MATLAB/SIMULINK MODELING OF A DRIVETRAIN TEST-RIG OF WIND/TIDAL STREAM TURBINES

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Abstract. *This present work shows a modelling of a wind-hydrokinetic test rig using MATLAB/Simulink. Block models are developed to simulate the dynamic behavior a dynamometer bench composed of shafts, gearboxes, and permanent magnet synchronous generator. Due to gearboxes' efficiency and dissipative torque caused by main bearing, energy dissipation was implemented on numerical model. Once all systems are validated and integrated, some simulations are run to study the test-rig behavior. In time domain, torque and mechanical power are used to verify the model behavior at low speed shaft (LSS) and high speed shaft (HSS). Finally, in frequency domain, we identify natural frequencies of test-rig model.*

Keywords: *Test Rig, Wind Turbine, Drivetrain, MATLAB/Simulink, Dynamic Systems*

1 INTRODUÇÃO

The estimation of power curve function of tip speed ratio (TSR) is a necessary task to wind turbine (and tidal stream turbine) accreditation by certification organisms. The accreditation phase is long and passible to fail. The use of intermediary's tests is a necessity to avoid problems of final product accreditation. For example, the dynamic characterization of wind powertrain can be done by a dynamometric bench (Aparecida, 2012) (Kalkmann, Morais, & Diniz, 2012) (Kalkmann, 2015).

A dynamometric bench is used to obtain electro-mechanic torque and electrical power generate by a known torque. Associated to numerical and/or experimental studies about wind blade aerodynamic, this characterization allows the estimation of dynamic behavior of wind turbine (and tidal stream turbine) in a controlled setting before accreditation.

The dynamometer bench is an electromechanical systems compound of two main subsystems. The mover system (or drive system) (Figure 1) emulates the wind turbine rotor transferring torque and angular speed to low-speed shaft (LSS). And the moved system (or drivetrain system) is the turbine's powertrain itself (LSS, gearbox, HSS and electric generator) (Figure 1). This test-rig allows monitor the dynamic behavior of a wind turbine powertrain in a very compact experimental set without necessity of complex facilities.

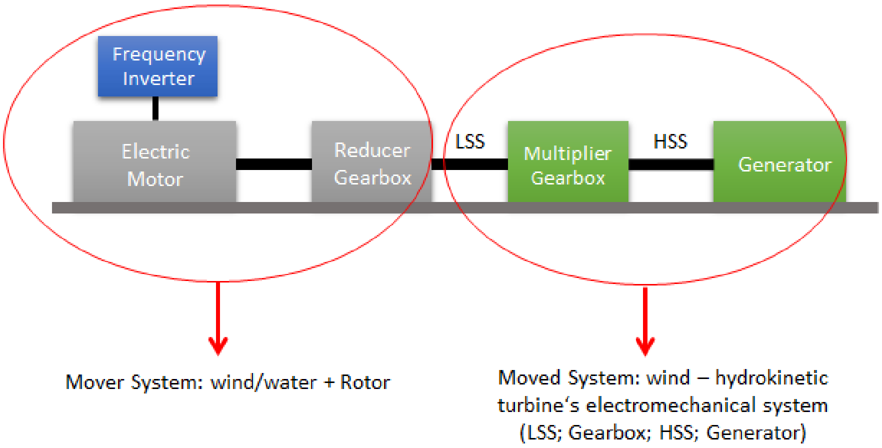

Figure 1 - Concept of the test rig. (Marrant, Vanhollebeke, & Peeters, 2010)

Although the experimental test in dynamometer test rigs has advantages, it's necessary preliminary analysis to validate this project concept. Thus, in this case, a numerical model of the test rig can be a very good option to obtain preliminary results.

This present work model a wind-hydrokinetic test rig using MATLAB/Simulink. Block models are developed to simulate the dynamic behavior a dynamometer bench compound of shafts, gearboxes, and permanent magnet synchronous generator. Due to gearboxes' efficiency and dissipative torque caused by main bearing, energy dissipation was implemented on numerical model. Once all systems are validated and integrated, some simulations are run to study the test-rig behavior. In time domain, torque and mechanical power are used to verify the model behavior at low speed shaft (LSS) and high speed shaft (HSS). Finally, in frequency domain, we identify natural frequencies of test-rig model.

2 THE TEST RIG

The dynamometer bench's concept tries to simulate dynamic behavior of a wind drivetrain. In functioning conditions, the flow fluid moves the rotor that transfers torque and angular speed to LSS (Figure 2a). Gearbox multiplies angular speed to rotate the electric generator via HSS. The generator is a Permanent Magnet Synchronous Generator (PMSG) converting mechanical to electrical power.

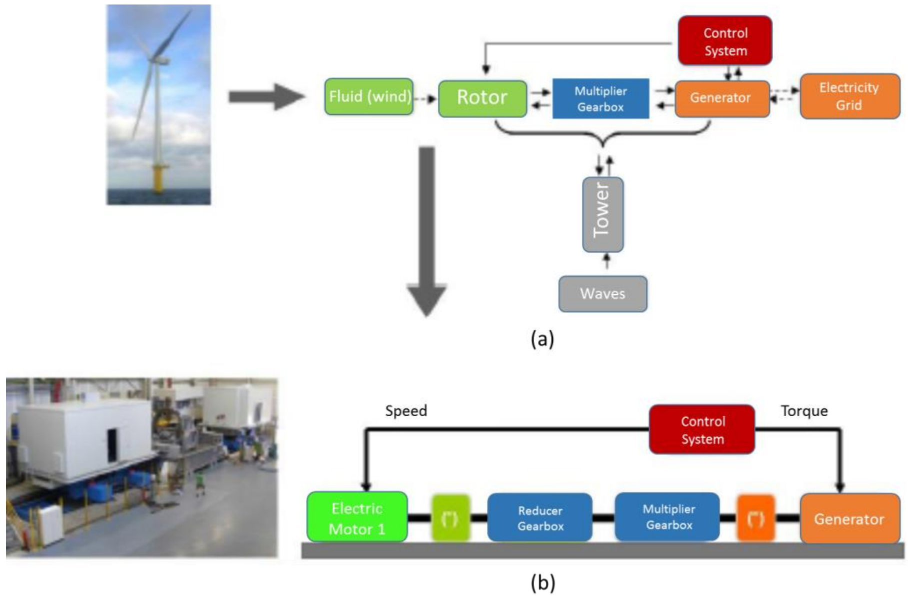

Figure 2 - Schematic functioning of a real wind turbine (a) and Test rig model (b) (Marrant, Vanhollebeke, & Peeters, 2010).

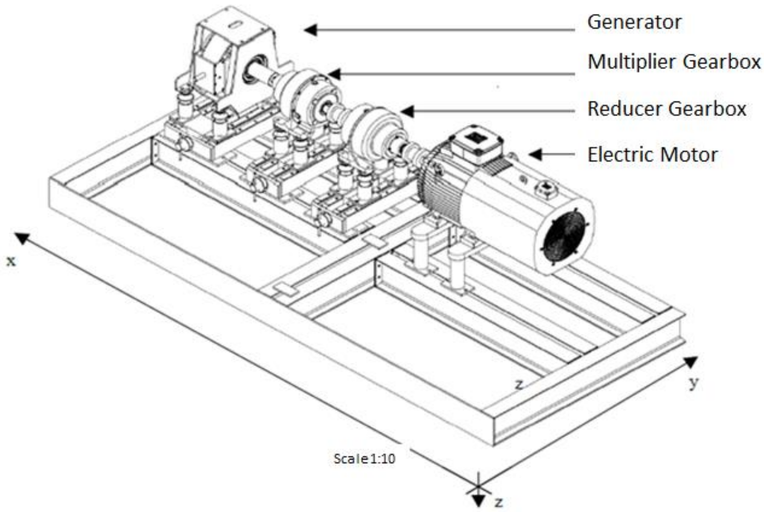

Figure 3 – Dynamometer Test rig Project of University of Brasília (Aparecida, 2012).

In the experimental test rig, a wind turbine drivetrain is coupled to the drive subsystem (an electric motor and a speed reducer gearbox), as seen in Figure 2. Marrant, Vanhollebeke and Peeters (2010) show this experimental concept to monitor the dynamic behavior of wind turbine. The University of Brasilia, in cadre of Tucunaré Project, presents his project concept of dynamometer bench to study the dynamic behavior of tidal stream turbines (Figure 3) (Aparecida, 2012).

3 MATLAB/SIMULINK MODEL AND SIMULATION TOOL

The Simulink is a graphical tool from MATLAB for dynamic simulations. It can be applied to linear and non-linear systems and continuous or discrete in time domain. It has a graphic interface, in which the systems are represented in block diagrams, and each block represents a mathematical operation of input and output (Vitorino, 2012).

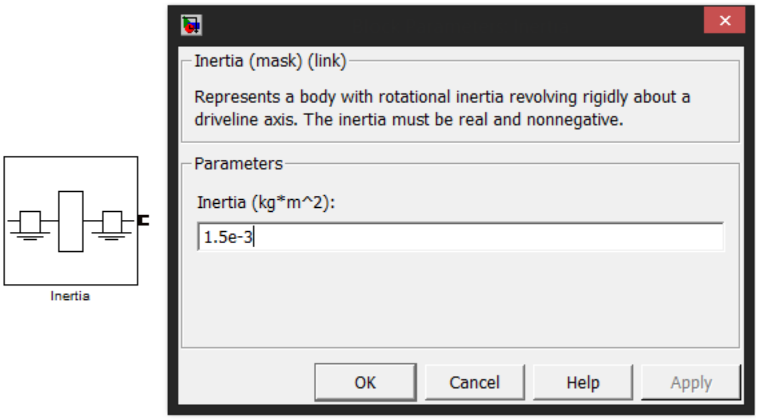

Figure 4 – Inertia block representation and its dialogue box.

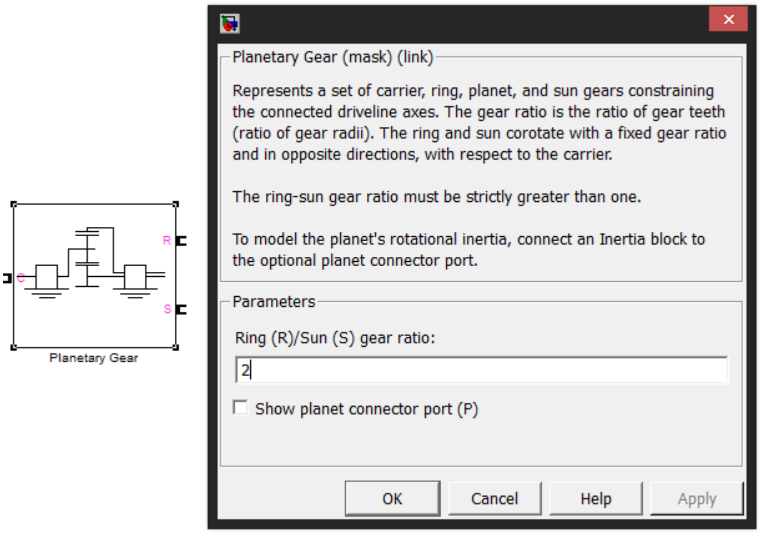

Figure 5 – Planetary Gear block representation and its dialogue box.

For the test rig modelling, the main blocks used were the blocks of *Inertia*, *Planetary Gears*, *Torsional Spring-Damper*, *Motion Sensor and Motion Actuator*, *Torque Sensor and Torque Actuators*, and also auxiliary blocks like source and sink blocks. Source blocks are used to introduce some sort of signal in the system (sine wave, constant, step, ramp and others) and sink blocks assist the visualization of some results and data gathering (for example *Scope*, *XY Graph* and *To Workspace* blocks).

Figure 4 to Figure 6 show the blocks of *Inertia*, *Planetary Gears*, and *Torsional Spring-Damper* (represents the shafts), which are the main blocks used to model the mechanical components of the test rig. These blocks can be found in the Simulink's library in the section *Simscape/SimDriveline*. On the right side of each block's representation, is the dialogue box associated to the block, which can be accessed with a double click over the block, with the left button of the mouse. In this dialogue box, the user can set the block's parameters (inertia values, stiffness of shafts, gear ratios, etc).

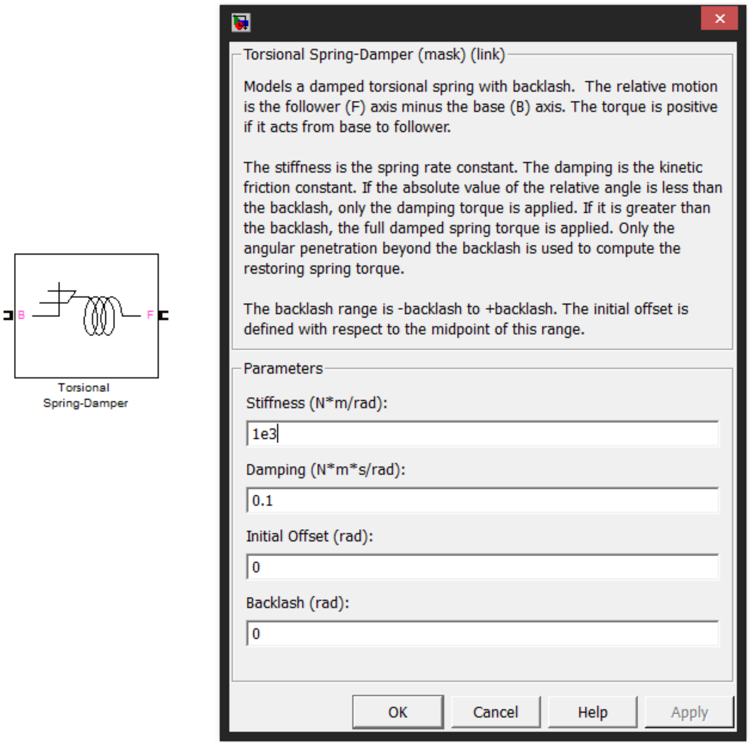

Figure 6 – Torsional Spring-Damper block representation and its dialogue box.

Other blocks like the *Permanent Magnet Synchronous Machine*, *RLC components* and *Grounded Neutral* are used to model the electrical system of the test bench. Those blocks can be found within the *Simscape/SimPowerSystems* section of the Simulink's library.

4 MATLAB/SIMULINK TEST RIG MODEL

The test rig to be modelled is based on Figure 3. This bench was designed at the University of Brasilia (Aparecida, 2012) and is composed of an electric motor, a speed reducer gearbox (with 2 epicyclical gearing stages), a LSS, a speed multiplier gearbox (also with 2 epicyclical gearing stages), a HSS and a generator, where all of these elements are connected in serie.

The test rig in Simulink was shown in Figure 7. Each of the elements is explained separately ahead on the text.

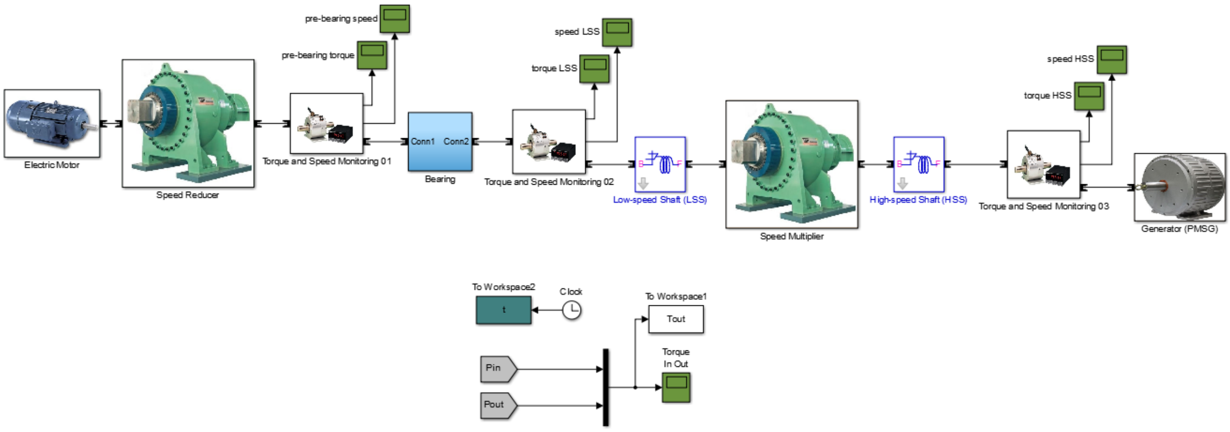

Figure 7 – Test rig model in MATLAB/Simulink

At the upper part of Figure 7, we find the test bench's block diagram. And at the bottom of Figure 7 is shown an auxiliary diagram. The last one is responsible for measuring the simulation time (and sending it to the MATLAB's workspace), and also for capturing the signals of torque from the electric motor and the torque on the HSS to plot them together in a same graphic. A detailed explanation about each of the elements from the test rig follows below.

4.1 The electric motor

Figure 8 shows the representation of the electric motor block (Figure 8(a)) and how it is built in Simulink (Figure 8(b)). The electric motor's block diagram is modelled connecting a source block, circled in red, which introduces a constant signal in the system (or a chirp signal, to obtain the system's frequency response-FRF). This signal is applied in the shaft through a torque actuator block. This way, the effect of the electric motor can be simulated, since one can control the amplitude of the torque on the source block.

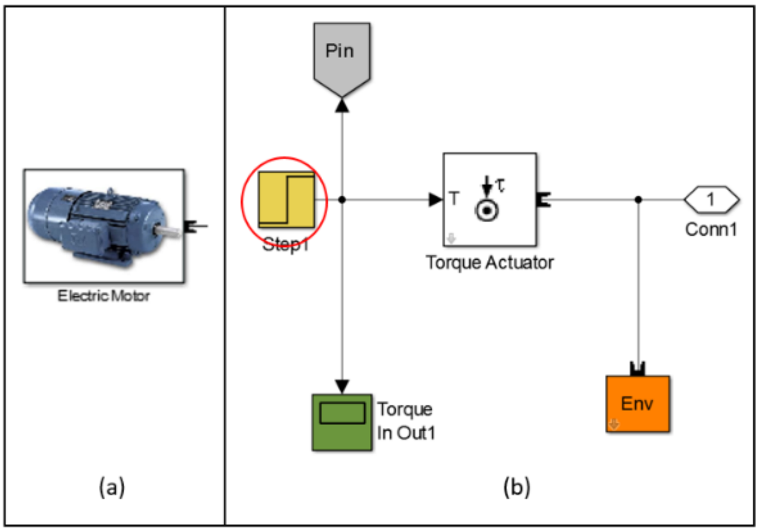

Figure 8 – Electric motor block representation (a).
Detailed construction of electric motor block diagram (b).

4.2 Gearboxes

Both the speed reducer and multiplier gearboxes have the same modelling in Simulink. The gearboxes (Figure 9) are composed of two planetary gearing stages connected by a spring element that represents the shaft. Inertia values (blocks with a black circle around) are associated to each gearing stage and blocks of motion sensors (circled in orange) are connected to the shafts, as can be seen in details in Figure 10. Blocks circled in green collect values of angular speed and position, and send them to be used in other part of the model (be it as input for other block or just output to workspace).

Figure 9 – Gearbox block representation

The highlighted subsystem in Figure 10 is a diagram that introduces energy losses in the gearboxes due its efficiency. It uses the value of torque measured on the exit of the gearbox, multiplies this value by (1-*n*) where *n* is the gearbox's efficiency, and send this final value to a torque actuator. In this manner, this system introduces a torque in the shaft that causes the same energy dissipation as that one provided by the gearbox's efficiency.

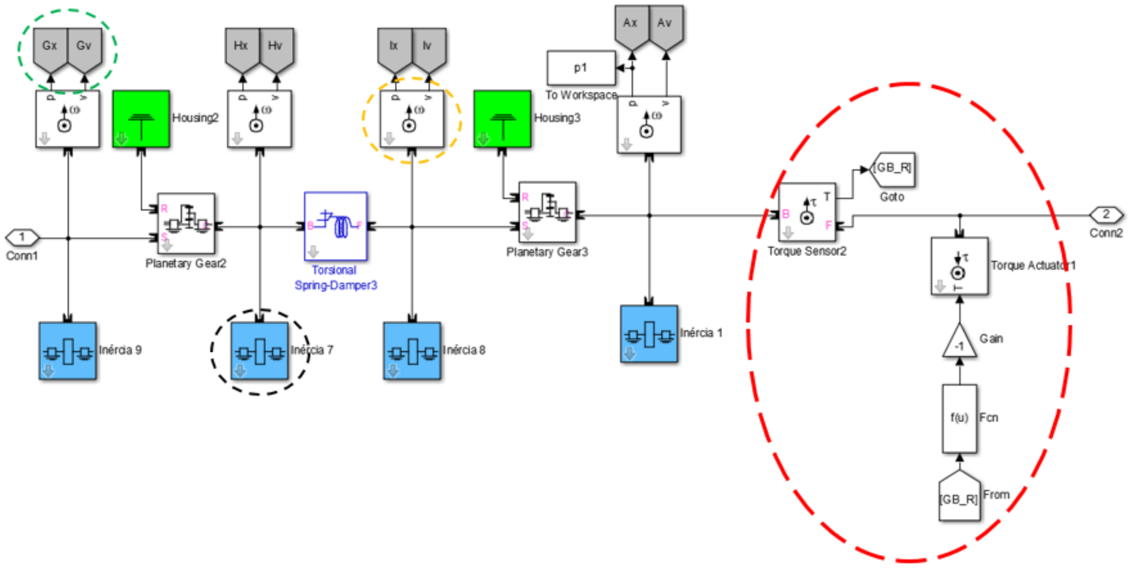

Figure 10 – Block diagram in Simulink for the gearboxes.

4.3 Bearing

According to previous investigations, the dissipative torque applied by the bearing on the shaft depends on the shaft's angular speed (Mesquita, Mesquita, Vaz, Morais, & Gonçalves, 2013). This way, the bearing block (Figure 11) is a system that captures the value of speed and uses it to evaluate the torque to be introduced in the shaft, so that it causes energy losses.

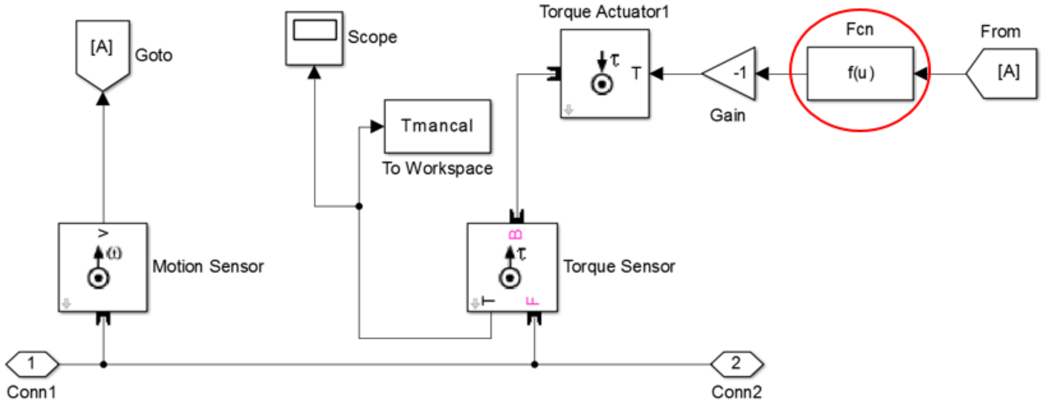

Figure 11 – Simulink model for the bearing.

The block *Function* (Fcn), highlighted with a red circle in Figure 11, receives as input the value of angular speed of the shaft, and gives as output the dissipative bearing's torque. Inside this block is set the Eq. (1) that calculates the value of torque. This equation is obtained from a study of case in the hydrokinetic turbine from the Tucunaré project (Mesquita, Mesquita, Vaz, Morais, & Gonçalves, 2013), which is a project developed by Eletronorte in partnership with UFPA.

$$T_D = 12{,}5712 + 132{,}106\omega + 0{,}0000525\omega^{\frac{1}{2}} + 3{,}55534\omega^{\frac{2}{3}} \quad (N.m) \tag{1}$$

where ω is the angular speed of the shaft.

4.4 Generator

The generator component (Figure 12) is a *Permanent Magnet Synchronous Machine*. Its inside circuit conection is described in Figure 13.

Figure 12 – Generator's box representation.

As it can be seen from Figure 13, the PMSG block receives as input the angular speed from the HSS, and as output, it sends an electromagnetic torque that actuates contrary to the speed's sense in the HSS. At a certain time, this contrary torque will make the speed on the HSS stabilize. The terminals from the block are still connected to an electricity grid, in which the voltages and currents in each branch are measured.

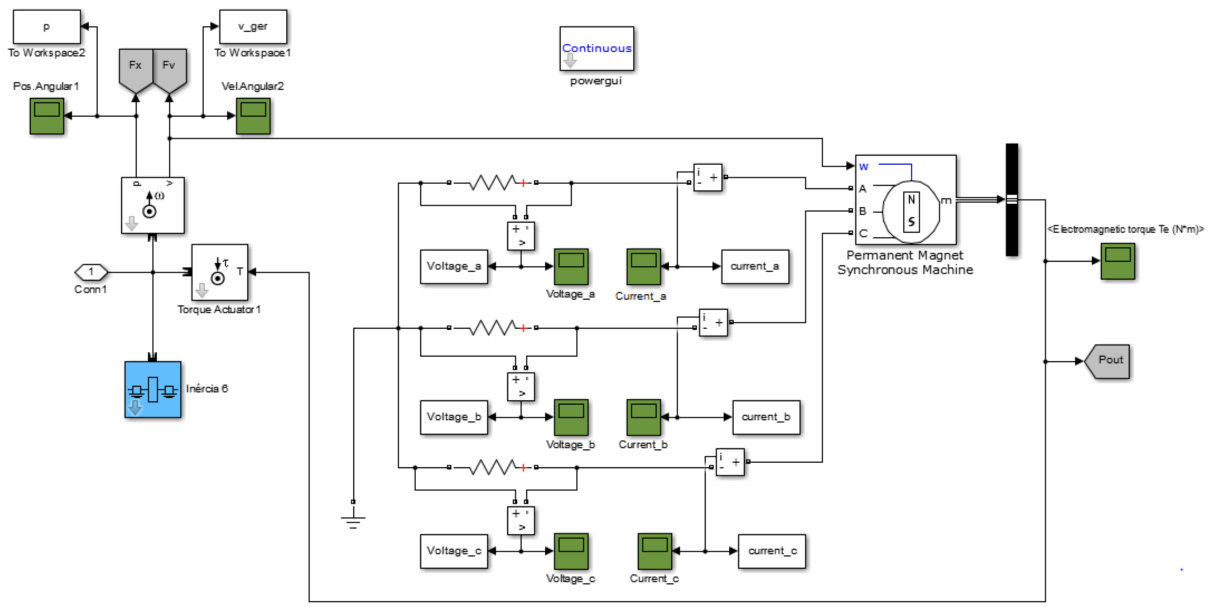

Figure 13 – Detailed view of the block diagram from the Generator.

5 RESULTS

Aiming to make an analysis of the dynamic behavior from the test rig's system, two of simulations are ran.

The first one (Simulation I) consists of making the electric motor to apply a step-shaped torque, and then graphs of torque and power on the shafts, speed and position on the HSS, dissipative torque on the bearing and voltages and current in the branches along the time were calculated.

The second one (Simulaion II) consists of making the electric motor to apply a chirp-shaped torque, and with support of a MATLAB script, the output signal was analyzed and the system's frequency response obtained.

Both situations (Simulation I and II), the amplitude of torque used was 9.35kN.m. With this value and for the gearboxes ratios specified below, it was possible to reach the amplitude of 318 kN.m for the torque on the LSS (it is a reference value from the hydrokinetic turbine of Tucunaré Project, when in operation (Fonseca & de Araújo, 2013).

Table 1 show the parameters used in the simulations for the gearboxes. And, in Table 2, can be found the parameter for shafts and generator.

Table 1 – Gearboxes parameters

GEARBOXES		
Element	**Total Inértia (Kg.m^2)**	***Gears Teeth Numbers (Z)***
Rotor	$J_1 = 13{,}7.\ 10^3$	---
Carrier 2	$J_2 = 160{,}9612$	---
Planet Gears 3	$J_3 = 5{,}7649$	25
Sun Gear 4	$J_4 = 2{,}2026$	17
Ring R1	---	67
Carrier 5	$J_5 = 53{,}0721$	---
Planet Gears 6	$J_6 = 3{,}2232$	42
Sun 7	$J_7 = 0{,}1765$	17
Ring R2	---	100
Generator	$J_8 = 22{,}2548$	---
Speed Ratio	*1:34*	---
Efficiency	*0,9*	---

Table 2 – Parameters from gearbox's shafts and from generator PMSG

SHAFTS		
Element	**Diameter (mm)**	**Length (mm)**
Shaft 1 (gearbox's input shaft)	340	710
Shaft 2 (gearbox's intermediate shaft)	220,5	438,75
Shaft 3 (gearbox's output shaft)	113,25	265,5
GENERATOR		
Stator's Resistance, Rs (Ohm)	0,0218463	
Inductance, Ld (H)	0,00899995	
Inductance, Lq (H)	0,00899995	
Magnetic Flux (V.s)	4.759	
Number of pole pairs	12	
Resistance on Terminals A, B and C (Ohm)	5	

For the Simulation I , the results obtained are shown in Figure 14 to Figure 19 below:

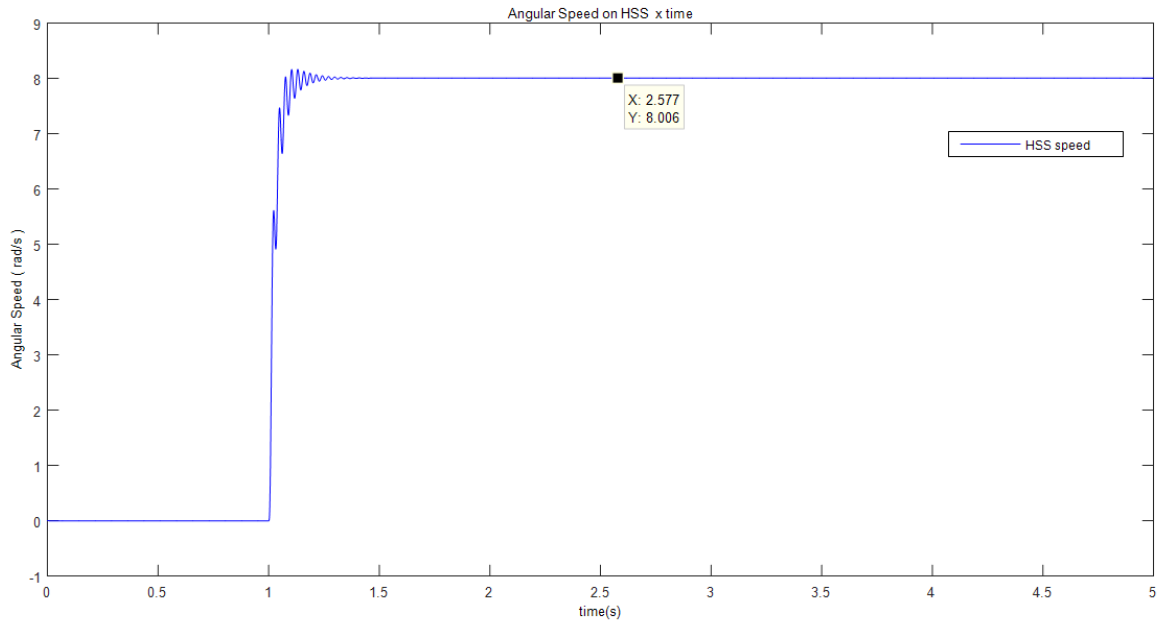

Figure 14 – Angular speed on the High-speed Shaft along the time.

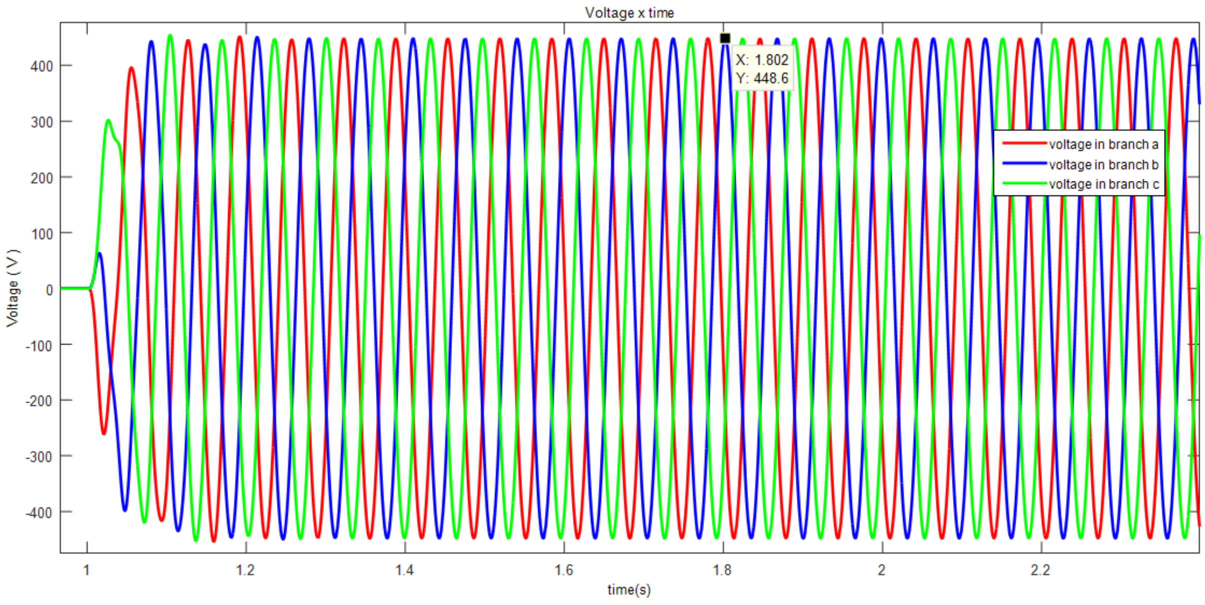

Figure 15 – Voltage in the branches a, b and c from the generator.

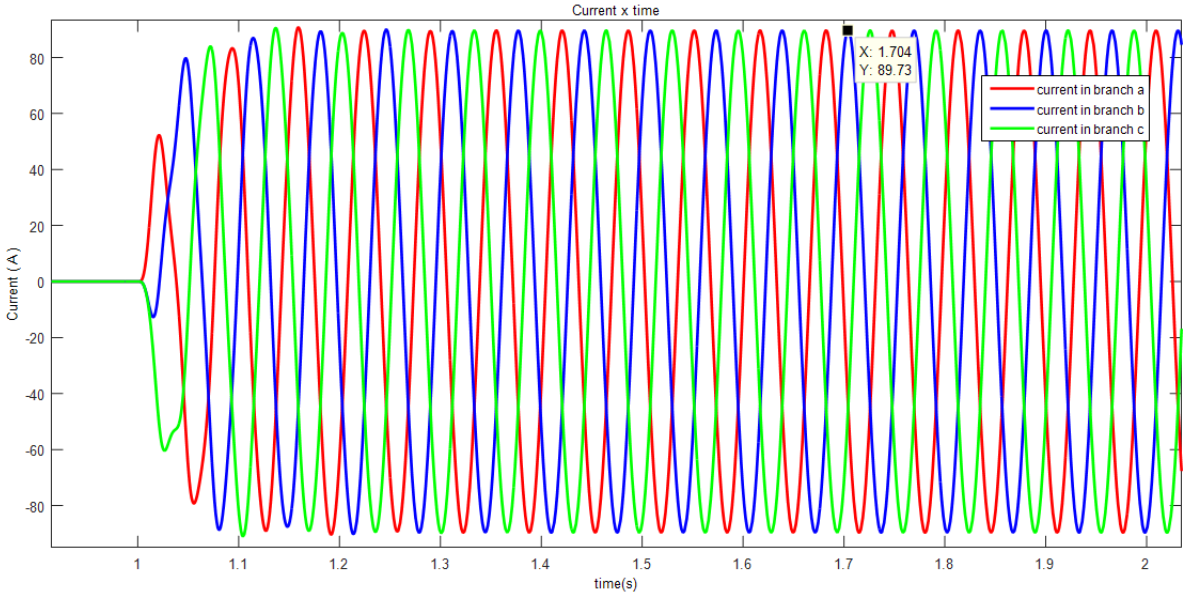

Figure 16 – Current in the branches a, b and c from the generator.

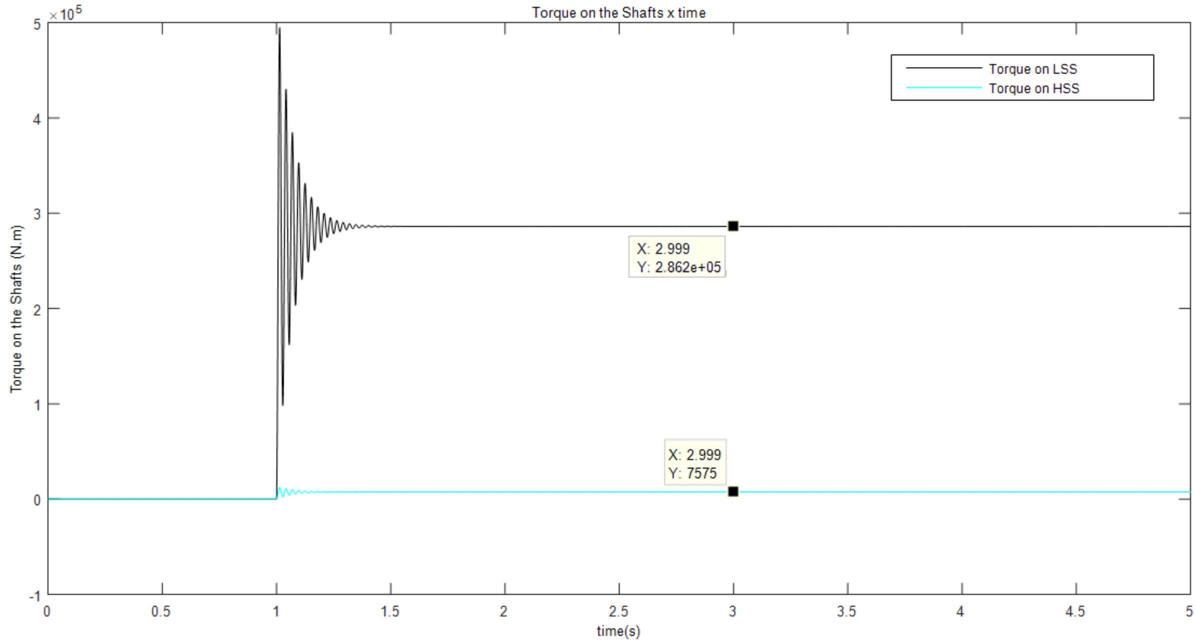

Figure 17 – Values of torque obtained on the LSS and HSS along the time.

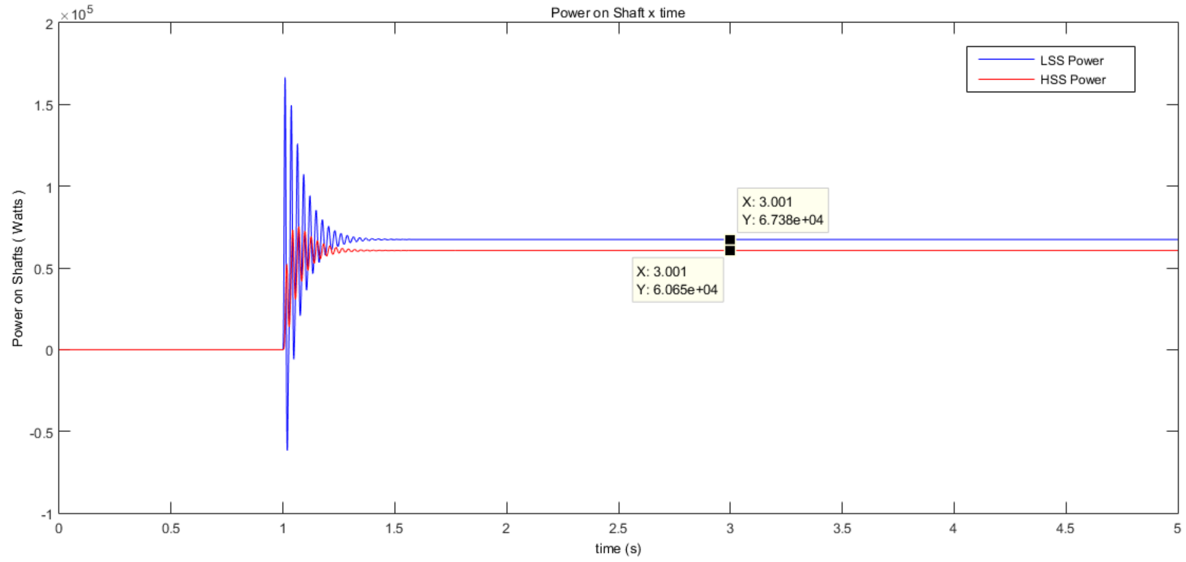

Figure 18 – Power on LSS and HSS calculated along the time.

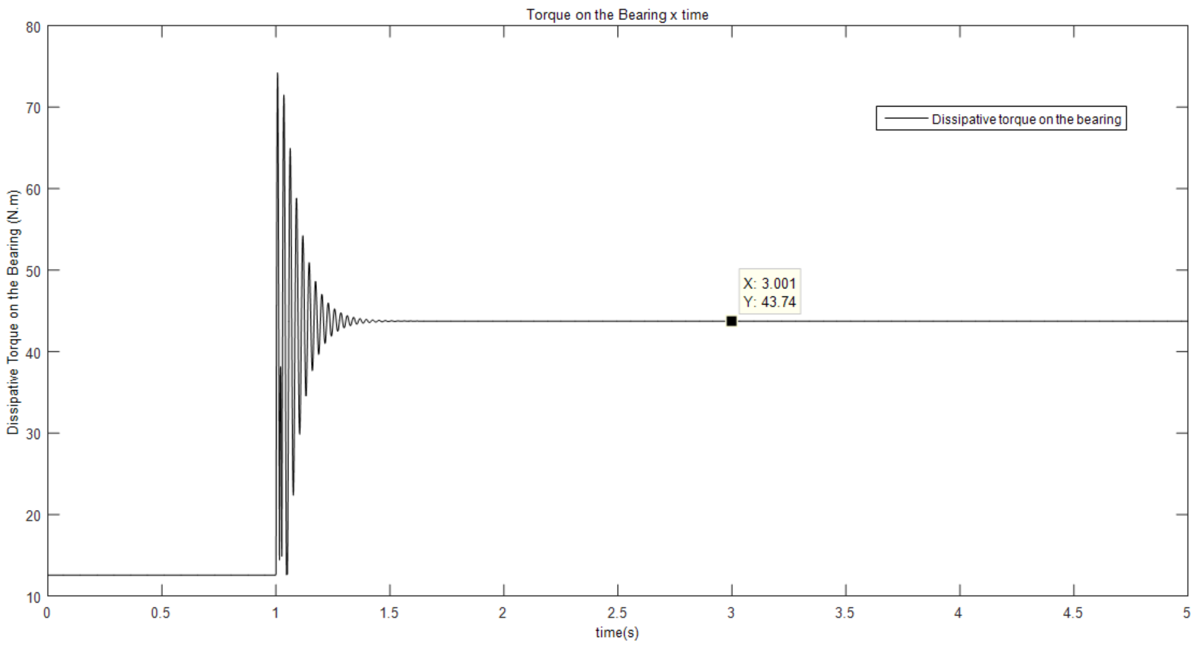

Figure 19 – Dissipative torque on the bearing along the time

For the simulation I (with a chirp-shaped torque signal), Figure 20 show the system's frequency response together with its phase diagram on the HSS and coherence function:

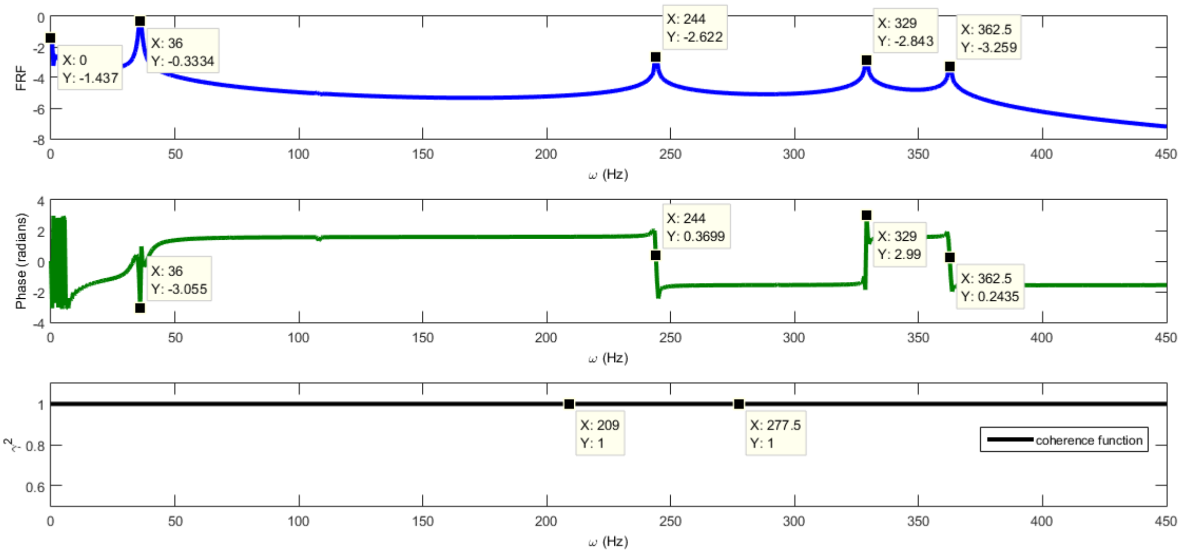

Figure 20 – Graphs of frequency response and phase diagram.

As the frequency response was obtained making the damping equal to zero, the frequencies identified on the resonance spikes are the natural frequencies. Thus, Table 3 exposes the values of natural frequencies of the test rig.

Table 3 – Idenfited test-rig's natural frequencies

NATURAL FREQUENCIES					
Hz	0	36	244	329	362,5
rpm	0	2160	14640	19740	21750

6 CONCLUSION

The MATLAB/Simulink was used to model a virtual wind – hydrokinetic turbine test rig. Block diagrams were built for the electric motor, gearboxes and generator, and these models were connected in order to compose the bench.

Once the systems were fully integrated, some simulations were run. First results were obtained and the dynamic behavior of the test bench studied. Time evolution of torque and power for LSS and HSS were obtained, as well as voltage and current behavior in generator's branches were measured. At the end, the system's frequency response was identified. Five natural frequencies were obtained.

This model can produce numerical responses quite next to those theoretical expected to appear. That means that this model can be trusted to predict some initial results and behaviors, but it still must be validated based on experimental results.

As further work, more advanced models for the electric motors and bearings can be developed and other devices like emergency breaks can be modelled and inserted in the test bench in Simulink.

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