Simulation of Variable Speed Wind Turbines based on Open-Source Solutions: application to Bachelor and Master Degrees

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Abstract

This paper describes variable speed wind turbine (Types 3 and 4, IEC 61400-27-1) simulations based on an open-source solution to be applied to Bachelor and Master Degrees. It is an attempt to improve the education quality of such sustainable energy by giving an open-source experimental environment for both undergraduate and graduate students. Indeed, among the renewable sources, wind energy is currently becoming essential in most power systems. The simulations include both one—mass and two—mass mechanical models, as well as pitch angle control. A general overview of the structure, control, and operation of the variable speed wind turbine is provided by these easy-to-use interactive virtual experiments. In addition, a comparison between commercial and open-source software packages is described and discussed in detail. Examples and extensive results are also included in the paper. The models are available in Scilab-Xcos file exchange for power system education and researcher communities.

Keywords

VSWT, Modeling, Education, FOSS

Nomenclature

BSc Bachelor degree DC Direct current

DFIG Doubly fed induction generator ECTS European Credit Transfer System EHEA European Higher Education Area

FOSS Free open-source solution FSWT Fixed speed wind turbine

MSc Master degree
PhD Philosophiæ doctor
RES Renewable energy sources
TSO Transmission system operator
VSWT Variable speed wind turbine

WT Wind turbine

Introduction

During the last decade, aspects such as climate change, energy dependence, fossil resource scarcity and the increasing costs of nuclear power, have promoted the integration of Renewable Energy Sources (RES) into power systems ¹. Among these renewable resources, wind power is the most popular alternative developed and currently integrated into the grid ². Actually, since 2001, the global cumulative installed wind capacity has suffered an exponential growth, see Figure 1. As a consequence, the wind energy sector is promoting new employment opportunities ³. These employment opportunities include direct employment — manufacturing companies, promotion, utilities, engineering and R&D— as well as indirect employment —providing services or components for wind turbines (WTs)—⁴. Figure ² shows the normalised employment (jobs/MW) for

manufacturing, installation, and O&M, including direct and indirect employments determined by Cameron and Van Der Zwaan. However, and in spite of this relevant employment opportunity, it was reported in 2017 a 'lack of talent' in the renewable energy sector. Consequently, it has been demanded by the sector new educational programs aiming to meet the increasing human capital requirement for RES, especially in wind power areas⁶. Moreover, these activities require heterogeneous educational backgrounds, involving engineering, technician, economics, marketing, management and customer services⁷. To overcome these deficiencies, some European universities have already started to implement new bachelor degrees (BSc), master degrees (MSc) and philosophiæ doctor (PhD), as summarised in Table 1. Other universities include renewable energy subjects in industrial engineering BSc, either as core academic or optional sub-

Engineering students need to experiment and observe what they are taught in the theory sessions to improve their knowledge in topic ¹⁰. In fact, virtual experimenting is considered an alternative solution for the practical sessions of the 'Wind energy' subject, facing the lack of wind energy experimental laboratories mainly due to the expensive costs of such teaching equipment. Laboratory scaled-workbench solutions ¹¹ and lab-scale experiments ¹² have been previously proposed to overcome the high

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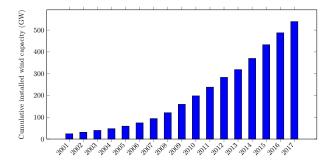


Figure 1. Global cumulative installed wind capacity in GW. Data from ⁸

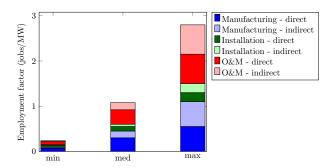


Figure 2. Direct and indirect jobs per deployment phase (in jobs/MW) for wind power. Data from ⁹

Table 1. European universities including new BSc, MSc and PhD related to energy and RES

Degree	Name	University	Country
BSc	Energy engineering	University of Southern Denmark	Denmark
BSc	Energy engineering	Aalborg University	Denmark
BSc	Energy engineering	Universidad Carlos III de Madrid	Spain
BSc	Energy engineering	Universidad Politécnica de Madrid	Spain
BSc	Energy engineering	Universidad Politécnica de Cataluña	Spain
BSc	Renewable energy engineering	Stuttgart University	Germany
BSc	Renewable energy engineering	Berlin International College	Germany
BSc	Renewable energy engineering	Universidad Autónoma de Barcelona	Spain
BSc	Renewable energy engineering	Universidad del País Vasco	Spain
BSc	Renewable thermal & power engineering	National Research University	Russia
MSc	Renewable energy engineering	Carl Von Ossietzky Universität Oldenburg	Germany
MSc	Renewable energy engineering	Universidad Politécnica de Cartagena	Spain
MSc	Renewable energy engineering	University of Aberdeen	UK
MSc	Renewable energy engineering	Kingston University	UK
MSc	Renewable energy engineering	Heriot Watt University	UK
MSc	Wind energy	Technical University of Denmark	Denmark
MSc	Wind energy	Norwegian University of Science and Technology	Norway
MSc	Wind energy	Universidad Nacional de Educación a Distancia	Spain
PhD	Renewable energy	Aalborg University	Denmark
PhD	Renewable energy	Universidad Politécnica de Cartagena	Spain
PhD	Renewable energy	Universidad de Jaén	Spain
PhD	Wind energy	Technical University of Denmark	Denmark
PhD	Wind energy	The University of Sheffield	UK

cost of such equipment. E-learning trends have also been considered by some authors as an alternative to lab-scale experiments. Other authors have developed a remarkable amount of modules for wind teaching purposes mostly based on commercial software packages ^{13,14} (Matlab, Multisim, LabView, DigSilent) or packages that must run within commercial solutions, such as SimPower 15,16 or MatDyn¹⁷. During the last decade, a continued effort to promote the use of Free Open-Source Solutions (FOSS) for engineering education has been developed under different projects, taking into account the educational and pedagogical benefits provided by such open-source software 18,19 Several advantages are found if comparing FOSS with commercial software, such as reducing costs of licenses, prevention of illegal copying and promoting self-learning and independent study²⁰.

Under this scenario, the present paper focuses on the simulation of Variable Speed Wind Turbines (VSWTs)

within the 'Wind energy' subject by using the Scilab open-source solution. These practical sessions are currently included in both Electrical Engineering BSc and Renewable Energy MSc —Universidad Politécnica de Cartagena, Spain—. Under this framework, we provide our students a visual, friendly and open-source tool for VSWT simulation purposes, including WT parameter analysis and a comparison between two WT mechanical models commonly used by researchers ²¹: one—mas and two-mass mechanical models. These simulations give the students a comprehensive view of VSWTs, and allow them to analyse their main curves. The contributions of the paper can be then summarised as:

- (i) Using an open-source mathematical software for simulation purposes.
- (ii) Analysing how wind speed variations can modify the pitch angle and, subsequently, the power coefficient and mechanical power of VSWTs.
- (iii) Determining the optimum tip speed ratio and power coefficient for different pitch angles, including the mechanical power and turbine rotational speed values.
- (iv) Comparing the responses of generator and turbine rotational speeds depending on the mechanical model used.

These objectives are developed under a teaching scenario according to the current European educational framework. The models are available in Scilab-Xcos file exchange for power system education and researcher communities.

Educational framework in Europe: EHEA

In 1999, 29 European Ministers of Education signed 'The Bologna Declaration', considered as the first attempt to create a new European Higher Education Area (EHEA)²². Nowadays, this EHEA involves 48 countries, and the main key-points can be summarised as follows:

- Harmonisation of the Grade-system to promote European mobility students among the different countries. It involves the development of comparable criteria and methodologies among the universities, as well as the recognition of foreign degrees in other institutions and countries.
- Introduction of the European Credit Transfer System (ECTS). Each ECTS credit accounts for between 25-27 hours, including the learning hours of the students. Therefore, assuming that students devote 40 h/week to study and learning tasks, each Grade level academic session should account for a maximum of 60 ECTS.
- Harmonisation of the teaching stages in all EHEA countries: BSc, MSc, and PhD. To access the following teaching cycle, it is required a successful finishing of the previous stage (BSc or MSc, respectively).

In most European countries, EHEA has thus promoted a significant change in the universities, moving from the traditional teacher-oriented approach to a more learner-centred approach. Moreover, in West European countries — such as Austria, Germany, and Spain—, the Bologna Process has been considered as a tool of domestic leverage by

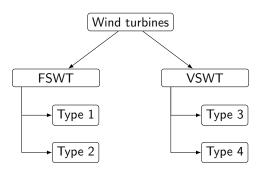
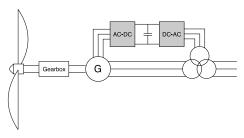
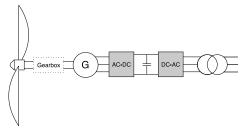


Figure 3. Classification of wind turbines.



(a) DFIG wind turbine. Type 3



(b) Full-converter wind turbine. Type 4

Figure 4. Variable speed wind turbines.

governments aiming to legitimate much wider projects of structural reform in the higher education sector ²³.

Wind turbines. Preliminaries

WTs are usually classified as fixed speed wind turbines (FSWTs) or variable speed wind turbines (VSWTs), see Figure 3. FSWTs work at the same rotational speed regardless of the wind speed. On the other hand, VSWTs can operate around their optimum power point for each wind speed, using a partial or full additional power converter, see Figure 4. As a result, VSWTs are considered as more efficient solutions than FSWTs²⁴. With the aim of providing generic electrical simulation models of wind power generation, different standards have been developed such as the IEC 61400–27–1.

Simulation tool review

Various mathematical computational packages are available for research and educational purposes. Among the different solutions, Matlab is widely considered as the most often used software ²⁵. Moreover, it is commonly recommended for electrical and electronics students, due to its user-friendly and easily understood by the students ²⁶. Matlab software

Table 2. Supported data types

Data type	Matlab	Freemat	Mathnium	Octave	R	Scilab
Integer	Χ	Χ	Χ	Χ	Χ	Χ
Double	Χ	X	X	Χ	Χ	Χ
Boolean	Χ	X	X	Χ	Χ	Χ
Complex	Χ	X	X	Χ	Χ	Χ
Matrices	Χ	X	X	Χ	Χ	Χ
Strings	Χ	X	X	Χ	Χ	Χ
Structures	Χ	X	X	Χ	Χ	Χ
Cells	Χ	X	X	Χ	Χ	Χ
Java class	Χ		X			
Sparse matrix	Χ	Χ	Χ	Χ	Χ	Χ

Table 3. Supported language constructs

Language constructs	Matlab	Freemat	Mathnium	Octave	R	Scilab
Object-oriented	Χ	Χ	Χ		Х	Χ
Dynamic allocation of memory	Χ	X			Χ	X
Sparse matrix	X	X	X	Χ	Χ	Χ
Parallel programming	Χ	Χ		X	Х	Χ

combines a desktop environment tuned for iterative analysis and design processes with a programming language that expresses matrix and array mathematics directly, as stated in its website. However, as Matlab is commercial software, alternative open-source solutions have been developed in the last decades ²⁷The most popular free mathematical software alternatives to Matlab are the following: Freemat, Mathnium, Octave, R and Scilab. One of the most comprehensive study found in the literature review has been addressed by Glavelis et al. 28, but excluding Matlab. Tables 2-5 summarise a full comparison between Matlab and the FOSS alternatives. These tables provide a complete characterisation by considering supported data types, language constructs, the functionality of the programming environment, help facilities and speed comparison analysis respectively. With regard to the computational time costs, Glavelis et al. 28 conclude that the best average performance between the aforementioned FOSS is Scilab. Rubtsova and Korolev²⁹ affirm that Scilab can be considered as the most complete open-source alternative to Matlab. Scilab also includes Xcos, a graphical editor of dynamic systems very similar to Simulink graphical editor in Matlab³⁰. Therefore, teaching material developed with Matlab/Simulink can be successfully replaced by equivalent material developed with Scilab/Xcos through some adjustments and moderate additional effort³¹. In conclusion, and considering the extended comparison depicted in Tables 2-5 as well as such contributions discussed in this Section, Scilab-Xcos is selected in this paper as the most suitable open-source software for our proposals. Nevertheless, other studies can be found in the specific literature to help learners in Bachelor and Master Degree levels based on other free software solutions. For example, Qin et al³² recently show the initial efforts in the creation of OpenRES-an open-source JModelica.org library for renewable energy resources. Kanoj et al33 simulate an autonomous wind energy conversion system for irrigation purpose employing induction machines using Python.

Simulation set-up & results

As was previously discussed, the authors have proposed practical sessions with Scilab-Xcos in the 'Wind energy' subject of both the Electrical Engineering BSc and

Table 4. Supported functionality of the programming environment

Functionality	Matlab	Freemat	Mathnium	Octave	R	Scilab
Debugger	Χ	Χ	Χ	Χ	Х	Х
Profiler	Χ	X			Χ	Χ
Syntax highlighting	Χ	X		Χ		Χ
Creation of graphical user interface	Χ					Χ

Table 5. Supported help facilities

Help facilities	Matlab	Freemat	Mathnium	Octave	R	Scilab
Help environment	Χ	Χ		Χ	Χ	Χ
Manual	Χ	X		Χ	Χ	Χ
Searching index	Χ	X			Χ	Χ
Online documentation	Χ	X	X		Χ	Χ
Mailing list/user forum	Χ	Χ		Χ	Χ	Χ

Renewable Energy MSc of Universidad Politécnica de Cartagena (Spain). The VSWT model is based on the GE 3.6 model available in the specific literature ³⁴. The model corresponds to a *type 3* WT, though the proposed simulation can be also applied to a *type 4* WT, as stated in ³⁵. Source codes and data models are provided to the students. Actually, files are also available to other researchers and students through the following link https://n9.cl/3hr0z. Additional analysis can be also proposed to extend these simulations toward a more complex study, mainly focused on post-graduate students. For example, a more complex wind turbine model discussed by the authors in ³⁶ can be used to analyse grid code compliance. In a similar way, more realistic wind speed profiles characterised in ³⁷ can be also considered for simulations.

Scilab simulation

Based on the different *scripts* prepared by the authors, students can graphically analyse the relationship among the main parameters of wind turbines (previously introduced in theoretical sessions): β , λ , v_w , C_p , P_{mech} and Ω_{WT} . By using the Scilab-Xcos *scripts*, the students can compare their graphical results facing the estimated VSWT curves. These curves are following described. Results are also included as examples of our practical sessions.

(i) $C_p - v_w$ curve: The rotor performance of a WT is characterised by its power coefficient C_p , having a limit of $\frac{16}{27} \approx 59\%$ according to the Betz limit. The power coefficient C_p can be estimated depending on the pitch angle β and the tip speed ratio λ :

$$C_p(\lambda, \beta) = \sum_{i=0}^{4} \sum_{j=0}^{4} \alpha_{i,j} \beta^i \lambda^j, \tag{1}$$

where coefficients $\alpha_{i,j}$ are taken from Table 6. The tip speed ratio λ is defined as

$$\lambda = \frac{\Omega_0 \cdot R \cdot \Omega_{WT}}{V_W},\tag{2}$$

where Ω_0 is the rotor base speed (rad/s), Ω_{WT} refers to the rotor speed (pu), R is the rotor radius (m) and v_w is the wind speed (m/s). According to Miller *et al.* ³⁴, the rotor reference speed is normally 1.2 pu, assuming that $\Omega_{WT}=1.2$. The pitch angle can vary between 0 and 27°. Cut-in and cut-out wind speeds for this WT model are 4 m/s and 25 m/s, respectively. With all these

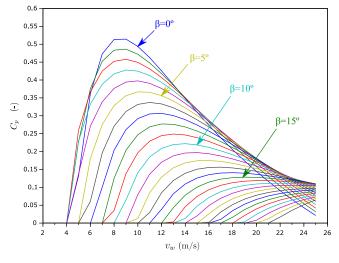


Figure 5. $C_p = f(v_w, \beta)$. Scilab: plot (Vw, Cp)

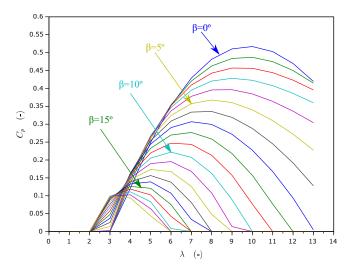


Figure 6. $C_p = f(\lambda, \beta)$. Scilab: plot (lambda, Cp)

considerations, the $C_p - v_w$ curve depending on the pitch angle can be estimated as depicted in Figure 5. From these results, students can graphically check that the higher pitch angle β , the lower power coefficient. These lower power coefficient values also reduce the shaft mechanical power, as explained afterwards.

(ii) $C_p - \lambda$ curve: According to the specific literature, C_p is usually considered as a function of the tip speed ratio λ Moreover, the $C_p - \lambda$ curve is necessary for developing the turbine control and guaranteeing a safe operation of the WT. According to the definition of λ in eq. (2), and considering a constant wind speed value, if the WT rotational speed is low, too much wind will pass undisturbed through the blades. On the contrary, if the rotational speed value is high ($\lambda \approx$ 13), the rotating blades appear as a 'solid disc' to the wind, creating a large amount of drag³⁸. In practice, the specific literature suggests that the optimum λ for a three-bladed WT is generally estimated as $\lambda_{opt} \approx$ 7³⁹. In the model under consideration, it is suggested that $2 \le \lambda \le 13$. Figure 6 shows the $C_p - \lambda$ curve depending on the pitch angle. According to the results and the theoretical sessions given to the students, the larger pitch angle β value, the lower power coefficient.

Table 6. Coefficients $\alpha_{i,j}$ to calculate $C_p(\lambda,\beta)$

i,j	0	1	2	3	4
0	$-4.19 \cdot 10^{-1}$	$2.18 \cdot 10^{-1}$	$-1.24 \cdot 10^{-2}$	$-1.34 \cdot 10^{-4}$	$1.15 \cdot 10^{-5}$
1	$-6.76 \cdot 10^{-2}$	$6.04 \cdot 10^{-2}$	$-1.39 \cdot 10^{-2}$	$1.07 \cdot 10^{-3}$	$-2.39 \cdot 10^{-5}$
2	$1.57 \cdot 10^{-2}$	$-1.01 \cdot 10^{-2}$	$2.15 \cdot 10^{-3}$	$-1.49 \cdot 10^{-4}$	$2.79 \cdot 10^{-6}$
3	$-8.60 \cdot 10^{-4}$	$5.71 \cdot 10^{-4}$	$-1.05 \cdot 10^{-4}$	$5.99 \cdot 10^{-6}$	$-8.91 \cdot 10^{-8}$
4	$1.48 \cdot 10^{-5}$	$-9.48 \cdot 10^{-6}$	$1.62 \cdot 10^{-6}$	$-7.15 \cdot 10^{-8}$	$4.97 \cdot 10^{-10}$

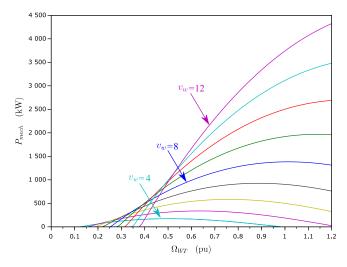


Figure 7. $P_{mech} = f(\Omega_{WT}, v_w)$. Scilab: plot (w, Pmec)

Moreover, it can be determined an optimum value of the tip speed ratio λ_{opt} for each β value —which addresses an optimum C_p value accordingly—. Due to the VSWT power converter performances, they are able to work on each optimum C_p^{Opt} value for each wind speed. This point is a spotlight that should be clarified and highlighted for the students.

(iii) $P_{mech} - \Omega_{WT}$ curve: The mechanical power P_{mech} is obtained from:

$$P_{mech} = K_{rotor} \cdot C_P \cdot v_w^3, \tag{3}$$

being $K_{rotor}=\frac{1}{2}\cdot\frac{1}{S_n}\cdot\rho\cdot A_r$ (S_n the rated power, ρ the air density, A_r the swept area by the blades), C_P the power coefficient, and v_w the wind speed. The power coefficient C_P is estimated with eq. (1). By considering $K_{rotor}=0.00145,\,P_{mech}$ is obtained in pu on the MW base of the wind turbine. In line with the literature review, P_{mech} is commonly plotted vs the rotor rotational speed Ω_{WT} , which can vary between 0 and the corresponding reference value (1.2 pu). Two different options are then proposed to analyse the $P_{mech}-\Omega_{WT}$ curve:

- (a) Constant pitch angle (β) and variable wind speed (v_w). β is fixed at 0° and the wind speed is gradually increased from 4 to 12 m/s for the sake of clarity of the figure, see Figure 7. $P_{mech} \Omega_{WT}$ curves then reach their maximum values at the optimum power coefficient according to results depicted in Figure 6. Moreover, due to the cubic dependence between v_w and P_{mech} , such mechanical power run up as wind speed increases (please compare, for instance, P_{mech} at $v_w = 4 \ m/s$ and $v_w = 8 \ m/s$).
- (b) Constant wind speed (v_w) and variable pitch angle (β) . In this case, wind speed is fixed

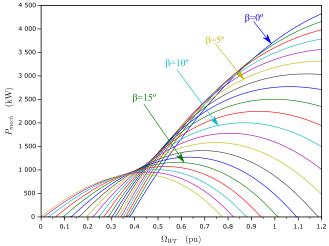


Figure 8. $P_{mech} = f(\Omega_{WT}, \beta)$. Scilab: plot (w, Pmec)

at $v_w=12~m/s$ and β is increased from 0 to 19°. Figure 8 shows the results obtained under this assumption. As in previous cases, a β increasing reduces the mechanical power due to the power coefficient decreasing. In our opinion, it is interesting for the students to estimate the mechanical power differences between $\beta=0^\circ$ and $\beta=19^\circ$ —which correspond $\approx 3250~\mathrm{kW}$ for the selected WT—. These results allow the student to evaluate in detail the severe mechanical power P_{mech} dependence on the pitch angle.

Xcos simulation

As was previously discussed, the selected VSWT has been simulated by the authors by using the Scilab-Xcos open-source solution. Apart from the parameters previously analysed $(\beta, \lambda, v_w, C_p, P_{mech})$ and Ω_{WT} , the graphical Xcos environment allows us to determine the electrical power P_e provided by the WT and the generator rotational speed Ω_q . The block diagram of the VSWT simulated within this graphical environment is depicted in Figure 9. A comparison between two different mechanical models of the rotor is also carried out in our practical sessions: (i) Onemass mechanical model and (ii) Two-mass mechanical model. Therefore, the block labelled as 'Mechanical model' in Figure 9 corresponds to both approaches. This block is then modified depending on the mechanical model under consideration. The reference rotational speed Ω_{ref} is estimated from the measured active power P_{ef} :

$$\Omega_{ref} = -0.67 \cdot P_{ef}^2 + 1.42 \cdot P_{ef} + 0.51, \tag{4}$$

being P_{ef} the measured electrical power P_e after a delay T_f . The block diagram is depicted in Figure 10. When the electrical measured power P_{ef} is below 0.75 pu, the rotational speed reference is calculated according to eq. (4). If P_{ef} is over 0.75 pu, the pitch controller must keep constant the rotational speed at $\Omega_{ref}=1.2$ pu.

The blades are pitched to limit the maximum mechanical power delivered to the shaft. It is carried out by a combination of two controllers 40 : (i) traditional pitch control and (ii) pitch compensation, see Figure 11. Both controllers

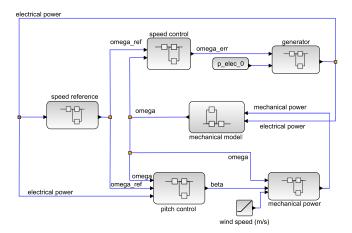


Figure 9. Wind turbine block model. Scilab-Xcos environment.

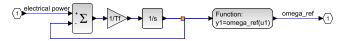


Figure 10. Rotational speed reference block diagram. Scilab–Xcos environment.

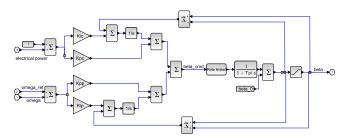


Figure 11. Pitch angle control block diagram. Scilab–Xcos environment.

are modelled through conventional PI controllers, and including an anti windup. In reference to the pitch angle controller, the input variable to such PI controller is the difference between the actual rotor rotational speed and the reference rotor speed $(\Omega_{err}=\Omega_{WT}-\Omega_{ref}).$ Regarding the pitch compensation PI controller, the input is determined from the difference between the electrical power P_e and the maximum power $P_{max}=1.$ The power coefficient and, subsequently, the mechanical power P_{mech} can be estimated by using eq. (1) and (3), respectively. The block diagram to calculate P_{mech} with Xcos is depicted in Figure 12. The WT rotational speed Ω_{WT} is estimated depending on the mechanical model. In this way, if the equivalent one-mass model is considered for simulations, the inertia equation provides $\Omega_{WT}=\Omega_q$,

$$\Omega_{WT}(s) = \frac{P_e(s) - P_{mech}(s)}{2H_{WT} \cdot s},\tag{5}$$

being H_{WT} the WT equivalent inertia constant. Figure 13 shows the one-mass mechanical model block diagram implemented in Scilab–Xcos.

With regard to the two-mass model approach, it assumes both rotor and blades as a single mass, and the generator as another mass, see Figure 14. Hence, two different rotational speeds are obtained: (i) rotor rotational speed Ω_{WT} and (ii) generator rotational speed Ω_q .

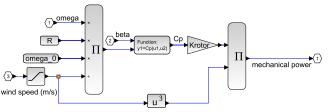


Figure 12. Mechanical power block diagram. Scilab–Xcos environment.

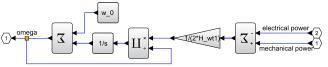
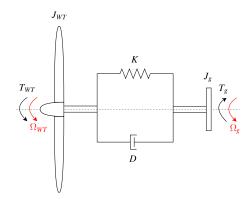
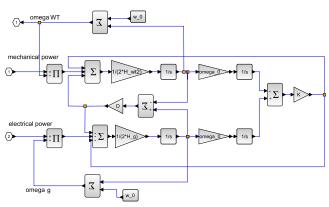


Figure 13. One-mass mechanical model block diagram. Scilab–Xcos environment.



(a) Two-mass model scheme



(b) Two-mass block diagram model

Figure 14. Two mass model: scheme and block diagram. Scilab–Xcos environment.

The speed control block estimates the difference between the current rotational speed (Ω) and the reference rotational speed value (Ω_{ref}) through a PI controller, as depicted in Figure 15. This error (Ω_{err}) is sent to the generator and power converter, determining the electrical power variation due to such rotational speed error (Ω_{err}) . A subsequent additional electric power value is then incorporated to the initial electric power value (p_elec_0) , as depicted in Figure 16.

Both parameters and values of the implemented model are summarised in Table 7. These parameters are tuned by using a set of typical wind speed values as an input.

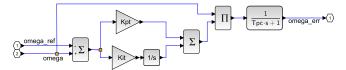


Figure 15. Speed control block diagram. Scilab–Xcos environment.

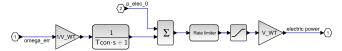


Figure 16. Generator block diagram. Scilab-Xcos environment.

With this aim, such wind speed input has been linearly increased from 5 m/s to 20 m/s in approximately 150 stime interval, see Figure 17(a). This wind speed variation is not a realistic evolution, but it represents an educational approach to analyse the evolution of the different parameters under wind speed variations. The results for the pitch angle, tip speed ratio, and power coefficient are summarised in Figure 17 for the one and two-mass mechanical models. As can be seen, pitch angle results (β) are very similar for both mechanical models, see Figure 17(b). However, more significant differences are obtained for tip speed ratio (λ) and power coefficient (C_p), see Figure 17(c) and 17(d) respectively. These discrepancies are directly related to the differences between Ω_{WT} to be applied on each mechanical model. To clarify this point, Figure 18 depicts the rotational speeds of the turbine and generator —Figure 18(a) and 18(b)—, as well as the mechanical and electrical power evolution —Figure 18(c) and 18(d)—. As can be seen, turbine and generator rotational speeds of both models have different values, more especially below the reference value $\Omega_{ref} = 1.2$ pu. These differences are mainly due to the inertia constant values of both mechanical models —parameters given in Table 7—, which imply slight differences between λ and C_p as shown in Figure 17. With regard to P_{mech} and P_e , shown in Figure 18(c) and 18(d), minor differences are obtained and similar results can be estimated from both mechanical models.

Conclusion

The high integration of wind energy into power systems has promoted new employment opportunities and a more relevance of such industrial sector. As a consequence, educational programs also need to evolve and upgrade in order to cover these sector requirements. Under this scenario, this paper describes the simulation of a VSWT proposed to the students of the 'Wind energy' subject in the Universidad Politécnica de Cartagena (Spain). An open-source software (Scilab-Xcos) is used and successfully assessed in our practical sessions. Through the different simulation proposals, the students are able to analyse graphically the influence among the main parameters of the wind turbines. Two different mechanical models of the rotor are introduced and simulated, comparing the differences of the results obtained between both mechanical models. The simulation experimenting proved to be an interesting alternative to conventional lectures and a suitable solution

Table 7. Wind turbine model parameters ³⁴.

Parameter	Value
K_{pp}	150
K_{ip}	25
K_{pc}	3
K_{ic}	30
T_{PI}	0.01 s
β_{max}	27°
β_{min}	0°
$d\beta/dt_{max}$	10°/s
$d\beta/dt_{min}$	-10°/s
$P_{e,max}$	1 pu
$P_{e,min}$	0.1 pu
dP_e/dt_{max}	0.45 pu/s
dP_e/dt_{min}	-0.45 pu/s
K_{pt}	3
K_{it}	0.6
V_{WT}	1 pu
K_{rotor}	0.00145
T_{con}	0.02 s
T_f	5 s
T_{pc}	0.05 s
H_{WT} (one-mass)	5.19 s
H_q (two-mass)	0.90 s
H_{WT} (two-mass)	4.29 s
D (two-mass)	1.5
K (two-mass)	296.7
Ω_0 (two-mass)	1.335

for practical sessions under a free open-source software environment.

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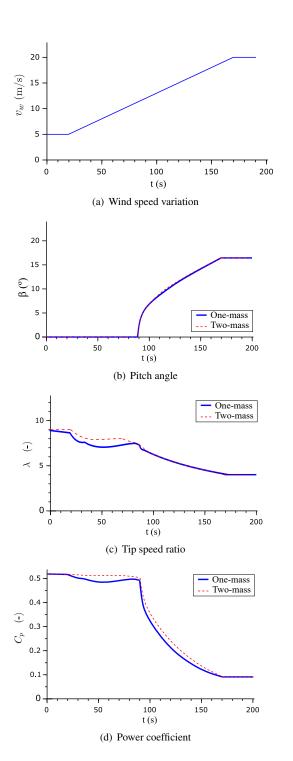


Figure 17. Wind speed variation, pitch angle, tip speed ratio and power coefficient results for one-mass and two-mass mechanical models

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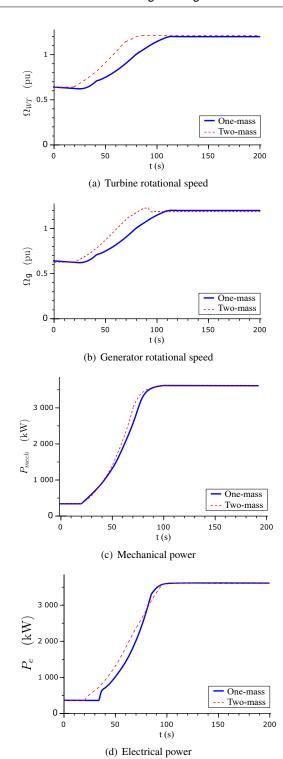


Figure 18. Turbine and generator rotational speeds, and mechanical and electrical powers for one-mass and two-mass mechanical models

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