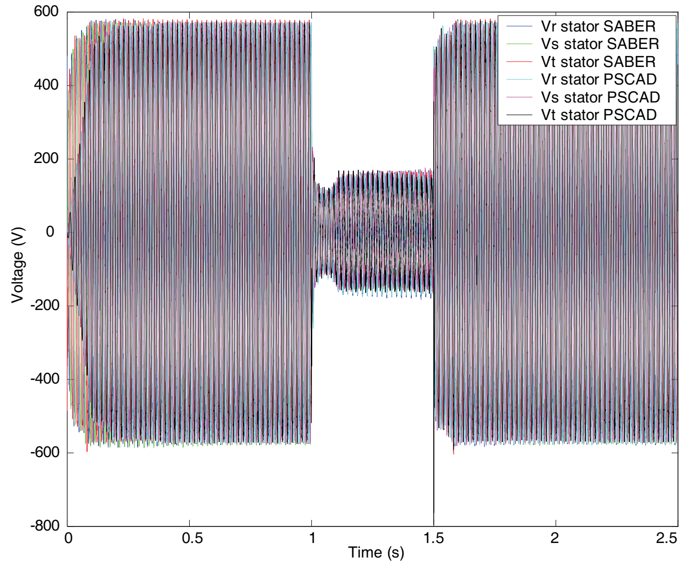

Fig. 6. Comparison of stator voltages during the three-phase voltage dip

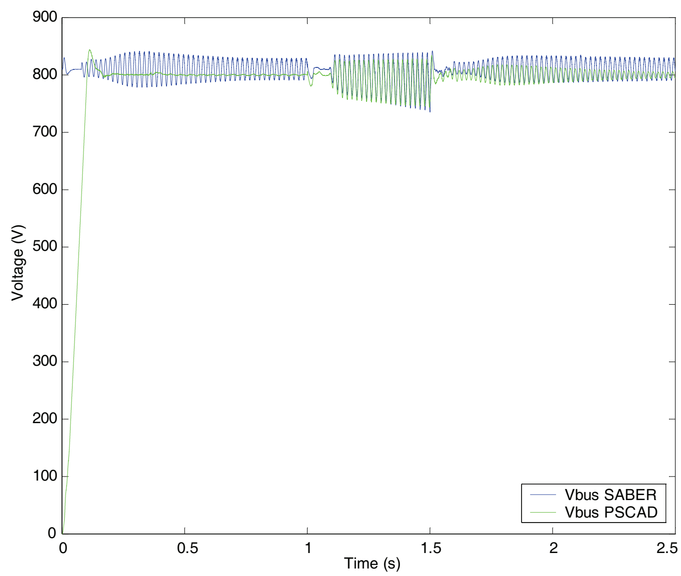

Fig. 7. Comparison of DC bus voltages during the three-phase voltage dip

Figure 10 represents the active power computed in different points of the model. In this particular case, the selected points are the stator of the dfig (Pstat) and the AC side of the rectifier (Prec) and it can be seen that there is a good agreement between the results obtained from both simulators during the dip. However, there is a slight difference in the peak values obtained at the beginning and at the clearance of the dip and during the startup of the simulation.

This could be explained because of small differences between the models of the different components used. For example, the IGBTs were modeled in PSCAD using the Power Electronic Switch, that takes into account the on and off resistance, the forward voltage and break-over voltage, the reverse withstand voltage and the minimum extinction time while in SABER the IGBTs are modeled using ideal switches

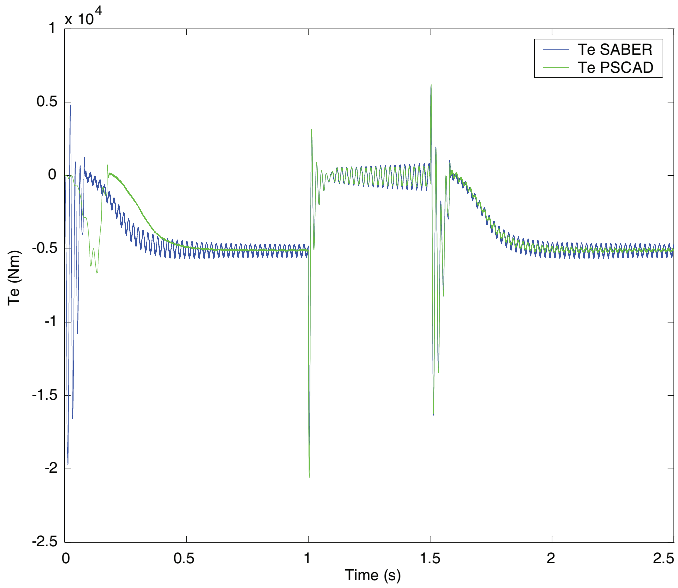

Fig. 8. Comparison of the electromagnetic torque during the three-phase voltage dip

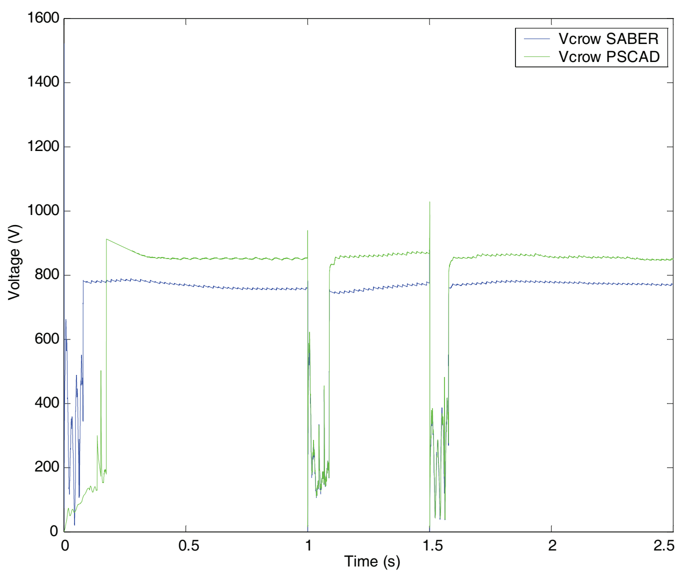

Fig. 9. Comparison of active crowbar voltages during the three-phase voltage dip

which only model the on and off resistance. In any case the differences are not significant. On the other hand, the differences at the startup are due to the different mechanisms used to initialize the simulation.

Finally, simulation time in a 3 second study is around 100 minutes for SABER and 3 minutes for PSCAD. Memory requirements for both simulators are quite similar, being 18Mb for SABER and 25Mb for PSCAD, even though, in this case, the memory requirements increase with time of simulation.

V. Conclusions

Some grid codes have been recently approved, while others are in the proposal stage, focusing in the ride-trough requirements. Wind turbine and wind farm validation and verification processes will be needed, and therefore precise wind turbine and wind farm models must be developed.

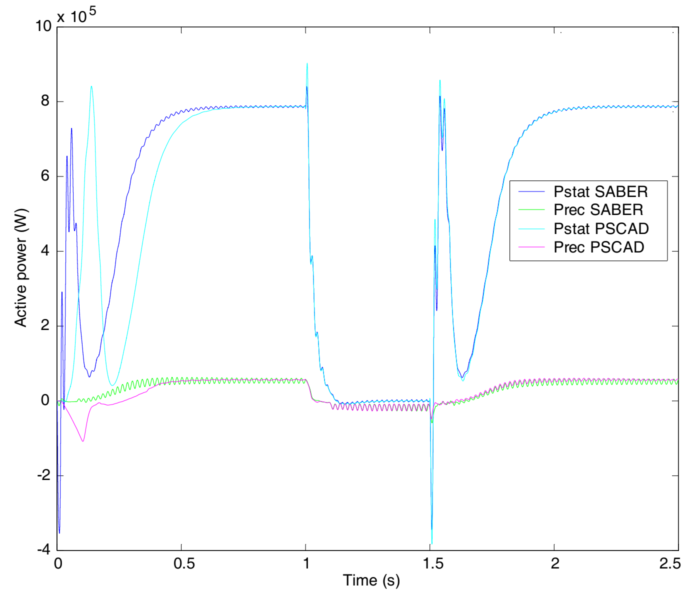

Fig. 10. Comparison of the stator active power during the three-phase voltage dip

In this paper, results obtained with two precise and complete models of a real wind turbine —Gamesa G52—, implemented in two transient analysis simulators, PSCAD/EMTDC and SABER, have been presented. Both models take into account the real G52 mechanical, electrical and electronic parameters, together with the same algorithms implemented in the real wind turbine, such as the power converter —IGBTs control level— or active crowbar algorithms.

In order to compare both models, the same case has been study —according to the document developed by the Spanish Wind Energy Association about the verification of requirements imposed by the Spanish grid code— with both simulators and it has been shown that the results obtained are quite similar along the simulation period except at its beginning, where the mechanism of assigning initial values is different. After reaching the steady state the voltage dip is applied and then their results are comparable.

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