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ELECTROMECHANICAL DRIVETRAIN SIMULATION

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ABSTRACT

The work presented in this paper is another step from the DTU Wind Energy efforts to advance understanding of the electromechanical drive-train loads and its interaction with the rest of the components in the wind turbine. The main objective of the PhD is to investigate the modelling and simulation of a wind turbine's drivetrain using an integrated simulation approach where different simulation tools are interconnected. Matlab and HAWC2 are used for this purpose. A contribution is expected to be in the study of the interaction between the mechanical loads in the gearbox due to gear mesh and bearing flexibilities, the generator dynamics and the grid, along with the structural loads in the wind turbine. In this paper, two simulation approaches are presented and conclusions are made according to their advantages and disadvantages. The drive-train is described by means of a torsional model composed of the main shaft, gearbox and generator. Special attention is given to the modelling of the gearbox and the generator in order to study the mechanical vibrations caused by turbulent wind and grid dynamics.

NOMENCLATURE

K_{ps_k}	sun/planets mesh stiffness
K_{pr_k}	ring/planets mesh stiffness
K_g	gear/pinion mesh stiffness
K_{s_j}	shaft stiffness
J_{i_k}	inertia
$r_{c_k}, r_{p_k}, r_{s_k}$	carrier, planet and sun base radius
r_{g_k}, r_{pi_k}	gear and pinion base radius
m_{p_k}	planet mass
α	gear pressure angle
cs	$cos(\alpha)$
ΣK_{pm}	$K_{pr_k} + K_{ps_k}$
ΔK_{pm}	$K_{pr_k} - K_{ps_k}$
$\mathbf{J_k}$	Inertia matrix of stage k
$\mathbf{K_k}$	stiffness matrix of stage k
gr	gear ratio
Sub-, Superscripts	
i	body type
j	shaft index
k	gearbox stage
c, p, s	carrier, planet, sun
g, pi	gear, pinion
Abbreviations	
HAWC2	Horizontal Axis Wind turbine simulation Code
MBS	Multi-body Systems
DOF	Degree Of Freedom
LSS	Low Speed Stage
ISS	Intermediate Speed Stage
HSS	High Speed Stage

INTRODUCTION

Wind turbines are complex structures that are subject to different dynamic loads from fluctuating wind loads and the dynamic behaviour of the grid. The DTU developed software HAWC2 is one of the leading simulation software used by industry and academic research to study the time domain response of wind turbines. The models used by the software are structures based on MBS dynamics theory and the aerodynamic part is based on the blade momentum theory [1]. One area that needs further investigation is the dynamics of the drive train. For example, the gearbox and generator system in aerolastic studies are often treated as ideal and it is represented by an inertia. In [2] the gearbox is considered ideal, therefore the drive train model is implemented by referring the generator rotor inertia to the low-speed shaft. Hence, there is no formulation that contains several DOFs that could describe the behaviour of the gearbox and its interaction with the rest of the turbine. The fundamental motivation for working on more detailed models of the wind turbine components is that it is possible to create a framework for reliability, by investigating the internal loads in the drive train, and how those loads interact with the rest of the wind turbine. Incidentally, the gearbox is the most expensive subsystem in the wind turbine to maintain [3] and the one that presents the most failure.

In [2], an integrated dynamic analysis platform using HAWC2 and Matlab/Simulink was developed and used to study the impact of grid faults on wind turbine structural loads. In this framework, HAWC2 is used to simulate the blades, shaft and tower of the wind turbine, while MATLAB and Simulink is used to simulate the electrical generator, the controllers and the power system. Existent work within the theory of gear transmissions have focused in modelling techniques of gear contacts [4] and the internal dynamics of a planetary stage gearbox [5] [6] using MBS. The main objective of this PhD is to create detailed drive train models with increasing complexity, such as [6] [7], in order to obtain more detailed information of the drive train loads in a wind turbine, hence create a framework for reliability of wind turbine drivetrains.

In this paper, two existing simulation approaches are presented and discussed based on their advantages and disadvantages. First, the external systems interface with HAWC2 through a DLL is presented and an example of an existing planetary stage gearbox [8] is presented. Later, the integrated dynamic analysis platform using HAWC2 and Matlab/Simulink is introduced, along with a description of a torsional model of the gearbox and a dynamic model of the generator. Finally, some preliminary results are described.

HAWC2's EXTERNAL SYSTEMS INTERFACE

One of the most important things in system simulation is to have flexibility within the simulation environment. Thus, being able to choose between different options in order to achieve the desired results is an important factor of the flexibility given in a simulation software. These options could be toolboxes within a software, or the possibility to integrate different simulations environments. Most of the time, when using commercial software, there are certain limitations such as high costs, or simply compatibility issues, which compromise flexibility. In the case of HAWC2, it is possible to connect an external system and to simulate the dynamics of such coupling [1]. So far, this capability has been used by [8] to simulate the reaction forces in the teeth of a planetary gearbox. The gearbox was defined as an external system DLL and constrained to the main shaft of a wind turbine. Thanks to this interface, it was possible to study the dynamics of the complete structure given variations in the wind field and the electromagnetic torque of the generator.

This model contains 9 DOF in total: 6 rigid body DOF and 3 torsional DOF for the ring, carrier and sun wheels. The main advantage of this approach is the flexibility to define a model and to constraint it to any body of HAWC2 via constraint equations. In this model, the rigid body DOF are constrained to the main shaft using a position and a rotation constraint. In this way, the low-speed torque is transferred via reaction forces to the gearbox. Then, a reaction force corresponding to the generator torque is applied to the sun wheel. This maintains the torque balance in the drivetrain and ensures that the reaction forces produced by the electromagnetic torque are transferred not only to the gearbox, but to the rest of the wind turbine structure.

Another advantage is that there is only one solver working at each time step, reducing computational time and avoiding the use of a different software. However, the disadvantage with the current gearbox model is that it has been defined using the gear ratio information, i.e. $gr = 97:1$, therefore the gearbox is condensed in only one stage. In addition, it is necessary to create and additional model of a bedplate as a HAWC2 body in order to transfer correctly the reaction forces from the drivetrain to the tower top of the wind turbine.

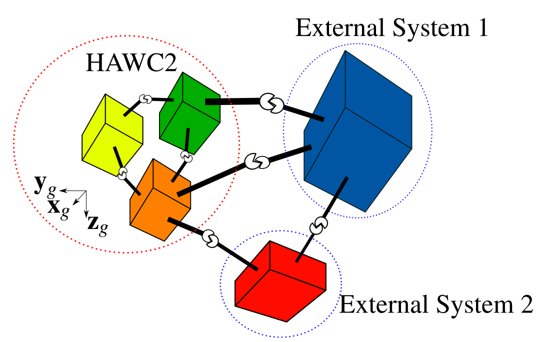

FIGURE 1: HAWC2 and the external systems interface.

Some preliminary results are presented here in order to demonstrate the value of the current model and as a motivation for expanding it towards a more realistic approach. The turbine used is the NREL 5MW Reference Wind Turbine [9] and the response of two IEC standard load cases is explored: 1.1 and 2.3. The first case is turbulent wind with a mean value of 14 m/s (Figure 2); the second case is a steady wind at 14 m/s but with a simulation of loss of power at 250 s, which is simulated by the loss of the electromagnetic torque of the generator.

The preliminary results in Figures 3 and 4 show the effects of changing conditions on the gearbox. It is important to pay

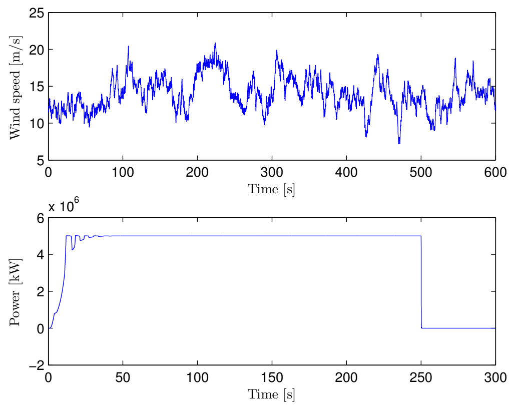

FIGURE 2: Simulation cases. *Top*: turbulent wind. *Bottom*: generator power at a steady wind of 14 m/s, with electrical fault at 250 s.

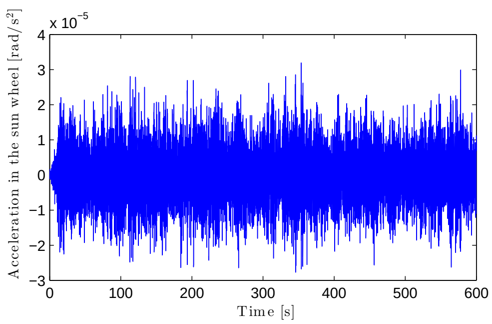

FIGURE 3: Acceleration in the pinion of the under normal operation and turbulent wind

attention to the kind of dynamics that the gear wheels are exposed to using the acceleration of the DOF. This information, along with the position and velocity states, can be used to calculate the loading in the DOF and therefore study the reliability of the gearbox in the context of a complete wind turbine simulation.

INTEGRATED SIMULATION APPROACH

The wind turbine is a complex system that involves different types of models such as aerodynamics, aerolasticity, mechanical and electrical. From this, it is safe to say that we want to use the most appropriate tools to obtain an accurate and robust model, along with a simple implementation. From the electrical and controls point of view, Matlab/Simulink provides a safe environment to develop such models and applications. The integrated simulation approach provides an interface between HAWC2 and Matlab. The main advantage is that it allows for the simulation of appropriate models using Matlab/Simulink for the electrical

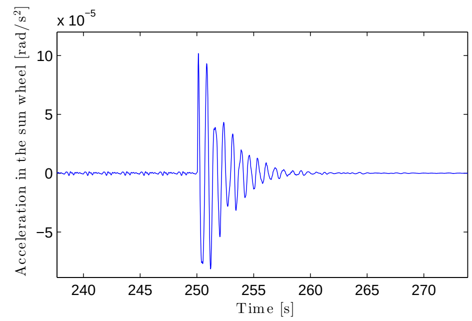

FIGURE 4: Acceleration in the pinion of the due to the loss of electromagnetic torque. The wind is constant at 14 m/s.

and controls "dimension" of the wind turbine, while using using HAWC2 to simulate the aerolastic and structural models. At each time step, the desired states are transfered and each tool solves their corresponding system until convergence. Once convergence is reached, they share the results and start over (Figure 5).

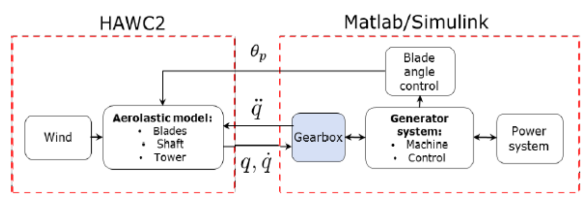

FIGURE 5: Wind turbine block diagram (modified from [2])

MODELS

The gearbox considered here is a 3 stage gearbox with a planetary gearbox as a LSS, then another planetary gearbox as ISS and finally a parallel gearbox as HSS. For a general purpose, a generic set of system matrices is presented and used to study the time response of the gearbox. These matrices contain only the DOF present on each stage, and can be expanded further to include the torsional stiffness of the low, intermediate and high speed shafts. The main objective with these set of system matrices is to provide flexibility to study different arrangements of the drivetrain, for instance, where sometimes a planetary stage is followed by two parallel stages [10]. The generic inertia and stiffness matrices are used to form a state-space model like the one in Equation (1). This model represents a set of first order differential equations and matrix **E** is set to zero because the output of the system does not affect the input.

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{E}\mathbf{u} \end{aligned} \tag{1}$$

where,

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{J}^{-1}\mathbf{K} & -\mathbf{J}^{-1}\mathbf{D} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{J}^{-1} \end{bmatrix}, \mathbf{C} = \begin{bmatrix} \mathbf{I} \end{bmatrix} \quad (2)$$

The model is solved using Matlab/Simulink together with the asynchronous generator dynamic model.

Planetary Stage

This section presents generic inertia and stiffness matrices that describe a planetary stage gearbox. This matrix was derived using the Lagrange equation and it is a modified model from [11]. The model has 5 torsional DOF: carrier, 3 planets and the sun; and it accounts for the teeth flexibilities such as planet-ring and planet-sun stiffness. A mechanical model of the system is shown in Figure 6 and the systems matrices correspond to Equations (3) and (4).

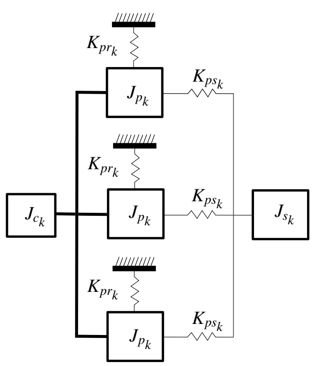

FIGURE 6: Torsional model of a planetary gearbox

$$\mathbf{J_k} = diag([J_{c_k} + 3m_{p_k}r_{c_k}^2 \quad J_{p_k} \quad J_{p_k} \quad J_{p_k} \quad J_{s_k}]) \quad (3)$$

$$\mathbf{K_k} = \begin{bmatrix} 3\Sigma K_{pm}(r_{c_k}cs)^2 & & & & \\ \Delta K_{pm}r_{p_k}r_{c_k}cs & \Sigma K_{pm}r_{p_k}^2 & & symmetric & \\ \Delta K_{pm}r_{p_k}r_{c_k}cs & 0 & \Sigma K_{pm}r_{p_k}^2 & & \\ \Delta K_{pm}r_{p_k}r_{c_k}cs & 0 & 0 & \Sigma K_{pm}r_{p_k}^2 & \\ -3K_{ps_k}r_{c_k}r_{s_k}cs & K_{ps_k}r_{p_k}r_{s_k} & K_{ps_k}r_{p_k}r_{s_k} & K_{ps_k}r_{p_k}r_{s_k} & 3K_{ps_k}r_{s_k}^2 \end{bmatrix} \quad (4)$$

Parallel Stage

This section presents generic inertia and stiffness matrices that describe a parallel stage gearbox. The model has 2 torsional DOF corresponding to the gear and pinion, and accounts for the teeth flexibilities.

$$\mathbf{J_k} = \begin{bmatrix} J_{g_k} & 0 \\ 0 & J_{pi_k} \end{bmatrix} \quad (5)$$

$$\mathbf{K_k} = \begin{bmatrix} K_g r_{g_k}^2 cs & K_g r_{g_k} r_{pi_k} cs \\ K_g r_{g_k} r_{pi_k} cs & K_g r_{pi_k}^2 cs \end{bmatrix} \quad (6)$$

Generator

The drivetrain model presented here includes a 3rd order dynamic model of an asynchronous generator [12], which is is connected to the gearbox model using the HSS angular velocity as input. The resulting electromagnetic torque is feedback as input for the HSS pinion DOF in the space-state model shown in Equations (1).

PRELIMINARY RESULTS

This section presents the preliminary results of the simulation corresponding to the torsional model of the gearbox coupled with the dynamic model of the generator. The purpose is to study the performance of the model to changes on the input and to present the additional loading caused in the gear wheels due to different conditions. Moreover, this serves as verification that the dynamical behaviour of the overall system reaches steady-state within a reasonable settling time.

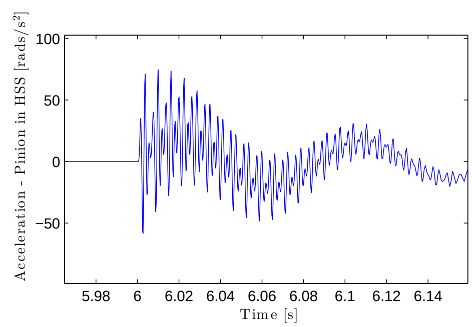

FIGURE 7: Acceleration in the pinion of the HSS due to a change in rotational speed

The first results in Figures 7 and 8, correspond to the acceleration of the pinion wheel in the HSS caused by a change in the rotational speed of the low-speed shaft. An additional experiment is carried out by simulating a grid fault with a loss of electromagnetic torque during 1 s starting at 9 s. It is simulated with a zero excitation of the generator model, and therefore, additional dynamics in the electromagnetic torque are experienced by the system due to the loss of torque balance. Immediately after the fault, the unbalance in the torque of the whole drivetrain creates a significant loading in the gear wheels. The torsional loading of the pinion due to the loss of excitation is shown in Figure 9. Notice the magnitude of the vibrations is higher specially when the torque balance is re-established at 10 s.

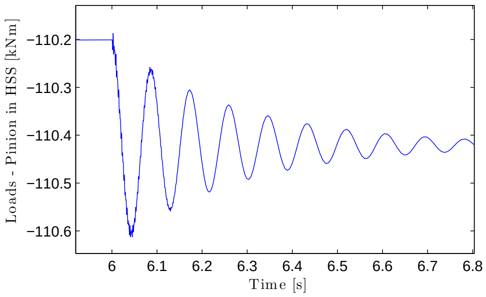

FIGURE 8: Torsional loads in the pinion of the HSS due to a change in rotational speed

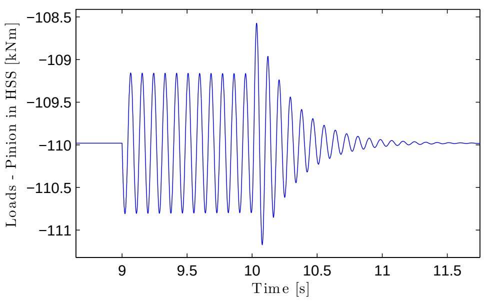

FIGURE 9: Torsional loads in the pinion of the HSS due to a loss of the electromagnetic torque in the generator

CONCLUSION

Two different approaches for electromechanical simulation of wind turbine's drivetrain has been presented here. The first one, allows for a fully coupled simulation between the DOF of the turbine and any external system, in this case, the gearbox. This allows to account for the force and moment components of each DOF per body, in the case of HAWC2, i.e $F = [F_x, F_y, F_z, M_x, M_y, M_z]$. However, additional work is required given the complexity of the overall system and the definition of an appropriate wind turbine structure and gearbox configuration. This means adding additional stages with their corresponding gear ratio.

In the second approach, it is possible to use the advantages that Matlab provides such as control and electrical systems toolboxes, in order to simplify the implementation of these kinds of models that are required on a proper simulation of a wind turbine. Here, Matlab/Simulink was used to implement a torsional model together with a dynamic generator model to find the effects of the variations of the electromagnetic torque in the torsional DOF of the gearbox. As a result, relevant loading in the HSS pinion was detected due to this variations, specially when a failure is present on the generator. Moreover, this kind of studies are meaningful on the investigation of the factors that affect the reliability of wind turbine drivetrains.

ACKNOWLEDGEMENTS

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