

Mechanical Load Analysis of PMSG Wind Turbines in Primary Frequency Regulation

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Abstract

As the level of wind power penetration increases, wind turbines can help overcome grid frequency dips and reduce maximum frequency deviations taking part in primary frequency response. This paper analyzes the structural loads of wind turbines when they are performing Active Power Control (APC) for primary frequency regulation. A model of the wind turbine defined in the 'Upwind' European project completed with a detailed model of a PMSG electrical machine is considered in GH Bladed. A collective pitch angle and generator torque H_∞ robust controllers of the wind turbine are augmented with a droop curve and an active power control system in order to allow the frequency regulation in addition to track active power set-points required by the grid operator. The PMSG wind turbine works with a defined reserve power capability in order to supply it when needed.

This paper focuses on the analysis of the mechanical loads induced when primary frequency regulation is performed, analyzing as well the best power transition ways from the point of view of the loads, but considering as well frequency response transients.

Keywords: Primary Frequency Regulation, PMSG, Active Power Control (APC), Droop Curve

1 Introduction

Frequency regulation services have been carried out historically by conventional power plants. For that, power plants involved require a certain level of active power reserved. As the level of wind power

penetration increases, wind turbines have to take more and more tasks of conventional power plants related to frequency control. This is reflected in a gradual development of harder requirements by system operators for the integration of wind turbines in frequency control [1]. Basic requirements include the capability of controlling the power output in order to meet external power set-point changes and to participate in frequency regulation. Moreover, some grid codes (for instance the Irish Grid Code [2]) require that wind turbines work in power reserve. This allows wind turbines to ramp power up and down in response to system frequency deviations. This primary frequency regulation should be activated immediately without any control signal from the system operator.

Some works in the literature [3][4][5][6] propose Active Power Control (APC) for wind turbines working with reserve power capability to help perform primary frequency control. Although different frequency control structures for wind turbines can be found in the literature [3][4], a basic APC structure consists of an augmented speed controller where pitch angle and generator torque set-point signals are generated according to a droop-curve [4]. An advantage of this is that the conventional speed controller can be used without any changes, especially if it is robust enough for all possible operating points.

Studies found in the literature normally use simplified models, especially from the aero-mechanical part of wind turbines. Moreover, the influence of APC on structural loads of wind turbines is not normally analyzed. In this paper, a complete model of the 'Upwind' 5MW wind turbine in GH Bladed is

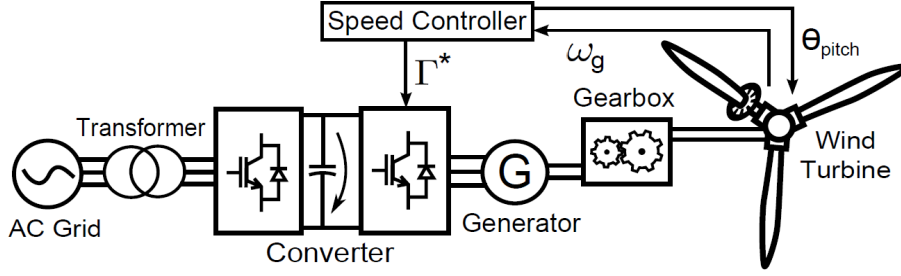


Figure 1: Schematic view of a wind energy conversion system (WECS)

used, where the power train has not been changed and a PMSG electrical machine has been designed instead of the initially defined ideal DFIG machine. A detailed model of the PMSG machine has been integrated in the model in GH Bladed. This model enables the analysis of the structural loads when different APC strategies are applied or different grid faults happen.

Firstly, this paper presents briefly the modelling of the wind turbine, the PMSG electrical machine and the grid in GH Bladed. Moreover, the robust speed controller and the APC structure are described as well. Then, some operating strategies of wind turbines for power demand changes or primary frequency control are summarized. After that, the results obtained with different operating strategies are presented, paying attention to mechanical load implications. Finally, some conclusions are stated.

2 Modelling of the PMSG Wind Turbine

2.1 Upwind 5 MW wind turbine

The Upwind wind turbine defined inside the Upwind European project was modelled in GH Bladed 4.0 software package and it is the reference wind turbine non-linear model used to implement the controllers presented in this paper. The Upwind model consists of a 5 MW offshore wind turbine with a monopile structure in the foundation. It has three blades and each blade has an individual pitch actuator. The rotor diameter is 126 m, the hub height is 90 m, it has a gear box ratio of 97, the rated wind speed is 11.3 m/s, the cut-out wind speed is 25 m/s and the rated rotor rotational speed is 12.1 rpm, so the nominal generator speed is 1173 rpm. Initially, an ideal DFIG electrical machine was considered and the complete model was used to design pitch angle and

generator torque H_∞ robust controllers. The generator model was changed and a PMSG electrical machine was modelled. The initial power train was not changed in order to maintain the main characteristics of the wind turbine.

2.2 Modelling of the PMSG and grid

The PMSG interacts with the AC grid through a fully-rated back-to-back converter. This converter can be directly connected to the grid or it can incorporate a power transformer to adapt the output voltages. In Fig. 1 a schematic view of the system under analysis is sketched.

Notice that this model combines a gearbox and a multi-polar PMSG, and this configuration is based on the model PMSG_3G presented in [7].

The PMSG is modelled as follows:

$$v_{gq} = -R_g i_{gq} - \omega_e L_d i_{gd} + \omega_e \Psi - L_q \frac{di_{gq}}{dt}$$

$$v_{gd} = -R_g i_{gd} + \omega_e L_q i_{gq} - L_d \frac{di_{gd}}{dt}$$

In particular, the nonsalient-pole generator under consideration has surface-mounted magnets and is described assuming the same inductance in the d and q axis (i.e. $L_q=L_d$). The characteristics of the model can be found in Table 1.

Parameter	Value
Generator resistance (R_g)	0.3192 Ω
Generator inductance (L_q, L_d)	0.0012 H
Rated generator frequency (ω_e)	3141.6 rad/s
Magnet flux linkage (Ψ)	1.0998 Wb
DC-link capacitance (C)	3000 μ F
Pole pairs (p)	25

Table 1: WECS model parameters

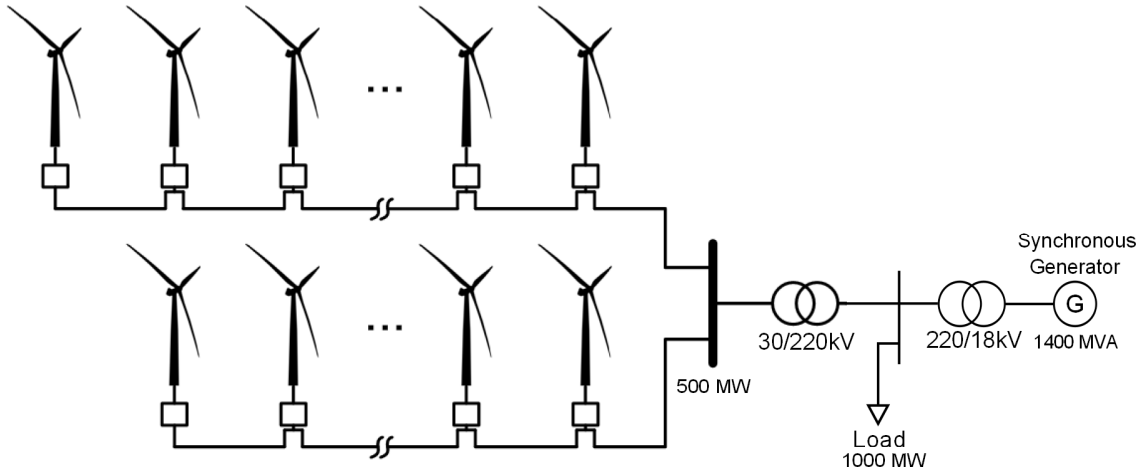


Figure 2: Grid model used in simulation

The control system consists of PI controllers with decoupling terms and anti-windup compensation. Each side of the power converter has its own individual controller implemented. The gains of the controllers have been computed using the Internal Model Control (IMC) method. The control system is based on vector control which is useful to manage active and reactive power independently. Being the Park transformation oriented to v_{gq} ($v_{gd} = 0$) the torque (Γ) and reactive power (Q_g) applied to the generator can be expressed as:

$$\Gamma = \frac{3}{2} p \Psi i_{gq}$$

$$Q_g = \frac{3}{2} v_{gq} i_{gd}$$

Analogously, the control system of the grid-side converter is oriented to the q-axis, as a result, the active (P_z) and reactive power (Q_z) in the q_d frame are given by

$$P_z = \frac{3}{2} v_{zq} i_{zq}$$

$$Q_z = \frac{3}{2} v_{zq} i_{zd}$$

An average model is used to describe the power converter. The voltage level of the DC-link is computed by making a balance of power at both sides of the converter, the DC voltage is then governed by

$$\frac{dv}{dt} = \frac{2}{C} \left(\frac{3}{2} v_{gq} i_{gq} - \frac{3}{2} v_{zq} i_{zq} \right)$$

where v is the square of the DC voltage and C is the capacitance. The output voltage of

the converter is 6 kV and the transformer steps this voltage up to 30 kV which is the voltage of the wind farm grid.

2.3 Grid model and integration in GH Bladed

In order to evaluate the evolution of the grid frequency a basic model, with a wind farm, a synchronous generator and a load, is proposed. The electrical grid is modelled as a series of impedances and inductances expressed in an admittance matrix.

The wind farm consists of one hundred wind turbines, all of them working in the same operating point and in the same conditions, with a combined power of 500 MW. This wind farm model includes the generator, converter and grid part of the WECS stated in Fig. 1.

The synchronous generator has a rated power of 1400 MVA and includes a droop control. The load is initially consuming 1000 MW, and a 30% increase of the load power is triggered during the simulations in order to cause a frequency deviation. Both generation plants are connected to transformers that adapt their output voltages to the network voltage, which is 220 kV. A schematic view of the proposed model including the main characteristics is depicted in Fig. 2. Further details regarding the grid and synchronous generator parameters can be obtained from [9].

The electrical model depicted in Fig. 2 has been developed in Matlab/Simulink. The electrical model is build into a dll using the Real-Time Workshop included in

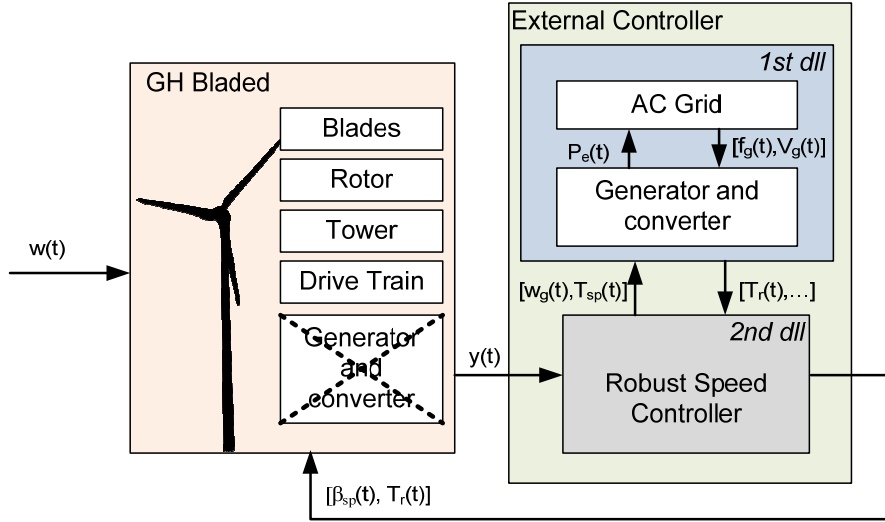


Figure 3: Simulation model scheme in GH Bladed

Matlab/Simulink. This dll library is named '1st dll' to be integrated in GH Bladed.

Fig. 3 shows the complete scheme of the wind turbine model used in the simulations in GH Bladed and how the model of the electrical machine and grid is integrated. The complete wind turbine model in GH Bladed considers an ideal variable speed generator and no network. The dll library of the electrical model is integrated inside the external controller. This implements basically the robust speed control of the wind turbine ('2nd dll'). But the generator torque calculated is passed to the '1st dll', where the real generator torque value $T_r(t)$ is calculated including the dynamics of the generator, converter and grid. This generator torque value $T_r(t)$ is obtained from the real generator speed $w_g(t)$ and the demanded generator torque set-point value $T_{sp}(t)$. Other variables used inside the dll, like grid frequency $f_g(t)$, grid voltage $V_g(t)$ or electrical power $P_e(t)$, are returned from the '1st dll' to be used or visualized in the external controller of GH Bladed.

wind turbine in the above rated power production zone. The generator speed and torque references, w_{ref} and T_{ref} respectively, could vary according to the operating point demanded from the Active Power Control.

The H_∞ MISO Generator Torque Controller reduces the wind effect in the drive train mode and tower side-to-side first mode adding a torque contribution T_{H_∞} to the generator torque reference. This torque contribution is calculated from the measured generator speed w_g and tower top side-to-side acceleration a_{Tss} .

On the other hand, the H_∞ MISO Collective Pitch Controller obtains the reference β_{H_∞} of the collective blade pitch angle to regulate the generator speed reducing the wind effect in the tower fore-aft first mode. The measured generator speed error e_{wg} and the tower top fore-aft acceleration a_{Tfa} are necessary to develop this control loop.

As presented in [6], for the design of the robust speed controller a family of linear plants is considered in the above rated

3 Augmented Controller for Primary Frequency Regulation

3.1 Robust speed controller

The 'speed controller' block of Fig. 1 consists of the two H_∞ robust main controllers [8], shown in Fig. 4, used to regulate the electrical power and to mitigate the loads in different components of the

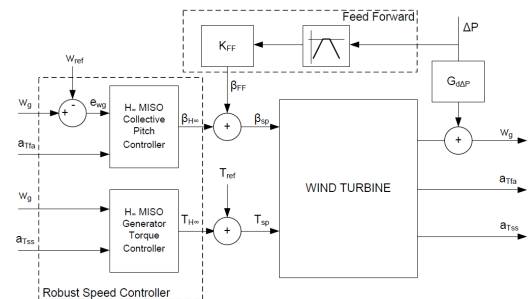


Figure 4: Speed controller based on the H_∞ norm reduction for the above rated zone

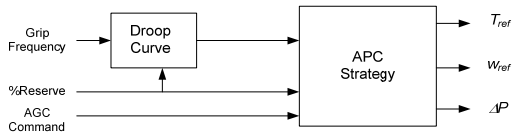


Figure 5: Block diagram of the APC command to generate references for the main controller

zone and the differences respect to a nominal model used in the design are evaluated as additive uncertainties in order to guarantee the robustness stability of the closed loop controller. A feed forward control loop has been added to the basic robust controller, which is explained in section 5.3.

3.2 Active Power Control (APC)

The speed controller is augmented with an Active Power Controller in order to perform primary frequency regulation, such as Fig. 5 shows. The wind turbine works in deloaded conditions and the APC algorithm generates the generator torque and speed references for the 'speed controller' (Fig. 3) of the wind turbine according to the input '%Reserve'. The APC strategy changes the operation condition of the wind turbine due to the new power set-point taking into account the grid frequency measured by the electrical machine, and the droop curve defined for the wind turbine. It can output a ΔP set-point value for the optional feed forward loop of the speed controller (Fig. 4).

The augmented control structure shown in Fig. 5 is able to track an Automatic Generation Control (AGC) power reference command and therefore it can provide secondary frequency services.

Fig. 6 shows an example of droop curve [9] as well as an example of frequency dip defined in some European grid codes where the wind turbine can contribute to the primary frequency regulation according to the droop curve if it has reserve power.

4 Operating Strategies for Power Demand Changes

Fig. 7 shows the working zones of the 'Upwind' wind turbine model when it works without power reserve (red line) or with a power reserve of 15% (blue line). In above rated zone, the wind turbine works at point A with reserve and at point B without

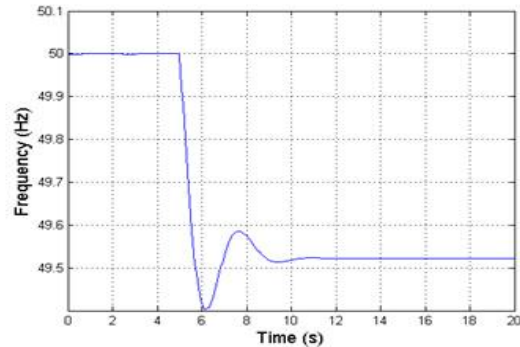
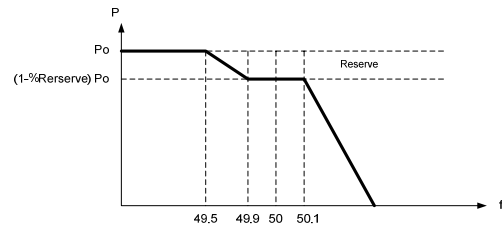


Figure 6: Example of droop curve for a wind turbine and example of grid frequency dip defined in some European grid codes

reserve. The power curves corresponding to 100%, 85% and 50% are shown as well.

When the power reference should be decreased to 50% for a limit time period due to an increase in grid frequency, the operation point of the wind turbine could shift from point A to point C, keeping the nominal speed by pitch actuation and decreasing the generator torque set-point value, therefore remaining at above rated zone if the wind speed is high enough. If due to a grid frequency dip and the droop curve the power reference should be increased to 100%, the operation point of the wind turbine could shift from point A to point B, keeping the nominal speed and increasing the generator torque set-point value to the nominal value. However, other alternative operation points could be considered on the power curves of 50% and 100%, for instance points D, E and F.

As Fig. 7 shows, the operation point in reserve can be as well the point A', where the wind turbine is working in over-speed. Other operation points on the same power curve, as point A'', could be considered as well. Working without power reserve, in the event of a frequency dip, a used control strategy is to increase the generator torque and therefore the turbine rotor decelerates, allowing a momentary rapid increase of the generated electrical power due to the kinetic energy delivered to the grid. For

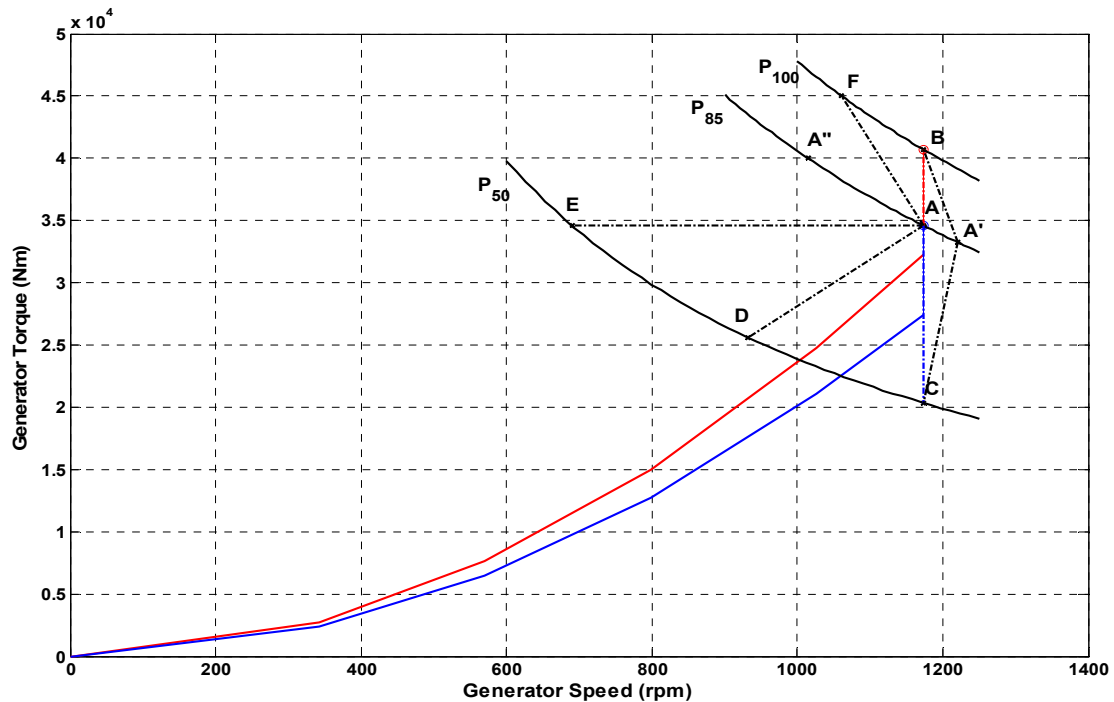


Figure 7: Operation zones of the upwind 5MM wind turbine without reserve power (red line) and with a reserve power of 15% (blue line)

instance, in Fig. 7 it would be the case of shifting from point A to point A'' in response to a frequency dip, keeping unchanged the power curve. This over-speeding technique is normally used in the below rated zone when working without power reserve.

The mentioned operation points can be taken into account for short time periods, while the primary frequency regulation is being carried out. The decision about the operating point to be used is the basis of the APC algorithm and it has influence on the working conditions of the generator and, especially, on the structural loads of the wind turbines during the operation point shift.

5 Simulation Results

5.1 Contribution to Primary Frequency Regulation

The primary frequency control support that the wind turbines can provide is evaluated in Fig. 8. As a response to a dip frequency caused by a load increase, the wind turbine can do nothing or can participate in its regulation. Supposing the operating point of the wind turbine is point A in above rated zone, the operating point can remain the same (black line) or, working without power

reserve, it can be shifted to the A'' point (red line). As observed in Fig. 8 the frequency nadir is improved, although the steady state level of the frequency after the disturbance is the same.

If the wind turbine is working in power reserve, the wind turbine can change the operation point from point A to point B or to point F in response to the frequency dip. In the case of shifting to point F the corresponding generator speed decreases and a part of the kinetic energy is delivered to the grid. In Fig. 8 frequency transients shown by green and dark blue lines are obtained. As observed, in both cases the frequency nadir and the steady state frequency level are improved respect to the case of working without power reserve. In the case of the A-F transition the frequency nadir is better than in the case of the A-B transition, but the change in generator speed and its load implication is the price to be paid.

The strategy for primary frequency regulation could be only to work in over-speed, although this strategy is normally used in the below rated zone. For instance, it could be to work in the A' operation point. Working without power reserve, a shift to point A'' in response to the frequency dip would improve the frequency nadir due to

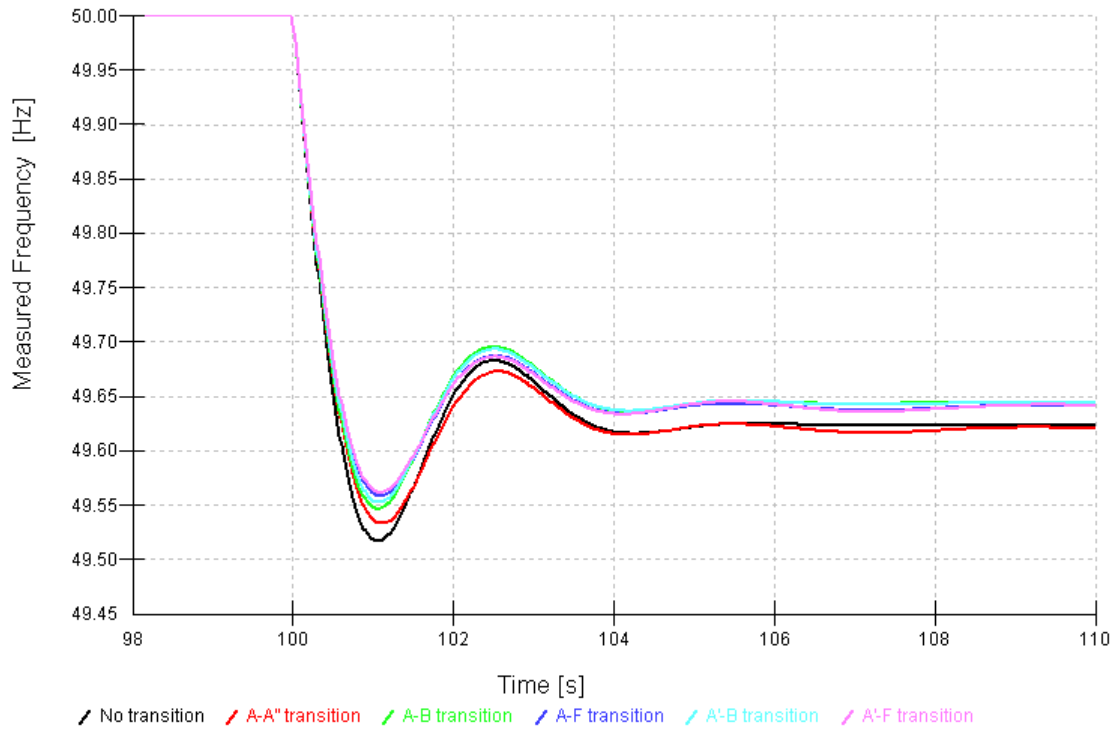


Figure 8: Frequency deviation caused by a sudden load increase. Responses with different transitions in operating points

the extra kinetic energy available. Working with power reserve, Fig. 8 shows the frequency transients obtained in the A'-B (cyan line) and A'-F (magenta line) transitions. The steady state frequency levels are the same but the frequency nadirs are slightly improved respect to transitions from the A point.

As mentioned, improvement in frequency

nadir is obtained when the shift in the operating point involves a generator speed decrease. But due to the fact that the operation point transition should be carried out quite fast for the primary frequency regulation, it implies load increments in the power train and in other mechanical elements of the wind turbine. Fig. 9 shows the Tower Base Mxy load for the different transition cases analyzed. As observed, the

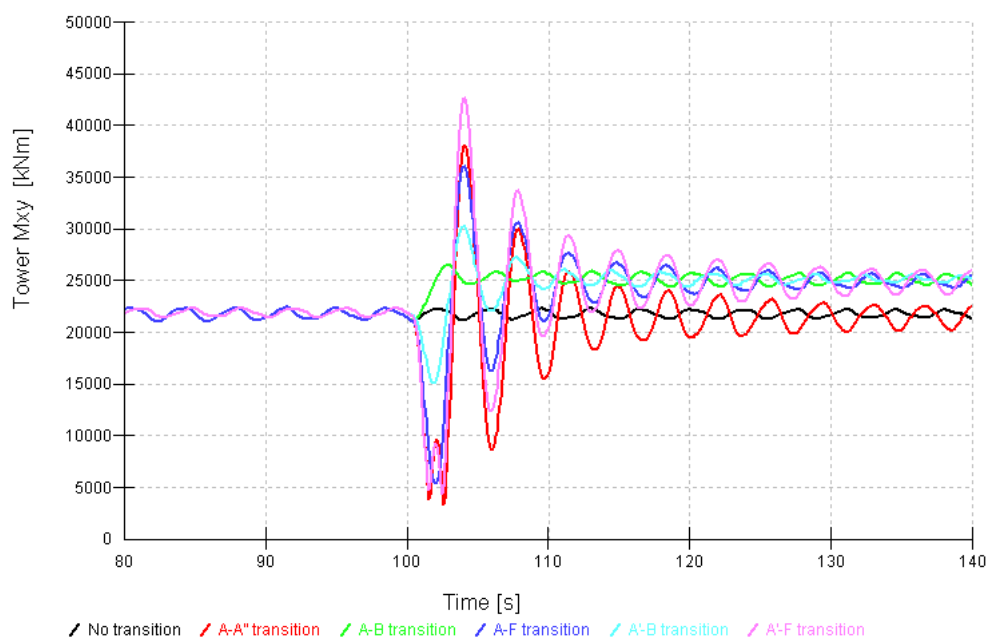


Figure 9: Tower Base Mxy load in different transition cases for Primary Frequency Regulation

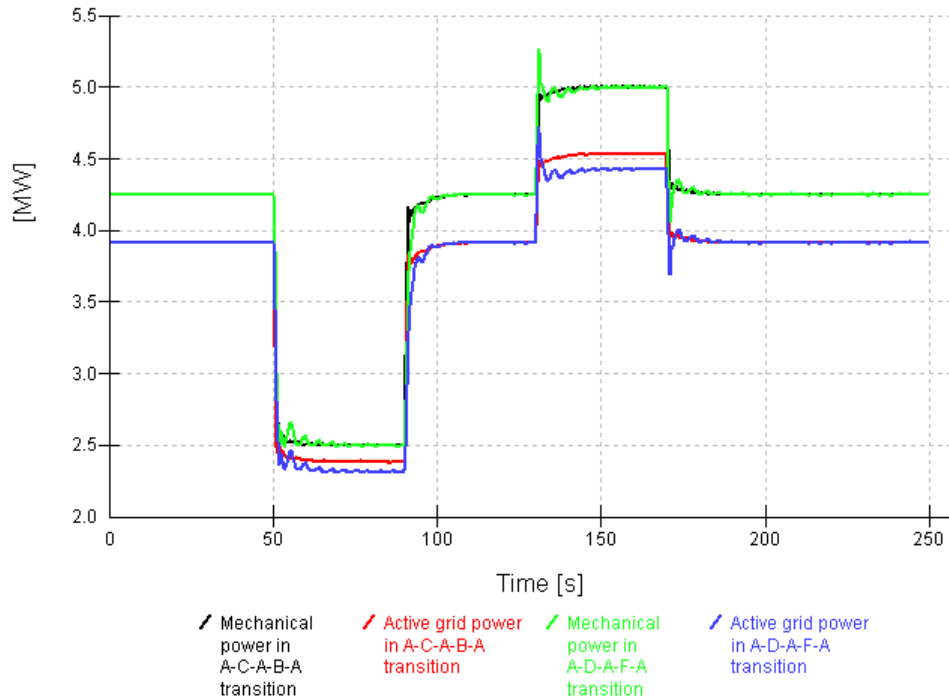


Figure 10: Mechanical power and active grid power in operating point transitions A-C-A-B-A and A-D-A-F-A at a wind of 19 m/s

load increases a lot when large nominal generator speed changes are demanded. In the cases analyzed, the operating point transitions have been performed in 0.1 s.

5.2 Analysis of mechanical loads

As observed in Fig. 5, power transitions can be generated by frequency dips/increases or by an AGC command for secondary frequency regulation. In this last case, where the power transitions could be much larger, the change can be performed with a limited power rate, slower than in the case of primary frequency regulation. In order to analyze load implication of power changes some power transitions from the operating point A are considered.

A power decrease from the operating point A to 50% power curve for 30 s and an increase from point A to 100% power curve for 30 s are considered. The power transition is made following the way A-C-A-B-A in one case and the way A-D-A-F-A in another case and the results obtained are compared. A constant wind of 19 m/s is considered in order to guarantee that the wind turbine remains working in above rated zone. The wind turbine collective pitch angle and generator torque H_{∞} controllers

are used without activating the tower side-to-side compensation.

Fig. 10 shows the mechanical power and the active power delivered to the grid in the two power transitions mentioned. The active grid power is the mechanical power decreased by the losses in the electrical machine. These losses depend on the generator torque. From this point of view, operating points D and F are worse than operating points C and B, because the torque is higher and the losses as well.

Generator speed, generator torque and pitch angle signals can be observed in Fig. 11, Fig. 12 and Fig. 13. As a general comment, the transition A-C-A-B-A is smoother than the transition A-D-A-F-A, because there is not speed change, which is penalized, as observed in the A-D-A-F-A case, with a high pitch action and it induces speed vibrations in the drive train and activity in the demanded generator torque to compensate them.

As an example of the influence on the mechanical loads, Fig. 14 shows the Tower Base Mxy load. As it can be observed, the fatigue and extreme values increase a lot in the transition A-D-A-F-A. Similar results can be observed in other structural loads.

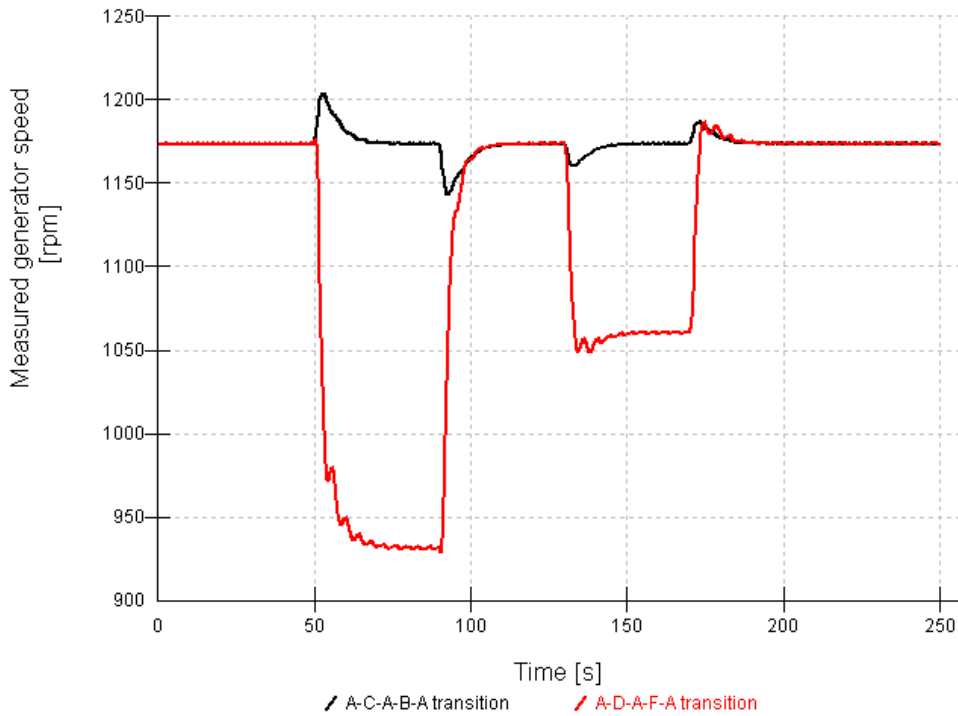


Figure 11: Generator speed in operating point transitions A-C-A-B-A and A-D-A-F-A at a wind of 19 m/s

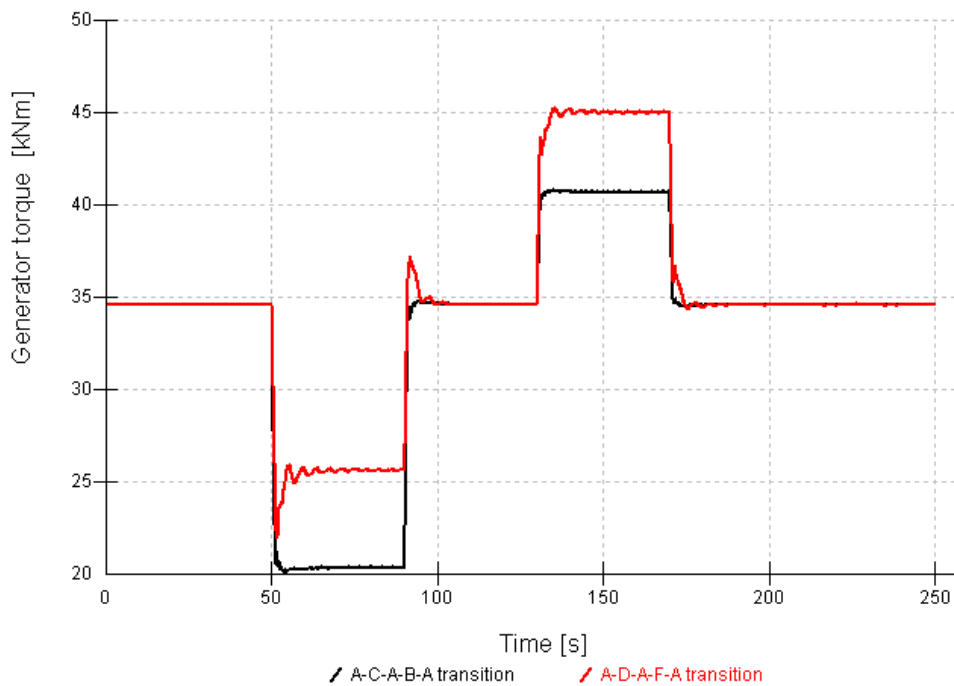


Figure 12: Generator torque in operating point transitions A-C-A-B-A and A-D-A-F-A at a wind of 19 m/s

As a conclusion, from the point of view of mechanical loads, power transitions carried out changing only the torque reference and keeping the generator speed set-point are the best ones compared to others where the operation point speed changes. Extrapolating the results to all working zones, the best option is to keep the

nominal speed in the above rated zone and to follow the corresponding maximum C_p curve in the below rated zone. However, working in reserve power capacity operation points with over-speed, like point A' in Fig. 5, could be interesting from the point of view of an extra kinetic energy to be supplied to the grid when required. Using this stationary operation point to

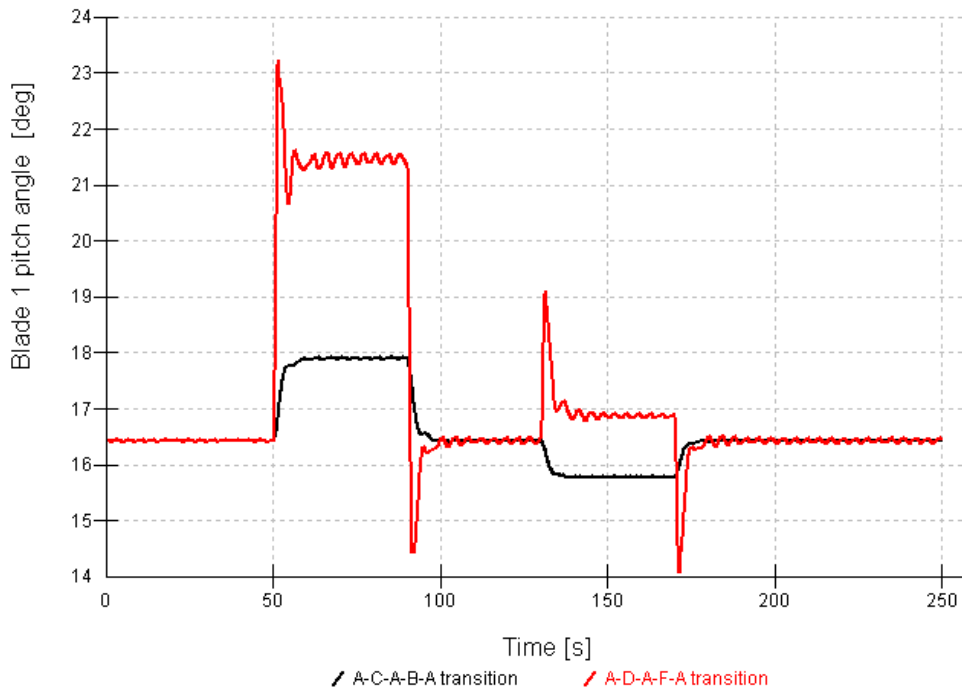


Figure 13: Pitch angle during operating point transitions A-C-A-B-A and A-D-A-F-A at a wind of 19 m/s

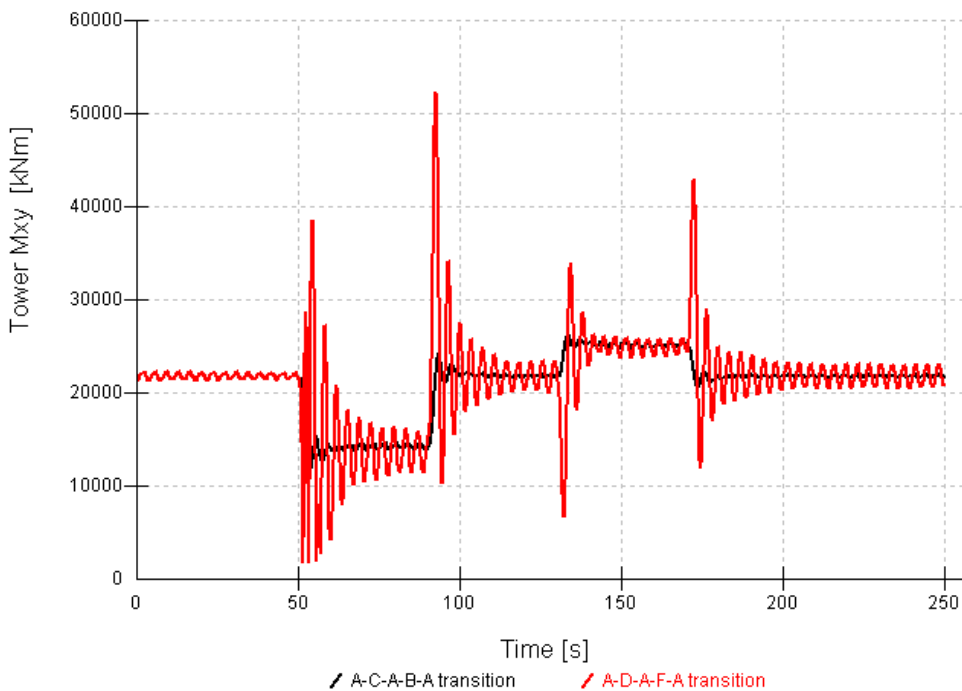


Figure 14: Tower Base Mxy in operating point transitions A-C-A-B-A and A-D-A-F-A at a wind of 19 m/s

make transitions similar to A'-C-A'-B-A' has less load implications than the previously analyzed one and some benefits can be obtained, because generator losses are lower. Moreover, as analyzed in section 5.1, improvement in primary frequency regulation can be obtained due to the extra kinetic energy.

5.3 Improvement of the speed controller

As shown in the analysis carried out, changes in operating points for primary or secondary frequency regulation could involve changes in nominal generator speed set-points and therefore speed transients and increment in mechanical loads. A feed forward control loop, shown in

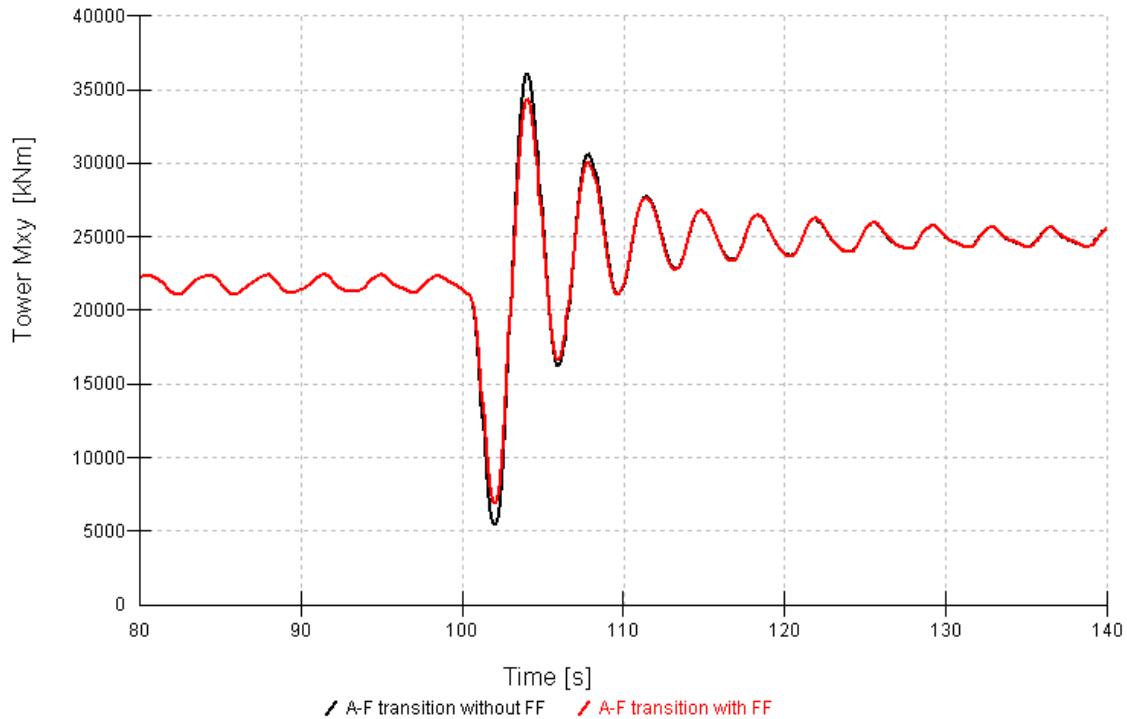


Figure 15: Tower Base Mxy load in the AF transition without/with feed forward loop in the speed controller

Fig. 4, is proposed to improve the generator speed regulation when the electrical power demand changes. The changes in the electrical power demand ΔP , mainly caused by the Active Power Control, are considered as known output disturbances which affect to the generator speed with the dynamics of $G_{d\Delta P}(s)$. The response of the collective pitch control loop can be faster, to have a better regulation of the generator speed, with an extra pitch contribution β_{FF} calculated from the changes in the electrical power ΔP . This feed forward control loop consists of a band-pass filter and a gain value. The band-pass filter has cut frequencies of 0.025 Hz and 1 Hz to limit the control activity only to this range of frequencies. The gain value ($K_{FF} = 1e-8$ rad/W) is used to scale the units of the input and the output of this control loop. In this design, the gain value K_{FF} is constant, but it can be variable, according to the power demand changes, to improve the response of this feed forward control loop in future control designs.

Fig. 15 shows the improvement in the Tower Base Mxy load when using the feed forward control loop in the generator speed controller, due to the improvement in the speed regulation in power demand changes.

6 Conclusions

A complete wind turbine model integrating a detailed model of a PMSG electrical machine and a grid model has been carried out in GH Bladed. At the same time, the generator torque and collective pitch angle H_{∞} robust controllers of the wind turbine have been augmented with a droop curve and an active power control system in order to allow the automatic frequency regulation in addition to track active power set-points required by the grid operator. This model enables the analysis in simulation of structural loads when different APC strategies are applied or different grid faults happen. Working the wind turbine in power reserve capacity, power transitions have been performed as responses to grid frequency dips/increases and the load implications analyzed. As a conclusion, from the point of view of mechanical loads power changes by means of torque changes are preferred. But from the point of view of primary frequency regulation, operating point transitions that involve nominal speed reductions improve the frequency nadir obtained. For a preferred APC strategy, the speed control algorithm can be improved with a feed forward control loop in order to limit over-speed during changes in power set-points and therefore mechanical loads.

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