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Iov, Florin; Cutululis, Nicolaos A.; Hansen, Anca D.; Sørensen, Poul

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Grid Faults Impact on the Mechanical Loads of Active Stall Wind Turbine

Nicolaos A. Cutululis, Anca D. Hansen, Florin Iov and Poul Sørensen

Abstract— Emphasis in this paper is on the fault ride-through operation impact on the wind turbines structural loads. Grid faults are typically simulated in power system simulation tools using simplified drive train mechanical model, approach which doesn't allow a thorough investigation of structural loads. This paper presents a two-steps simulation procedure, where two complimentary tools are combined, i.e. power system simulation tool and advanced aeroelastic simulation code. The goal is to investigate the whole integrated wind turbine design and to provide insight both into the structural as well as the electrical design of the wind turbine response during grid faults. The two-step simulation procedure is assessed by means of a simulation example. The effect of a grid fault on the structural part of a typical fixed speed wind turbine, equipped with an induction generator, is assessed.

Index Terms— grid fault, mechanical loads, aeroelastic computer code, fault-ride trough.

I. INTRODUCTION

THE increased penetration of wind energy into the power system over the last years has resulted in the power system operators revising and increasing the grid connection requirements.

Basically, for wind power, these grid codes require an operational behaviour similar to that of conventional power plants. Especially the requirements for wind turbines to stay connected to the grid during and after a voltage sag, imply potential challenges in the design of wind turbines.

From an electrical point of view, these new grid codes have initiated important research activity on the development of advanced wind turbines controllers adapted to fulfil the grid requirements. These controllers influence the structural loads on the wind turbines. However, at the moment there isn't any clarified knowledge on how the fulfilment of the new grid codes, especially of the fault ride-through requirement, affects the structural loads and thus the lifetime of the wind

turbines. Practical experience shows that the new grid requirements pose challenges for the design of both electrical system and mechanical structure of wind turbines.

A typical approach for simulating grid faults uses a dedicated power system simulation tool, where only a simplified drive train mechanical model is considered. Such investigation doesn't provide a thorough insight into the fault ride-through operation impact on the structural loads.

The paper presents a two-step simulation procedure of the dynamic response of a wind turbine to a grid fault using two complimentary simulation tools, namely DIGSILENT and HAWC2. This approach permits assessing both the electrical and the structural design aspects of the wind turbine during grid faults. HAWC2 is an advanced aeroelastic simulation code with a detailed model for the flexible structure of the wind turbines, taking the flexibility of the tower, blades and other components of the wind turbines into account. The wind turbine loads are thus simulated and analysed in HAWC2 while the wind turbine electrical interaction with the grid during grid faults is assessed in DIGSILENT.

The paper is organized as follows. Section II presents a quick overview of the grid requirements – with respect to fault ride through capabilities – for wind turbines and a brief statistic of the most common grid fault types. The simulation tools used in this paper are presented in section III. Section IV and V present the simulation setup and the simulation results, respectively. The simulations are intended to assess the influence of electrical events on the mechanical loads of an active stall wind turbine, with and without a fault ride-through control strategy. The paper ends with some concluding remarks and future work directions.

II. GRID REQUIREMENTS AND GRID FAULTS

Wind turbines connected to the grid are frequently subjected to grid faults. Initially, when the installed wind power capacity was not very high, wind turbines and wind farms were disconnected from the grid when a grid fault occurred. Today, the requirements for wind turbines have changed, i.e. they are required to remain connected during grid faults and, furthermore, to provide active support to the grid. In that respect, all existing grid codes require fault ride-through capabilities for wind turbines.

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N.A. Cutululis is with Risø DTU, National Laboratory for Sustainable Energy, Frederiksborgvej 399, Roskilde, Denmark. (phone: +45 4677 5989; fax: +45 4677 5083; e-mail: nicolaos.cutululis@risoe.dk).

A.D. Hansen is with Risø DTU, Denmark. (e-mail: Hanca.daniela.hansen@risoe.dk).

F. Iov is with Aalborg University, Denmark. (e-mail: fi@iet.aau.dk).

P. Sørensen is with Risø DTU, Denmark. (e-mail: Hpoul.e.soerensen@risoe.dk)

TABLE 1
 SUMMARY OF NATIONAL FAULT RIDE-THROUGH REQUIREMENTS

Country	Voltage Level	Fault ride-through capability				
		Fault duration	Voltage drop level	Recovery time	Voltage profile	Reactive current injection
Denmark	DS	100 msec	25% U_r	1 sec	2, 3-ph	no
	TS	100 msec	25% U_r	1 sec	1, 2, 3-ph	no
Ireland	DS/TS	625 msec	15% U_r	3 sec	1, 2, 3-ph	no
Germany	TS	150 msec	0% U_r	1.5 sec	generic	Up to 100%
Great Britain	TS	140msec	15% U_r	1.2sec	generic	no
Spain	TS	500 msec	20% U_r	1 sec	generic	Up to 100%
Italy	> 35 kV	500 msec	20% U_r	0.3 sec	generic	no
USA	TS	625 msec	15% U_r	2.3 sec	generic	no
Ontario	TS	625 msec	15% U_r	-	-	no
Quebec	TS	150 msec	0% U_r	0.18 sec	Positive-sequence	no

An overview of the national grid codes in several countries is provided in the report [1] and a summary of the fault ride-through requirements is given in Table 1.

Some of the national grid codes, e.g. Denmark and Ireland, have different requirements for distribution networks as well as for transmission networks, while most of the national grid codes focus only on the transmission network. The voltage profiles are defined in terms of the depth of the voltage drop and the clearance time.

One can easily observe that there is a significant span in the fault ride-through requirements in different countries. For example, the fault duration varies from 100 msec (in Denmark) to 625 msec (in Ireland, USA and Canada). On the other hand, the Danish grid code requires wind turbines to be able to withstand consecutive faults. The voltage sag values vary from 25% of the rated voltage in the Point of Common Coupling (PCC), in Denmark and Ireland, down to 0% in Germany. Moreover, a reactive current injection up to 100% during the fault is required, in the German and the Spanish grid code.

Grid faults are events occurring in the electrical networks and they are characterized by a change in the voltage magnitude and by their duration, i.e. they can have time duration from milliseconds up to hours [2].

In [1] statistics regarding the grid faults in different countries are presented and analysed. The grid faults, per year, in the transmission system for the Nordic countries (Denmark, Finland, Norway and Sweden) are presented in Fig. 1.

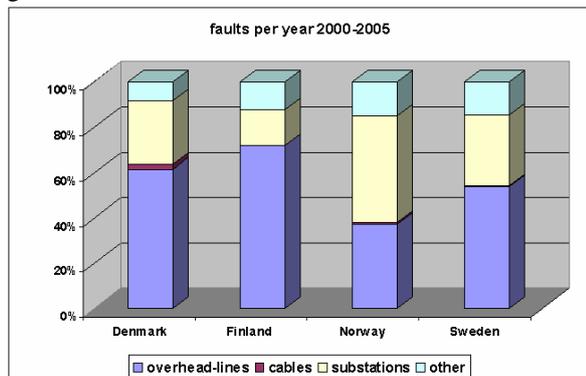


Fig. 1. Types of faults in the Nordic countries transmission system – source [1].

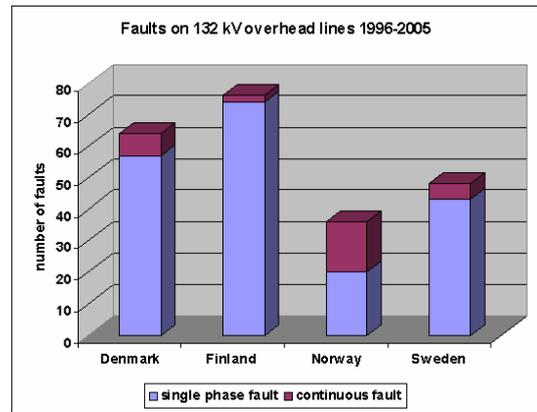


Fig. 2: Frequency of different fault types on 132kV overheads lines – source [1].

Notice that, excepting Norway, the most faults per year – for the period 2000-2005 – are located in the overheads lines. Actually, in this period, the number of faults located in cables is less than 2.5% of the total number of faults [1].

Most of the grid faults in the 132 kV overhead lines in the Nordic countries are asymmetric, i.e. single phase fault type, as presented in Fig. 2. Nevertheless, preliminary simulation results presented in [1] indicate that the way the asymmetric affect the wind turbines depend strongly on the connection of the transformer windings. They may not have a big impact on the mechanical structure of the wind turbine.

The same preliminary simulation results show that symmetric (three phase) faults can potentially have biggest impact on the mechanical part, producing high torque oscillations in the drive-train and a high stress in the gear-box. The worst case scenario seems to be the case in which the symmetric fault occurs at lower wind speeds and hence low driving torque, when the generator goes into motoring mode of operation.

Based on these preliminary simulation results, the impact of symmetrical short-circuit, defined according to the Danish grid code, is assessed in the present paper.

III. SIMULATION TOOLS

At the moment, the design and the research of wind turbines take place in specific dedicated simulation tools, which are specialized either in the mechanical design area or in the electrical design area regarding grid integration issues of wind turbines. The expertise in these wind turbine design areas is thus built-up independently, with very specific focus and without any influence from another parallel research area. In spite of this fact, practical experience shows that there is a considerable interplay between these design areas, which it is necessary to take into account. It is for example well-known that the increased requirements regarding wind turbines responsibility on the grid during grid faults has significant influence on the structural loads of the wind turbine.

The attention in this paper is therefore drawn to how to define a simulation procedure in order to assess the effect

of grid fault on wind turbine structure. The idea of such simulation procedure is to be able to assess the real interaction between the electrical and the mechanical aspects of the wind turbine response during grid faults.

In this respect, two complimentary simulation tools, namely Power Factory from DIgSILENT and HAWC2 (Horizontal Axis Wind turbine Code) are considered in this work. These and other similar simulation tools are used intensively by the wind energy industry at the moment to verify grid code compliance and structural loads respectively.

DIgSILENT is a dedicated electrical power system simulation tool used to model the dynamic behaviour of power systems and for assessment of power quality and analysis of wind turbines grid integration [3]. DIgSILENT simulations are performed based on one hand on very detailed models for the electrical components of the wind turbine and the grid, but on other hand on simplified aerodynamic and mechanical models for the wind turbine. These simulations reflect thus the electrical interaction between wind turbines and grid, but they do not provide a detailed insight on the wind turbine structural loads.

HAWC2 is an aeroelastic simulation code, developed at Risø National Laboratory. The core of this code is an advanced model for the flexible structure of the wind turbines, taking the flexibility of the tower, blades and other components of the wind turbines into account. It contains thus detailed models for the aeroelastic and mechanical aspects in a wind turbine, while the models for the electrical components and control of the wind turbine are typically very simplified [4].

The combination of structural dynamics and generator dynamics, using these two simulation tools with complimentary abilities is based on the attempt to put them to work together to the extent that is possible. As illustrated in Fig. 3, DIgSILENT is used to simulate the grid faults and the electrical interaction between the wind turbine and the grid, while HAWC2 is used to simulate and analyze the structural loads of the wind turbine.

The combination of DIGSILENT and HAWC2 provides new insight into the structural as well as the electrical design and this is very important in order to quantify the loads' impact on the wind turbines' lifetime,

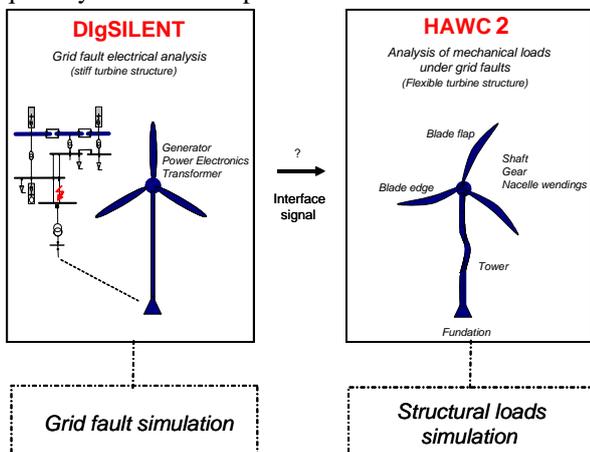


Fig. 3: Simulation tools.

during and after grid faults. Once the whole complex model in DIgSILENT and HAWC2 is established, it is possible to investigate simultaneously the whole integrated wind turbine design.

The key to access a successful combination of these two different simulation tools is strongly dependent on a proper definition of the interface signal in between them. In a previous stage of the work [5], it has been experienced that for wind turbines with directly connected induction generators, it is not sufficient to use the electromagnetic generator torque, as interface signal between DIgSILENT and HAWC2, as there does not exist any close loop between the generator torque and the generator speed.

In order to overcome this, a generator dynamic model was implemented inside HAWC2 environment. The generator dynamic model is a reduced order model obtained by neglecting the electrical transients of the stator. The model is written in the state space form only in terms of the rotor fluxes in dq synchronous reference frame [6] and [7].

IV. SIMULATION SETUP

The impact of a grid fault on a 2MW active stall wind turbine has been investigated. The wind turbine is equipped with a squirrel-cage induction generator.

The wind turbine model used in DIgSILENT is the benchmark model presented in [8]. The only difference from that simulation model is that the generator is not driven by a constant aerodynamic torque, as in the benchmark model. The model of the active stall wind turbine is discussed in details in [9].

The single line simulation diagram of an active stall wind turbine is illustrated in Fig. 4.

The mechanical system is represented in DIgSILENT as a simplified 2 mass-model [9].

The electric network is represented in Fig. 4 by a Thevenin equivalent, consisting of a constant magnitude/frequency voltage source and a serial impedance. The 3 phase short circuit on 10kV busbar, with duration 100ms, is simulated in DIgSILENT by using the RMS simulation feature. Sørensen et. al. [9] confirms that the wind turbine mechanical torque shaft during grid faults is predicted in DIgSILENT in the same way no matter whether a detailed EMT or a reduced RMS generator model is used.

In order to assess the maximum wind turbine structural stresses developed during grid faults, the worst scenario is simulated, i.e. the wind turbine operates at rated power, minimum fault impedance and fault closest to the wind turbine.

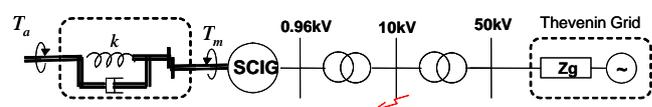


Fig. 4: Single line diagram of active stall wind turbine used in DIgSILENT.

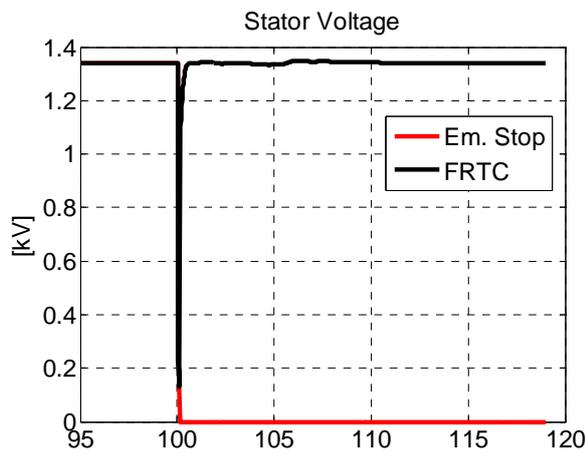


Fig. 5. Generator stator voltage during the grid fault

It is also assumed that in the case study the wind turbine protections are not taken into account, but they can be of course considered if their settings are well known.

The only control degree of freedom in active stall wind turbines is the pitch control. The aim of this control is to enable fast control of the wind turbine power, which is attractive especially in case of grid faults, when a quick reduction of the aerodynamic power production is necessary as soon as a grid fault is detected. Riding through grid faults implies thus that the active stall wind turbine has to change its pitch angle as quickly as possible (maximum pitch rate). Such fast control is also necessary in case when specific and fast power demands are imposed to wind turbines by the system operator.

Two simulations were conducted. First, the active stall wind turbine is assumed to disconnect from the network when the fault is detected. In this case, emergency stop procedure is activated. In order to stop the wind turbine, the pitch angle ramps to minus 90 degrees. The ramp slope is dictated by the pitch servo speed. In this simulation it is assumed to be 10 deg/sec.

The second simulation is of an active stall wind turbine equipped with an advanced fault ride-through control which, during the fault, modifies the pitch angle according to the control strategy described above. In both cases, the interface signals between DIGSILENT and HAWC2 are the generator voltage and the pitch angle.

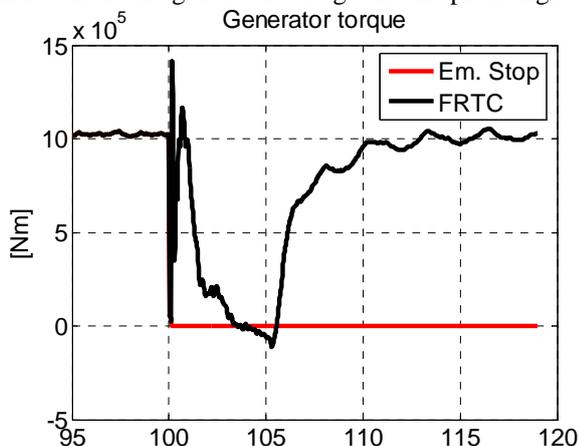


Fig. 6. Generator torque during grid fault

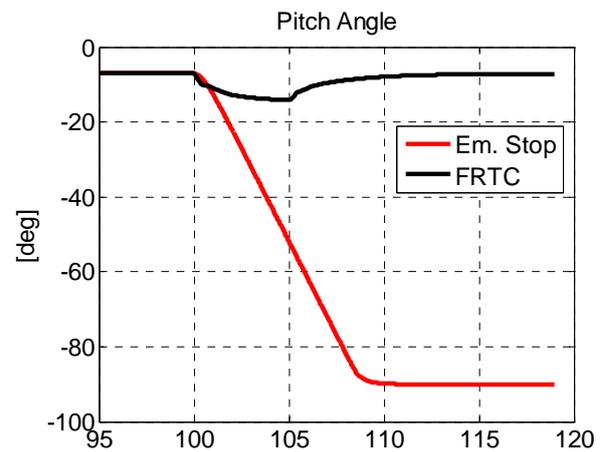


Fig. 7. Pitch angle during grid fault

V. SIMULATION RESULTS

In the following, the simulation results of the two mentioned scenarios are presented.

The interface signals between DIGSILENT and HAWC2, varying in time, are the pitch angle and the generator voltage.

As soon as the fault is detected, the pitch angle is modified in order to reduce the aerodynamic power. The evolution of the pitch angle depends on the chosen control strategy, i.e. disconnect the wind turbine or employ fault-ride through control. The evolution of the generator voltage, the generator torque and the pitch angle, during the grid fault, are presented in Fig. 5, Fig. 6 and Fig. 7, respectively.

The shaft mechanical loads, during grid fault, are presented in Fig. 8. If the wind turbine is disconnected, the shaft torque oscillations are rather significant and they even change sign. In the fault-ride through case, the generator torque is transmitted to the shaft, as expected. The bending and twisting shaft torques don't seem to be significant.

The tower moments, both at the top and at the bottom, are presented in Fig. 9 and Fig. 10, respectively. As it can be observed, the coupling between the generator and the tower top is clearly visible in the tower top bending torsion. This coupling shows the interaction between electrical (grid fault) and mechanical (tower top moment) parts of the wind turbine. The grid fault also affects the fore-aft and lateral bending moments of the tower top, as it can be seen in Fig. 9, in a rather significant manner. For the lateral bending moment, the fault-ride through strategy leads to an obvious increase of the moment. The same can be observed for the fore-aft bending moment.

The tower bottom moments, presented in Fig. 10, indicate that the grid fault induces oscillations all the way down the tower. All of them seem to be poorly damped.

The blade root moments, presented in Fig. 11, show that the grid fault does not have an impact on the blades.

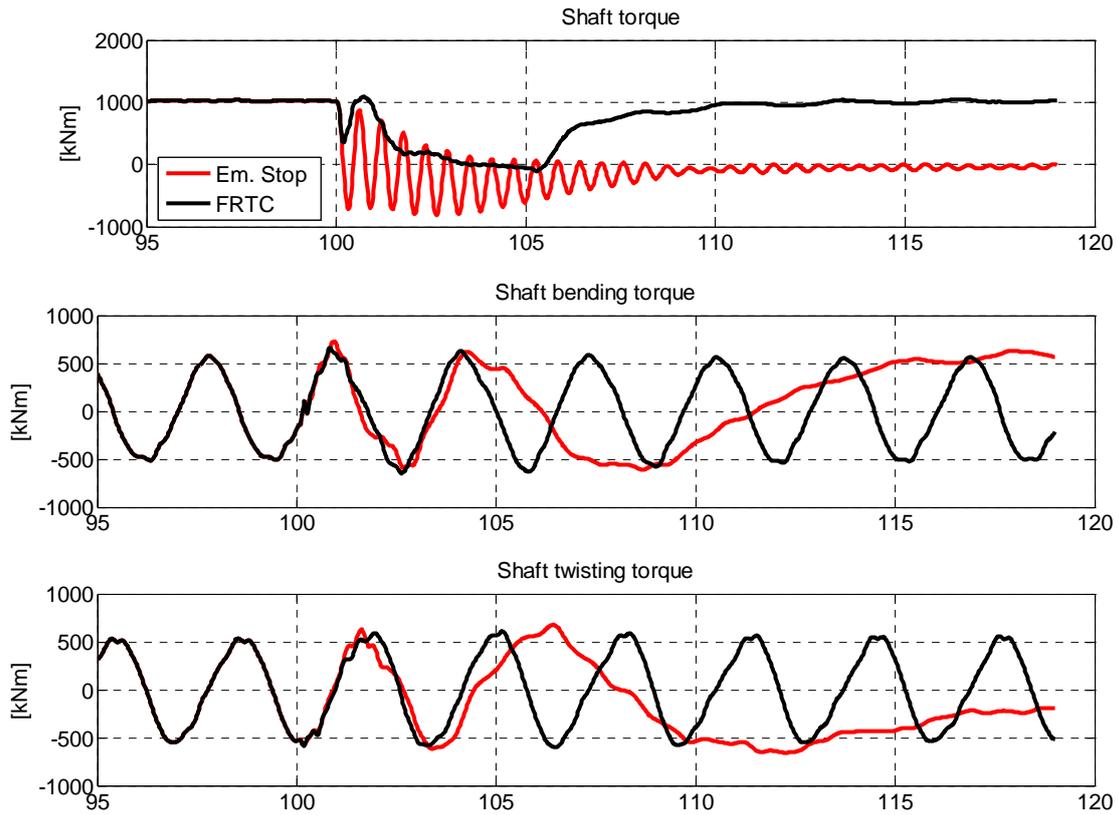


Fig. 8. Shaft loads during grid fault

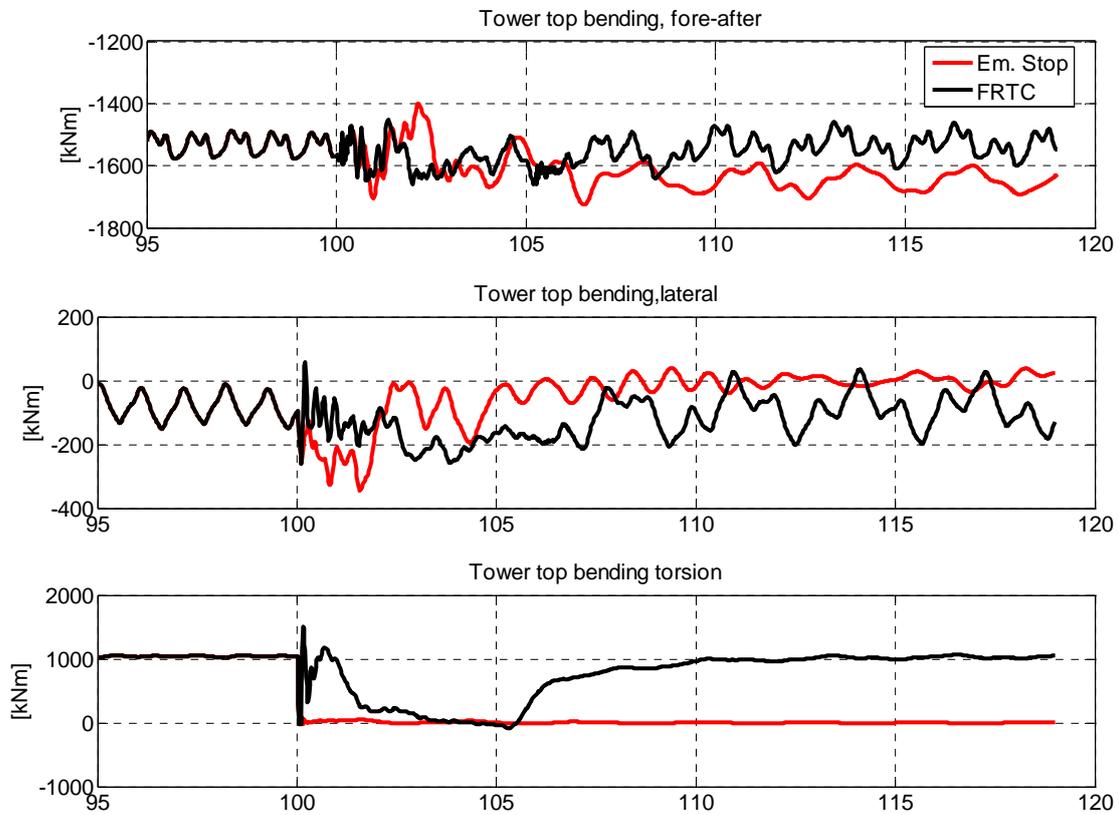


Fig. 9. Tower top loads during grid fault

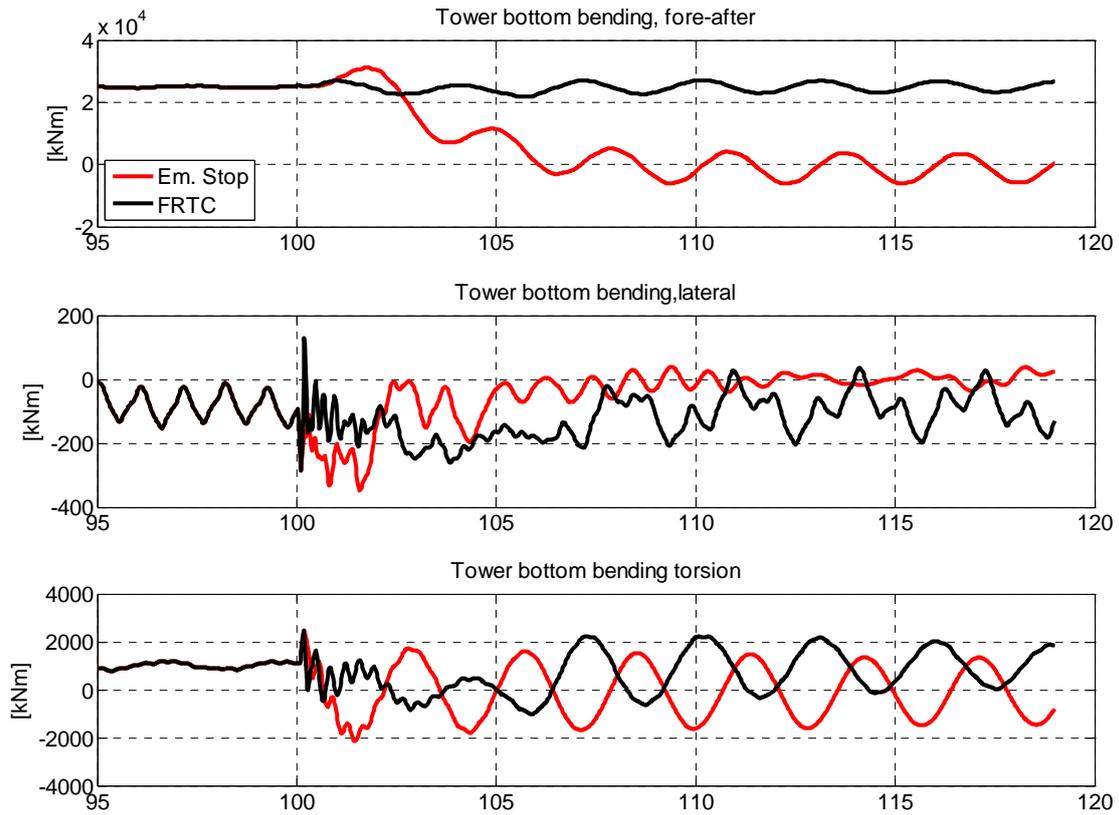


Fig. 10 Tower bottom moments during grid fault

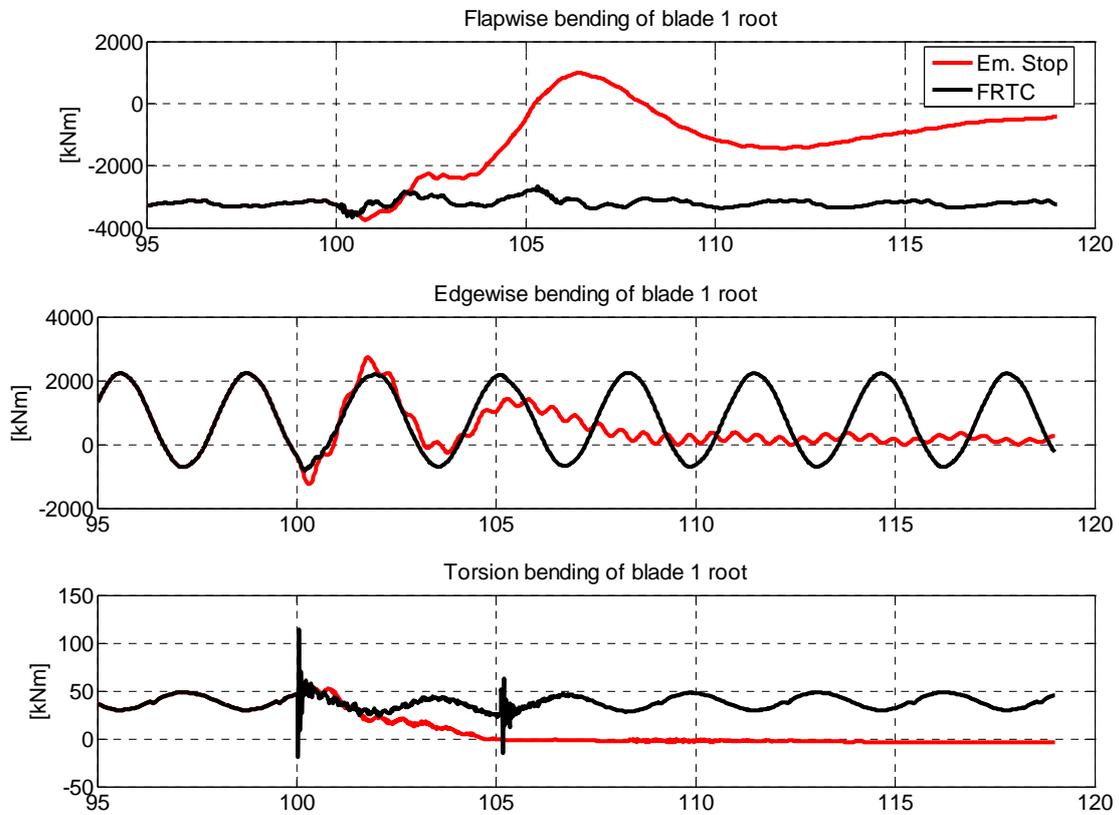


Fig. 11 Blade root moments during grid fault

V. CONCLUSIONS

Wind turbines today are required to have fault ride-through capabilities and, furthermore, to provide active grid support.

Significant research has been and is currently done to develop advanced fault ride-through controllers, both at electrical (generator) and aerodynamic (pitch) level. On the other hand, there is no clarified knowledge and investigations on how the fulfilment of the new wind turbine grid codes affects the structural loads.

This paper presents a two step simulation approach that allows assessing the impact of electrical events and their control on the structural loads of a wind turbine, using two complementary simulation tools, each specialized in different wind turbine design area. The goal with such approach is to be able to investigate the whole integrated wind turbine design with focus simultaneously on both structural and electrical design aspects.

The presented simulation approach uses DIGSILENT for modelling and simulating the detailed interaction between wind turbine and the grid during grid faults, while HAWC2 is used to assess the impact of the electrical events on the structural loads of a wind turbine.

The two step simulation procedure is used to investigate the interaction between electrical and mechanical, during grid fault, subsystems of an active stall wind turbine.

As a case study, a 2MW active stall wind turbine is considered. The first simulation scenario assumes that the active stall wind turbine does not have a fault ride-through controller hence only the generator voltage – simulated in DIGSILENT – is used as input to the reduced order generator model implemented in HAWC2. The second simulation scenario assumes that the active stall wind turbine is equipped with an advanced fault ride-through controller. In this case, besides the generator voltage, the pitch angle – constant in the first case – is the second interface signal.

The simulation results show that grid faults do have an impact on the mechanical loads of the wind turbine, especially on the shaft and the tower, while the blades do not seem to be affected in a significant way.

The time series simulation results presented in the paper can offer a quantitative image of the grid fault impact on the structure of the wind turbine but for a deeper insight analysis and evaluation of the fatigue and life time is needed.

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Nicolaos A. Cutululis (M'06) was born in 1974. He received the M.Sc. and Ph.D. degrees in electrical engineering and automatic control from the University of Galati, Romania, in 1998 and 2005, respectively. Since February 2005, he has been employed at Risø DTU, Denmark, presently as a Scientist. His main technical interest is integration of wind power into power systems, involving a variety of technical disciplines including integrated design, dynamic modeling and control of wind turbines and farms and wind fluctuation statistics.

Anca D. Hansen received her Ph.D. in modelling and control engineering from Denmark Technical University in 1997. Since 1998 she has been employed at Risø National Laboratory in the Wind Energy Department – first as Post Doc., scientist and afterwards as senior scientist. Her working field and research interests are on the topics of dynamic modelling and control of wind turbines, as well as dynamic modelling and control of wind farms and on wind farm grid interaction.

Florin Iov (SM'98, M'04, SM'06, Cigre Expert, Reuters Insight Expert) was born on 26 August 1968 in Galati, Romania. He received the Dipl. Eng. degree in electrical engineering from University of Brasov, Romania, in 1993 and a PhD degree from University of Galati, Romania in 2003 with a special focus in the modeling, simulation and control of large wind turbines. He was staff member at University of Galati, Romania from 1993 to 2001. Since 2001 he is with Institute of Energy Technology, Aalborg University, Denmark where he currently is associate professor. During the last years he was involved mainly in research projects regarding the wind turbine systems financed by the Danish authorities as well as by the industrial partners. His fields of interest are electrical machines, power converters including their control for grid integration of renewable energy sources, modeling and control of large wind turbines/farms and their grid integration. He is author or co-author of more than 70 journal/conference papers and several research reports in his research fields.

Poul Sørensen (M'04, SM'07) was born in 1958. He received M.Sc. in electrical engineering from the Technical University of Denmark in 1987. Since 1987 he has been employed at Risø National Laboratory in Roskilde, presently as a Senior Scientist. His main technical interest is integration of wind power into power systems, involving a variety of technical disciplines including power system control and stability, dynamic modeling and control of wind turbines and wind farms, and wind fluctuation statistics. He is a member of the maintenance team of IEC 61400-21 on measurement and assessment of power quality of grid connected wind turbines.