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Impact of fault ride-through requirements on wind turbine structural loads

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Abstract

This paper is mainly focusing on the impact of the fault ride-through requirements on the wind turbine structural loads. In this respect, it proposes a computer simulation approach for the quantification of wind turbines structural loads, caused by the fault ride-through grid requirements. This approach, exemplified for the case of an active stall wind turbine, can be used by the industry as a design tool. It relies on a combination of complimentary simulation tools, with different specialised expertises.

In order to quantify how the grid faults and grid requirements do affect the wind turbines loads and thus their lifetime, a rainflow analysis of the structural loads is performed and presented for two cases, i.e. one when the turbine is immediately disconnected from the grid, when a grid fault occurs and one when the turbine, as it is equipped with a fault ride-through controller, remains connected to the grid during the grid fault.

Keywords: grid codes, structural loads, HAWC2, DIgSILENT

1 Introduction

Currently, as more and more wind power is expected to enter into the electrical network, the power system becomes more vulnerable and dependent on the wind energy production. This increased penetration of the wind power into the electrical network is reflected directly into the grid connection requirements, imposed and revised periodically by TSOs all over the world.

The fulfilment of the grid connection requirements poses challenges for the design of both the electrical system and the mechanical structure of wind turbines. From an electrical point of view, these challenges imply development of advanced controllers for the wind turbines, controllers which are designed and adapted to fulfil different grid requirements, as is for example the fault ride-through requirement. Beside a good electrical performance, the design of such controllers also requires a careful investigation on how grid requirements do affect the wind turbines' structural loads and thus their lifetime.

This work presents some results of the research project, titled "Grid fault and design-basis for wind turbines" and carried out at Risø-DTU National Laboratory [1]. The objective of this project has been to assess and analyse the consequences of the new grid connection requirements on the fatigue and ultimate structural loads of wind turbines. The investigation has in particularly been focused on fault-ride through (FRT) requirements, whose fulfilment specifies the wind turbines to remain connected to the grid even during and after an abnormal grid voltage is detected.

The paper is organized as follows. First a motivation of using complimentary simulation tools in wind turbine design is explained. A computer simulation approach, where two dedicated simulation tools, with different wind turbine design expertises, are coupled sequentially to each other, i.e. in an offline procedure, is then described. Different simulations reflecting both the electrical and the structural dynamic response of a fixed speed active stall wind turbine to a grid fault are then presented and analysed. A rainflow analysis for fatigue and ultimate structural loads is performed and analysed.

2 Motivation

The increased penetration of wind power into the power system implies basically that the wind turbines are getting more responsibility in network operation. Their action and complex interaction with the power system have to be therefore analysed carefully by using detailed electrical power system models. On the other hand, the fact that, the wind turbines are being designed larger and more flexible than ever before implies larger blade deflections, which require special design and advanced computational aeroelastic models. This is for example why it is a real need for detailed calculations for the wind turbines dynamical structural loads caused by grid faults.

Nowadays, the design and the research of wind turbines take place in specific dedicated simulation tools, which are specialised either in the mechanical design area or in the electrical design area. The expertise in these wind turbine design areas is thus built-up independently, with very specific focus and without any influence from one design area to another. In spite of this fact, there is a considerable interplay between these design areas and this became even stronger in the last years, due to the continuous increasing size of wind turbines [2]. Wind turbine loads are result of a very complex combination of dynamics and excitations both of individual sub-systems and of the whole entire system, dynamics which are difficult to decouple. An example for such interplay, especially related to large wind turbines, is the risk of the coupling between the generator electrical eigenfrequency and the tower structural frequency, aspect described in details in [2].

A better understanding of the interplay between wind turbine design areas is strongly conditioned by being able to perform a wind turbine design, where the strengths of different design research areas (i.e. mechanical, electrical design and control and grid integration area) can be jointly exploited, as sketched in Figure 1.

By combining complimentary simulation tools, to the extent that it is possible, a detailed insight into the structural as well as the electrical design and control can be thus achieved, and this is very important in the quantification of grid faults' impact on wind turbines' structural loads and lifetime.

Grid faults are typically simulated in dedicated power system simulation tools, based on detailed models for the electrical components of the wind turbine and of the grid, while structural loads of wind turbines are typically assessed in advanced aeroelastic computer codes, which take the flexibility of the tower, blades and other structural components of the wind turbines into account.

In this work, the interaction between the structural and electrical dynamics of a wind turbine with the dynamic of the grid during grid faults has been studied by running two complimentary simulation tools in a combined simulation approach.

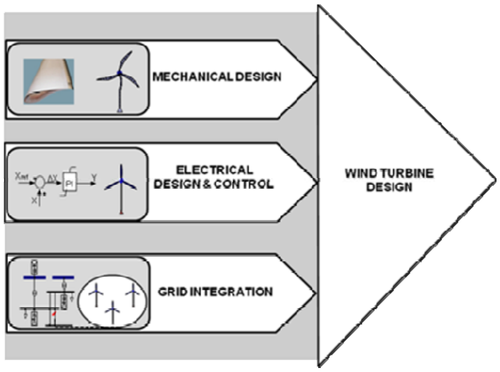

Figure 1: Design areas in the wind turbine design.

3 Computer simulation approach

A combined simulation approach between two complimentary simulations tools has been implemented and assessed for a fixed speed active stall wind turbine. This procedure is combining sequentially two complimentary simulation tools, DIgSILENT and HAWC2, in an offline approach.

DIgSILENT from PowerFactory is a dedicated electrical power system simulation tool, which provides deep insight on the electrical interaction between wind turbines and grid [3]. HAWC2 is an aeroelastic simulation code, developed at Risø-DTU National Laboratory for Sustainable Energy, which provides a deep insight on the aeroelastic and mechanical loads of the wind turbine [4]. These and other similar simulation tools are used intensively by the wind energy industry at the moment to verify grid codes compliance of wind turbines.

The detailing level in the modelling of different wind turbine components for the two considered simulation tools is very different. DIgSILENT contains very detailed models for the electrical components of the wind turbine and the grid, and simplified models for the aerodynamic and mechanical parts of the wind turbine. On the other hand, HAWC2, as it takes the flexibility of the tower, blades and other components of the wind turbines into account, it contains very detailed models for the aeroelastic and mechanical aspects in a wind turbine.

The idea of the proposed simulation approach is to jointly assess both the electrical and the structural design aspects of the wind turbine during grid faults, by coupling these tools consequently. The wind turbine electrical interaction with the grid during grid faults is thus assessed in DIgSILENT, while the wind turbine loads caused by grid faults are simulated and analysed in HAWC2. The chain of the joint simulation approach starts with DIgSILENT, as here the grid fault is simulated. As illustrated in Figure 2, the generator stator voltage and the pitch angle simulated in DIgSILENT are used as interface signals, namely as inputs into the wind turbine model of HAWC2.

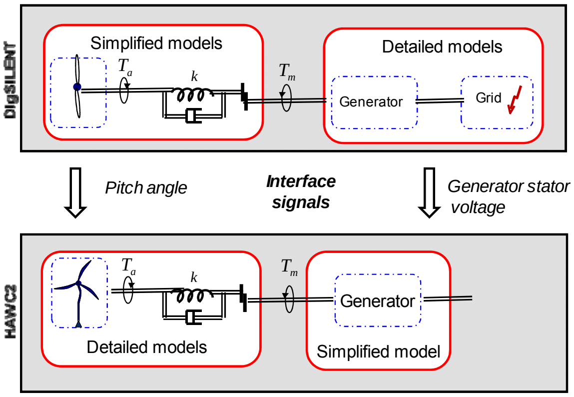

Figure 2: Wind turbine models in DIgSILENT and HAWC2 and their interface signals.

It is worth noting that the key to access a successful combination of these two complimentary simulation tools is strongly dependent on a proper definition of the interface signal between them. During this investigation, it has been experienced, that especially for wind turbines with directly connected squirrel-cage 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 toque and the generator speed [5-6]. In order to overcome this, a simplified generator model has to be implemented inside HAWC2 environment. This model is written in a state space form only in terms of the rotor fluxes in dq synchronous reference frame [7], i.e. the electric transients of the stator are neglected.

4 Case study

A case study is presented in the following in order to reflect both the electrical and the structural response of an active stall wind turbine during grid faults by using the proposed computer combined simulation procedure.

A simplified simulation scenario of a short circuit in a reduced wind power installation is performed and presented together with a rainflow analysis of the structural loads. The rainflow analysis is accomplished for two cases, one where the turbine is immediately disconnected from the grid when a grid fault occurs and one where the turbine is equipped with a fault ride-through controller and therefore it is able to remain connected to the grid during the grid fault.

Notice that the quantitative results of this investigation are not representative for variable speed wind turbines, where the presence of frequency converter can imply different behaviour and protection issues. Moreover, the variable speed wind turbines where the generator is connected to the grid through a full-scale converter may be relatively immune to grid faults from a structural point of view.

4.1 Simulation setup

The simulation setup is sketched in Figure 3.

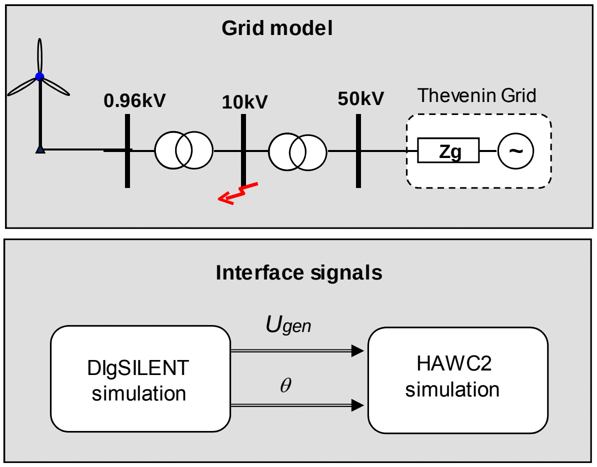

Figure 3: Grid model and interface signals between DIgSILENT and HAWC2 for the case of an active stall wind turbine.

A fixed speed 2MW active stall wind turbine, equipped with a squirrel-cage induction generator is connected to a typical-medium voltage (MV) distribution network through a step-up transformer.

Besides the control strategy for fault-ride through operation, the wind turbine model in DIgSILENT contains detailed models for the electrical components of the wind turbine, while the wind turbine model in HAWC2 contains detailed models for the aeroelastic and mechanical aspects in a wind turbine [8].

The grid model is represented by a Thevenin equivalent, consisting of a constant magnitude/frequency voltage source and a serial impedance. Such representation is typically used, when no specific grid is in focus and generalised conclusions are sought. Grid faults may occur at any point in the system. However, in this study, a 3 phase short circuit on 10kV busbar, with duration 100ms, is simulated in DIgSILENT by using the RMS (electromechanical transient models) simulation feature for longer-term dynamics.

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

Besides the simulation layout, Figure 3 sketches also the offline combined simulation approach between DIgSILENT and HAWC2. Notice that the DIgSILENT simulation is performed first with main focus on the electrical interconnection between the wind turbine and the grid during the grid fault. Once DIgSILENT simulation is finished, the generated time series for the generator voltage and the pitch angle, i.e. the interface signals between DIgSILENT and HAWC2, are further transferred to the HAWC2 model. With these signals from DIgSILENT as inputs, the HAWC2 simulation is then performed in order to achieve information about the structural behaviour of the wind turbine during the grid fault.

4.2 Simulation results and rainflow analysis of loads

In order to quantify how the grid faults and grid code fulfilment affect the active stall wind turbine structural loads, an analysis of the fatigue and ultimate loads in the lifetime of the wind turbine is performed using the rainflow method.

In the present analysis, the design load cases are considered according to the design load cases described in the IEC standard [9]. This standard includes a comprehensive list of design situations for fatigue and ultimate load analysis. The load cases selected for the analysis regarding fault ride through are as follows:

- Power production with normal wind conditions (i.e. load case DLC1.2 in [9]) - for each wind speed between cut-in and cut-out, six 10-minute simulations with different turbulence seed are performed.
- Power production with normal wind condtitions plus fault occurrence (i.e. load case DLC2.4 in [9]) – for each wind speed between cut-in and cut-out, twelve 10-minutes simulations with different turbulence seed are performed.

In this case study, for each load situation, 10-minutes simulations are performed from 6m/s to 24m/s with a 2m/s step. A normal turbulence model (NTM) is used according to [9]. A 20 years lifetime is assumed and the probability of each wind speed is calculated based on the Weibull distribution. The turbulence intensity is for a Class A turbine (high turbulence). The case for power production with normal conditions is referred in the following as Case0.

For the power production with fault occurrence situation, it is assumed that the fault occurs half-way through the simulation time. Moreover, a number of 50 fault occurrences during 20 years is considered to be realistic [10]. This amounts to 8.3 hours of fault sequences included in the load calculations.

The present fatigue analysis for the load situation with power production with fault occurrence, considers the following two cases:

Case1: Emergency stop - the wind turbine is immediately disconnected from the grid, when a grid fault occurs. The turbine is stopped by ramping the pitch angle to minus 90 degrees. The ramp slope is dictated by the pitch servo speed, which in this work is considered to be 10 deg/sec (maximum pitching rate).

Case2: Fault ride-through - the wind turbine is equipped with a fault ride-through controller, as described [8], and it is therefore able to remain connected to the grid even during grid faults. The idea of such controller is that, when a grid fault is detected, the production power is reduced, i.e. to 20% of the rated power. After the fault is cleared and the voltage has recovered during at least 5 seconds, the power reference is again set to its rated value. A similar technical solution for fault ride-through control for active stall wind turbines is applied at the Danish offshore wind farm at Nysted constructed in year 2003 [11].

The interface signals between DIgSILENT and HAWC2 for these two cases are illustrated in Figure 4.

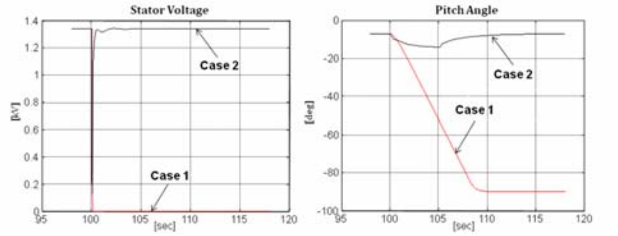

Figure 4: Interface signals (generator voltage and pitch angle) during grid faults for Case 1 and Case 2.

In Case1 the generator voltage drops to zero right after the grid fault and remain there as result of the wind turbine disconnection from the grid, while in Case2 the generator voltage drops to about 80% of the nominal voltage (less than 20% retained voltage) and recovers to its initial value when the fault is cleared after 100msec. The pitch angle in Case 1 is ramped down to -90 degrees, while in Case2, during and after the fault, the pitch angle corresponds to the predefined reduced setpoint of the aerodynamic power. As soon as the fault is detected, the normal operation controller is switched off and replaced by the fault ride-through look- up table containing the pitch angle function of wind speed. When the grid fault is cleared, the pitch angle continues to stay at the fault ride-through look-up table pitch value for a few more seconds, after which it starts to ramp up and reaches its initial normal operation value.

In order to assess the impact of the fault ride-through requirement on the turbines structural loads, a rainflow analysis for different fatigue measures has been performed. Table 1 illustrates the results of this analysis, by providing the ratio of the equivalent loads for the blade, tower and shaft of the turbine for two comparisons:

Case2/Case0 – compares the case of power production with normal wind conditions Case0 and the case of power production with fault occurrence and fault ride-through capability Case2.

Case2/Case1 - compares the case of power production with fault occurrence with emergency stop Case1 and the case of power production with fault occurrence and fault ride-through capability Case2.

Both comparisons are performed for an assumed fault occurrence of 50 in a 20 year lifetime. Similar results have been also obtained for an assumed fault occurrence of 500 or 3000 in 20 years. The latter case was investigated based on feedback from developers in India, for whom such a high occurrence of grid faults is to be expected.

Table 1: Ratio of the equivalent loads for the blade, tower and shaft of the turbine for Case2/Case0 and Case 2/Case1.

Equiv. load ranges for N=10E7		
Load sensor (1Hz eq. load)	**Case 2/Case0**	**Case2/Case1**
Blade flap moment, m=12	1.00	0.78
Blade edge moment, m=12	1.00	1.00
Tower top tilt moment, m=6	1.00	1.00
Tower top yaw moment, m=6	1.00	1.00
Tower bottom tilt moment, m=6	1.00	1.00
Tower bottom side moment, m=6	1.00	1.00
Shaft bending moment	1.00	1.00

The following remarks are concluded:

- Comparison Case2/Case0 shows that the fault ride-through (FRT) capability does not increase the fatigue measures on the turbine when added to the normal operation case.
- Comparison Case2/Case1 shows that fault ride-through (FRT) capability does not change the fatigue measures on the turbine compared to the traditional emergency stop. However, one can notice that, for flap loads Case2 shows a 22% reduction compared to Case1. The blade flap load reduction in Case2 is most likely due to the excessive speed overshoot of the emergency stop strategy used in HAWC2 simulations. As shown in Figure 5, an emergency shut-down strategy (Case 1) implies pitching, as fast as the pitch servo mechanism allows, to -90 degrees for shutdown and idling. However, to be able to run HAWC2 idling in stall, it was necessary to pitch to a positive 90 degrees instead of -90 degrees and therefore to initially increase the aerodynamic torque instead of decreasing it, leading to a high rotational speed overshoot in Case 1, as illustrated in Figure 5. This speed overshoot in Case 1, has an immediate influence on the blade flap moment and tower for-aft moment, as illustrated in Figure 5. Otherwise, the emergency shut-down would not be

typically expected to increase the equivalent flap loads, especially due to the low number and duration of fault occurrences compared to the whole lifetime of a wind turbine.

The fatigue load analysis shows thus that for the considered case study, the fulfilment of the fault ride-through requirement by an active stall wind turbine does not change the fatigue loads for all sensors, in comparison to the traditional emergency stop.

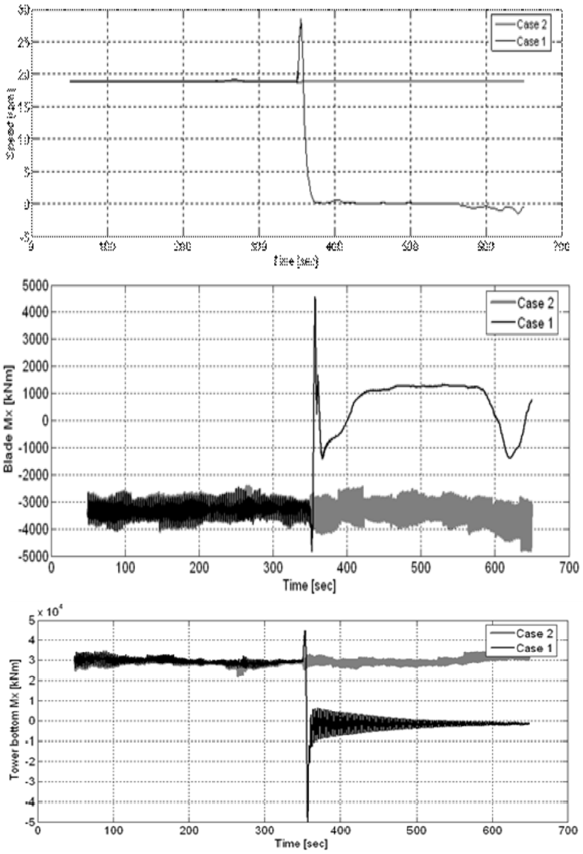

Figure 5: Rotor speed, blade flap moment, tower bottom moment in HAWC2 during CASE1 (emergency stop) and CASE2 (fault ride-through).

It can be concluded that, as expected, the normal operation is dominant for fatigue loads.

Besides the fatigue loads, the ultimate loads for the case of a fault ride-through has been also investigated, based on the following cases defined in the IEC standard [9]:

- Power production with normal wind conditions (i.e. load case DLC1.1 in [9])
- Power production with extreme turbulence model (i.e. load case DLC1.3 in [9])
- Power production with normal wind conditions plus occurrence of fault (i.e. load case DLC2.1 in [9])

As in the fatigue analysis, in the ultimate analysis 10-minutes simulations are performed from 6m/s to 24m/s with a 2m/s step for each load situation, six simulations with different turbulence seed for power production with no fault, and twelve in the case with fault. A statistical analysis is performed, and the maximum absolute value for each simulation is used as a measure of the ultimate load.

Figure 6 illustrates, for example, the mean, maximum, minimum and standard deviation values for the blade flap moment. Notice that the maximum of the absolute value of the maximum and minimum moment gives the ultimate load, which in this case is for DLC1.3, power production with extreme turbulence, at 24m/s.

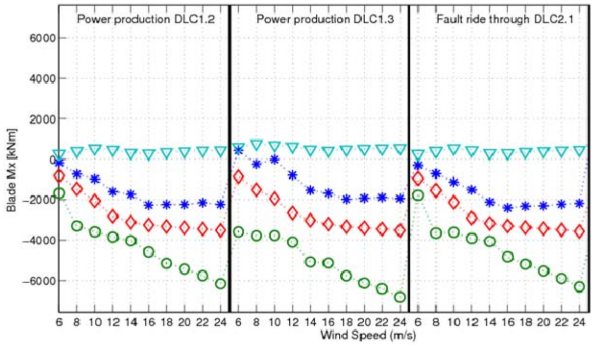

Figure 6: Maximum (*), minimum (○), average(◊) and standard deviation(▼) of the blade flap moment for one random seed.

The result of the ultimate load analysis is that the fulfilment of the fault ride-through requirements by an active stall wind turbine, does not have the maximum effect on the loads of the wind turbine components (blade flap moment, blade edge moment, tower top tilt moment, tower top yaw moment, tower bottom tilt moment, tower bottom side moment, shaft bending moment) compared to the situation of power production with extreme turbulence model (DLC1.3).

5 Conclusions

Emphasis in this paper is on the impact of the fault ride-through requirements on the wind turbine structural loads and on the need for an integrated wind turbine design with simultaneous focus on both structural and electrical design aspects.

In this respect, a computer combined simulation approach for the quantification of wind turbines' structural loads, caused by the fault ride-through grid requirement, has been proposed and exemplified for a case study of an active stall wind turbine subjected to a 100ms three phase short circuit fault on the grid.

In order to quantify how the grid faults and grid codes fulfilment do affect the wind turbines loads and thus their lifetime, a rainflow analysis of the structural loads for fatigue and ultimate loads, respectively, has been accomplished. Two cases were considered, i.e. one when the turbine is immediately disconnected from the grid when a grid fault occurs and one when the turbine, as it is equipped with a fault ride-through controller, remains connected to the grid during the grid fault.

The investigations have shown that for an active stall wind turbine, neither the fatigue nor the ultimate structural loads on the tower and the blades are affected by the fulfilment of the fault ride-through requirements.

Acknowledgement

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