Wind power
Universitat Politècnica de Catalunya BarcelonaTECH
CITCEA-UPC
Course second assignment

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Contents

Summary

This document includes the description of the second assignment of the Wind power course. In addition, it also details how to create a fixed-speed wind turbine model, required to complete the second assignment.

1 Second assignment

The second assignment objective is to analyze the steady-state and dynamic behaviour of a type 1 wind turbine. Students are asked to develop the following tasks:

- Develop an steady-state model of a Type 1 wind turbine connected to the grid. Using the parameters described in the Section 2 of this chapter (specifically see Section 2.2) and using the methodology discussed in class, based on the Exercises conducted.
- Develop a dynamic model of the same wind turbine. The Section 2 of this document describes the required steps to build the model.
- Study the obtained results looking at key variables like: mechanical power and torque, C_p coefficient, λ tip speed ratio, grid active and reactive power, generator efficiency, slip, wind turbine and generator speed, stator current. If the mechanical power available exceeds the nominal power of the wind turbine, take into account that the wind turbine will limit the available power to the nominal value.
- Validate that the two models match for different wind and grid conditions:
  1. Grid voltage = 960 V Grid frequency = 50 Hz Wind speeds = 7, 11, 14 m/s
  2. Grid voltage = 850 V Grid frequency = 50 Hz Wind speeds = 7, 11, 14 m/s
  3. Grid voltage = 960 V Grid frequency = 53 Hz Wind speeds = 7, 11, 14 m/s
  4. Grid voltage = 960 V Grid frequency = 47 Hz Wind speeds = 7, 11, 14 m/s
- Illustrate graphically the results obtained, both for steady-state analysis using the mechanical and electrical characteristics, and for dynamic analysis using simulation results. For the dynamic case, show how the system reacts to changes in the wind speed, grid voltage or grid frequency. Highlight the convergence of steady-state and dynamic results.
- Discuss the results obtained. How the results change for different wind and grid conditions?
- (Optional) For the dynamic model, implement the pitch system model and the pitch control to regulate the maximum mechanical power. For this purpose, consider different C_p parameters to enable the pitch system. Use the following C_p curve parameters: $c_1 = 0,73$, $c_2 = 151$, $c_3 = 0,58$, $c_4 = 0,002$, $c_5 = 2,14$, $c_6 = 13,2$, $c_7 = 18,4$, $c_8 = -0,02$, $c_9 = -0,003$. Take into account, that the look-up Table calculating C_p should be modified to include the dependency on both the tip speed ratio λ and the pitch angle β.

2 Fixed-speed wind turbine simulation model

2.1 Introduction

This section describes a procedure to create the simulation model of the wind turbine. This model is based on the implementation of the differential equations of the aerodynamic, mechanical and electrical turbine parts, which are non-linear and difficult to manipulate in an analytical manner. This way, the simulation has to be performed necessarily using numerical integration tools, employing software packages as Matlab. In this case, it has been decided to use the simulation tool embedded within Matlab, called Simulink.

Simulink is an extremely useful tool for dynamic systems simulations. Its visual programming interface based on connectable blocks shows an abstraction level superior to Matlab's programming language, which allows the user to implement the quations of a system in a simple and intuitive manner, without requiring a high level of code programming knowledge. Simulink also incorporates several packages or toolboxes related with different engineering fields, such as Automatic control, Electrical Engineering, Electronic Engineering, Signal processing, etc.

Being a visual programming interface, Simulink permits implementing the equations and the dynamic systems based on a wide variety of blocks. Specifically, the wind turbine model will be build based on a combination of Simulink library blocks and the Simscape-SimpowerSystems toolbox fundamental blocks. In order to access Simulink and the libraries, the characteristic icon of Simulink must be selected (it might vary depeding on the Simulink version). The intial appearance of the program is shown in Fig. 1, where the libraries are shown, organized by packages and block topologies. Once Simulink has started, in order to create a new model (extension *.slx), the white paper icon needs to be selected, obtaining a similar window to the one shown in Fig. 2.

From now on, selecting the convenient blocks from Simulink's library, dragging them (Fig. 3) to the model window and configuring them properly, it is possible to build the wind turbine model.

In the following sections, a detailed procedure to build the turbine model is explained. First, the document explains how to introduce the wind turbine data into the simulation environment. Next, several characteristics of the Simulink framework and the configuration blocks required to implement the model are shown. Finally, the model construction procedure is detailed dividing the system in three parts: the turbine, the transmission and the electrical machine. Each of this parts is explained in the following manner: first the equations that represent the subsystem dynamic behaviour are presented and after the Simulink blocks used for its implementation are exposed, together with its configuration.

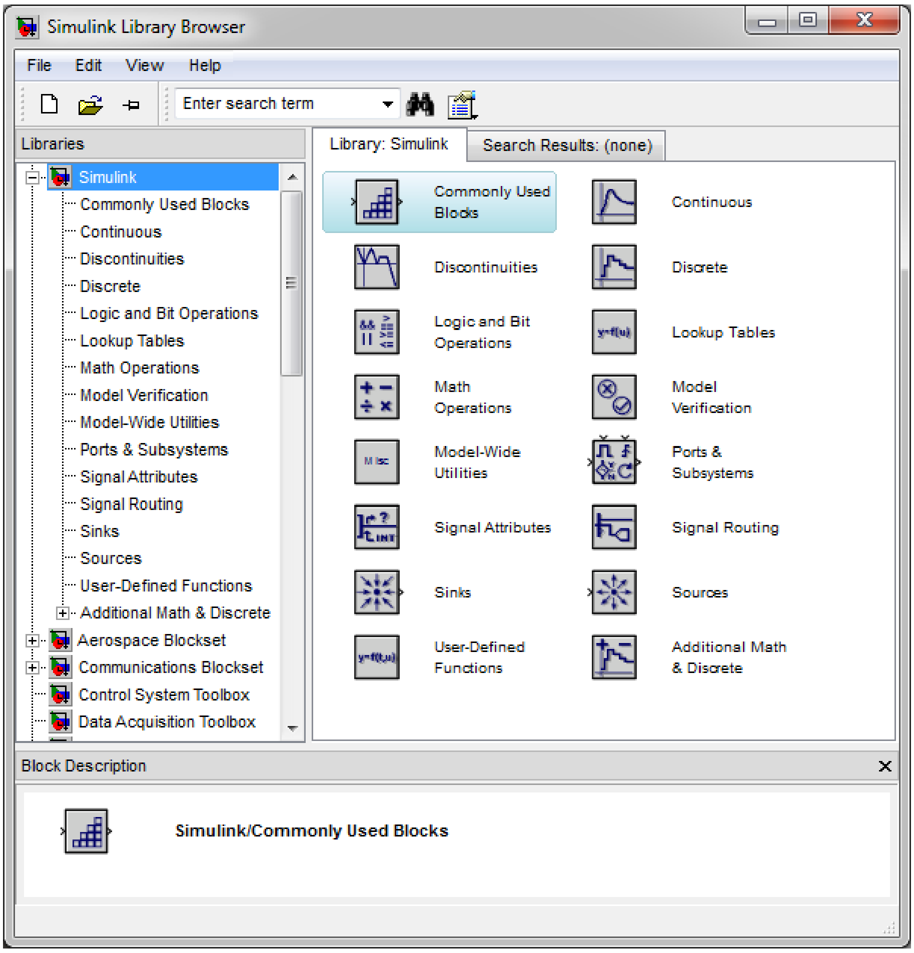


Figure 1: Main view of the Simulink library

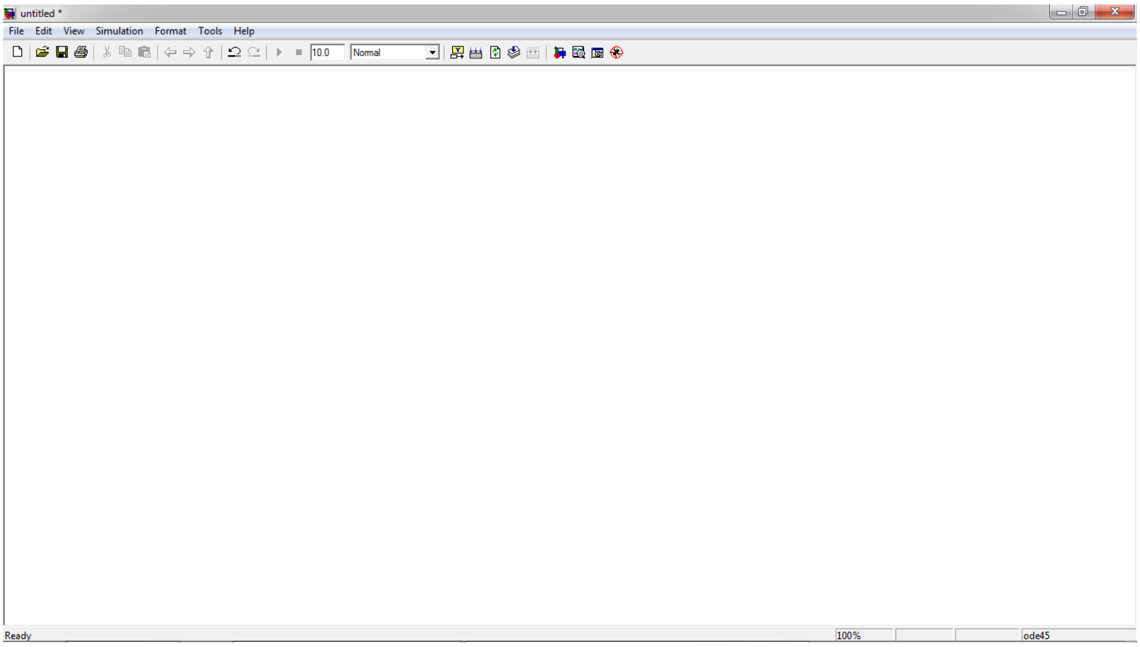


Figure 2: Initial window view of a Simulink model

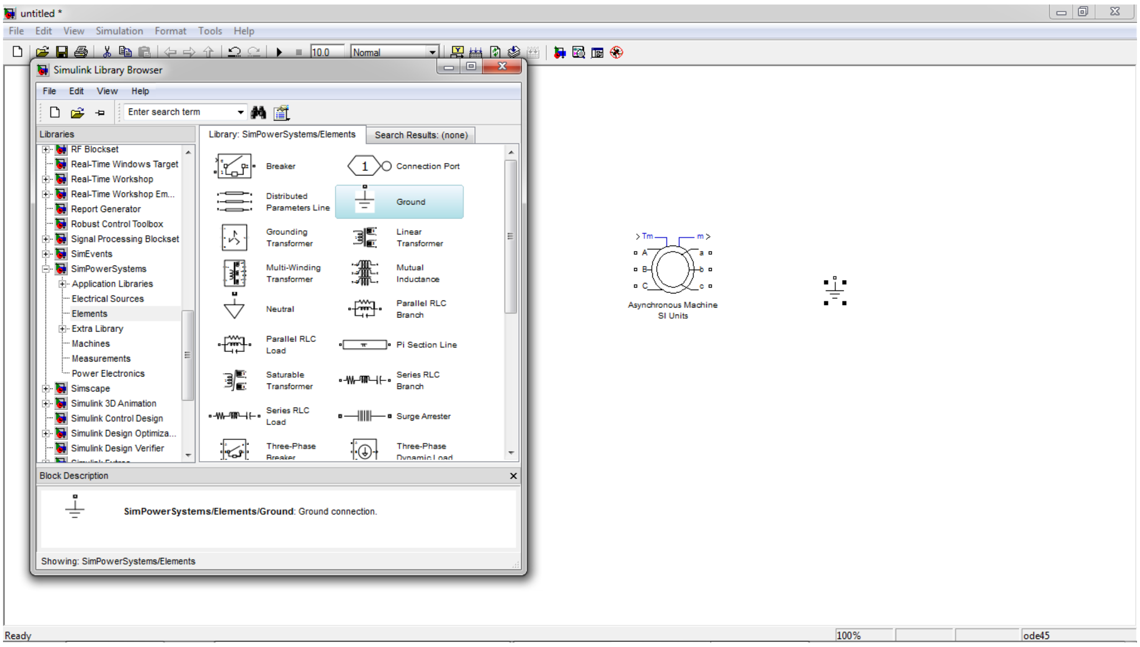


Figure 3: View of the introduction of blocks into Simulink interface

2.2 Wind turbine data

In this section, the data of the wind turbine is presented. Table 1 show the mechanical data of the wind turbine and Table 2 presents the electric parameters of the system. Besides, in order to obtain the power coefficient value (C_p), the fixed-speed constants [c_1.. c_9] defining the turbine aerodynamics are shown in Table 3.

Aerodynamic and mechanic parameters of the wind turbine	Value	Units
Wind speed *cut-in*	3	m/s
Wind speed *cut-off*	20	m/s
Rotor diameter	76	m
Rotor nominal speed	16	min^{-1}
Moment of Inertia	$9,0 \cdot 10^6$	kgm^2
Damping factor	$7,5 \cdot 10^6$	Nm/rad
Transmission ratio	80	-

Table 1: Parameters of a 2 MW wind turbine

Electrical parameters of the wind turbine	Value	Units
Power	2	MW
Nominal voltage	960	V_{ph-ph}
Nominal current	1300	A
Connection	Delta	-
Pole pairs	2	-
Rated speed (50 Hz)	1500	min^{-1}
Moment of inertia	90	kgm^2
Stator resistance	0,005	Ω
Stator leakage inductance	$4 \cdot 10^{-4}$	H
Rotor resistance	0,009	Ω
Rotor leakage inductance	$3 \cdot 10^{-4}$	H
Magnetizing inductance	$15 \cdot 10^{-3}$	H
Iron branch equivalent resistance	140	Ω

Table 2: Parameters of a 2 MW wind turbine

In order to introduce the system parameters, the use of a Matlab M-file archive is recommended (extension *.m). Inside the M-file, the wind turbine parameters can be assigned to variables that later can be used during the simulation. Next, a code example is shown:

Matlab code 1: Parameters introduction through an M-file

```
                  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                  %         Dynamic anlaysis of a fixed-speed wind turbine         %
                  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all; % Clean the workspace
close all; % Close all windows
clc; % Clean command window

%% Simulation duration
Tsimul=10;

%% Wind parameters
vv_vent=11; % Wind speed

%% Nominal machine electrical parameters
Pnom=2e6; % Nominal power of the machine
Vnom=960; % Nomincal voltage of the machine

%% Turbine parameters
```

Parameter	Value
c_1	0,44
c_2	125
c_3	0
c_4	0
c_5	0
c_6	6,94
c_7	16,5
c_8	0
c_9	-0,002

Table 3: C_p [c_1.. c_9] parameter a 2 MW wind turbine

```
% Cp values [Table]
c1=0.44;
c2=125;
c3=0;c4=0;c5=0;
c6=6.94;
c7=16.5;
c8=0;
c9=-0.002;

R_turbina=38;              % Turbine radius
A=pi*R_turbina^2;          % Area swept by the blades
rho=1.225;                 % Air density
angle_pitch=0;             % Pitch angle
w_ini=2*pi*25/80;          % Initial speed of the machine
Jtot=9e6;                  % Total inertia of the system
n_multiplicador = 80;      % Transmission ratio

%% Generator electrical parameters

Rs=0.005;             % Stator resistance
Xs=2*pi*50*4e-4;      % Stator leakage impedance
Rr=0.009;             % Rotor resistance
Xr=2*pi*50*3E-4 ;     % Rotor leakage impedance
Xm=2*pi*50*15E-3;     % Magnetizing branch impedance
Rm=140;               % Magnetizing branch resistance
V=Vnom/sqrt(3);       % Nominal voltage applied to the machine
pols=2;               % Machine pole pairs
ws=2*pi*50/pols;      % Machine synchronous speed
```

Once the parameters have been introduced, to execute the *.m file the key F5 should be pressed or either selecting the button . Then, the commands listed in the M-file are executed and the variables are stored in the Workspace with its corresponding value. Fig. 4 shows an example the Workspace variable summary.

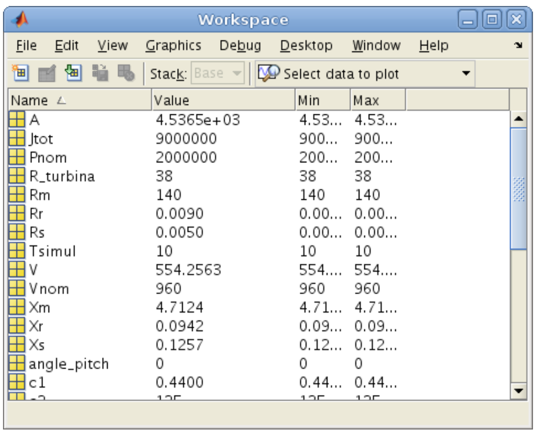


Figure 4: Main view of the Workspace variables in the Matlab environment

With this assignation, Simulink is able to understand the value associated to the variables. This results specially useful to parametrize the simulation model, increasing its flexibility. Once we have defined and introduced the wind turbine variables, the next section describes how to build the complete model.

2.3 Building the Simulink model

Fig. 5 presents the complete control diagram of a fixed speed wind turbine directly connected to the network. Next, the different parts are described using their physical equations in order to implement the simulation model in Matlab Simulink.

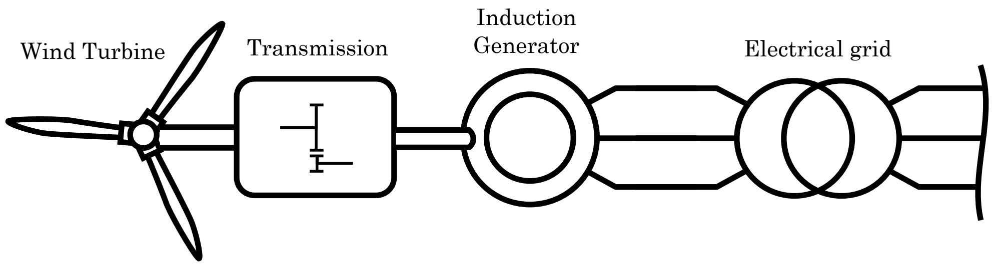


Figure 5: Conceptual view of the wind turbine

2.3.1 Basic Simulink elements

In this section, the different elements used to build the wind turbine simulation model are described. As mentioned above, basic Simulink blocks will be used together with the package Simscape-SimPowerSystems. Tables 4 and 5 show the mentioned blocks corresponding to Simulink, whereas Table 6 focuses on the SimPowerSystems blocks. In these tables, the functioning of each of these blocks is detailed, together with its configuration details. Typically, a double *click* allows accessing to the block configuration window.

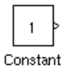
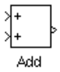
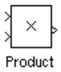
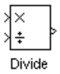
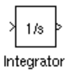
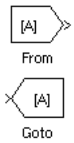
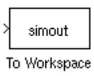
Block name	Image	Functionality and configuration
Constant		Output value defined by the user
Gain		Multiplies the input signal by a value defined by the user
Add		Sums two or more input signals
Product		Multiplies two or more input signals.
Divide		Divides two or more input signals
Integrator		Integrates the input signal
Saturation		Saturates the input between the maximum and minimum values
Goto-From		El bloc *Goto* assigns a 'tag' to a system signal. Using it complementary block *From* it is possible to use the input value in any point of the simulation model.
Mux-Demux		Block *Mux* gathers signals within the same bus. On the contrary, the block *Demux* separates the signals within the same bus
To Workspace		Exports the values during the simulation to the *workspace*. It is recommended to configure it in the Array mode, in order to use it as a vector.

Table 4: Part 1 - Basic Simulink blocks

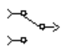
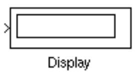
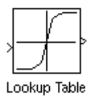
Block name	Image	Functionality and configuration
Switch		Manual selector to select between two possible inputs
Scope		Use for variable time domain visualization during and after a simulation
Display		Use for variable instantaneous value representation during a simulation
Lookup Table		Establish the relation (function) between an input and an output vector. The input is included with the output based on the established relation
Clock		Clock related with the simulation time

Table 5: Part 2 - Main Simulink blocks

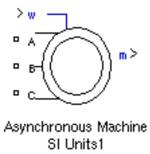
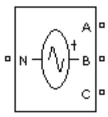
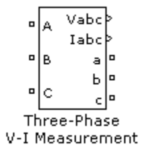
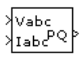
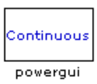
Block name	Image	Functionality and configuration
Asynchronous Machine		SCIG machine model provided by SimPowerSystems library. It is possible to modify the block configuration to obtain a DFIG model
Three-phase Programmable Voltage Source		Three-phase configurable voltage source. Using this block it is possible to create a network where the machine can be connected
Three-phase V-I Measurement		This blocks allows measuring the system voltages and currents. Its outputs are two vectors gathering voltages and current components of the three phases
3-phase Instantaneous Active & Reactive power		Calculation of the active and reactive power based on the voltages and currents of the system
Bus Selector		Allows accessing the SCIG variables
Ground		Ground connection
Powergui		Block required to perform simulations using SimPowerSystems. It allows to define the simulation type, the parameters of the simulation and other preferences.

Table 6: Main SimPowerSystems blocks

In terms of the configuration of the simulation parameters (Simulation - Configuration Parameters), Simulink provides a wide variety of 'solvers' or numerical methods to solve the differential equations of the model. In the configuration dialog, several simulation aspects can be defined, such as the selection of the solver, the maximum and minimum simulation time steps, etc. For the assignment simulation model, it is recommended to use the values provided in Fig. 6. Possibly, these values would need to be updated during some of the steps of the assignment.

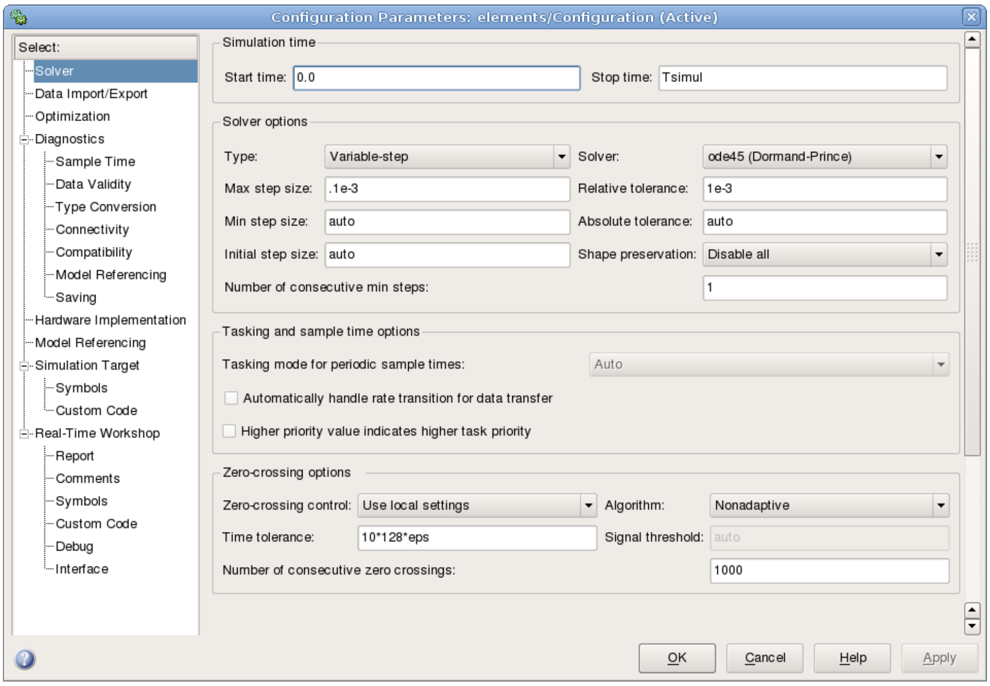


Figure 6: Configuration parameters of the Simulink simulation

In the next section, the differential equations of the system and the blocks combination required to complete the model are described. The creation of the model, as mentioned before, it is divided in three parts, turbine, transmission and electrical.

2.3.2 Wind turbine equations

First, the equation of the mechanical power is described

$$P_t = \frac{1}{2}\rho A C_P(\lambda,\theta)v_w^3 \tag{1}$$

where
- ρ is the air density
- A is the area swept by the blades
- C_P is the power coefficient
- θ is the pitch angle
- λ is the tip speed ratio

Based on the turbine power, the torque Γ_t applied to the shaft can be obtained, knowing the rotational speed, then

$$\Gamma_t = \frac{1}{2}\rho A C_P(\lambda,\theta)v_w^3\frac{1}{\omega_t} \tag{2}$$

To complete the previous expression, the equation of the power coefficient should be included, which is function of the tip speed ratio

$$C_P(\lambda,\theta) = c_1\left(c_2\frac{1}{\Lambda} - c_3\theta_{pitch} - c_4\theta_{pitch}^{c_5} - c_6\right)e^{-c_7\frac{1}{\Lambda}} \tag{3}$$

$$\frac{1}{\Lambda} = \frac{1}{\lambda + c_8\theta_{pitch}} - \frac{c_9}{1+\theta_{pitch}^3} \tag{4}$$

The tip speed ratio, can be defined as the relation between the speed at the end of the blade and the wind speed

$$\lambda = \frac{\omega_t R}{v_w} \tag{5}$$

Finally, it is interesting to observe that for a fixed-speed wind turbine, $\theta \equiv 0$, expressions are slightly simplified, as follows

$$\frac{1}{\Lambda} \equiv \frac{1}{\lambda} \tag{6}$$

Fig. 7 shows the blocks required to implement the turbine part.

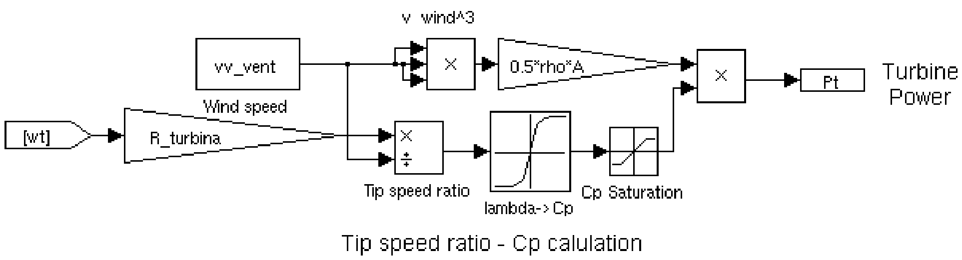


Figure 7: Simulation model blocks used to represent the turbine

It is interesting to comment the configuration of the lookup table and the saturation block. The lookup table is computing an approximation of the function y = f(x), for two given vectors x and y. Defining 'x' as a tip speed ratio vector and 'y' as its corresponding Cp value, the function λ - C_P is completely defined. Thus, introducing

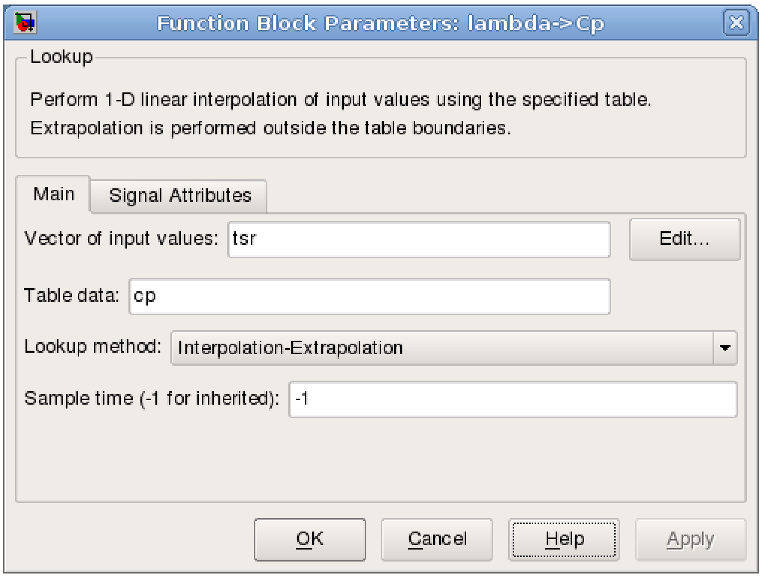


Figure 8: Block configuration lookup table

to the block a certain value of tip speed ratio, the block will output the current value of the Cp. The block configuration is shown in 8.

In order to define the vectors 'x' and 'y' it is recommended to use the parameter definition M-file. The parameter definition can be done adding the following code

Matlab code 2: Configuration of the lookup table

```
%% Obtention of the turbine [tip speed ratio (TSR)-Cp] curve
% CP vs tsr curve creation

tsr=0:.1:17;  % tsr vector from 0 a 17 with increments of 0.1
k1=(tsr+c8*angle_pitch).^(-1)-c9/(1+angle_pitch^3); % Aux variable to calculate Cp
cp=max(0,c1*(c2*k1-c3*angle_pitch-c4*angle_pitch^c5-c6).*exp(-c7*k1)); % calculation of the Cp for ↩
    different tsrs


% Graph [tip speed ratio - Cp]
figure();                            % Crea una nova figura
plot(tsr,cp,'LineWidth',2);grid on;  % Graficar la corba Cp en funcio del tip speed ratio
xlabel('\lambda','FontSize',14);     % Etiqueta de l'eix x
ylabel('C_p','FontSize',14);         % Etiqueta de l'eix y
```

The saturation block saturates the Cp value between 0 and 1, in order to avoid negative values.

2.3.3 Transmission equations

Next, the equations of the wind turbine transmission model are presented. Initially, a single-mass model is used, where the mechanical dynamics of the turbine, gearbox and generator are combined in a signle inertia with two torques (turbine Γ_t and generator Γ_m), acting on it, as

$$\Gamma_t + \nu\Gamma_m = J_t \frac{d}{dt}\omega_t \tag{7}$$

and

$$\omega_r = \nu\omega_t \tag{8}$$

on	ν	gearbox ratio
	Γ_m	torque of the generator
	ω_m	generator speed
	J_t	combined inertia

Usually, the inertia of the generator is neglected provided that the turbine inertia is considerably larger. Fig. 9 shows the simulation blocks of the transmission.

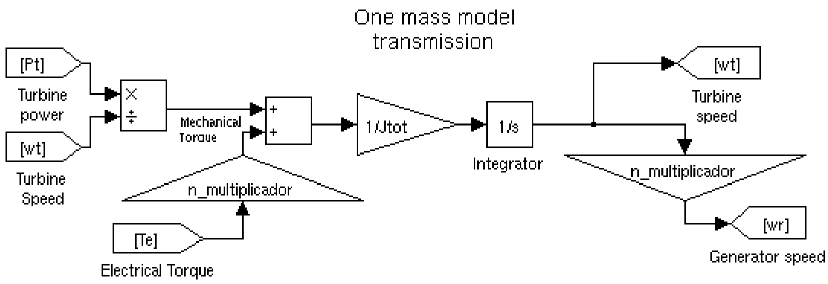


Figure 9: Transmission simulation model

2.3.4 Electrical system equations

In this section, the equations of the electrical part (grid and generator) are presented. In order to implement this part of the model, SimPowerSystems blocks will be used. The electrical components of the model are the electrical network source and the SCIG machine.

For the case study, we are considering the grid as an ideal voltage source. Then, the voltage can be expressed as

$$v_s^{abc} = A \begin{bmatrix} \cos(\omega_t) \\ \cos(\omega_t - \frac{2\pi}{3}) \\ \cos(\omega_t + \frac{2\pi}{3}) \end{bmatrix} \tag{9}$$

Fig. 10 shows the block to implement the network voltage source and its configuration generador.

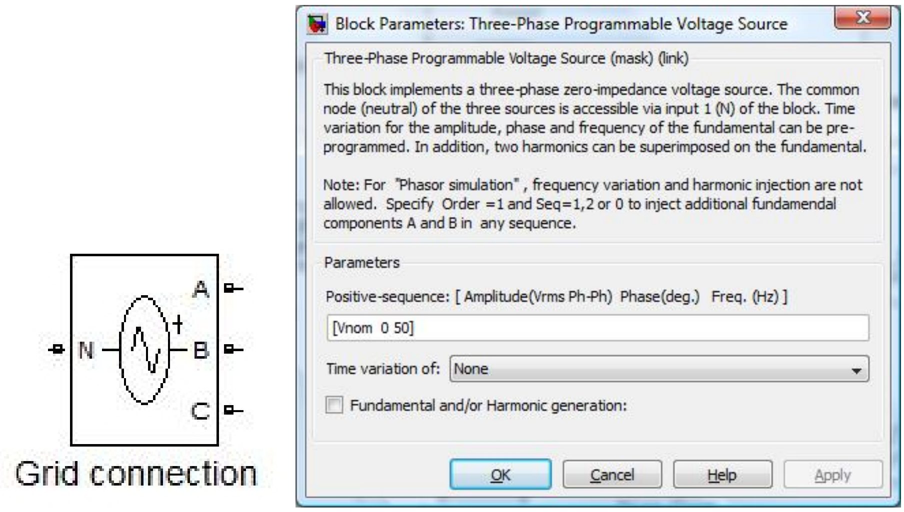


Figure 10: Network SimPowerSystems block and configuration

On the other hand, the SCIG can be modelled as a DFIG machine with a short-circuited rotor, as

$$v_r^{abc} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

The dynamic equations of the machine are:

$$v_s^{abc} = r_s i_s^{abc} + \frac{d}{dt}\lambda_s^{abc} \tag{11}$$

$$v_r^{abc} = r_r i_r^{abc} + \frac{d}{dt}\lambda_r^{abc} \tag{12}$$

where v_s^{abc} i v_s^{abc} is the vector of stator and rotor voltages
i_s^{abc} i i_s^{abc} is the vector of stator and rotor currents
λ_s^{abc} i λ_s^{abc} are the vectors of stator and rotor flux linkages
r_s is the resistance of the stator windings
r_r is the resistance of the stator windings

The expression of the flux linkage, considering a linear magnetic system is

$$\begin{bmatrix} \lambda_s^{abc} \\ \lambda_r^{abc} \end{bmatrix} = \begin{bmatrix} L_{ss}^{abc} & L_{sr}^{abc} \\ L_{rs}^{abc} & L_{rr}^{abc} \end{bmatrix} \begin{bmatrix} i_s^{abc} \\ i_r^{abc} \end{bmatrix} \tag{13}$$

with

$$L_{ss}^{abc} = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix} \tag{14}$$

$$L_{rr}^{abc} = \begin{bmatrix} L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & -L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} & L_{lr} + L_{mr} \end{bmatrix} \tag{15}$$

$$L_{sr}^{abc} = \left\{L_{rs}^{abc}\right\}^t = L_{sr} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r) & \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r) \end{bmatrix} \tag{16}$$

where L_{ls} i L_{lr} are the leakage stator and rotor inductances
L_{ms} is the inductance of one stator winding due to the flux crossing the airgap
L_{mr} is the inductance of one rotor winding due to the flux crossing the airgap
L_{sr} is the maximum value of coupling inductance between stator and rotor
θ_r is the rotor angle seen from the electrical circuit.

The machine torque can be obtained as

$$\Gamma_m = \frac{P}{2} \begin{bmatrix} i_s^{abc} \\ i_r^{abc} \end{bmatrix}^t \begin{bmatrix} 0 & N_{sr}^{abc} \\ N_{rs}^{abc} & 0 \end{bmatrix} \begin{bmatrix} i_s^{abc} \\ i_r^{abc} \end{bmatrix} \tag{17}$$

with

$$N_{sr}^{abc} = \left\{N_{rs}^{abc}\right\}^t = -L_{sr} \begin{bmatrix} \sin(\theta_r) & \sin(\theta_r + \frac{2\pi}{3}) & \sin(\theta_r - \frac{2\pi}{3}) \\ \sin(\theta_r - \frac{2\pi}{3}) & \sin(\theta_r) & \sin(\theta_r + \frac{2\pi}{3}) \\ \sin(\theta_r + \frac{2\pi}{3}) & \sin(\theta_r - \frac{2\pi}{3}) & \sin(\theta_r) \end{bmatrix} \tag{18}$$

These expressions are not practical, so typically they are being transformed using the Park T transformation:

$$T(\theta) = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{19}$$

and

$$T^{-1}(\theta) = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \tag{20}$$

Applying the matrix T to voltages and currents and operating, it can be obtained

$$\begin{bmatrix} v_s^{qd} \\ v_r^{qd} \end{bmatrix} = \begin{bmatrix} \frac{3}{2}L_{ms} + L_{ls} & 0 & \frac{3}{2}L_{sr} & 0 \\ 0 & \frac{3}{2}L_{ms} + L_{ls} & 0 & \frac{3}{2}L_{sr} \\ \frac{3}{2}L_{sr} & 0 & \frac{3}{2}L_{mr} + L_{lr} & 0 \\ 0 & \frac{3}{2}L_{sr} & 0 & \frac{3}{2}L_{mr} + L_{lr} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_s^{qd} \\ i_r^{qd} \end{bmatrix}$$
$$+ \begin{bmatrix} r_s & \left(\frac{3}{2}L_{ms} + L_{ls}\right)\dot{\theta} & 0 & \frac{3}{2}L_{sr}\dot{\theta} \\ -\left(\frac{3}{2}L_{ms} + L_{ls}\right)\dot{\theta} & r_s & -\frac{3}{2}L_{sr}\dot{\theta} & 0 \\ 0 & \frac{3}{2}L_{sr}\left(\dot{\theta} - \omega_r\right) & r_r & \left(\frac{3}{2}L_{ms} + L_{ls}\right)\left(\dot{\theta} - \omega_r\right) \\ -\frac{3}{2}L_{sr}\left(\dot{\theta} - \omega_r\right) & 0 & -\left(\frac{3}{2}L_{ms} + L_{ls}\right)\left(\dot{\theta} - \omega_r\right) & r_r \end{bmatrix} \begin{bmatrix} i_s^{qd} \\ i_r^{qd} \end{bmatrix} \tag{21}$$

$$v_{s0} = L_{ls}\frac{di_{s0}}{dt} + r_s i_{s0} \tag{22}$$
$$v_{r0} = L_{lr}\frac{di_{r0}}{dt} + r_r i_{r0} \tag{23}$$

$$\Gamma_m = \frac{9}{4}PL_{sr}\left(i_{sq}i_{rd} - i_{sd}i_{rq}\right) \tag{24}$$

Usually, to simplify the previous expressions, the following variable changes are applied

$$L_s \triangleq \frac{3}{2}L_{ms} + L_{ls} \tag{25}$$
$$L_r \triangleq \frac{3}{2}L_{mr} + L_{lr} \tag{26}$$
$$M \triangleq \frac{3}{2}L_{sr} \tag{27}$$

then

$$\begin{bmatrix} v_s^{qd} \\ v_r^{qd} \end{bmatrix} = \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_s^{qd} \\ i_r^{qd} \end{bmatrix}$$
$$+ \begin{bmatrix} r_s & L_s\dot{\theta} & 0 & M\dot{\theta} \\ -L_s\dot{\theta} & r_s & -M\dot{\theta} & 0 \\ 0 & M\left(\dot{\theta} - \omega_r\right) & r_r & L_r\left(\dot{\theta} - \omega_r\right) \\ -M\left(\dot{\theta} - \omega_r\right) & 0 & -L_r\left(\dot{\theta} - \omega_r\right) & r_r \end{bmatrix} \begin{bmatrix} i_s^{qd} \\ i_r^{qd} \end{bmatrix} \tag{28}$$

$$v_{s0} = L_{ls}\frac{di_{s0}}{dt} + r_s i_{s0} \tag{29}$$
$$v_{r0} = L_{lr}\frac{di_{r0}}{dt} + r_r i_{r0} \tag{30}$$

$$\Gamma_m = \frac{3}{2}PM\left(i_{sq}i_{rd} - i_{sd}i_{rq}\right) \tag{31}$$

Instead of implementing the state-space representation of the induction machine, the Simulink block shown in Fig. 11 is used, adequately configured with the generator values.

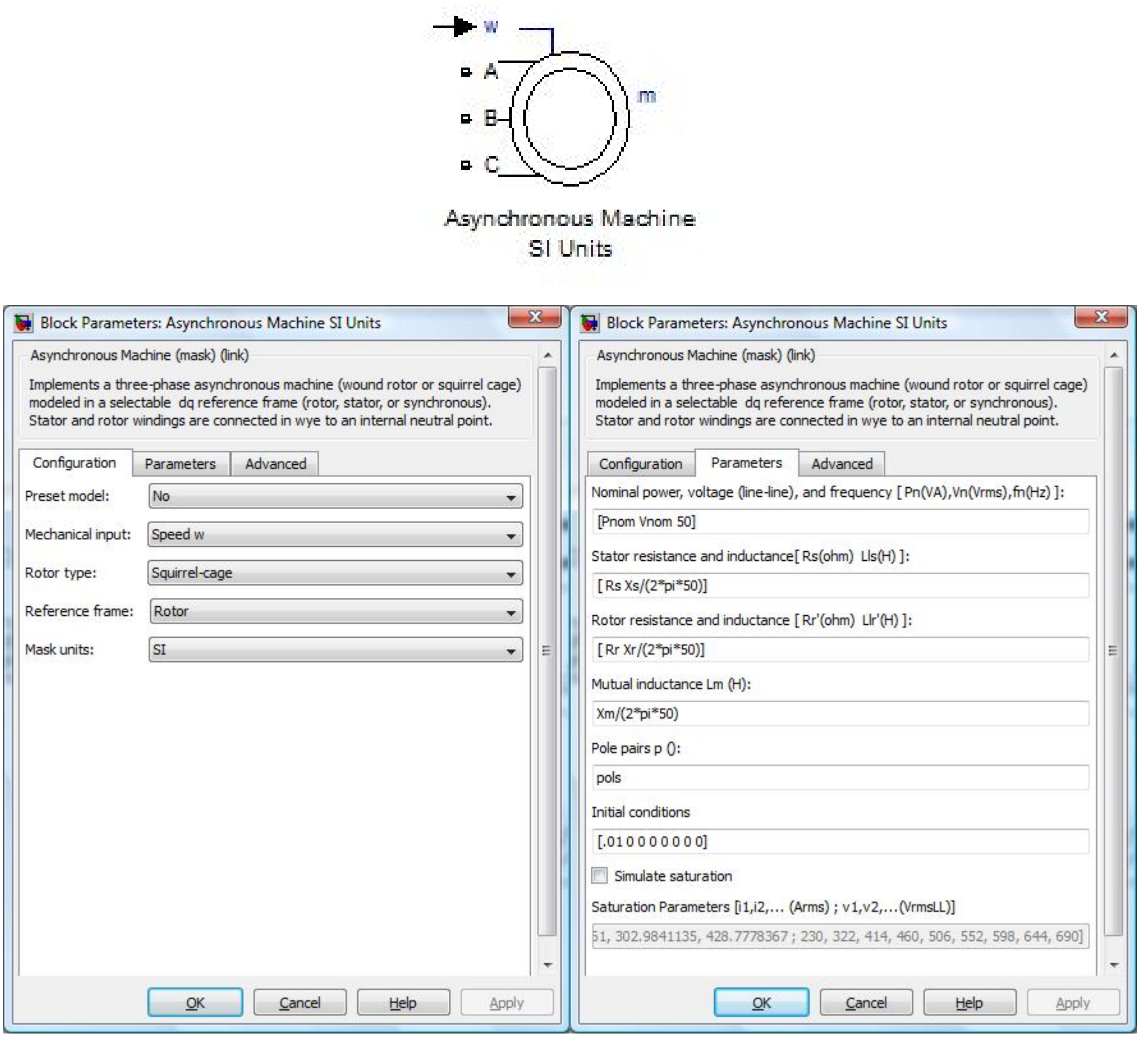


Figure 11: Generator SimPowerSystems block

Finally, the electrical system model is shown in Fig. 12, including the generator, the grid and the measurement blocks.

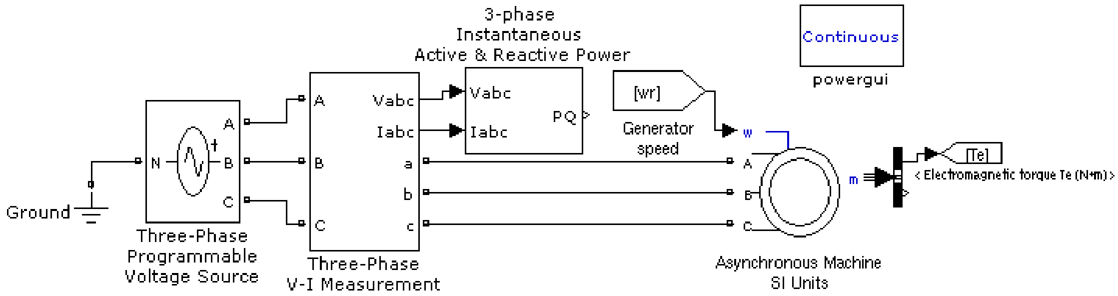


Figure 12: Electrical part of the wind turbine model

2.4 Complete simulation model

Once the different subsystems have been created, they need to be combined in a single model to run the wind turbine simulation. After combining the different subsystems, the model is ready for simulation.

2.4.1 Routine to export data to Matlab workspace from Simulink

Variables connected to a 'To workspace' block can be used in the Matlab console in a vector format. It is recommended to use the vector format *Array*. An example code to represent the variable *Pe* depending on *t* can be the following one.

Matlab code 3: Creation of a graphic using an M-file

```
figure();                                   % Creation of a new Figure
plot(t,Pe,'LineWidth',2);                   % Graph of the variable Pe in function of t
                                            %(Pe - Electrical power , t - times)
grid on;                                    % Graphic grid on
xlabel('Time','FontSize',14);               % x axis label
ylabel('Electrical power [W]','FontSize',14); % y axis label
title('Electrical Power - Time')            % title
legend('Pelec')                             % legend
```

2.4.2 Example results

Figs. 13, 14, 15, 16, 17, 18, 19, 20 and 21 show example results.

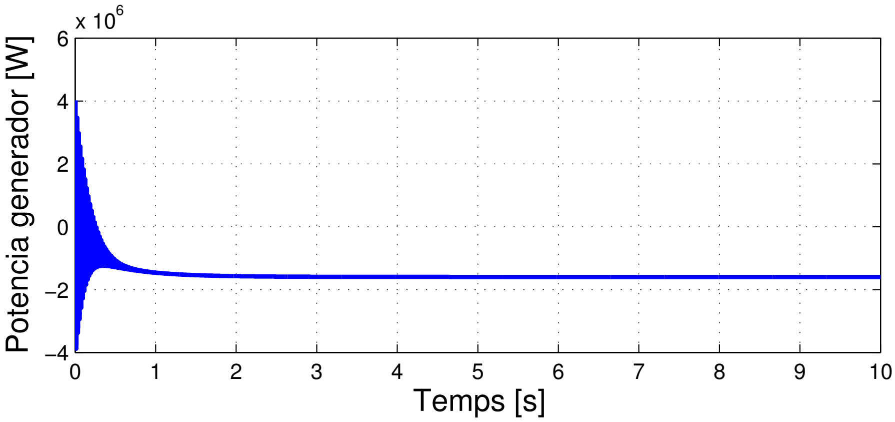


Figure 13: Active power

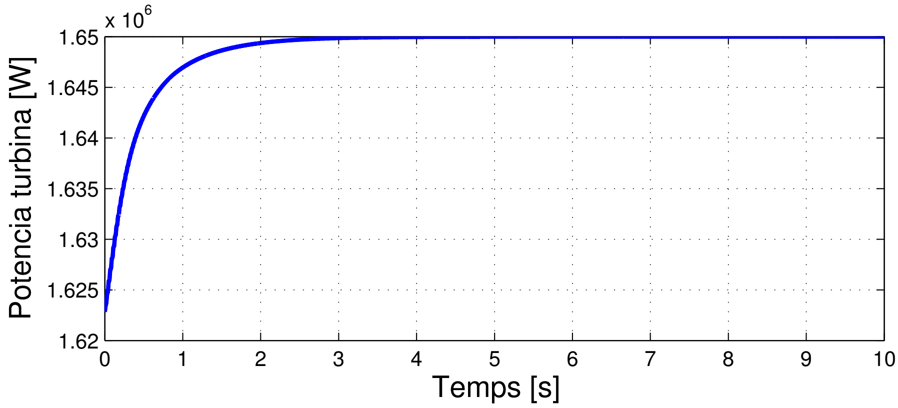


Figure 14: Turbine power

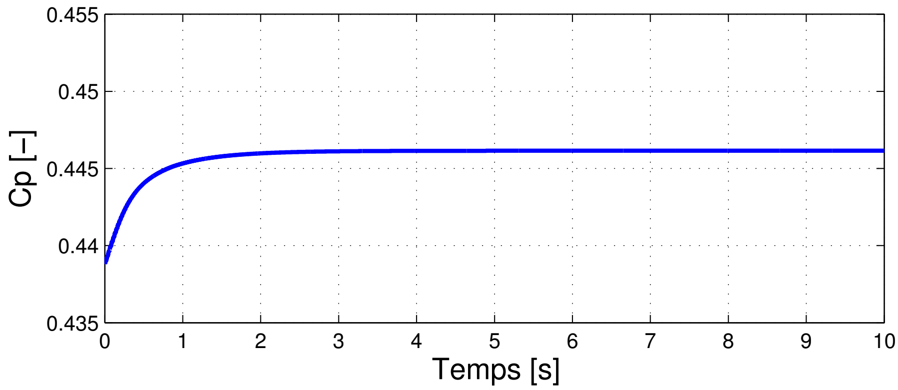


Figure 15: Power Coefficient

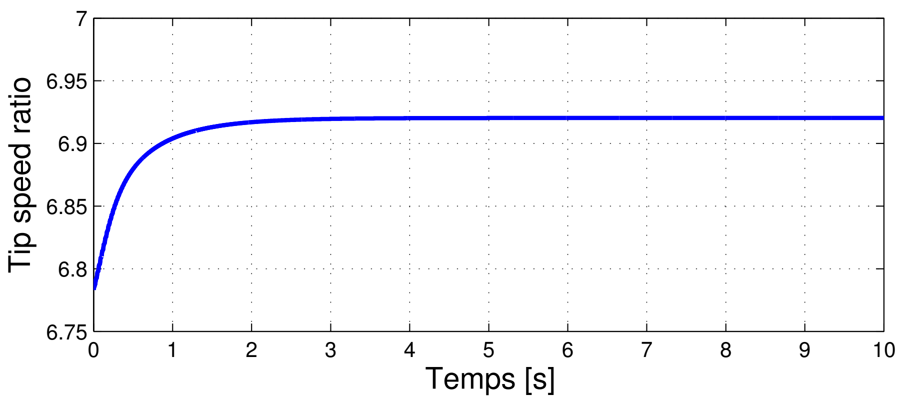


Figure 16: Tip speed ratio

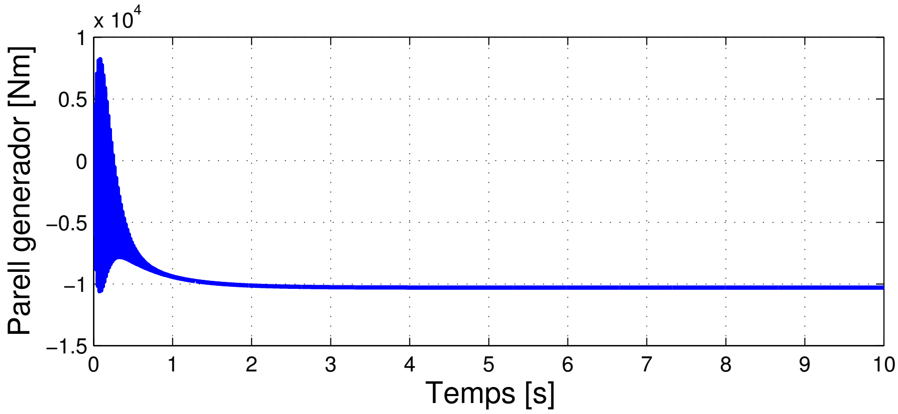


Figure 17: Generator torque

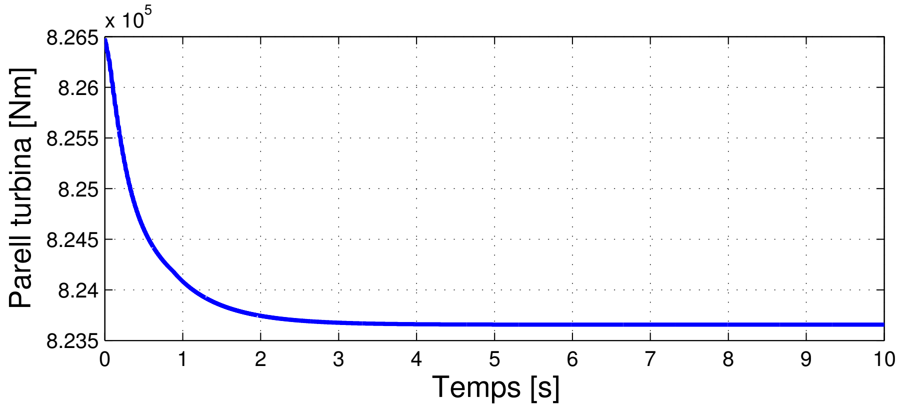


Figure 18: Mechanical torque

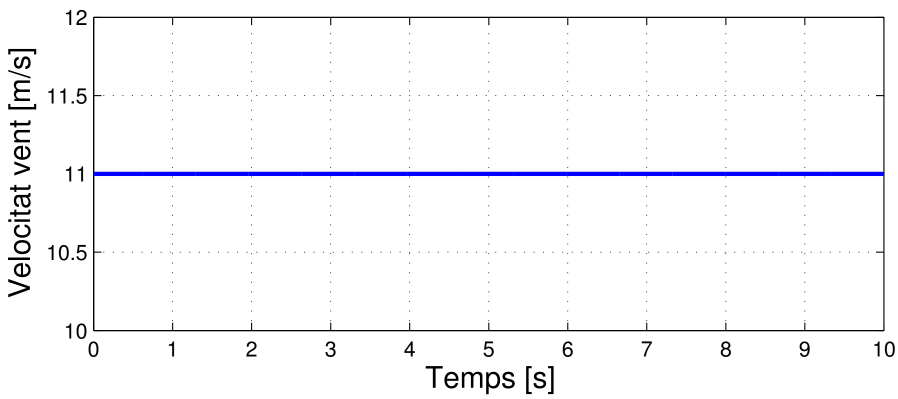


Figure 19: Wind speed

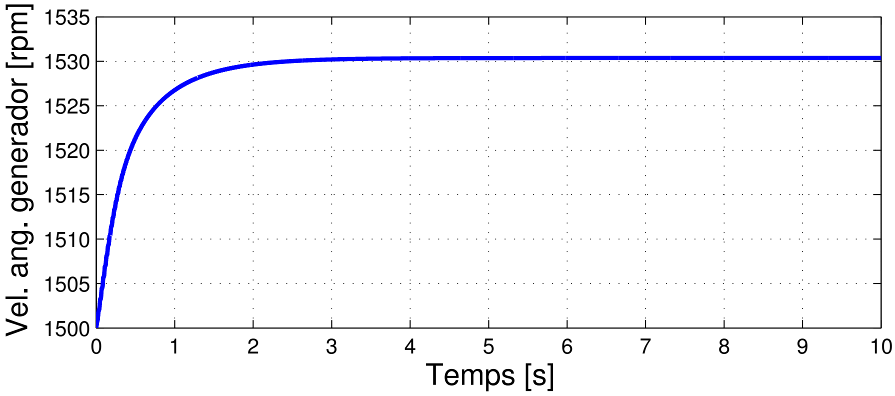


Figure 20: Generator speed

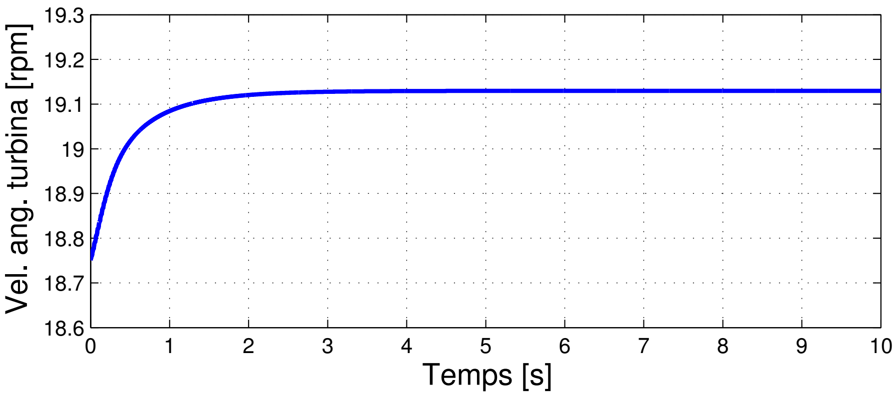


Figure 21: Turbine speed