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"ANALYSIS AND CONTROL OF FLOATING OFFSHORE WIND TURBINES"

CANDIDATA

Silvia Polverini

RELATORE
Prof.Alberto Borghetti

CORRELATORI
Dott. Fernando Bianchi
Dott. Mikel De Prada

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Sessione I

Prefazione

Le principali motivazioni che mi hanno spinto ad approfondire lo studio riguardanti la produzione di energia hanno radici propriamente etiche. Già da tempo, ormai, è appurato come la questione energetica sia strettamente interconnessa al concetto di risanamento e difesa dell'ecosistema. Infatti, qualsiasi processo di produzione di energia ha un impatto sull'ambiente, diverso per entità e conseguenze. Questo impatto non è una variabile da considerare ad ultimazione dei lavori, ma bensì fondamentale nella valutazione di progetto. Tuttavia, vi è una notevole difficoltà nell'elaborare una strategia "giusta" e funzionale, data dalla mutevole relazione esistente tra energia e società, economia, politica e ambiente.

Quindi vi è la necessità di riscrivere il programma energetico, volto alla riduzione delle emissioni inquinanti per contrastare il cambiamento climatico, orientato verso una logica di efficienza: un uso efficiente e razionale delle risorse naturali e del riutilizzo delle materie nella produzione. Attraverso questo sarà possibile una trasformazione sociale e produttiva che tenderà ad una eliminazione degli sprechi.

Due, quindi, sono le parole-chiave da sottolineare: quantità e qualità dell'energia.

Si pone come obiettivo la diminuzione dei consumi, guidato da un piano energetico interconnesso all'innovazione di prodotto e processo. Ciò è necessario, poiché la società contemporanea occidentale non applica più la politica della parsimonia.

Per ottenere un risparmio energetico è necessaria una collaborazione in ambito tecnico, scientifico e di produzione. Collaborazione che porti ad una organizzazione fatta da interconnessioni distribuite e capillari tra produzione e consumi. In tal maniera non sarebbe così utopico il raggiungimento di un'efficienza ed una competitività maggiore della produzione da fonti rinnovabili.

Da qui, il secondo obiettivo: un'assoluta necessità di sviluppo, mirato alla qualità dell'energia. Infatti, non vi è la possibilità di risanare l'ambiente senza un più alto livello tecnologico e di capacità produttiva. Sono necessari notevoli investimenti nel campo della ricerca scientifica, un coordinamento delle iniziative ed un collegamento tra istituti scientifici internazionali. Tali ricerche devono essere orientate allo sviluppo di nuove tecnologie per l'utilizzo di fonti rinnovabili.

Quindi è necessaria una partecipazione della comunità scientifica per aumentare la potenza di ricerca, la capacità tecnologica e conoscenze professionali adeguate.

Per concludere possiamo affermare che l'energia è da considerarsi un elemento strategico per l'innovazione economico e sociale. La dipendenza della sua produzione necessita di una ri-regolazione: il nuovo modello energetico deve essere fatto non solo in base alle necessità economiche di ogni singolo paese, ma soprattutto deve tener in conto del metabolismo socio-naturale.

Per le motivazioni qui brevemente esposte ho deciso di scegliere come progetto tesi un tema relativo alle nuove tecnologie per la produzione di energia eolica: analisi e controllo di turbine eoliche galleggianti.

Preface

Ethical reasons pushed me to study the field of renewable energy.

Each energy production process has an environmental impact, different for entity and consequences. This impact is a fundamental parameter for the project evaluation. Therefore, there is the necessity to rewrite the energy program with the aim to reduce *greenhouse gas (GHG)* and, consequently, defeat climatic change.

The evaluation of a right and efficient energy production strategy is difficult because of the mutual relationship between energy, society, economy, politics and environment.

There are two key-words to keep in mind: energy quantity and quality.

Energy quantity can be controlled, opposing today's trends due to which society does not apply the parsimony. For this reason there is an urgent necessity to decrease the consumption with a straight energy plan, face to product and process innovation, through an efficient and rational use of natural resources and recycled material.

In order to save energy, a strong collaboration between technical, scientific and production parties is necessary. This collaboration creates distributed and capillary interconnections between production and consumption. Hence, the efficiency of renewable energies could increases and become economically competitive.

From there, the second objective: a real necessity to increase energy quality. As a matter of fact, there are no possibilities to restore the environment without a higher level of technology and production capacity.

Investments are fundamental in the scientific research field, as well as good initiatives coordination with the international scientific institutes' connections. Researches are orientated to develop new technologies for renewable power production. Additionally, the participation and the collaboration of the scientific community can increase the level of technology and knowledge.

To sum up, energy is a strategic element for social and economic innovation, but in the first place for the environment. Therefore, the dependence to its production has to be re-regulated: a new energy model has to be built in front of not only economical purpose, but has to consider the social and environmental metabolism.

For the reasons here briefly exposed, I decided to choose as thesis project a topic focused on a relatively new technology of wind power production: analysis and control of floating offshore wind turbines.

Sommario

Il concetto di turbina eolica galleggiante (*Floating Offshore Wind Turbine – FOWT*) è relativamente nuovo dovuto alla rapida crescita del mercato dell'energia eolica, soprattutto quella offshore.

Come le turbine fisse offshore, anche le strutture galleggianti sono pensate per essere installate in mare aperto, dove, rispetto alla terraferma, il vento possiede una intensità maggiore ed è meno turbolento; ciò implica la possibilità di aumentare la potenza effettiva di ogni singola turbina.

I parchi eolici galleggianti, inoltre, sono pensati per essere installati in acque profonde. Questi costituisce un elemento innovativo e vantaggioso, in particolare a livello Europeo, dove vi è il problema di reperibilità di aree marine poco profonde (meno di 50m di profondità).

Ad oggi vi sono differenti tipologie di piattaforme, che provengono dalla tecnologia dell'industria Oil&Gas; la quale già da tempo ha testato la loro flessibilità di esercizio in mare aperto. Successive modifiche sono state apportate per adattare i modelli delle piattaforme alle esigenze della tecnologia *wind energy*.

Ad oggi l'ostacolo maggiore per lo scaling-up delle turbine eoliche galleggianti è dovuta alle difficoltà di analisi e controllo degli effetti combinati del vento e del mare. Tuttavia, l'esperienza nel campo della modellazione e dei controlli sta continuamente migliorando nella risoluzione di tali problemi.

Attualmente già sono state realizzati ed ultimati i lavori di parchi eolici pilota per testare l'effettiva capacità delle FOWTs.

L'obiettivo della tesi qui presentata è quello di costruire un modello semplificato di turbina eolica galleggiante, studiando i movimenti che maggiormente affettano la sua vita utile: quelli della torre e della piattaforma.

Per capire appieno il comportamento del sistema di tale turbina, si è passati prima alla modellazione di una onshore, soggetta alle medesime condizioni metereologiche.

Successivamente si è unito, ad entrambi i modelli, un *PI control* (controllo Proporzionale Integrativo), con l'obiettivo di ridurre i movimenti e stabilizzare il sistema (in termini di velocità del generatore, tensioni e potenza generata) ai valori ottimali.

Nel processo di validazione si è utilizzato come riferimento un modello più dettagliato, elaborato dalla *National Renewable Energy Laboratory* (*NREL*) e simulato utilizzando il programma FAST. FAST è l'acronimo di *Fatigue-Aerodynamics-Structure-Turbulence* e, attraverso un codice numerico dettagliato, ci fornisce un'analisi accurata delle simulazioni di differenti modelli di turbine eoliche. I modelli poi sono stati implementati e comparati utilizzando il programma MATLAB con interfaccia in Simulink.

I differenti profili di vento, utilizzati come segnali di disturbo del sistema, sono stati presi dalla normativa IEC 61400-1.

Date la non linearità del problema e l'alto numero di interconnessioni tra la cinematica del vento e del mare, i valori delle caratteristiche dei componenti del modello

della FOWT sono stati trovati usando un approccio empirico; ovvero attraverso l'analisi della risposta dinamica del modello dettagliato di FAST. Infatti, l'impossibilità di trovare parametri puntuali di caratteristiche distribuite ha fatto sì di dover cambiare strategia di approccio al problema.

La risposta del sistema alle perturbazioni mostra, in linea generale, un buon andamento; quindi può essere considerato come un modello valido per lo studio di controlli, dove si è soliti utilizzare modelli semplificati di sistema.

Ulteriori studi si concentreranno sul miglioramento del modello semplificato qui elaborato. Futuri accorgimenti, inoltre, saranno rivolti allo studio di nuove strategie di controllo, per ridurre i movimenti della torre e della piattaforma, quindi dei carichi.

Abstract

Floating Offshore Wind Turbine (FOWT) is a relatively new technology that has emerged recently due to the fast growth of the offshore wind market.

Just like the offshore bottom-fixed turbines, the floating ones are suitable to be installed in open sea, where the wind is more intense and less turbulent, meaning that they have the possibility to increase power capture for each turbine. However, floating wind power plants arise due to the scarcity of shallow water, particularly when talking about Europe.

Nowadays several different concepts of FOWT exist. The flexibility of platform models is yet proved by Oil&Gas industry and the capacity to sustain the turbine is tested. However, the biggest compliances refer to the interconnections between wind and wave effects. On the other hand, the experience in modelling and control is continuously improving. In fact, there are different pilot floating wind farms under testing.

The aim of the present thesis work is to increase our understanding of floating wind turbine behaviour, developing a simplified model of a Floating Offshore Wind Turbine, in order to consider motions that provoke the most influent mechanical loads: tower and platform tilt motions.

Before building and analysing a floating wind turbine model, an onshore one is studied, in order to understand the behaviour under the same environmental conditions.

Afterwards, a Proportional Integrative (PI) control is coupled with the objective to reduce tilt motions and stabilize the system at the optimal values of each control region.

In order to analyse the proper response of the platform structure, taking into account interconnections between wind and wave kinematics, a detailed model, elaborated by the *National Renewable Energy Laboratory (NREL)* using FAST simulator, is considered. FAST is the acronym for *Fatigue-Aerodynamics-Structure-Turbulence* and it gives a full and accurate analysis simulating different wind turbine models, using a high-fidelity numerical code. Models, then, are compared and implemented by using MATLAB and Simulink interfaces.

As disturbances different wind profiles are used, according to the standard IEC 61400-1.

Due to the non-linearity of the problem, created by the high number of interconnections of wind and sea kinematics, specific values are found using an empirical approach, with the analysis of dynamic response of FAST floating turbine model. Results are acceptable according to the approximations done.

Lastly, further developments are considered to obtain a more detailed model of wind turbine. Additional suggestions aim to change control strategy, in order to reduce tilt tower and platform motions.

Table of Contents

1. Introduction

Wind is a form of solar energy. The term *wind power* describes the transformation process of wind in mechanical power and, using a generator, into electricity.

Wind is one of the renewable and inexhaustible energy sources. It is clean, in the mean that does not produces emissions during operation and the impact on the environment are less problematic than non-renewable power sources.

Figure 1: Wind offshore power plant [37].

Nowadays wind power production is a mature technology, and it is continue to grow its installations across Europe more than the other renewable technologies, as WindEurope report in the key trends and statistics of 2016: "*Wind in power - 2016 European statistics*" (figure 2).

With the increasing in size scale and substantial investments (figure 4), wind technology overtakes fuel oil, nuclear, hydro and coal power generation capacity: Figure 2 shows this change from 2005 until now.

Furthermore, according to WindEurope estimations [1], more than €25bn of new annual investments will be needed to meet the 2020 targets. Those targets defined during the Kyoto conference [2] are:

- reduce in Europe a 20% of greenhouse gas emission;

- the 20% of EU's final energy consumption has to be deriving from renewable sources;

- both have to be achieved by 2020.

This decision shows the importance and growth of wind energy.

It would be expected that in 2030, wind could serve a quarter of the EU's electricity needs and be fundamental in the European energy system [1].

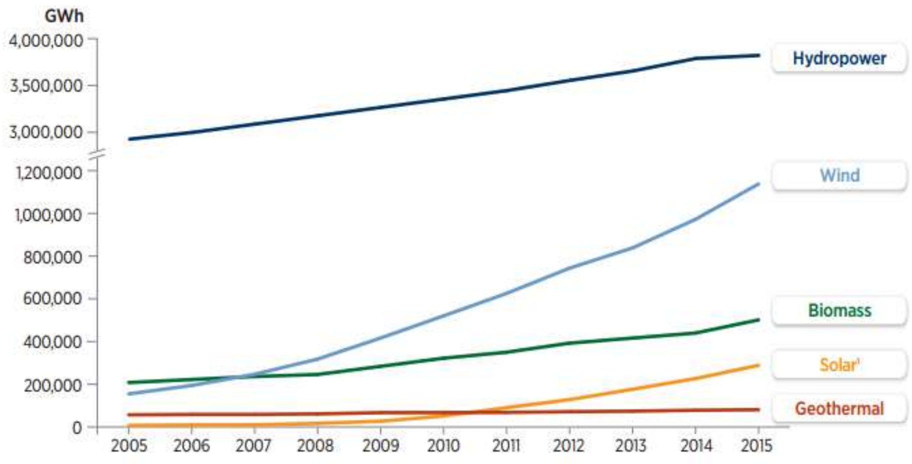


Figure 2: Global renewable electricity generation by technology. [1]

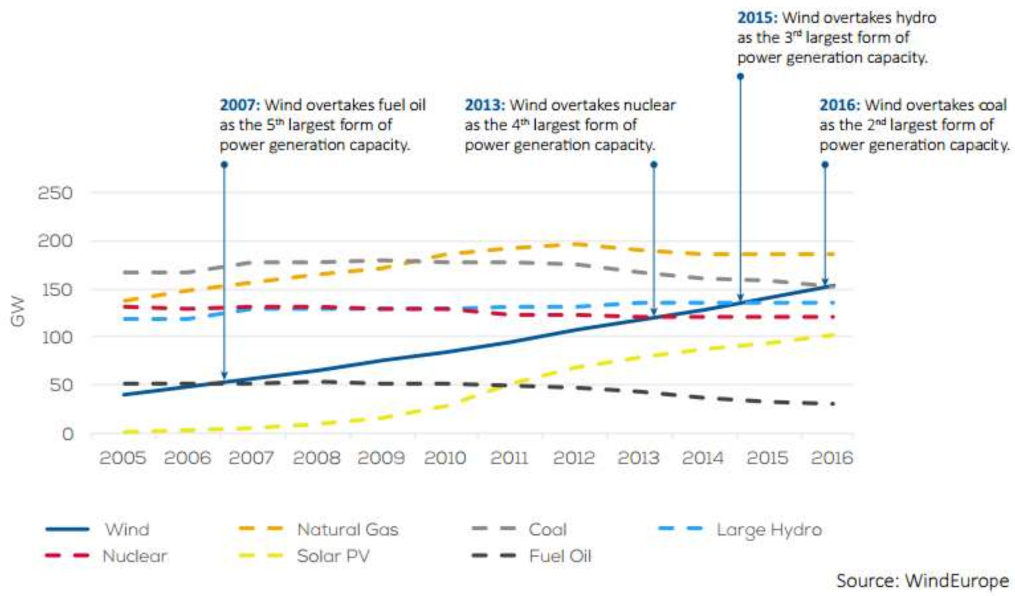


Figure 3: Cumulative power capacity in EU 2005-2016. [1]

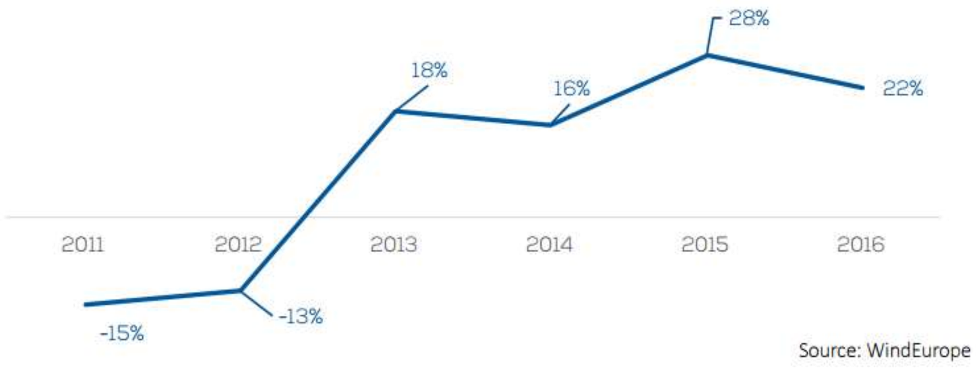


Figure 4: Year on year rate of increase in total wind energy investments. [1]

With the continuous growing of wind energy as a clean source for electricity production there is an increasing interest in the location of wind turbines in offshore areas in which there are fewer space restrictions and less turbulent wind. This increases the interest to develop floating wind turbines, which are not mounted in the sea-bed and can be used in deep waters. In fact, for their low environmental impact, the demand for FOWTs could easily be fostered.

Wind turbines are large and complex mechanical structures that require advanced control strategies to ensure acceptable loads in order to guarantee a long lifetime. Floating turbines are even more complex as a consequence it is necessary to adapt control strategies to these systems.

With the object to reduce fatigue loads, different design control approaches are studied in literature: controller to reduce the negative damping problem [3] - [4], individual control pitch to reduce blades vibrations, and more.

To design the control, simplified models are needed.

The purpose of this thesis is to develop a simplified Floating Offshore Wind Turbine (FOWT) model considering aero-dynamical loads to assess the performance of the system.

The aerodynamic forces are derived and implemented in a more accurate code, FAST, to evaluate the overall loads acting on a FOWT.

The developed FAST computer program simulator is applied here to investigate the reliability of simplistic wind turbine models, coupled with a variable-speed variable-pitch-to-feather control.

In this manner the research aims to understand firstly how to model a floating wind turbine, in particular the spar-buoy model. Studying a simplification of the turbine model means identify the dominant physical dynamics behaviour that implies a good knowledge of wind turbine dynamics.

The simplified model is useful when a linear control theory is applied. This means that there is the possibility to choose degrees of freedom (DOFs) and study independently, because a system where the superposition theory can be applied is considered. Then, for control study the selection of different problem is easier to be solved.

In the following chapters FOWT technology is presented.

In chapter 2 a general classification of offshore and floating offshore wind turbines are described, considering their pros and cons. A perspective of different FOWT models is also presented.

In chapter 3 dynamic simple models that follow the *NREL Offshore 5MW Baseline Wind Turbines* characteristics are described.

Starting from a basic drive-train model, the main characteristics for load studies of a FOWT, as tower bending and platform pitch displacement, are added.

For validations a representative and more accurate model is also described.

In chapter 4 general operating conditions for a wind turbine are described. Afterwards, the applied control strategy is explained in each part: a variable-speed variable-pitch-to-feather control.

In chapter 5 models validations between the simple models and the more detailed one is presented. The models are implemented in the MATLAB and Simulink simulation environment.

In chapter 6 conclusion are given, followed by further developments that will be useful to upgrade the models used.

In chapter 7 all the algorithms, used to run simulations in MATLAB and Simulink, are reported.

2. Overview of Floating Offshore Wind Turbine

2.1 Introduction

With the increasing of wind technologies, offshore wind farms promise to become an important source for the energy future [5].

One of the main qualities of offshore wind farms is that, far from the shore, wind speed intensity is higher and turbulence and shear are smaller [6]. Those advantages need to be considered, because a more constant energy capture and a reduction of fatigue loads on the turbine could be achieved.

Additional advantages of sea-based wind turbine installation include the following [6]:

- A great reduction of noise and visual impacts;
- Less logistic problems for the installations (road constructions, trucks capacity …), as the open sea is available and without having the problem to occupy useful lands.

Against these there are several disadvantages of offshore installations as [6]:

- Supplier expenses are necessary for the costs associated with marine foundations, support structure, installations, maintenance and connections with the grid.
- Loads due to the interaction of the wind turbine with sea waves and currents are not negligible. Those are coupled with the existing aero-dynamical loads. In addition also ice conditions and the corrosion from salt water are possible compliances.

As a result, the complexity of the design increases. However, combining the large experience in wind turbine technologies with the continuous decrease of wind energy production costs, the offshore industry is going to find a productive energy market path.

In Europe, where vacant land is scarce, offshore wind farm projects could be preferred commissioned. Nowadays offshore wind energy represents the 13% of the European wind energy market, and in the last year an additional net capacity of 1.558 MW was connected to the grid: totally 3589 turbines are installed and active, producing a cumulative power of 12631 MW [7].

These numbers can prove that offshore wind energy is technically and economically viable [8] and it could have an important role in the European renewable energy market.

2.2 Floating Offshore Wind Turbines

In the upcoming years, as the necessity to accelerate the development of bigger and higher rated power wind turbine increases, FOWT could be one of the feasible solutions for wind power production.

Figure 5 represents the trend of the technological evolution of wind turbines [8], where is visible that in deeper water there is the possibility to increase the rotor size and then the rated power output [6]. The potential to scale wind turbine up to very large rated power could mean to reduce the total costs of the energy produced.

In fact, for water depth up to 50 m, bottom-fixed turbines are not economically feasible, due to very high tower constructions that increase installation costs and complexity [6]. In this regard, instead of fixed-foundation offshore, FOWT offers several advantages as [9]:

- The offshore installation procedures become simpler considering that no pile has to be plant in the sea ground;
- Tower and platform coupling is easier to do and it is done ashore;
- Anchors are significantly cheaper to install than fixed foundations;
- The overall wind turbine is less sensitive to water depth (only the mooring system is influenced);
- The load transfer is different: for FOWT the path to reach the sea-bed is shorter than the bottom-fixed, because the first load goes to the water and with the bending movement and the different flexibility the peak forces are reduced.

However there is a sensitive increase in design complexity that induce a more expensive and complicated installation processes.

One of the first problematic challenges for FOWT is the wave and wind induced platform tilt motion, which influences [10]:

- Nacelle and tower loads, dominated by inertia and gravitational forces.
- The dynamic coupling between mooring system and sea currents. It has to be combined with the dynamic coupling between platform and wind turbine motions.
- Blades control;

On the contrary it was tested that power capture and rotor loads are not deep influenced by platform motions; instead these are dominated by the rotor aerodynamic [10].

It is clear that, to prove the feasibility of floating wind turbines, one of the first objectives is to minimize tilt motions to lead a more stable structure. This could be solved firstly with the reduction of top tower weight and blades. As a consequence strong and lights materials are necessary as the vibrations reduction, done with a full analysis and control strategy of the loads induced by wind and waves. This type of interactions is one of the limits that there are in FOWT modelling, which constrains the effectiveness of linear time-domain analysis [4]- [11].

Furthermore, for optimal performances and scaling up, the model design has to estimate the dynamical effects over the electrical parts.

The development of FOWT technology is continuing increasing: scaling up the size of installations and improving the operational processes are required.

Afterwards constrains of reducing costs is now really important, because wind energy has to be competitive on price with traditional energy sources. However the pilot projects and potential economic benefits are yet demonstrated [8]- [12].

Citing what Matthieu de Tugny (Senior Vice-President and Head of Offshore, Bureau Veritas) said in his first release after a preliminary design approval for a FOWT installation: "*we can ensure designs for new FOWTs will be safe, reliable and will produce power over the expected range of environmental conditions*."

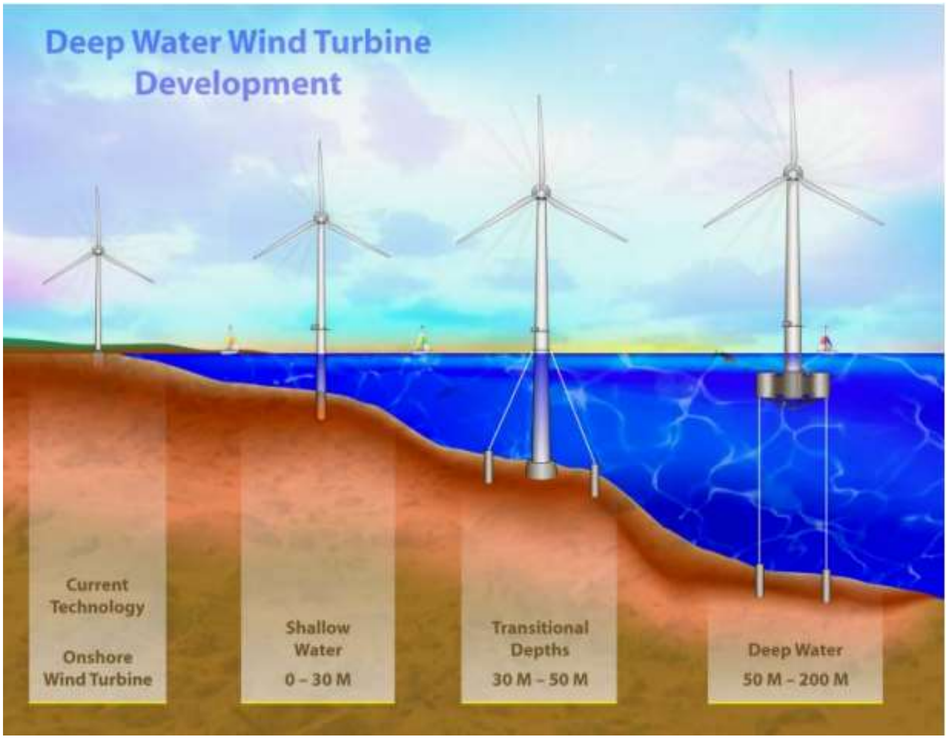


Figure 5: Progression of expected wind turbine evolution to deeper water [8].

2.3 Different Concepts of FOWT

The idea of floating platforms is not new: the Oil&Gas industry has installed and proved their potentials and feasibility. Several floating platforms have been yet proposed and demonstrated their long-term survivability to support large wind turbines in deep sea regions [13]. There is a wide range of prototypes, changing in structure, moorings, anchoring and cable connection, selected in base of met-ocean conditions, optimal cost, construction, installation, O&M, decommission, … .

Is commonly used classifying FOWTs based on the most relevant stabilized system of the platform [14](figure 6):

- Buoyancy-stabilised, through hydrostatics: leads to a large surface structure, *Barge Platform*;
- Mooring-stabilised, through taut moorings tension: leads to a slender highly loaded submerged structure, *Tension-Leg Platform* (TLP).
- Ballast deep-drafted stabilised: leads to a vertical structure, *Spar Platform;*
- Hybrids concepts, as *Semi-Submergible Platform*, are also a possibility (not represented in the figures).

The design modifications are due to reduce platform motions, improving the turbine response, and eliminating instabilities. These suggestions are aimed to obtain cost-effective prototypes that achieve desirable performances, maintaining the structural integrity.

Following, a brief description of the three main concepts is presented.

The *Barge* platform reaches its stability by buoyancy effect due to the large water-plane area. This provides to have a great restoring moments (ballast with seawater). The turbine can be anchored with slack catenary or taut vertical mooring lines. From the results of [15], this typology is more affected from waves than wind perturbations.

Barge FOWT is the easiest concept of the three, because the installation and the assembly can be done near the coast. Also the effort is reduced: the anchoring system is less complicated than the other concepts. However for its design it has a high cost of fabrication.

The *Tension-Leg-Platform* or *TLP* is a floating platform that took its stability by taut vertical mooring lines, brought about by excess buoyancy in the tank. The cables are under tension in order to prevent the platform from moving.

From [14] is verified that TLP concept has the lowest platform excursion motions, and it has the best ratio for ultimate and fatigue loads, compared with Barge and Spar concepts.

The disadvantage is that the TLP is the most expensive design for its mooring and anchoring systems. Another disadvantage is that the platform has a very high volume. Furthermore, compliances with installation and stabilities of the entire turbine exist.

The *Spar-buoy* concept achieves stability by using ballast strategy: the centre of mass is below the centre of buoyancy. It has a platform in the form of a vertical cylinder at the top of which the wind turbine is installed. To remain vertical and stay afloat the entire structure is supported by three catenary or taut mooring lines. To increase the yaw stiffness of the platform, the lines are attached to the hull via a delta connection.

One of the first advantages of the *spar-buoy* platform is that it can be installed in deeper water than the other. It has also an easy structure and a more stable structure, despite problems of tower loads.

The spar concept is chosen for its simplicity in design, suitability to modelling. It is interesting because it is being tested in full scale in 2009 by Statoil of Norway and its first floating wind farm will be active this year in Scotland. The "*HYWIND®—Statoil's floating wind turbine concept—has been designed to generate electricity offshore with minimal environmental impact.*" [16].

In the following chapter the modified model of the *Hywind* concept, called *OC3-Hywind*, is modelled. The *OC3-Hywind*, used by Jonkman [17], is adapted in the way that the platform can support a 5MW wind turbine designed by *NREL*.

Firstly, to better introduce and study the model, the onshore wind turbine is described, starting from the modelling of the drive-train, passing through the tower and blade bending motions, and then the platform is added with changes on tower characteristics.

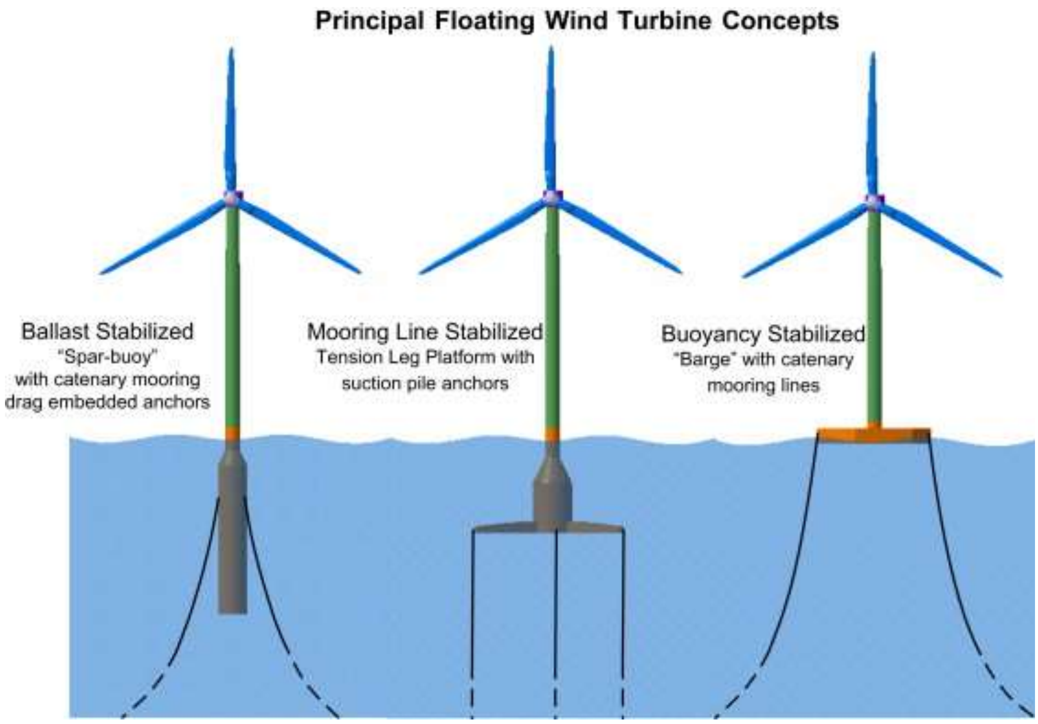
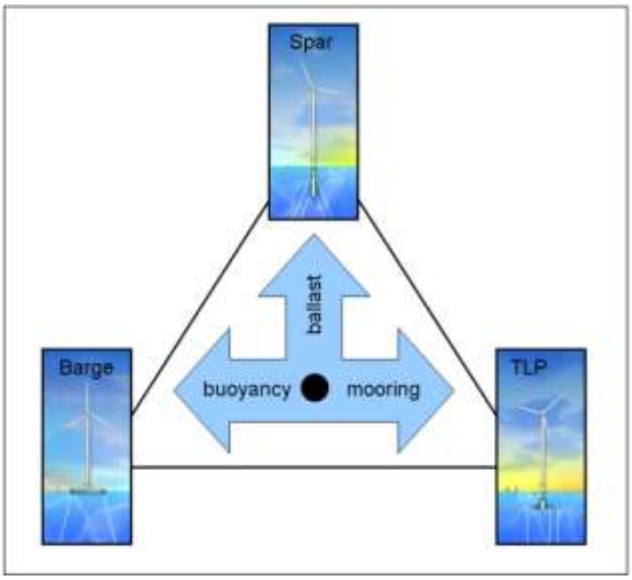


Figure 6: Floating wind turbine concepts (up) [39] and their classification (left).



3. Floating Offshore Wind Turbine Modelling

3.1 Introduction

In this chapter the modelling of the *OC3-Hywind* Spar wind turbine model, taken from [18] [19] [20], is described.

Figure 7 shows on the left a prototype of the *Hywind* prototype and on the right side the general degrees of freedom (DOFs) for a general wind turbine mounted on a spar-buoy platform.

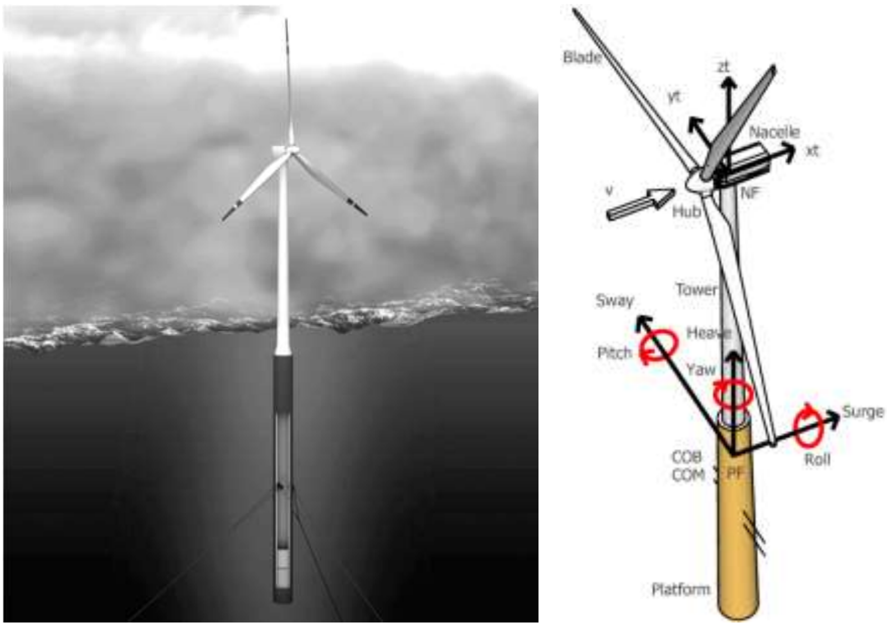


Figure 7: Hywind concept [4](on the left) and description of the structure and movements of a Spar wind turbine [21](right).

The reference system is formed by the *XY*-plane, which designates the Sea-Water-Level (SWL), the *Z*-axis is directed upward opposite gravity along the centreline of the tower, and PF is the centre of the orthogonal axis.

The tower can be modelled mainly with two translational DOFs: *fore-aft* (FA) and *side-to-side* (SS) deflections, which move on the x- and y- axis respectively.

Blades have two degrees of freedom (figure 8): they bend in-plane (Y-Z plane), *edgewise* deflection, or out-of-plane (X-Y plane), *flapwise* deflection.

The platform relative possible movements, representative of the 6 degree of freedom along the x-, z- and y-axis are respectively (figure 7): three translational, *surge*, *heave* and *sway* and three rotational, *roll*, *yaw* and *pitch*.

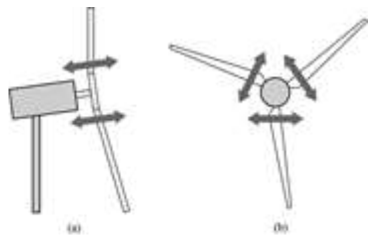


Figure 8: (a) Flapwise (out-of-plane) and (b) edgewise (in-plane) deflections [22].

In this thesis, for the modelling and validation only the most characteristic and influent DOFs for the wind turbine life loads are considered: tower fore-aft bending and platform pitch displacement for the FOWT; for the onshore model also the flap-wise movement is taken in consideration. Tis selection is made following the suggestion of Shirazi et al. [19] and Stewart et al. [20].

To resume in the following validations the DOFs considered are: collective-blades flapwise displacement and tower FA bending movement for the land-based wind turbine and tower FA bending movement and platform pitch displacement for the floating one.

To give a general overview of how the modelling of wind turbines is done, a representative block scheme is presented below in figure 9:

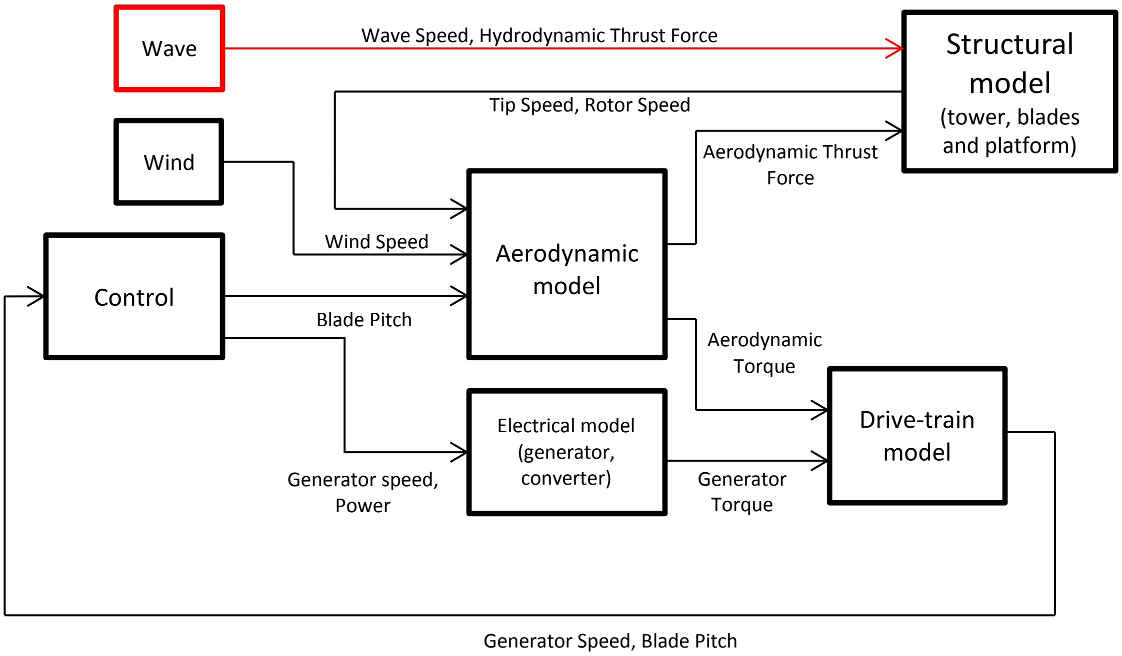


Figure 9: Block scheme of Wind Turbine Plant.

The aero-elastic model represents the aerodynamic phenomena. It is where the conversion from kinetic energy into mechanical energy takes place.

The drive train model includes the rotational dynamics of the drive-train.

The structural model includes tower and blades properties for the onshore wind turbine, tower and platform properties for the FOWT.

The controller block represents the variable-speed variable-pitch control algorithm.

The electrical model represents the conversion of mechanical energy into electricity.

Wind profiles models, which are used for the validations, are taken from the standard IEC 61400-1 [23].

Wave profiles are not included in the following analysis; however further studies will include them using the models of the standard IEC 61400-3.

3.2 Turbine Specifications

The present thesis reports a representative three-bladed 5MW wind turbine model, developed by *NREL* for simulations comparisons. This turbine model is widely used by many other researchers as [11]- [19]- [20].

The general properties of the *NREL offshore 5-MW baseline wind turbine* are representative for the onshore and offshore wind turbines, bottom-fixed and floating ones. The full properties of each component of the wind turbine are given in [18]. Here only general specifications and undistributed structural properties are reported.

The rated power for a three-bladed wind turbine is equal to 5 MW (that include the electrical efficiency of 94.4%). The wind speeds that define the power curve regions are: cut-in (3 m/s), rated (11.4 m/s), and cut-out (25 m/s) wind speeds. The control algorithm, that follows the power curve, is a Variable Speed-Collective Pitch Controller.

General Specifications NREL 5MW Baseline Wind Turbine	
Rating	5 MW
Rotor orientation, configuration	Upwind, 3 blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126m, 3m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s

Table 1: General specifications of a 5MW baseline wind turbine.

The specifics of the drive-train of *NREL 5-MW baseline wind turbine* are the same of REpower 5M machine [24]: rated rotor speed of 12.1 rpm, rated generator speed of 1173.7 rpm. The gearbox is considered as ideal, without frictional losses, having a ratio equal to 97:1. An induction generator is considered. The driveshaft properties are taken from [18], where it is calculated the linear damping and spring constants, considering a structural damping ratio of 5% that is associated with a drive-train composed of rigid rotor and generator.

Drive-Train properties	
Rated Rotor Speed	12.1 rpm
Rated Generator Speed	1173.7 rpm
Gearbox Ratio	97/1
Electrical Generator Efficiency	94.40%
Generator Inertia about High-Speed Shaft	534.116 kg m^2
Rotor Inertia about Low-Speed Shaft	38759227 kg m^2
Equivalent Drive-Shaft Torsional-Spring constant	867637000 N m/rad
Equivalent Drive-Shaft Torsional-Damping constant	6215000 N m/(rad/s)

Table 2: Undistributed drive-train structural properties.

The *NREL 5MW baseline wind turbine* has three blades and here they are considered as a collective rigid body. All the structural undistributed properties, shown in Table 3, are considered as concentrated in the centre of mass (CM) of each blade located along the longitudinal axis at 20.475 m. Each blade has a length of 61.5 m. The overall blade mass is 12024 kg. The first bending natural frequency of the flapwise displacement is 0.6993 Hz and the damping-ratio considered is of 0.477465% [19]. From there linear damping and spring coefficients are calculated.

Blade structural properties	
Length (along longitudinal Axis)	61.5 m
Overall Mass (each blade)	12024 kg
CM Location (along longitudinal Axis)	20.475 m
Structural-Damping Ratio (All Modes)	0.477465%
First bending natural frequency of a blade	0.6993 Hz

Table 3: Undistributed blade structural properties.

The tower is considered as a rigid body; its properties change slightly in function of the installation site considered (elevation of the installation site, water depth, wind and wave properties, soil type ...) and the land-based provides to give a basis to design further towers for different support structures and installations. The tower height is always considered to be 87.6 m above the ground and the hub height of 90 m. The characteristics of the hub and nacelle are included in tower properties.

The overall tower mass for the land-based is 656330 kg centred in the CM of the tower, located along the tower centreline at 38.234 m above the ground. For the fore-aft the first natural frequency deflection and the structural-damping ratio are considered respectively equal to 0.324 Hz and 1%.

For the tower properties of the *FOWT* we referred to [17]. The FOWT considered is the *OC3-Hywind* concept. The tower properties are given for the static position of the platform. Mooring lines and anchoring properties are included in the platform characteristics.

The tower basement and the top of the platform are coincident, located 10 m above the SWL. The tower height is coincident with the land-based: 87.6 m above the SWL with a hub height of 90 m SWL.

The resulting tower mass is 249,718 kg and is centred in its CM at 43.4 m above the SWL. The structural damping ratio for the fore-aft bending tower is estimated as 0.09% with first natural frequency of 0.373 Hz. From those the damping and spring coefficient are evaluated.

Tower properties		
	Land-Based	***FOWT***
Height above Ground (or SWL) (m)	87.6	
Overall mass (kg)	656330	249718
Location Centre of Mass (m)	38.234	43.4
Structural damping ratio (%)	1.00%	9.00%
First Natural Frequency for FA (Hz)	0.324	0.373

Table 4: Undistributed tower structural properties.

The floating platform is considered as a rigid cylindrical body. Its structural properties are all relative to the static platform [17]. The length of the platform is 120 m. It is composed by two cylinders connected to reduce the hydrodynamic force near the surface. The cylinder above has a diameter of 6.5 m instead of the other that is of 9.4 m. The mass of the floating platform is 7466330 kg. It includes the ballast system (located in the bottom part) plus the weight of the mooring system in water. This mass is centred in the CM of the platform, at 89.9155 m along the platform centreline below the SWL. The pitch inertia of the floating platform about its CM is 4,229,230,000 kg m^2 [17]. For the pitch displacement the first bending natural frequency of the platform 0.73 Hz and a constant damping ratio of 0.027 are considered.

Platform properties	
Depth to Platform Base Below SWL	120 m
Elevation to Platform Top (Tower Base) above SWL	10 m
Platform Diameter Above Taper	6.5 m
Platform Diameter Below Taper	9.4 m
Platform Mass, Including Ballast	7466330 kg
CM Location Below SWL	89.9155 m
Platform Roll Inertia about CM	4229230000 kg*m^2
First Natural Frequency for pitch (Hz)	0.73
Damping ratio (%)	0.027

Table 5: Undistributed platform structural properties.

In the modelling two-mass drive-train, blades and tower properties are considered for the land-based wind turbine, on the contrary two-mass drive-train, tower and platform characteristics for the floating one.

3.3 Aerodynamic Model

3.3.1 Aerodynamics

The basic concept of a wind turbine is to transform kinetic energy into mechanical power and then, through an aerogenerator, into electricity.

The wind power, passing through a surface *A* with a velocity v_w (mean wind speed) is defined as:

$$P_{wind} = \frac{1}{2}\rho A v_w^3 \qquad (1)$$

Where ρ is the air density.

As the equation (1) shows, the power increases as the square of the rotor diameter and, more significantly, as the cube of wind speed. This power can only partially be converted into mechanical power by the turbine and it is largely influenced by the aerodynamic efficiency of blades design. The power fraction is expressed adding the *power coefficient,* $C_{p.}$ Therefore, the power generated by the wind turbine is given by:

$$P = \frac{1}{2}\rho A C_p(\beta, \lambda) v_w^3 \qquad (2)$$

Where C_p is the power coefficient, which is function of wind turbine characteristics and wind speed. Every single value of C_p is empirically found for well-defined operating points. It is common to represent graphically the dependence of C_p from β and λ, as figure 10 shows. The C_p presents a maximum value at β_0 and λ_0. The theoretical maximum is equal to 16/27 (Betz limit) and the real one is closed to 0.45 [25].

β is the blade pitch angle and λ is the *tip-speed-ratio*, defined as the ration between the speed of the rotor tip and the free stream wind speed:

$$\lambda = \frac{\omega_r R}{v_w} \qquad (3)$$

Where ω_r is the rotor rotational speed and *R* the rotor radius.

λ depends on the blade air foil profile, number of blades and the type of wind turbine. A high value of λ is desirable because it means a high shaft rotational speed, which provokes a high efficiency for electrical generation. However it is favourable neither to exceed in its value because it could provoke:

- Edge erosion for high wind speed;
- Noise and blade vibrations;
- A reduction of rotor efficiency due to the increase of loses (tip loses and drag force);
- A high value of rotational speed requires a large braking system to prevent the disintegration of the turbine.

Then, the optimal value to reach the maximum power extraction has to relate:

- the time to re-establish the disturbed wind;
- the time required for the next blade to move into the location of the blade before.

The full demonstration of the optimal *tip-speed-ratio* and the formulation of Betz equation we refer to [26].

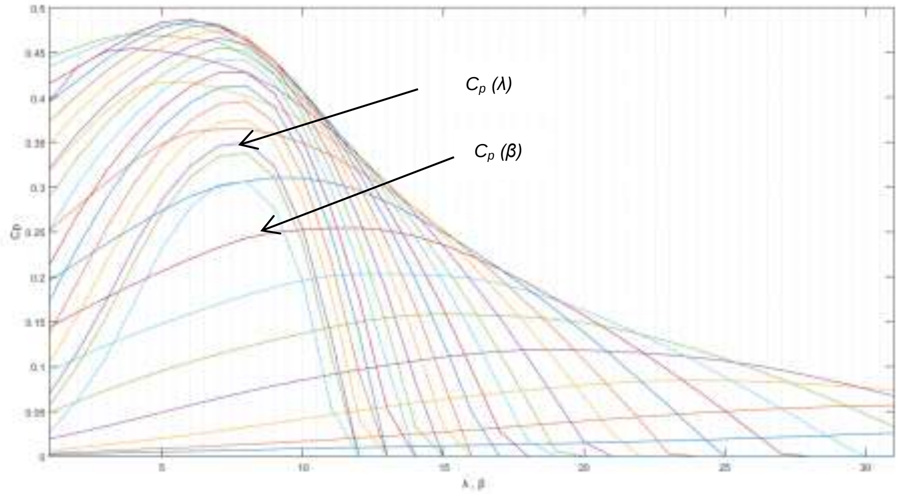


Figure 10: Cp(β,λ) table avaiable on MATLAB.

The wind produces an aerodynamic thrust force F_t and it is given by:

$$F_t = \frac{1}{2}\rho\pi R^2 C_t(\beta,\lambda){v_w}^2 \qquad (4)$$

Where C_t is the thrust coefficient, function of β and λ.
The aerodynamic torque, T_r, consequently produced by the wind turbine is given by:

$$T_r = \frac{P_r}{\omega_r} = \frac{1}{2}\rho\pi r^2 \frac{c_p(\lambda,\beta)}{\omega_r}{v_w}^3 \qquad (5)$$

The aerodynamic torque is transferred through the gearbox (with N_g as gearbox ratio) and the stator side of the generator induced an opposite torque motion (T_g). Then the power generated is:

$$P = N_g T_g \omega_g \qquad (6)$$

Where ω_g is the generator rotational speed.

3.3.2 Blade Pitch Actuator

To actuate the mechanical power conversion a blade pitch actuator has to be inserted. It is a non-linear servo that permits the rotations of blades along their longitudinal axes [25].

It can be described by a differential equation:

$$\dot{\beta} = \frac{1}{\tau}(\beta_d - \beta) \qquad (7)$$

A saturation level in amplitude is included in the actuator to avoid reaching the maximum rotor speed; that means reducing the risk of fatigue damage.

A block scheme representation is shown in figure 11.

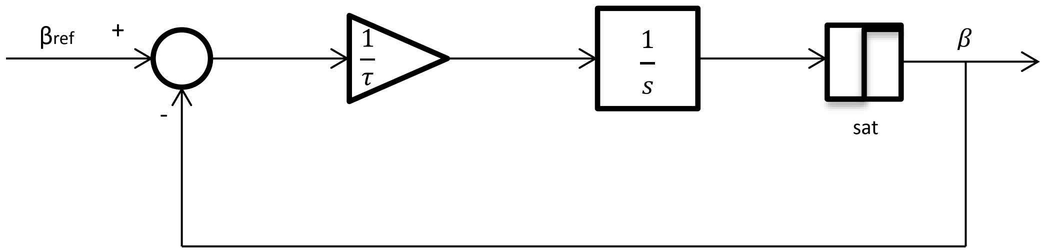


Figure 11: Blade pitch actuator.

3.4 Drive-Train Models

Two models of drive-train are presented. The first is with a single mass and the second considers two shafts: Low-Speed Shaft (LSS - rotor side) and High-Speed Shaft (HSS - generator side).

3.4.1 One Mass Drive-Train Model

To describe the drive-train motion the equilibrium torque equation is considered. If the rotor and the generator torques are not equal, an acceleration of the rotor will be visible and it is given by:

$$J\dot{\omega}_r = T_r(\beta, v_w, \omega_r) - T_g N_g \qquad (8)$$

where J is the total drive-train inertia considered from the LSS side.

The total inertia includes the rotor (J_r) and generator (J_g) inertias:

$$J = J_r + J_g N_g^{\,2} \qquad (9)$$

The torques are functions of blade pitch angle (β), wind speed (v_w) and aerodynamic rotational speed (ω_r). For this model the generator torque is considered as a constant input, in front of a variable aerodynamic torque:

$$T_g = P_g / N_g \omega_g \qquad (10)$$

$$T_r(\beta, v_w, \omega_r) = P_r(\beta, \omega_r) / \omega_r \qquad (11)$$

As a result a simplified system is obtained. It can be built with an input error signal given by the difference between the generator and the aerodynamic torques (called *reference* and *system signal* respectively). The output is the generator velocity (given by sum the output with the reference generator velocity). The block scheme of figure 12 represents the one mass drive-train model.

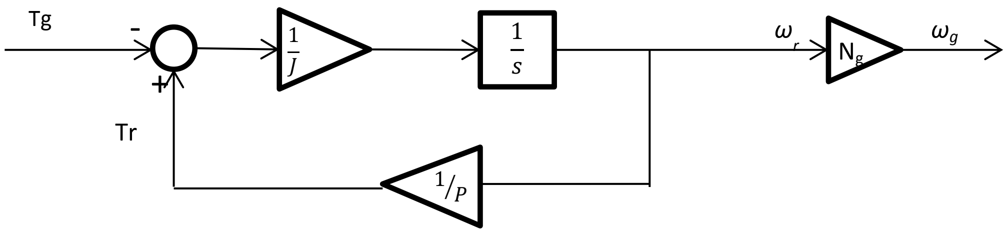


Figure 12: one mass drive-train model scheme.

3.4.2 Two-Mass Drive-Train Model

A more detailed drive-train model is given by two-mass model system. It allows us the study of the first oscillation mode of the drive-train.

Figure 13 shows a representative two-mass drive-train system, where the rotor and the generator shafts are connected via a gearbox (ideal gear-box ratio N_g). K_s and B_s are the stiffness and the damping coefficients from the rotor side, representative of the overall structural properties of the drive-train.

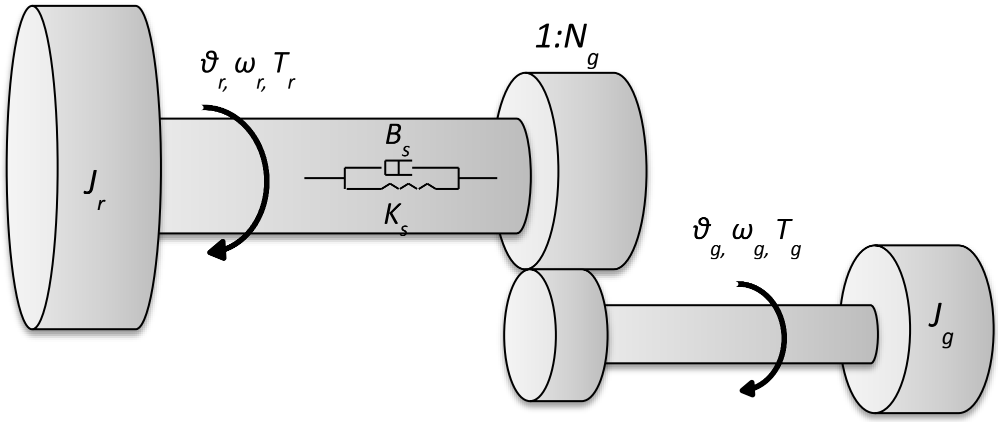


Figure 13: two mass drive-train model.

A third order system is obtained reformulating the balance equation (6), considering the LSS side and the HSS side:

$$
\begin{aligned}
J_r \dot{\omega}_r &= T_r - B_s \omega_s - K_s \theta_s \\
J_g \dot{\omega}_g &= \frac{B_s}{N_g}\omega_s + \frac{K_s}{N_g}\theta_s - T_g
\end{aligned}
\qquad (12)
$$

Where θ_S is the difference between the angle of rotation of the rotor shaft and the generator one:

$$
\begin{aligned}
\dot{\theta}_s &= \omega_r - \frac{1}{N_g}\omega_g; \\
\theta_s &= \theta_r - \frac{1}{N_g}\theta_g
\end{aligned}
\qquad (13)
$$

Putting the equations (10) and (11), the result is a two mass drive-train model:

$$
\begin{bmatrix} \dot{\theta}_s \\ \dot{\omega}_r \\ \dot{\omega}_g \end{bmatrix} = \begin{bmatrix} 0 & 1 & -\frac{1}{N_g} \\ -\frac{K_s}{J_r} & -\frac{B_s}{J_r} & \frac{B_s}{J_r N_g} \\ \frac{K_s}{J_g N_g} & \frac{B_s}{J_g N_g} & -\frac{B_s}{J_g N_g{}^2} \end{bmatrix} \cdot \begin{bmatrix} \theta_s \\ \omega_r \\ \omega_g \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{T_r}{J_r} \\ -\frac{T_g}{J_g} \end{bmatrix} \qquad (14)
$$

Figure 14 shows the block scheme implemented in Simulink. After the drive-train model is coupled with the aerodynamic model and pitch actuator (figure 15).

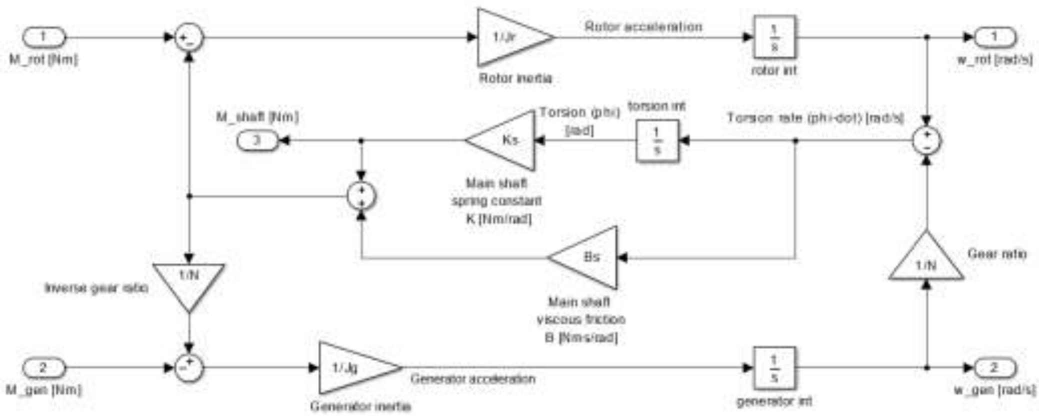


Figure 14: two mass drive-train model plant.

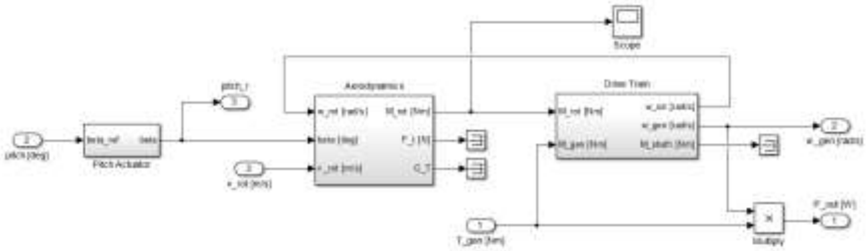


Figure 15: block scheme of the 5MW baseline wind turbine two mass drive-train model.

3.5 Onshore Wind Turbine Structural Model

The model of an onshore wind turbine is presented. The following model adds structural DOFs to the two-mass drive-train model: the fore-aft tower deflection and the blade flap-wise movement that are shown in figure 16

The fore-aft displacement is considered because it has the highest loading from wind (and waves), and the highest tower fatigue damage is calculated to be in the direction of the wind [20]. The flapwise movement is considered in order to have a more accurate model.

Both have to be considered for the effective wind speed, v_e that becomes:

$$v_e = v_w - \dot{y}_t - r_b\dot{\xi} \qquad (15)$$

Where v_w is the mean wind speed, y_t and ξ are the tower fore-aft bending and blades flapping respectively, and r_b is the average of the radius where the lumped thrust force is supposed to be applied [19].

To describe the physics of the tower and blades displacements the forces and the momentum equilibrium equations are considered. The equations are written in matrix form that, according to [25], is:

$$\begin{bmatrix} m_t + N_b m_b & N_b m_b r_b \\ N_b m_b r_b & m_b r_b^2 \end{bmatrix} \begin{bmatrix} \ddot{y}_t \\ \ddot{\xi} \end{bmatrix} + \begin{bmatrix} B_t & 0 \\ 0 & B_b r_b^2 \end{bmatrix} \begin{bmatrix} \dot{y}_t \\ \dot{\xi} \end{bmatrix} + \begin{bmatrix} K_t & 0 \\ 0 & K_b r_b^2 \end{bmatrix} \begin{bmatrix} y_t \\ \xi \end{bmatrix} = \begin{bmatrix} N_b \\ r_b \end{bmatrix} F_t \qquad (16)$$

$$M\ddot{y} + C\dot{y} + Ky = QF_t$$

Where N_b is the number of blades; m_t, m_b the masses, B_t, B_b the damping coefficients and K_t, K_b the stiffness coefficients of the tower and a blade respectively. F_t is the lumped thrust force that acts at r_b distance from the hub centre.

The values are taken from the study of Shirazi et al. [19] and they give a complete description of the turbine structure considered.

Adding equation (12) the whole mechanical subsystem can be rewritten. Then a simplified structural model for an onshore wind turbine is built and connected with drive-train and aerodynamic models, as figure 17 shows.

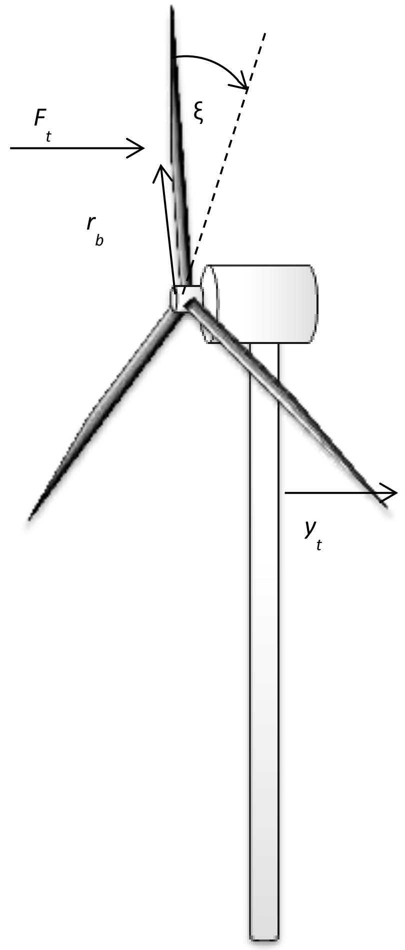


Figure 16: Simplified structural model for an onshore wind turbine.

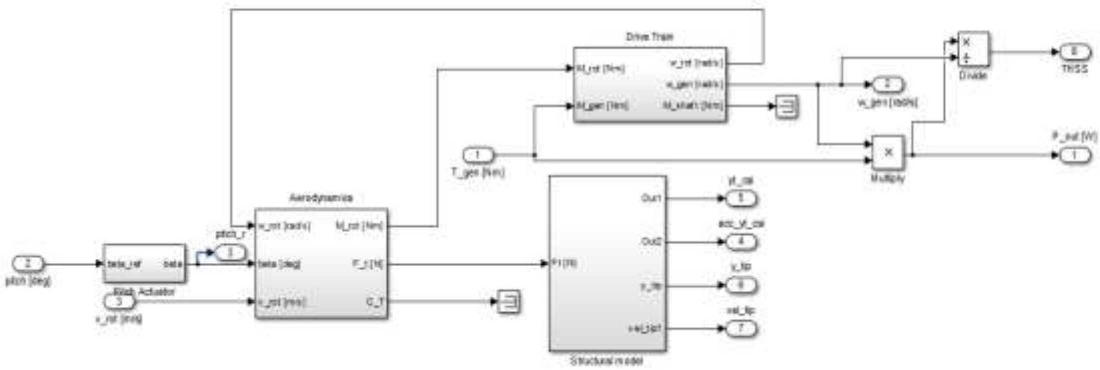


Figure 17: Onshore wind turbine model implemented in Simulink.

3.6 FOWT Structural Model

The formulation of a floating wind turbine model is presented here: we consider the spar-buoy model (OC3-Hywind), taken from [27].

FOWT is subjected to different foundation properties instead of the onshore wind turbine. The dynamic coupling between the support platform and supported wind turbine motions are important to develop the full system of motion equations.

To upgrade the existing land-based wind turbine model and makes it useful for analysing FOWT is necessary to introduce DOFs for platform characterization. In particular we are focusing on the rotational platform displacement along the y-axes: only the pitching degree of freedom is considered to insert the floating platform. The selection of the pitching DOF is selected due to its influence on loads and tower bending [20].

A diagram of the model is shown in figure 18 and the equation of the system is written in the matrix form:

$$\begin{bmatrix} I_p & 0 \\ 0 & I_t \end{bmatrix}\begin{bmatrix} \ddot{\vartheta}_p \\ \ddot{\vartheta}_t \end{bmatrix} + \begin{bmatrix} d_t + d_p & -d_t \\ -d_t & d_t \end{bmatrix}\begin{bmatrix} \dot{\vartheta}_p \\ \dot{\vartheta}_t \end{bmatrix} + \begin{bmatrix} k_p + m_p g R_p + k_t & -k_t \\ -k_t & k_t - m_t g R_t \end{bmatrix}\begin{bmatrix} \vartheta_p \\ \vartheta_t \end{bmatrix} = \begin{bmatrix} 0 \\ R_t \end{bmatrix} F_t \qquad (17)$$

$$J\ddot{\vartheta} + D\dot{\vartheta} + K\vartheta = RF_t$$

The θ_t, θ_p values are the angular rotation of tower and platform respectively. The platform and tower mass moments of inertias, I_p and I_t, are computed about their respective centre of mass. The damping constant of the platform, d_p, includes linearization of hydrodynamic damping. The spring constant of the platform, k_p, represents the effect of moorings lines and the buoyancy. The R_t represents the distance from the joint between tower and platform to the centres of mass of the DOFs considered. The terms $mgR\theta$ are the ballast terms due to the gravity.

The aerodynamic thrust force (*Ft*) applied to the centre of mass of the tower is considered; the platform is treated as it was submerged in still water.

J, D and *K* are the inertia, damping and stiffness matrices and *R* is the vector where the thrust force is applied.

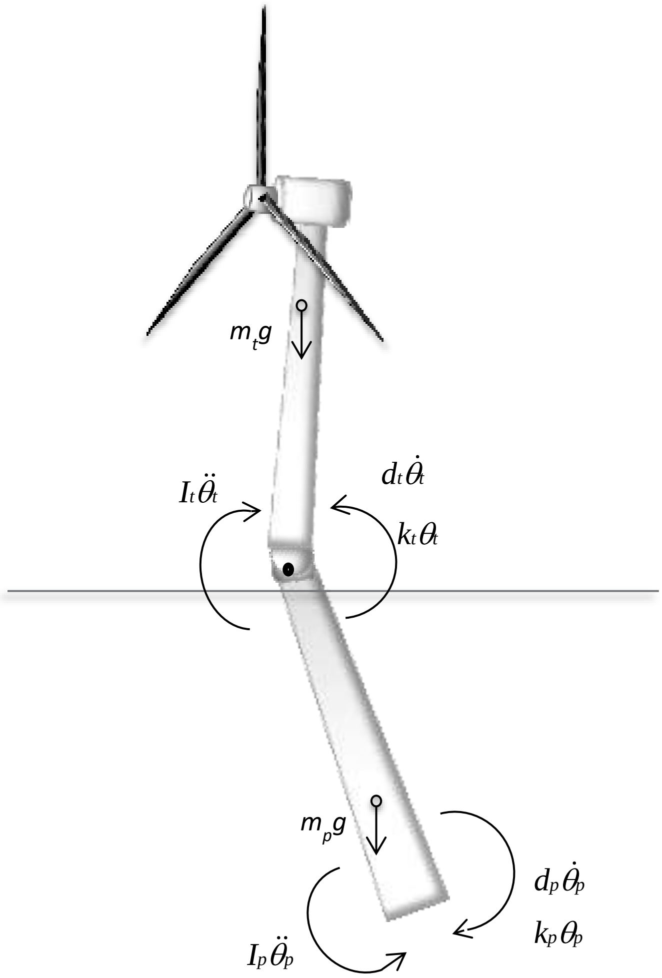


Figure 18: Diagram of the limited DOF model for the spar.

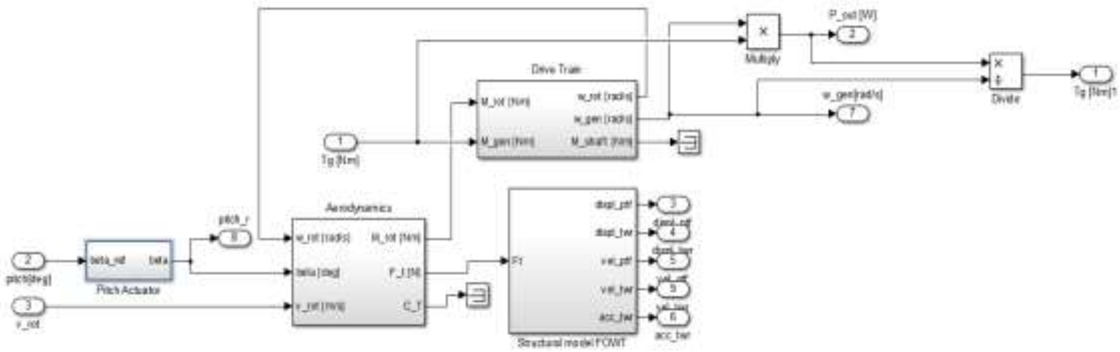


Figure 19: Offshore wind turbine model implemented in Simulink

3.7 FAST Aeroelastic Model

The models used to validate the simplified models are taken from the specifications of [18]. They are the *5MW baseline wind turbines* onshore and FOWT spar type. Those are modelled with a high accuracy using FAST simulator.

FAST is an acronym for *Fatigue-Aerodynamic-Structural-Turbulence* code. This code is elaborated by *National Renewable Energy Laboratory (NREL)* and it is publicly available.

FAST gives a time-domain response using a high-fidelity numerical code for wind turbine system dynamics and loads, fatigue damage and costs assessment.

It has the ability to couple the wind turbine model with hydro- aero-dynamic models, distributed by the *National Wind Technology Centre (NWTC)*.

As shown in figure 20, the external conditions and the related loads are evaluated using additional simulator codes (*InflowWind, AeroDyn, TurbSim* -not displayed here-, and *HydroDyn*), which generate time-series of wind and wave fields.

The wind turbine dynamic models are described using *ElastoDyn* and *MAP++* (or other equivalent only used for the FOWTs models) codes.

For the control part *ServoDyn* is used. There is also the possibility to introduce a different control system or inputs using Simulink and MATLAB interface, as it is done in the present thesis.

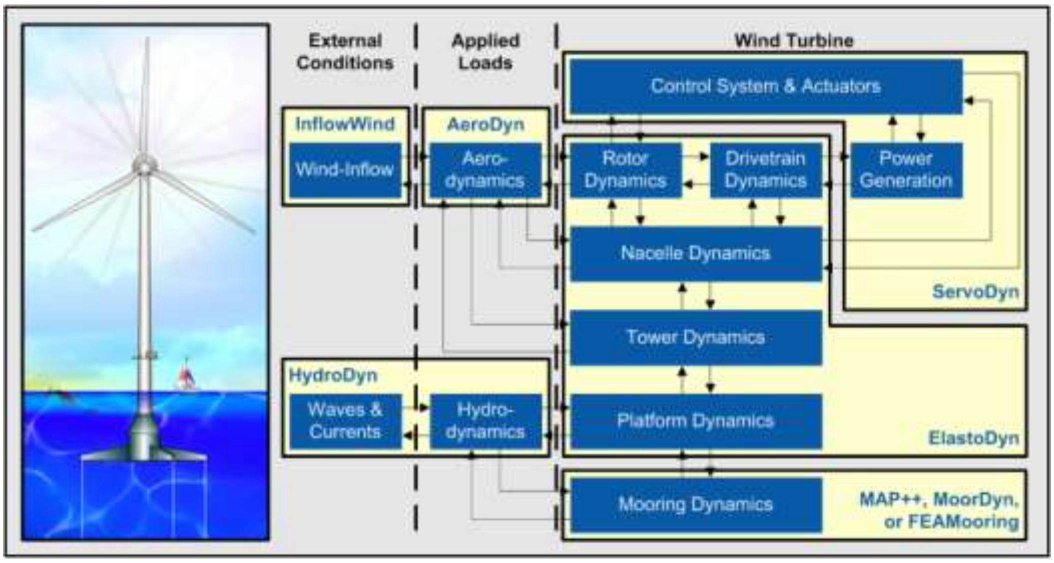


Figure 20: FAST control volumes for floating system.

In FAST structural models are considered flexibles and they are evaluated using a second-order linearized representation that assumes small deflections of each structure. The flexibility characteristics are determined by specifying distributed stiffness and mass properties, all tabulated in the report that defines the *5MW baseline wind turbine* [18].

This type of analysis allows developing linearized state matrices for a wind turbine plant [28], obtaining a nonlinear aeroelastic equation of motion for a wind turbine:

$$M(q,u,t)\ddot{q} + f(\dot{q},q,u,u_d,t) = 0 \qquad (18)$$

where M is the mass matrix, f is the forcing function, u and u_d are the wind turbine control inputs and wind inputs, respectively, q is the vector of wind turbine motions, and t is the time.

Furthermore FAST simulator has 24 DOFs that can be activated or deactivated.

As can be seen in figure 21, an interface from FAST to Simulink and MATLAB is possible, enabling the users also to implement different controllers.

More information about FAST code can be found in [28].

Onshore and floating wind turbine FAST models are taken into account in order to have a reasonable comparison between land- and sea- based installations.

In the present thesis to validate the models described in chapter 3.5 and 3.6, which are simpler than FAST ones, a selection of DOFs of FAST model is necessary. The DOFs allowed and of our interest in FAST are:

- Generator DOF;
- Drivetrain rotational-flexibility DOF;
- Two flapwise and one edgewise bending-mode DOFs per blade;
- Two fore-aft bending-mode DOFs in the tower;
- Pitch DOF in the platform.

In any case within the selection of the DOFs, FAST model gives a more accurate simulation.

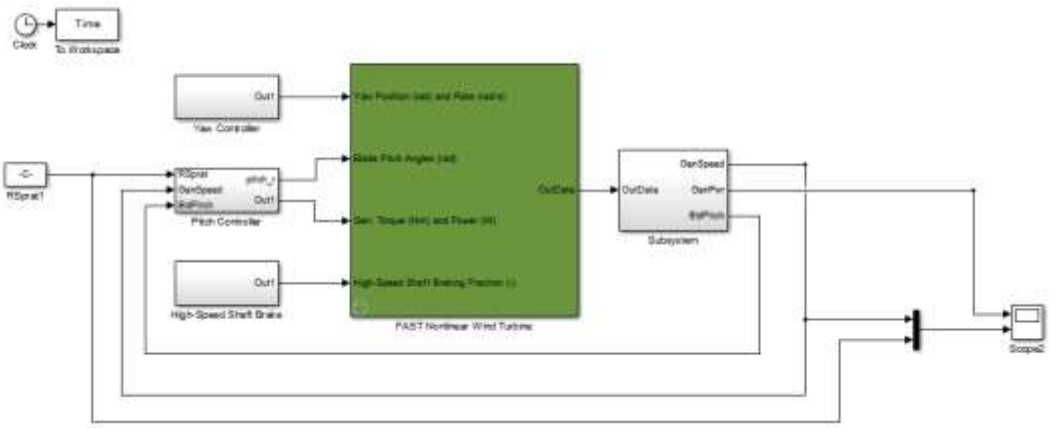


Figure 21: FAST nonlinear wind turbine with the controller.

4. Floating Wind Turbines Controller

4.1 Introduction

The aim of a traditional wind turbine control algorithm is to ensure a safe operation and an efficient energy conversion. Another objective to consider is the minimization of poor power quality. In fact wind energy, due to the variability of wind flow, is conventionally considered as poor quality suppliers to not produce constant power, one of the main problems of renewable sources.

Control specifications depend on wind speed conditions:

- With a low wind speed, below the rated 11.4 m/s, the objective is to maximize the energy conversion.
- With high wind speed, more than the rated (11.5-25 m/s), the objective is to regulate power production.

For each condition it is good to ensure the minimization of mechanical loads to avoid failure of the turbine.

In addition the control priorities for a wind turbine change slightly if we are considering an onshore or an offshore wind turbine. For an onshore WT, when the rated wind speed is reached, is important to limit the tower FA bending. On the contrary for an FOWT the FA displacement is weakening because the tower movement is modulated by the platform. Therefore other inconveniences arise: for example the *negative bending problem*, explained in the following chapters.

In this thesis is a Variable Speed (VS) controller is presented, which controls the generator torque and the collective-blade pitch. The first is following the VS control curve to maximize power capture; the second is designed to regulate generator speed by a Proportional Integrative (PI) controller, one of the most common used for wind turbine control.

4.2 Wind Turbine Operating Regions

The control design presented is taken from the specification of Jonkman et al. [18]. For each region the controller is selected to reach the optimal power capture and, simultaneously, the reduction of vibrations and loads. Variable-Speed control has become an industry standard largely because it optimizes energy capture over a large range of wind speeds.

Variable-speed variable-pitch wind turbine mode of operation takes into account rotor speed and power limitations. With the rotor speed measurement and power limitations different regions are selected for each modes of operation.

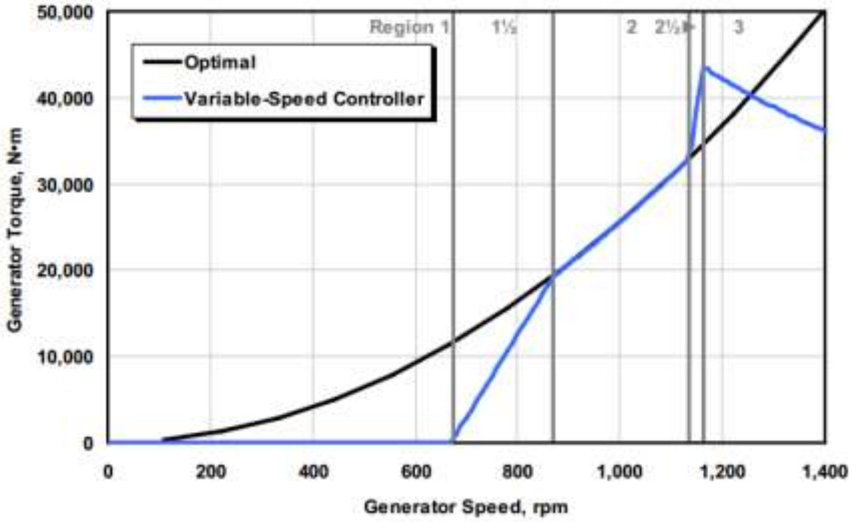


Figure 22: Torque-versus-speed response of the variable-speed controller [18].

The Variable-Speed controller has to regulate the generator torque in function of the generator speed. As figure 22 displayed, five control regions are classified in function of the generator speed (ω_g):

- *Region I:* $\omega_g \leq \omega_{g\_cut\text{-}in}$, the generator speed is below the cut-in value and the wind turbine does not reach the minimum speed to generate energy.

- *Region I ½:* Operation at minimal value (near to the cut-in value) the tip speed ratio is optimised by pitch control. The torque is a line ramp: this region is call *start up region*.

- *Region II*: $\omega_g < \omega_{g,rat}$, the generator speed is below the rated value. The object is to reach the maximum power capture, maintaining constant the tip speed ratio (at the optimum value of λ^*=7.55), as the blade pitch angle (β^*=0°) and changing the generator speed. The operating point describes the optimal regime's characteristic. In this region the generator- torque controller is used, which follows the *quadratic control law* (described after).

- *Region II ½: n*ear the rated generator speed value the control aims to not surpass this value. The pitch angle remains at the optimum and the rotor speed is limited to maintain acoustic noise emission within admissible levels [29].

- *Region III*: $\omega_g \geq \omega_{g,rat}$, the generator speed is over its rated value; the power is at the rated value, 90% of the maximum power capture admitted. In this region the generator speed is fixed, while a variable-pitch operation limits the rotational speed at its rated value. Pitch angle controller achieves power limitation modifying the blades aerodynamics; as a consequence the torque applied on the turbine is reduced. This area is extremely of our interest because the regulation around the rated value extremely influences the wind turbine life. The control in above rated conditions is described further.

- *Region IV:* $\omega_g \geq \omega_{g\_cut\text{-}out}$: the generator speed is over the cut-out value. This means that, to avoid failures for excessive mechanical loads, the turbine is braked.

4.2.1 Region II

The quadratic control law defines the objective of *region II*: the generator torque value is evaluated to achieve the maximum power capture, reachable only below rated wind speed [18].

Taking the equation (2), considering the $C_{p,max}(\beta^*,\lambda^*)$, the torque associated is:

$$T_{g,opt} = \frac{P^*(\beta^*,\lambda^*)}{\omega_g^*} \qquad (19)$$

where λ^*, β^* are the tip speed ratio and the pitch angle at C_{p_max} value, and ω_g is the HSS generator speed. From equation (4), replacing the values λ, β, v_w with λ^*, β^*, $\frac{R\omega_g^*}{\lambda^*}$ respectively, we can define T_g, which maximizes output power as [25]:

$$T_g = \frac{1}{2\lambda^{*3}} \rho \pi R^5 c_{p\_\max} \omega_g^2 = K \cdot \omega_g^2 \qquad (20)$$

Then the quadratic control law is written.

From equation (17) it is explicit that the optimal gain, *K*, varies from turbine to turbine, even if they have the same rated power. Furthermore, these can also be changed during a turbine life's period.

4.2.2 Region III

The collective blade pitch is adopted to control the turbine in above rated conditions. Here the object is to operate at the rated electrical power. Starting from writing the steady state thrust curve:

$$P_{rat} = constant;$$

$$dP = \omega_g \left(\frac{\partial T}{\partial v}\delta v + \frac{\partial T}{\partial \beta}\delta\beta\right) = 0 \qquad (21)$$

To produce constant power at rated generator speed for a given wind speed, the steady state pitch controller can be built following the operating curve:

$$\delta\beta = -\frac{\partial T}{\partial v}\left(\frac{\partial T}{\partial \beta}\right)^{-1}\delta v \qquad (22)$$

More information can be taken from [18].

Focusing on figure 22, it is evident that there is a point where the torque has a maximum peak, and after (up to ω_g*) it decreases immediately: a negative gradient is present. This means that when the wind speed increases a diminution of the thrust force is necessary [30]- [31]: here the blade-pitch control is activated.

Negative damping problem

In a FOWT always three main regions for power regulation are present, as the land-based. Major problems arise at rated conditions for the tilt stability in full load.

For onshore wind turbine the control applied in region III has to maintain a steady-state thrust force and regulates the pitch angle in order to maintain the power at its rated value. As mentioned before, for rated conditions the thrust force has to decrease with the increasing of the wind speed. For each operating point the thrust force it is calculated [31].

Considering a floating wind turbine model differences from the land-based are visible.

In fact two situations have to be distinguished: when the tower is moving forward and backward. If the tower is going forward the same control of the land-based is used in order to not exceed the rated rotor speed and, consequently, damage the turbine. On the contrary, when the tower goes backward, the effective wind speed decreases and the control tries to reduce tilt oscillations: this is the so-called *negative damping problem*. Available solutions are the implementation of a passive or active control [31] or combined. In fact a good structure design coupled with a control can avoid the resonance problems.

A passive control is a Tuned Mass Dumpers (TMD) located or in the nacelle or in the platform structure [20].

For active control it is necessary to maintain the control-response natural frequency smaller than the platform pitch natural frequency to avoid the possibility of negative damping of the platform pitch motion. This makes a positive damping of the support structure motions of a FOWT, when the pitch control is activated but at the same time causes fluctuations of rotational speed and, consequently, of power.

To limit these variations the control actuated for the onshore wind turbine model could be slightly changed [3]- [4]- [32]:

- Decreasing the PI factors to have a controlled frequency smaller than the natural frequency of the platform;

- In *region III* instead of using a constant power approach is used a constant torque or tracking and control the tower displacement.

In this thesis only the PI parameters are modified.

4.3 *NREL 5MW Wind Turbine* Controller

A representative block scheme of the control used by Jonkman [18] for the *NREL 5MW baseline wind turbine* is shown in figure 23. When the turbine is under the optimal operating conditions the generator torque is controlled and the other parameters are maintained constant at their optimal value (β^*, λ^*). To evaluate the generator torque a look-up table is inserted in the control. The table is the power curve, and in *region II* the torque has to follow as much as possible the power locus.

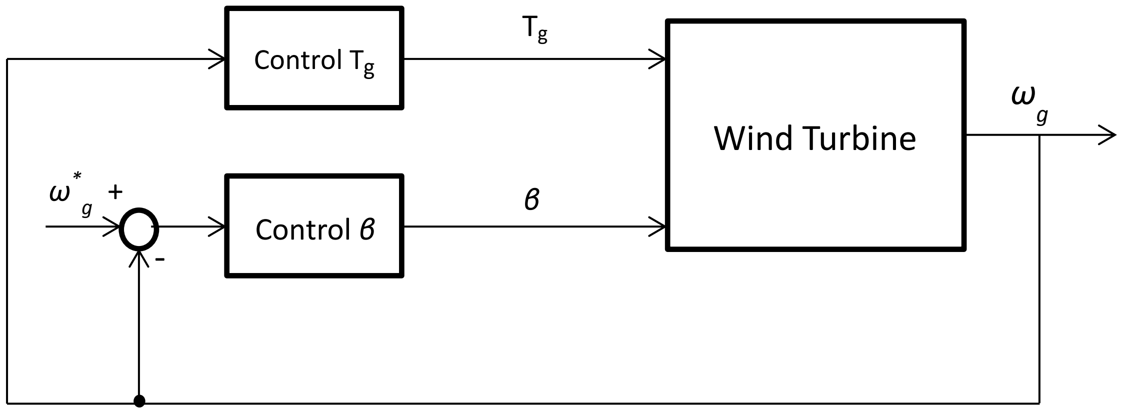


Figure 23: Variable speed variable collective-pitch controller scheme.

The collective-blade pitch angle is useful to manage the aerodynamic response in above rated conditions (*region III*). In this way it is possible to have the same operating condition (ω_r, T_r) for different wind speed, changing blade pitch from its optimal value.

Then to evaluate the blade pitch aerodynamics, the measured generator speed is compared with the target. A Proportional Integrative (PI) controller is used as a controller of the collective blade pitch angle.

To know the integrative and proportional parameters (k_i and k_p) the torque balance equation (6) has to be considered.

The rotor and generator torques are linearized (first order Taylor linearization) around an operational trajectory which is a series of mean values at the operating point (β_0, ω_0, v_0) calculated experimentally [18]:

$$
\begin{aligned}
T_g(\omega_g) &= \frac{P_g(\beta_0)}{N_g \omega_g(\beta_0)} - \frac{P_g(\beta_0)}{N_g \omega^2{}_g(\beta_0)} \Delta\omega_g \\
T_r(\beta_0) &= \frac{\mathrm{P_r}}{\omega_r} + k_\omega(\beta_0)\Delta\omega_g + k_\beta(\beta_0)\Delta\beta + k_v(\beta_0)\Delta v_w
\end{aligned}
\qquad (23)
$$

Where $k_\omega(\beta_0)$, $k_\beta(\beta_0)$, $k_v(\beta_0)$ are respectively the partial derivative of power in function of ω_g, β and v_w at a fixed operating point (β_0). We consider $\Delta\omega_g$ as the small perturbation of the state, $\Delta\beta$ and T_g as the control inputs and Δv_w as the disturbance.

$k_\omega(\beta_0$ and $k_v(\beta_0)$ are neglected

The perturbation of blade pitch angle, $\Delta\beta$ function of the error generator speed ($e= \omega_g$*- $\Delta\omega_g$), is the controller and is given by:

$$\Delta\beta = -N_g(k_p e + k_i \int e) \qquad (24)$$

Putting the equations (18) and (19) into the balance equation (6), neglecting the constants and the negative factor from the generator torque and considering the generator angle θ_g as a variable instead of its derivate (ω_g), the result is given by:

$$\left[Js^2 + (k_\beta k_p N_g)s + (k_\beta k_i N_g)\right]\Delta\theta_g = 0 \qquad (25)$$

Where $(k_\beta k_p N_g)$ can be related to the damping coefficient and $(k_\beta k_p N_g)$ to the stiffness coefficient. The relationship between those coefficients, damping ratio (ζ) and natural frequency (referred with ω_n) is given by:

$$2\zeta\omega_n = \frac{k_\beta k_p N}{J} \qquad (26)$$

$$\omega_n^2 = \frac{k_\beta k_i N}{J}$$

For the operating trajectory, using $\zeta=0.6$ and $\omega_n=0.7$ *rad/s*, k_i and k_p are obtained. From [33], the resulting gains are obtained at minimum blade-pitch setting for the baseline wind turbines: $k_p= 0.01882681$ *s*, $k_i=0.008068634$.

The integrative parameter, k_i, adds the capability to stabilize the system and the proportional, k_p, adds the damping effect. The derivative parameter is not considered because its effect (its inertia sensibility of the system) is included into the inertia.

Here a standard structure of a *tracking anti-windup* is inserted in the pitch controller.

The anti-windup scheme is used in control to avoid the *integral windup.* This is an effect when the control signals saturate the actuator and, with an increasing of the control value, it leads to a slower response to the system. This is due to the increasing value of the integrator and it will or not has any effect on the response, or it could lead to an opposite effect: increasing the overshot time and the settling time.

Adding an *anti-windup* scheme means using a saturation element. Referring to [34], in the controller a difference between the saturated and unsaturated control signal is used to generate a feedback that acts over the integrator factor, as shown in figure 24.

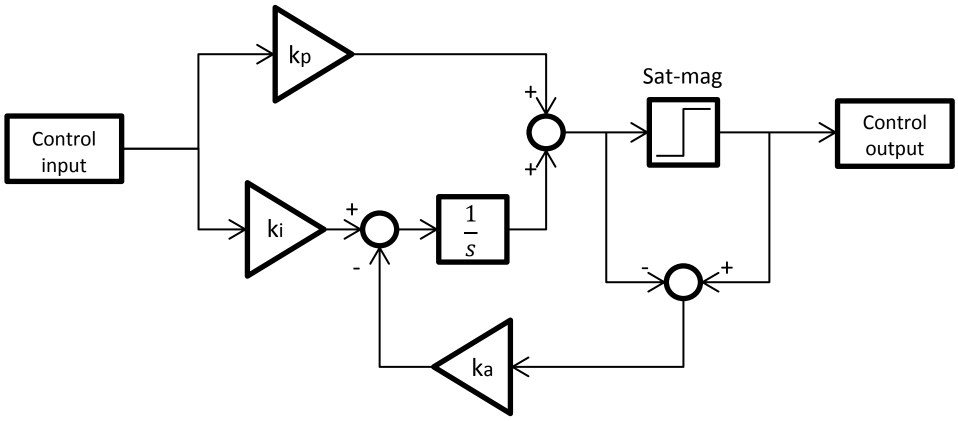


Figure 24: Classical tracking anti-wind up scheme.

Furthermore, to avoid excessive torque changes, a rate limiter in torque magnitude is inserted before the output torque signal, as it possible to see in figure 25.

The control parameters used for the floating structure are changed to avoid the platform pitch resonance. In fact the control-response natural frequency is reduced in the way that the motions of the floating platform with control remain positively damped [4]. NREL [17] recommended the optimal gain values: kp (β = 0°) = 0.006275604 s and ki(β = 0°) = 0.0008965149.

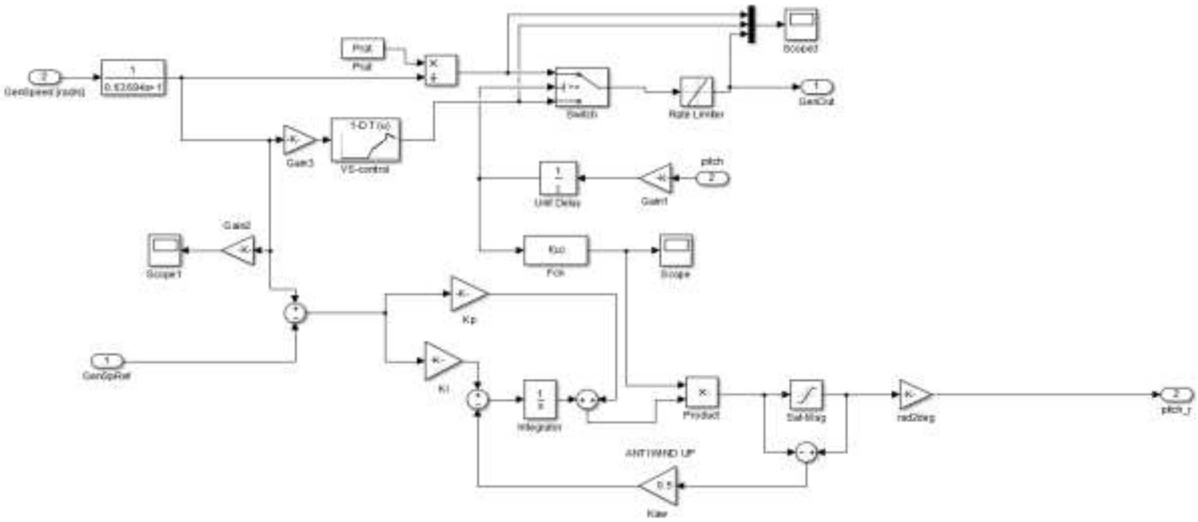


Figure 25: Control design implemented in Simulink.

5. Model validations

5.1 Introduction

In this chapter validations and comparisons of wind turbines simplified models are described.

Validations are simulated in order to see if the simplified model of a wind turbine system can reach the stability under different perturbations as well as the more detailed FAST model. Another step is implementing the controller and seeing the capability with it to stabilize faster the model system.

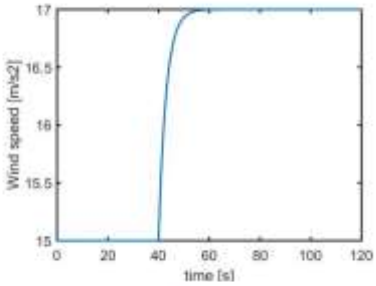
Understanding the dynamic response is necessary to perform a comprehensive validation analysis. The analysing project needs also to determine the properties of the floater. Series of design load cases are studied, varying different wind profiles.

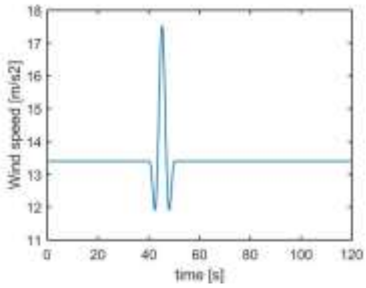
The purpose of this thesis is also to consider how the operating point is varying along *region III*, where wind speed rated is reached, and in which way can be improved control performances. In this way only mean wind speeds over the rated are considered, or a variation that consider the transition between *region II* and *region III*.

It is assumed that wind turbine rotor is always aligned with mean wind speed direction (following the positive x-direction). The mean wind profiles used to run the simulations are shown in figure 26.

- Step wind profile: starting from 15 m/s to 17 m/s at 40s of simulation time;
- Extreme Operating Gust wind profile (EOG) with mean wind speed of 13.5 m/s, maximum peak of 17 m/s, taken from the standard IEC 61400-1;
- Normal Turbulence Model wind profile (NTM) with mean wind speed of 16 m/s, taken from the standard IEC 61400-1 [23];

The simulation time is 120 seconds. A constant time step of 0.0125 s fixed-step-size time-integration scheme is applied.





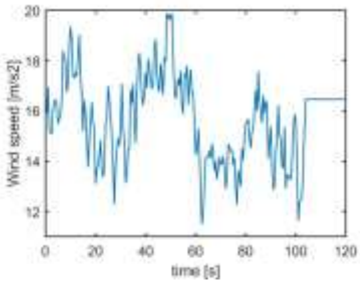


Figure 26: Wind profile along the x-axis, perpendicular to the rotor (m/s): a)step wind profile (from 15 to 17 m/s), b) EOG wind profile, mean wind speed of 13,5 m/s. c) NTM wind profile, mean wind speed of 16 m/s.

In the Appendix all the models formulations in MATLAB are presented.

In table below a list of all the simulations run with MATLAB&Simulink and presented here is shown.

	Open-Loop or Closed-Loop	Wind profiles used
One-Mass and Two-Mass Drive-Train models comparison	Closed-Loop	Step wind profile
Two-Mass Drive-Train with FAST validation	Open-Loop and Closed-Loop	Step, EOG and NTM wind profiles
Onshore Wind Turbine with FAST validation	Open-Loop and Closed-Loop	Step, EOG and NTM wind profiles
FOWT with FAST validation	Open-Loop and Closed-Loop	Step, EOG and NTM wind profiles

Table 6: List of simulations.

5.2 One Mass Drive-Train, Two Mass Drive-Train models comparison

A comparison between the two drive-train models coupled with the control is done. The two models are explained before in chapter 3 as well as the control in chapter 4.

A simulation considering wind step perturbation (from 15 to 17 m/s) is run.

Figure 27 shows differences between them in terms of power capture (W), and generator speed (rpm).

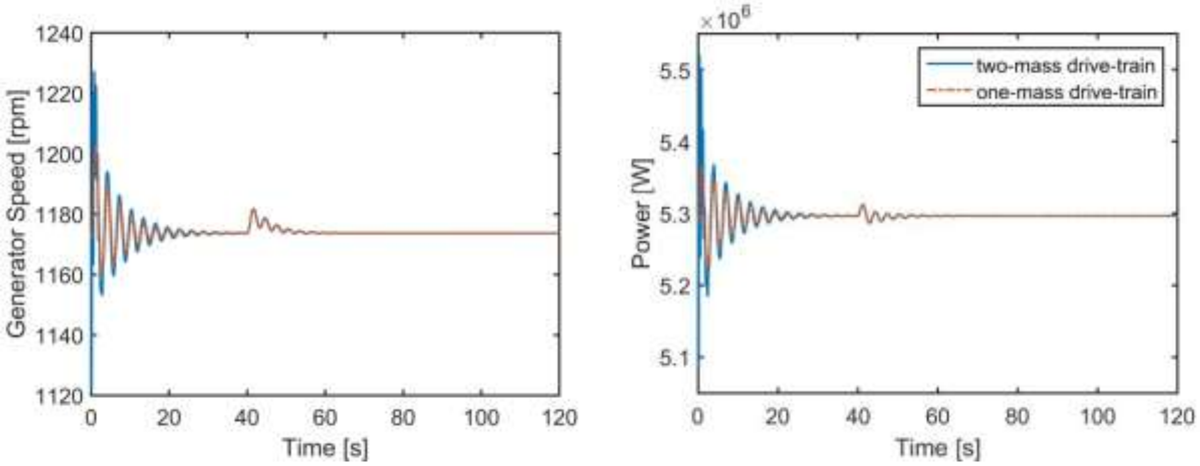


Figure 27: Generator speed (rpm) and power (W) validation for one and two mass drive-train models.

When the perturbation is applied (for t=30 s), generator speed changes in the same way for both models. The one mass drive-train model presents fewer oscillations due to not consider the same torsion effects.

The stability to rated generated speed is reached in both.

Without considering the initial transient, the two models match together, and a study with a simplified control is possible.

For dynamic control purpose, it is commonly used to study a wind turbine model that has a two mass drive-train. Also in FAST model two mass drive-train model is used.

5.3 Two-Mass Drive-Train model validation

Two-mass drive-train model validation with controller is presented.

To have a reasonable comparison, for the more accurate FAST model a selection of degrees of freedom is necessary:

- Drive-train rotational-flexibility DOF;
- Generator DOF.

Simulations run a step and EOG wind profiles.

Validations are done in terms of generator torque (Nm), generator speed (rpm) and blade pitch angle (deg).

Step wind profile

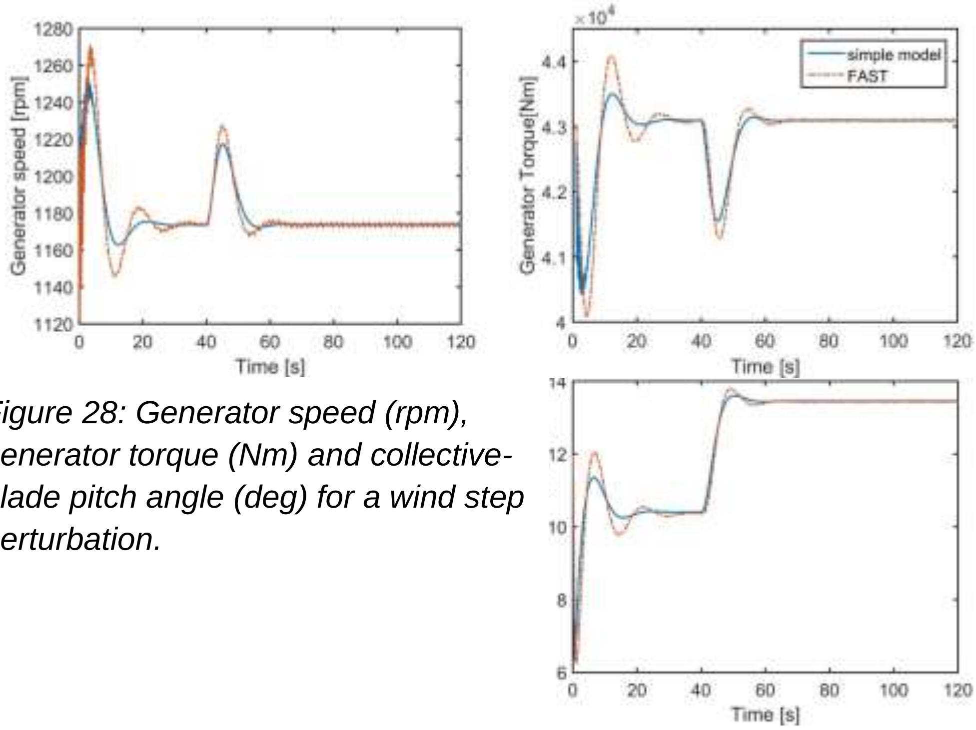
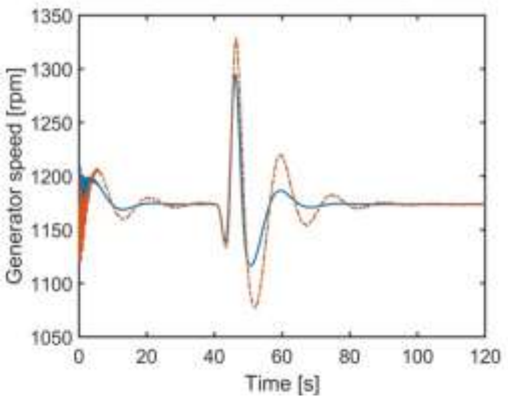


Figure 28: Generator speed (rpm), generator torque (Nm) and collective-blade pitch angle (deg) for a wind step perturbation.

Extreme Operated Gust wind profile



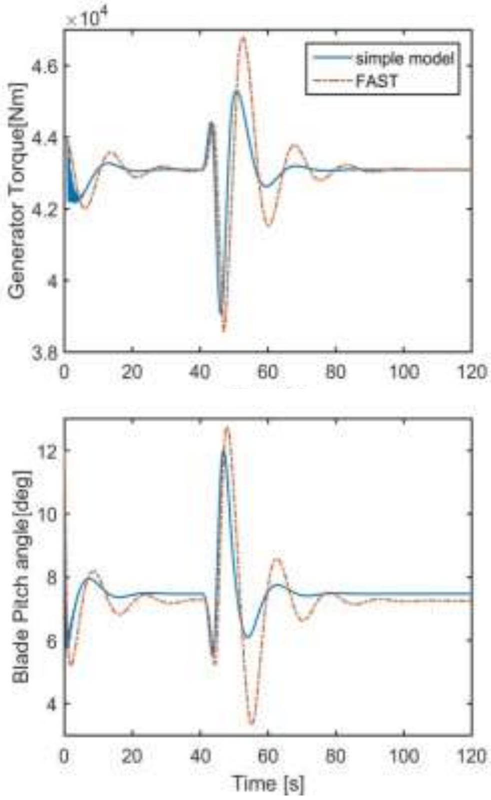


Figure 29: Generator speed (rpm), generator torque (Nm) and collective-blade pitch angle (deg) for a wind step perturbation.

Normal Turbulence model wind profile

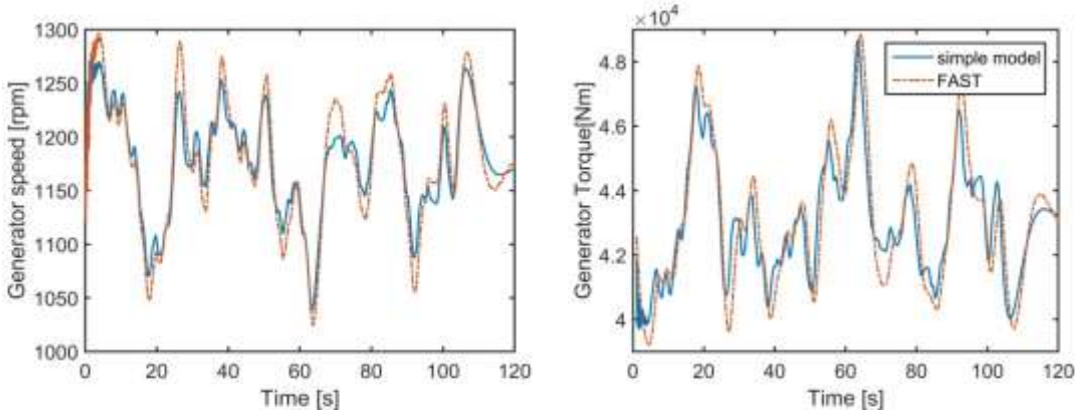
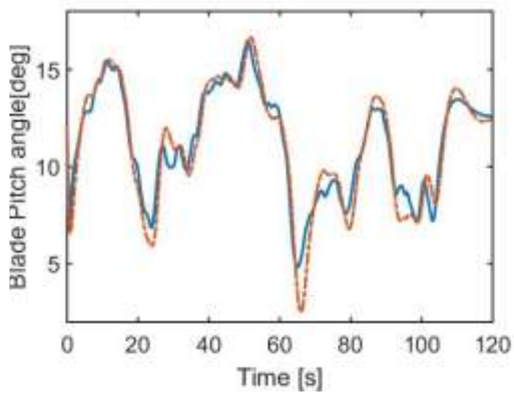


Figure 30: Generator speed (rpm), generator torque (Nm) and collective-blade pitch angle (deg) for a wind step perturbation.



As we expected, models follow the same trend reaching the stability for each wind perturbation input.

Both models are in good agreement analysing their responses. Only a relative error of 2% is visible in the blade pitch angle that can be negligible.

However, during the perturbation generator speed and torque and blade pitch angle oscillations are quite different due to different complexity of the two models.

From those simulations it is possible to foster this drive-train model adding a structural part and prove its validity.

5.4 Onshore Wind Turbine model validation

To verify the reliability of the onshore wind turbine simplified model, described in chapter 3, validations, using the more detailed FAST model, are run. Those simulations are made to prove its stability with and without implementing a control.

Firstly numerical estimations of coherent spring and damping coefficients and natural frequencies for blades and tower are evaluated in the state-of-art [19]. Those values are necessary to achieve model validation, that mean built with reasonable properties the model system.

After a selection of FAST model DOFs is necessary:

- Drive-train rotational-flexibility DOF
- Generator DOF;
- First and second flap-wise blade mode DOF;
- First and second tower fore-aft bending-mode DOF.

Wind profiles used to run simulations are: step wind perturbation, EOG wind profile and NTM wind profile.

For tip displacement we referred to the displacement at blades tip, given by:

$$y_{tip} = y_t + R\xi \qquad (27)$$

Figure 31 shows the block scheme implemented in Simulink, representative of the land-based wind turbine structural model.

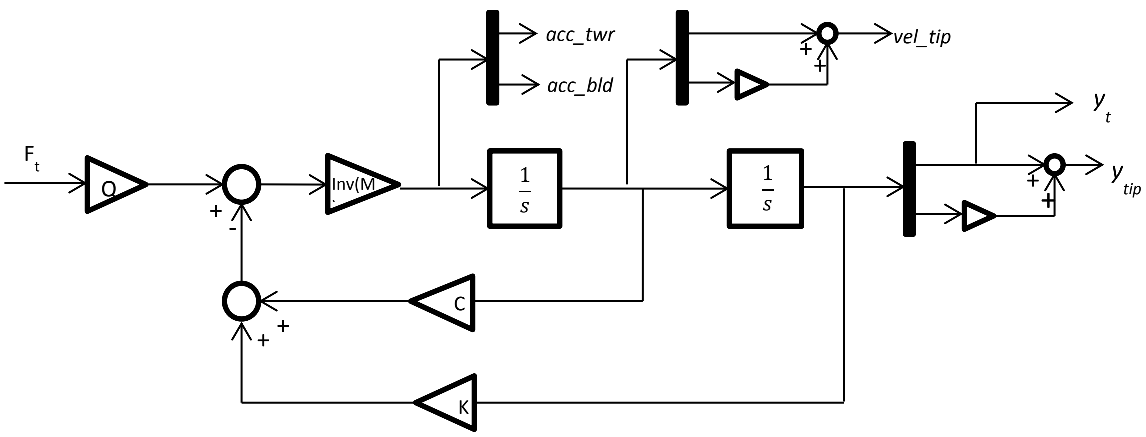


Figure 31: Block scheme for the onshore wind turbine structural model (implemented in Simulink).

Validations are done in terms of generator speed (rpm), tower acceleration (m/s^2) (acc_twr), tower (m) and tip displacement (m) (y_t, y_{tip}).

In the figure the gains Q, M, C, K are the same described in chapter 3.

Collective-blade pitch displacement and generator torque are not displayed because those are fixed at their rated values: 12° and $4.3094*10^4$ Nm respectively.

Step wind profile

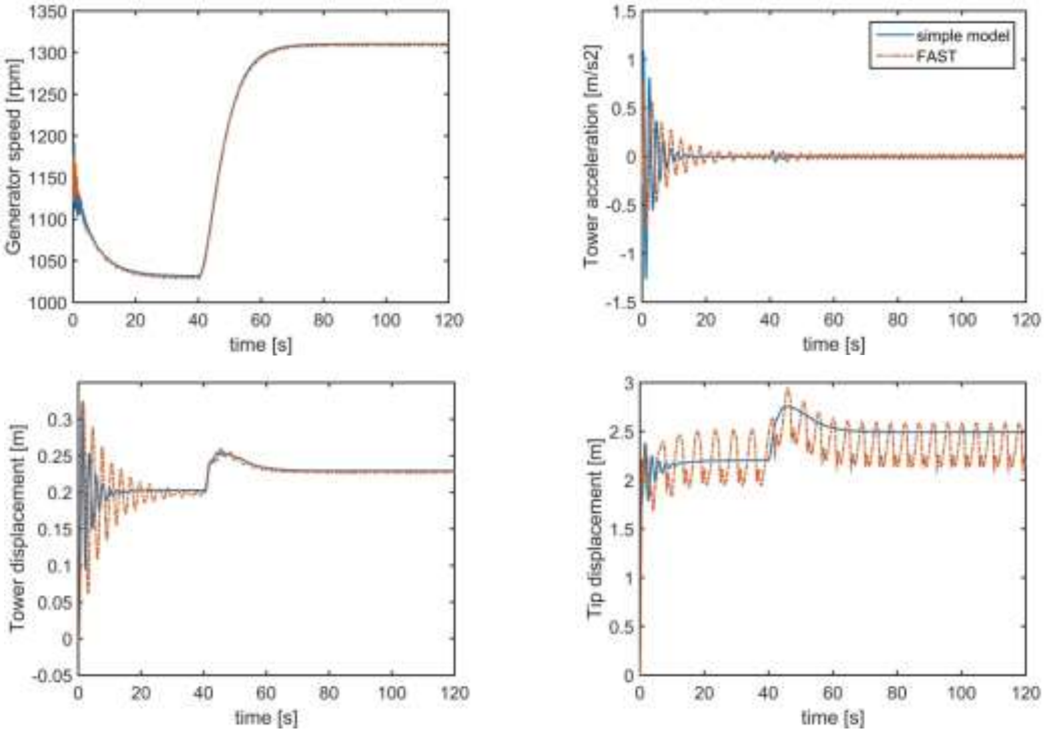


Figure 32: Validation for a wind step perturbation. From left to right, in order: generator speed (rpm), tower bending acceleration (m/s^2), tower and tip displacements (m).

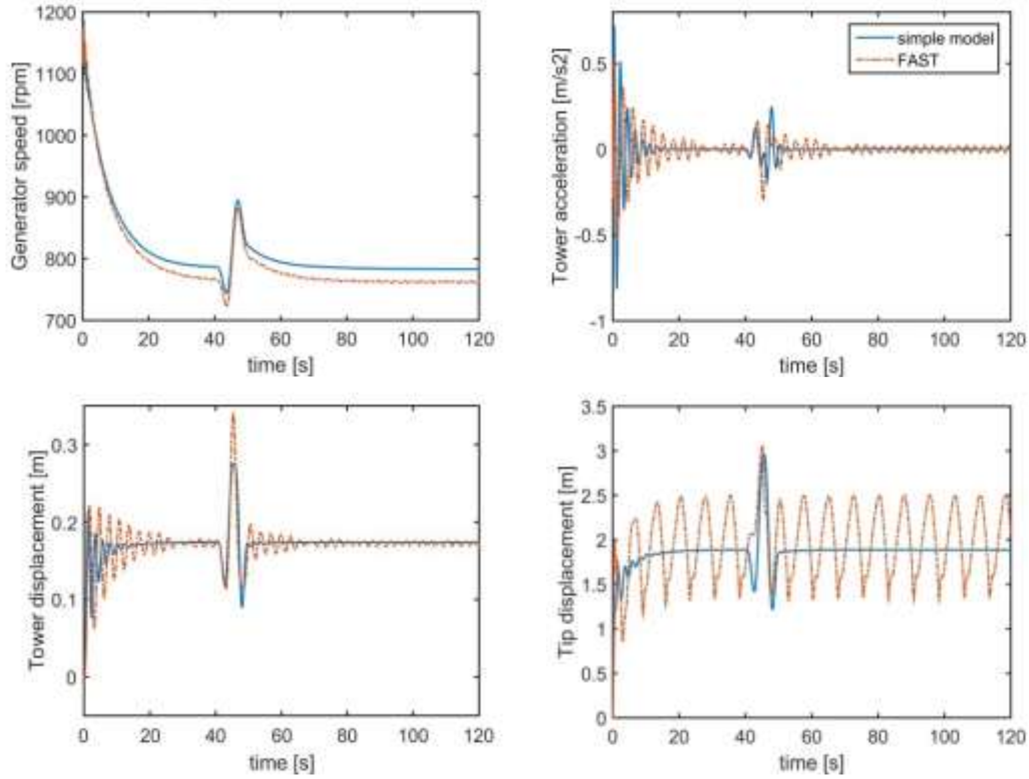


Figure 33: Validation for an EOG wind perturbation. *From left to right, in order: generator speed (rpm), tower bending acceleration (m/s^2), tower and tip displacements (m).*

Normal Turbulence Model wind profile

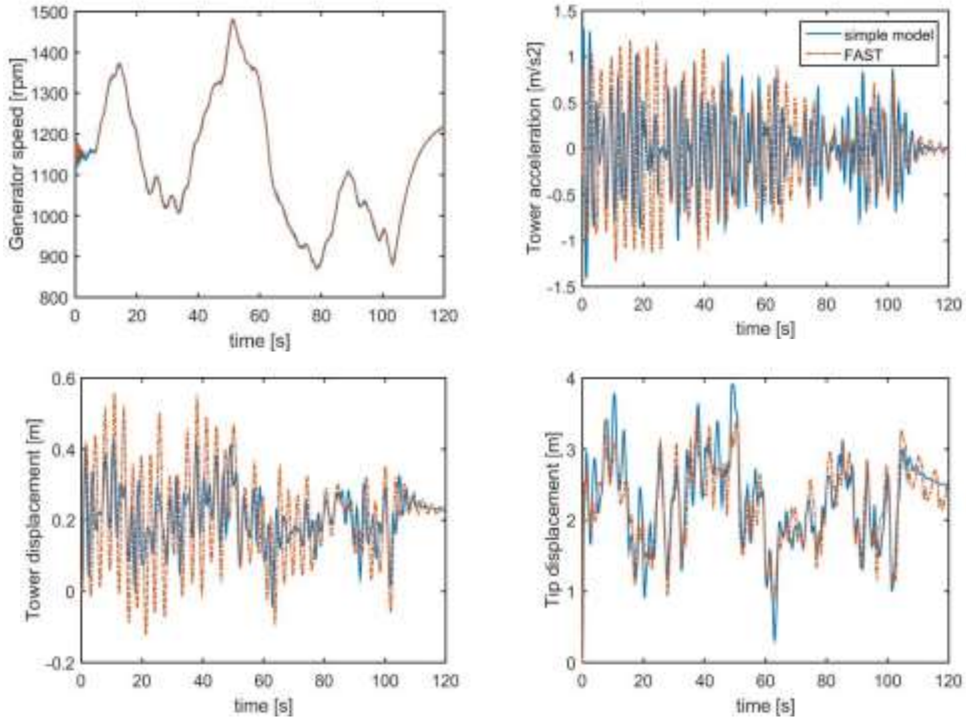


Figure 34: Validation for NTM wind perturbation. *From left to right, in order: generator speed (rpm), tower bending acceleration (m/s^2), tower and tip displacements (m).*

Running simulations, and analysing firstly the step perturbation, it is noticeable that blades spring coefficient influences the transient time and tower spring coefficient the steady-state error.

Models never arrived to be instable, only instabilities of the generator speed are visible during the transition time that can be neglected.

Tower and blades maximum displacements are 0.5m and 4m during the NTM wind perturbation. Otherwise only small oscillations are present.

From the two models differences are visible, which are always related to model details: in particular the oscillations of tip blades are visibly more accentuated in FAST model.

However the error is negligible and the trend for each wind perturbation input is the same; then validations can be considered successful.

Following the PI controller is added in both models; afterward a comparison with the open-loop is done.

5.5 Onshore Wind Turbine with controller validation

After considering only the open-loop response of the onshore wind turbine model, the controller is inserted to obtain a minimization of instabilities.

The simulations are run using the same parameter for wind turbine models, wind profile and FAST DOFs.

Validations are done in terms of generator speed (rpm), generator torque (Nm) tower acceleration (m/s^2), blade pitch angle (deg), tower (m) and tip displacements (m).

Step wind profile

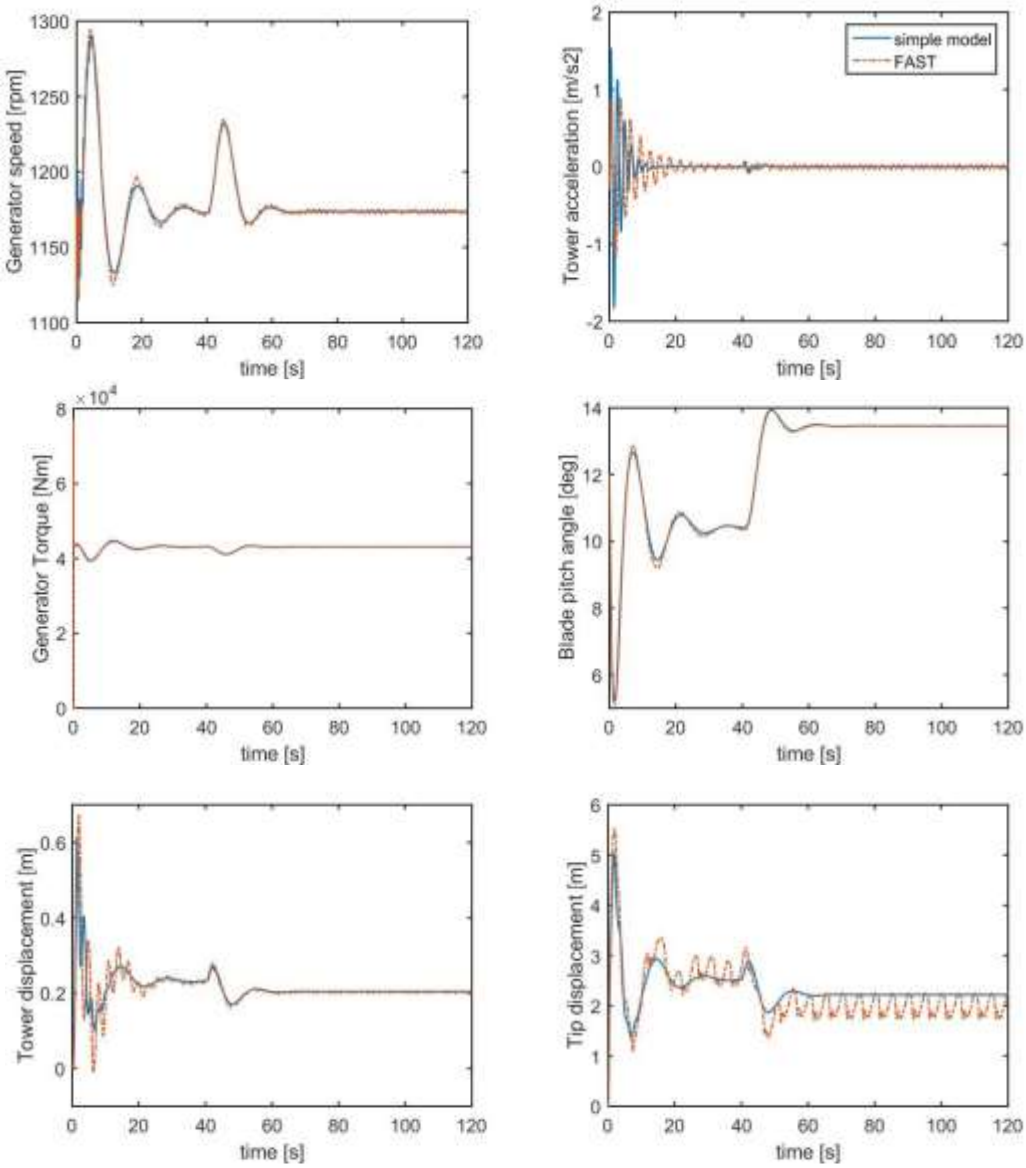


Figure 35: Validation for a step wind perturbation. From left to right, in order: generator speed (rpm), tower bending acceleration (m/s^2), generator torque (Nm), blade pitch angle (deg), tower displacement (m) and tip displacement (m).

Extreme Operated Gust wind profile

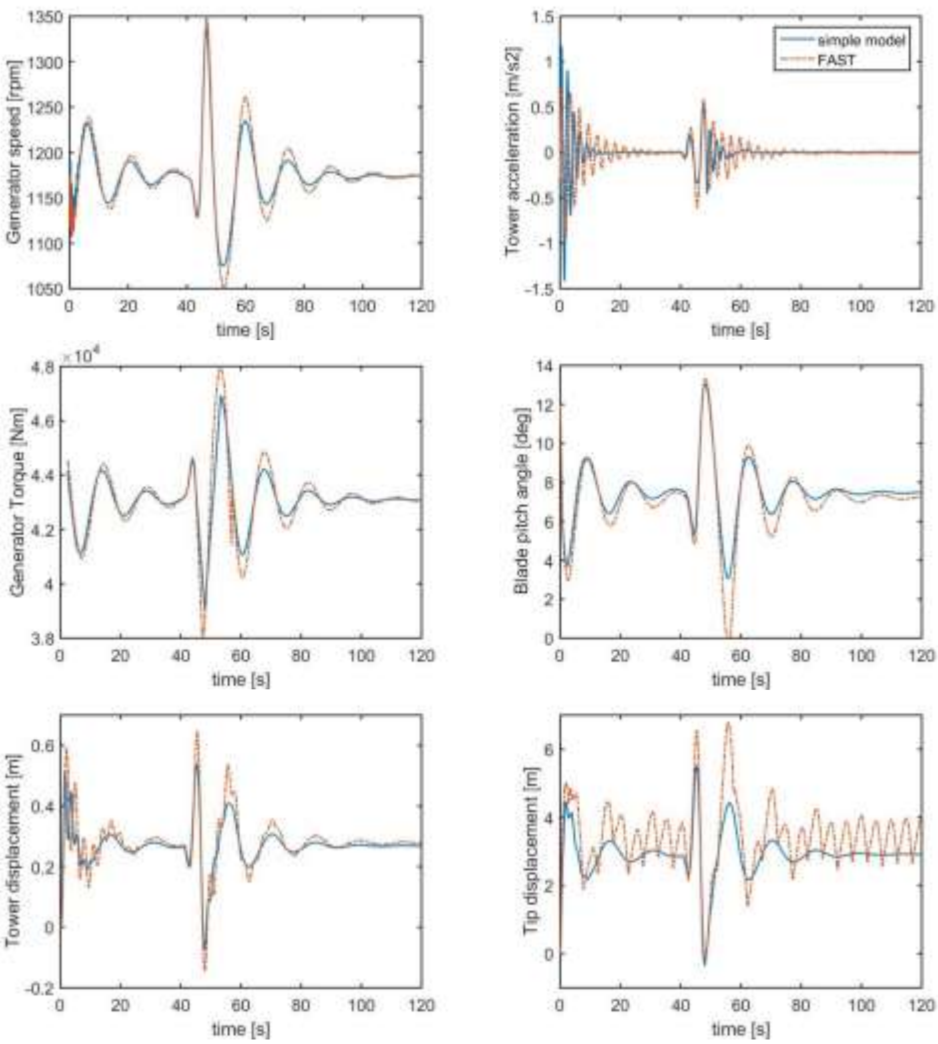


Figure 36: Validation for EOG wind perturbation. From left to right, in order: generator speed (rpm), tower bending acceleration (m/s^2), generator torque (Nm), blade pitch angle (deg), tower displacement (m) and tip displacement (m).

Normal Turbulence model wind profile

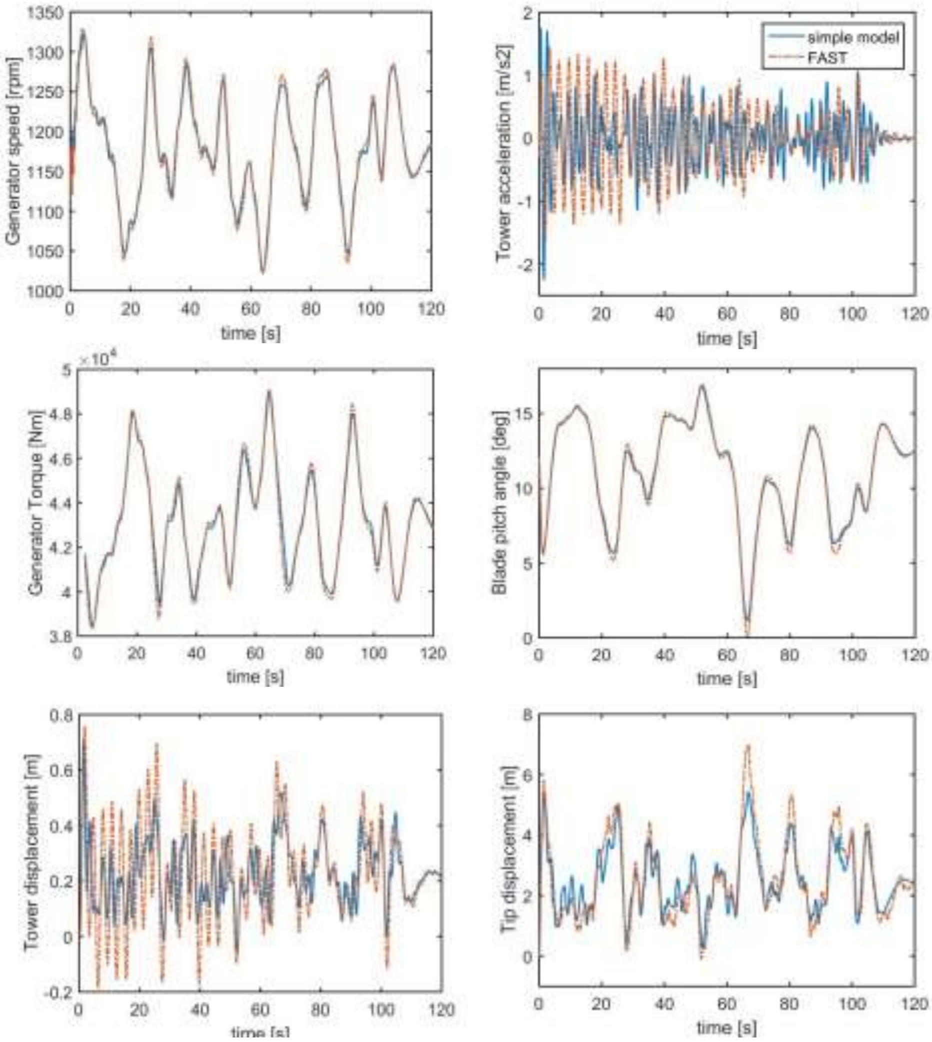


Figure 37: Validation with NTM wind perturbation. From left to right, in order: generator speed (rpm), tower bending acceleration (m/s^2), generator torque (Nm), blade pitch angle (deg), tower displacement (m) and tip displacement (m).

As figures show, results match together with some differences. In particular tip blade displacement of FAST model has more oscillations for all the run cases.

There are also some differences between closed-loop and open-loop responses. With the controller different behaviour of tower and tip displacements are noticeable for wind perturbations. In fact comparing with the open–loop system, for the step wind perturbation a reduction of ~12% of the mean values is visible. On the contrary differences under the EOG wind perturbation are not evident.

The PI control however allows guaranteeing a more stable generator speed in terms of mean value and the optimum power can be better achieved in each region.

All the examples proposed have an acceptable response in terms of tip and tower displacements.

It is noticeable to say that a sudden response of the control is not always relished: saturation levels in rate and magnitude of blade-pitch angle are integrated (*anti-windup*).

5.6 FOWT model validation

The purpose is to find the equivalent system of the non-linear time-variant system with distributed parameter. This dynamic system is supposed to be linear time-invariant with lumped-parameter components.

Analysing the state-of-art, it was not possible to find reasonable and concrete values for damping and stiffness constants in order to complete the characterization of the whole system.

However those are established experimentally, changing the type of system analysis. In fact, from a structural dynamics analysis we pass through a modal analysis. This means that, instead of studying how structures respond when they are subjected to applied loads, the modal characteristics of the structure is used to determine the response of the system. The model is decomposed to express the structure parts in terms of its modal characteristics (frequency, damping and shapes).

The advantage of this analysis is that the characteristics are defined from measurements and damping ratios are evaluable. Once established, a state-space function gives a full description of the dynamic characteristics of the system, as distinct from its physical description.

To find natural frequencies and damping ratios the response for a step perturbation is studied.

Then from the system given by (14) a linear transformation into principal system of the forth order form can be developed: starting from considering as space vectors the platform and tower speeds and positions respectively and as input the thrust force, the state-space function can be written as:

$$A = \begin{bmatrix} 0 & I \\ -J^{-1}K & -J^{-1}D \end{bmatrix}; B = \begin{bmatrix} 0 \\ -J^{-1} \end{bmatrix} \qquad (28)$$
$$C = \begin{bmatrix} I & 0 \end{bmatrix}; D = \begin{bmatrix} 0 \end{bmatrix}$$

Where *A, B, C* and *D* are the state-space system matrices -related to equation (14) -, which are transformed into A_d, B_d, C_d and D_d:

$$A_d = \begin{bmatrix} -\sigma_p & \omega_p & 0 & 0 \\ -\omega_p & -\sigma_p & 0 & 0 \\ 0 & 0 & -\sigma_t & \omega_t \\ 0 & 0 & -\omega_t & -\sigma_t \end{bmatrix}; B_d = \begin{bmatrix} -1 \\ 1 \\ -1 \\ 1 \end{bmatrix} \qquad (29)$$
$$C_d = \begin{bmatrix} c_1 & c_1 & 0 & 0 \\ c_2 & c_2 & c_3 & c_3 \end{bmatrix}; D_d = \begin{bmatrix} 0 \end{bmatrix}$$

The matrices are described by: natural frequencies ($\omega_{p,}$ ω_t) and damping ratios (σ_p,σ_t) of platform and tower. A_d is written in the canonical form with complex eigenvalues. c_1, c_2 and c_3 coefficients describe the dependences of tower and platform to each other.

Model properties are found analysing FAST response.

Before a selection of the DOFs of FAST model is necessary:

- Drive-train rotational-flexibility DOF
- Generator DOF;
- First and second tower fore-aft bending-mode DOF;
- Platform pitch rotation DOF.

From here there is the possibility to build the FOWT simple model.

Evaluating pitch angle deviation and fore-aft tower displacement of FAST response, some considerations can be done:

- Pitch motion is not evidently dependent from fore-aft displacement, the contrary can be said for tower motion;
- Platform pitch bending motion has a low natural frequency (as it was supposed) with a little damping ratio, due to a more rigid body of the structure;
- Fore-aft displacement has a higher frequency with a higher damping ratio.

This considerations help to find their natural frequencies, and the dependency coefficients for tower and platform.

For damping ratio value an analysis of response decay is done.

Different wind perturbations are presented: step, EOG and NTM wind profiles.

Response validations are evaluated considering tower and platform displacement (m), tower acceleration (m/s^2) and generator speed (rpm).

Generator torque and blade pitch angle are always constant (not displayed), because the controller is not activated.

Step wind profile

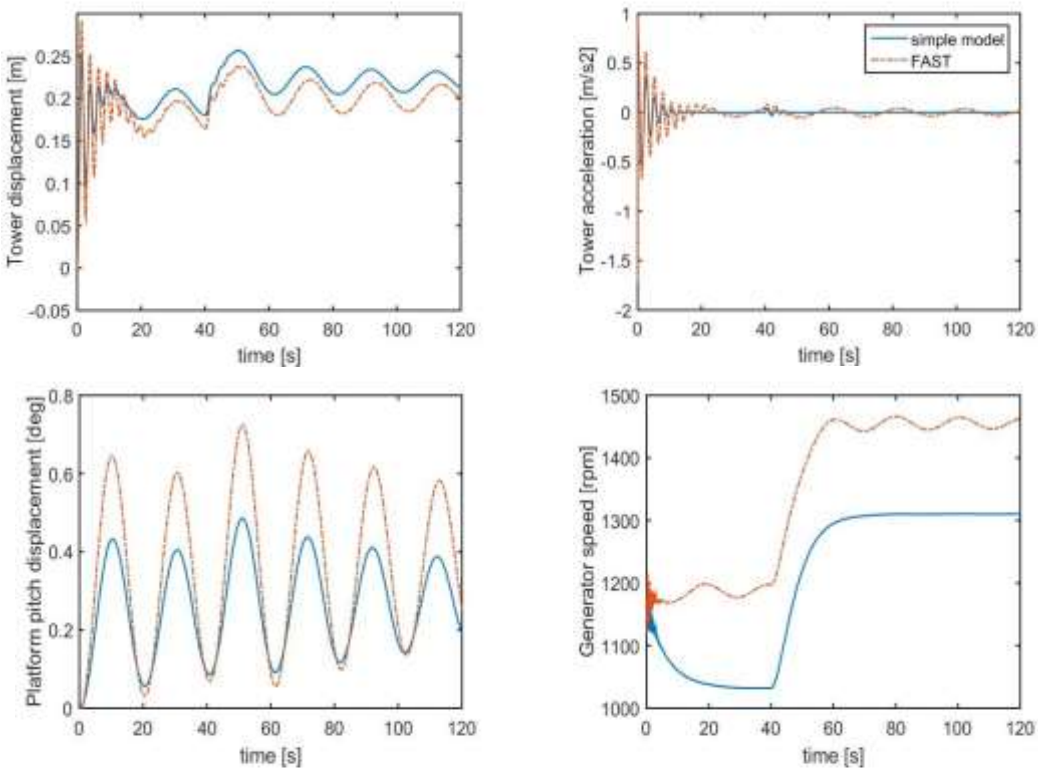


Figure 38: Validation for a step wind perturbation. From left to right, in order: tower displacement (m), tower acceleration (m/s^2), platform pitch angle displacement (deg), generator speed (rpm).

Extreme Operated Gust wind profile

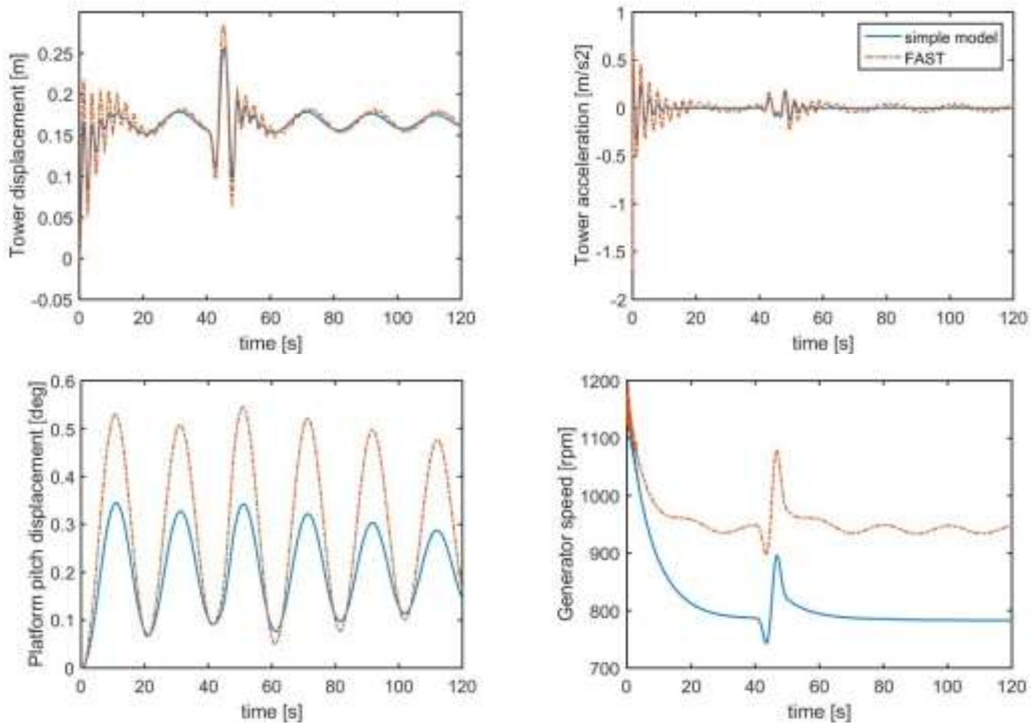


Figure 39: Validation for EOG wind perturbation. From left to right, in order: tower displacement (m), tower acceleration (m/s^2), platform pitch angle displacement (deg), generator speed (rpm).

Normal Turbulence model wind profile

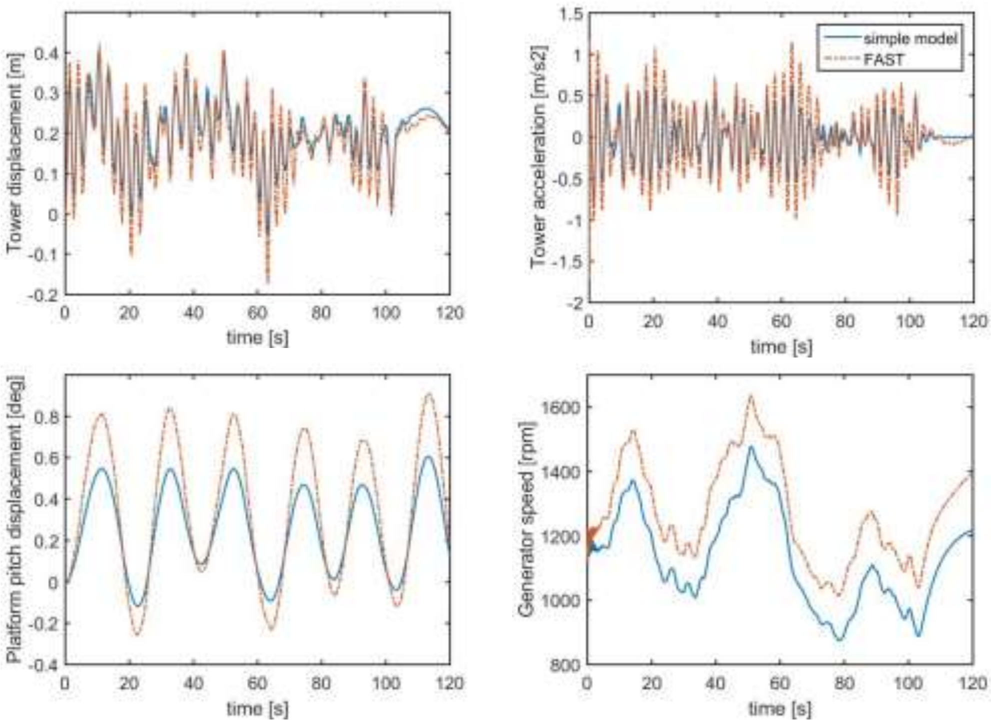


Figure 40: Validation for NTM wind perturbation. From left to right, in order: tower displacement (m), tower acceleration (m/s^2), platform pitch angle displacement (deg), generator speed (rpm).

Analysing the responses, tower damping is sufficiently high to stabilize the structure; on the contrary the platform has always a bending moment oscillation (a periodic oscillation is noticeable). Platform displacement is smaller in the simple model, due to the characteristic assumptions that we assumed as undistributed and constant. Usually, the modelling is done using not constant parameters, but integrated in beams module, as FAST does. However, for a first study of control implementation a simplified model is always favourable to understand, at least, the main effects.

In general the relative errors are considerable for platform pitch movement (~35%) and for generator speed (~15%). Those are due to accumulations of simplifications that are assumed.

However, reasonable responses are obtained because each of them follow the same trend of FAST model, but having differences in amplitude.

Further developments will aim to increase the simplified model accuracy.

5.7 FOWT model validation with controller

After a first step that considers only the open-loop response of the FOWT model, the controller is inserted to obtain a minimization of instabilities.

Here the objective is to have an optimum control for each control region. Therefore, in region III the regulation of power capture and reduction of platform movements are simplified to the regulation of generator speed and try to reduce the platform pitch movement, changing the PI parameters, as suggested by [17].

The simulations are run using the same parameter for wind turbine models, wind profile and DOFs activated in FAST used for the open-loop system analysis.

Validations are done in terms of generator speed (rpm), generator torque (Nm) tower acceleration (m/s^2), blade pitch angle (deg), tower displacement (m) and platform pitch displacement (deg).

Step wind profile

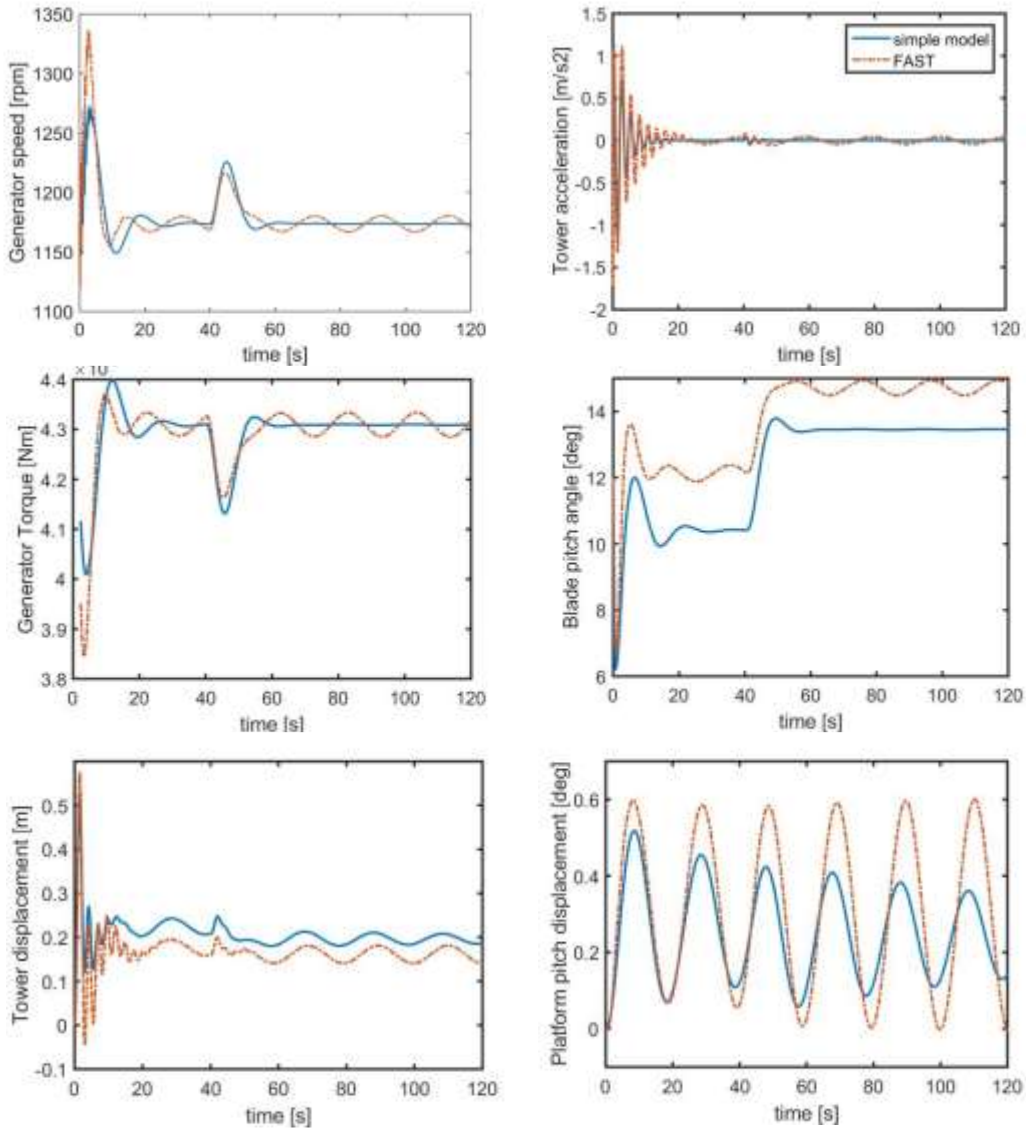


Figure 41: Validation for step wind perturbation. From left to right, in order: generator speed (rpm), tower acceleration (m/s2), generator torque (Nm), blade pitch angle (deg), tower displacement (m), platform pitch angle (deg).

Extreme Operated Gust wind profile

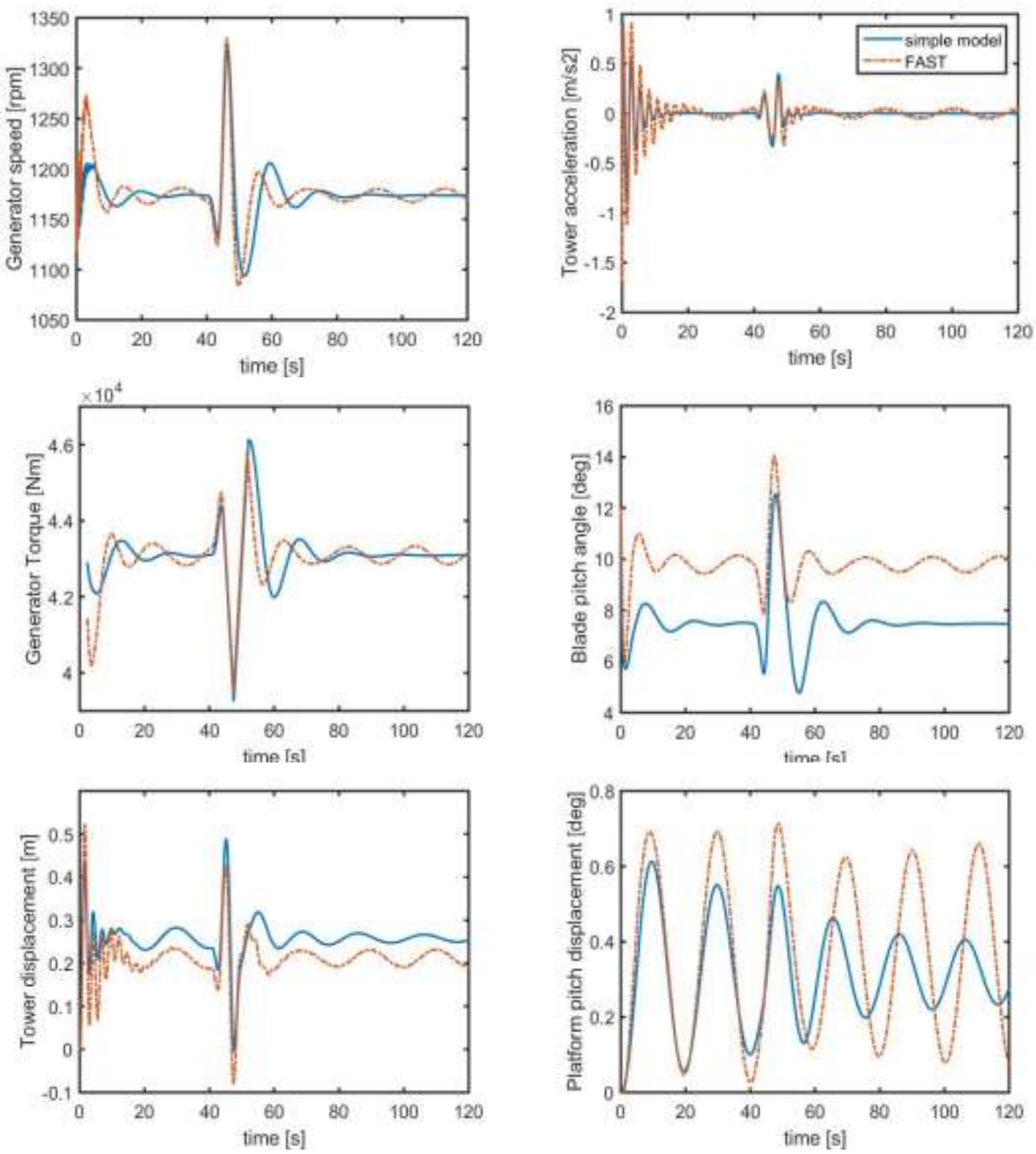


Figure 42: Validation for EOG wind perturbation. From left to right, in order: generator speed (rpm), tower acceleration (m/s2), generator torque (Nm), blade pitch angle (deg), tower displacement (m), platform pitch angle (deg).

Normal Turbulence model wind profile

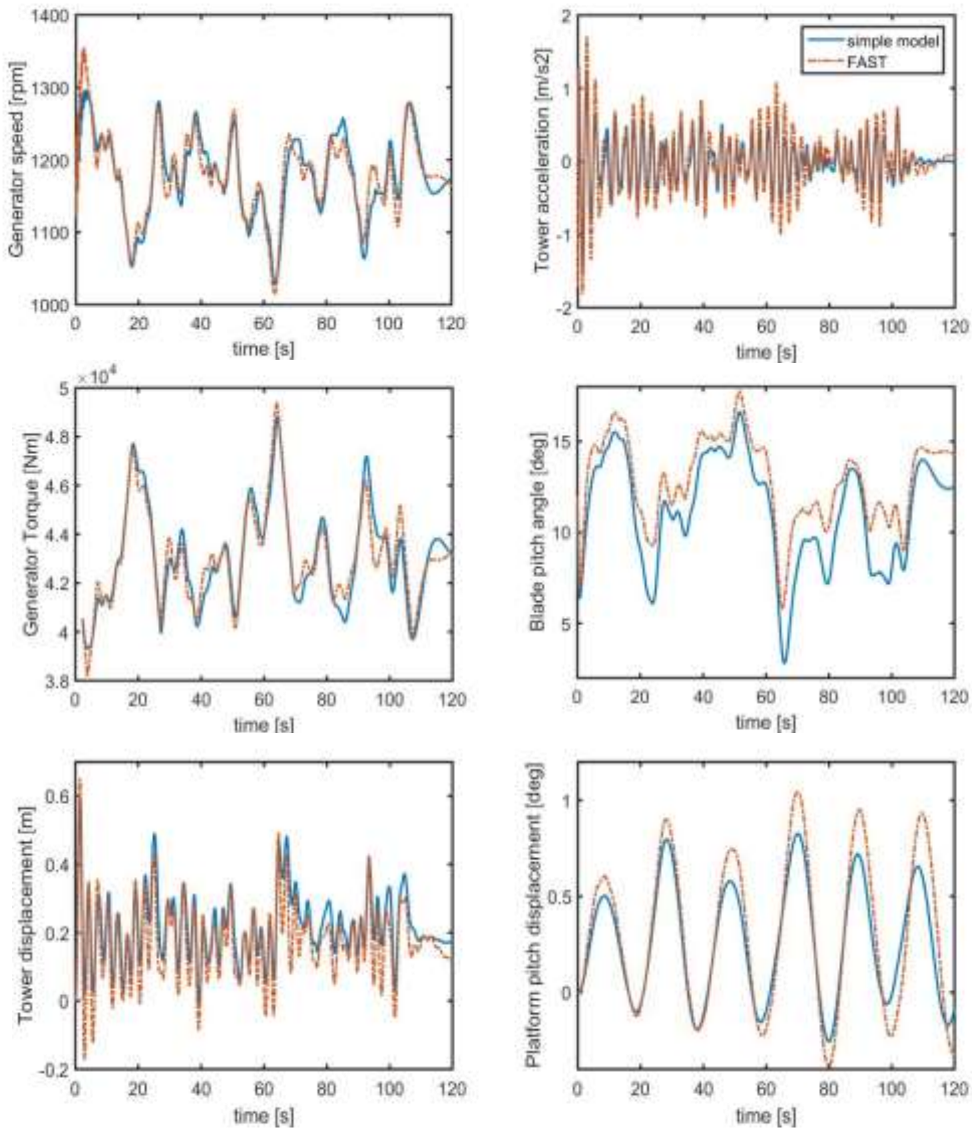


Figure 43: Validation for NTM wind perturbation. From left to right, in order: generator speed (rpm), tower acceleration (m/s2), generator torque (Nm), blade pitch angle (deg), tower displacement (m), platform pitch angle (deg).

From all the tests we can deduct in which way the controller can affect oscillations.

Therefore, platform pitch and tower fore-aft bending movements are not affected significantly by the control activation.

The damping problem relative to the platform is not solved changing the onshore controller in terms of k_i and k_p parameters. This means that there is the necessity to advance and modify the controller.

However a more constant generator speed is obtained for all of the perturbations.

It is also verified that using the onshore controller (with the same PI parameters) the fore-aft bending movement increase as platform oscillations. This is a well know problem [4] that affect platform response, when a controller used for the onshore turbine is applied to the floating one. Different authors report the use of the land-based controller for the FOWT, but obviously adding some adjustment to avoid critical conditions [4] - [17] - [35].

For FOWT the coupling effects cannot be considered linear then, control system strategies have to be rethought, trying to achieve the stability and reduce tower bending movements.

6. Conclusions and further developments

The aim of the project is to build a simplified model of a Floating Wind Turbine that allows studying the general physical system behaviour under applied forces. Deriving a reasonable simplified mathematical model implies neglecting certain inherent physical properties of the system.

Wind turbine models are considered as rigid bodies, time-independent and with lumped parameters characteristics.

The onshore wind turbine is studied before, in order to develop a reasonable floating model. The onshore simplified model is validated and good results are obtained with the open-loop response. It could be considered as a good model for further extensions.

The floating wind turbine studied here is limited to a basic aerodynamic research and hydrodynamic effects are out of the scope.

A preliminary analysis of the complex dynamic of FOWT model, using a linearized one, results to provide a general behaviour that is representing the frequency response.

For the physical system of the floating wind turbine a linear lumped-parameter mathematical model is adopted.

Neglecting nonlinearities, distributed parameters properties may become an important factor in the system dynamic behaviour that has not be forgotten.

In this case, the high number of assumptions affects the frequency response in its amplitude. However, its simplicity permits to understand turbine behaviour and the coupling with control model. Furthermore, there is the capability to extend this model, adding other DOFs.

In this manner studying a simplification of the spar-buoy model aims to identify the dominant physical dynamics behaviour. Furthermore, there is the possibility to add degrees of freedom (DOFs), for future investigations.

However the simplified model is useful for control studies because there is more possibility to solve the problem due to the selection of DOFs (that means selection of applied loads).

For a more accurate analysis, further investigations have the objective to build a more complete mathematical model of the system. Consequently the control can be developed implementing the proposed solutions in the state-of-art [3]- [4] to avoid the negative damping problem.

7. Appendix

7.1 Files “.m” to compile and simulate wind turbine models

```
% initial conditions
wrot0  = 1.2664;                    %rad/s
wgen0  = wrot0*N;
pitch0 = 12;

CertTest_Dir = '..\..\CertTest';
FileRoot='Test26';
   FAST_InputFileName = [CertTest_Dir filesep FileRoot '.fst'];
   TMax            = 120;

% Utilities
rpm2rs = pi/30;
rs2rpm = 30/pi;
deg2rad = pi/180;
rad2deg = 180/pi;

% Cp & Ct tables
load 5MW_NREL_CpCtdata.mat

% ---------------------------------------------------------------------
% wind turbine data
eff      = 0.944;                         % 94.4%
Prat     = 5296610.0;             % Rated power (W) (no losses)
rho      = 1.225;
R        = 63;
Cpmax    = 0.48546;
Trat     = 5296610.0/122.9096;
Precone   = -2.5*pi/180;
TSRo     = 7.55;
Ng = 97;

% ---------------------------------------------------------------------
% drive train model
Bs  = 6215000;              % damping LSS (Nm*s/r)
Ks  = 867637000;            % stifness LSS (N/r)
Jr  = 38759227;             % rotor inertia LSS (kg*m^2)
Jg  = 534.2;                             % generator inertia (kg*m^2)
% pitch actuator
```

```
tau = 1/3;
% -----------------------------------------------------------------------
% Baseline control
%
% sampling time
Ts      = 0.0125;
s       = tf([1 0],1);
%
% speed filter
CornerFreq =   1.570796;            % corner frequency of generator speed filter
alpha   = exp(-Ts*CornerFreq);
%
% control GS-PI: rotational speed
PC_KI        =   0.008068634;     % Integral gain for pitch controller at rated pitch (zero), (-).
PC_KK        =   0.1099965;      % Pitch angle were the the derivative of the aerodynamic %power w.r.t.
% pitch has increased by a factor of two relative to the
                                                    % derivative at rated pitch (zero), rad.
PC_KP        =   0.01882681;     % Proportional gain for pitch controller at rated pitch (zero),s
PC_MaxPit    =   1.570796;       % Maximum pitch setting in pitch controller, rad.
PC_MaxRat    =   0.1396263;    % Maximum pitch rate (in absolute value) in pitch  %controller, rad/s.
PC_MinPit    =   0.0;                % Minimum pitch setting in pitch controller, rad.
PC_RefSpd    = 122.9096;       % Desired (reference) HSS speed for pitch controller, rad/s.
PchLim       = [PC_MinPit PC_MaxPit];       % pitch limits
PchLimR      = [-PC_MaxRat PC_MaxRat]; % rate pitch limits

% VS control look-up-table (constant power)
RSpmin    = 817;                  %rpm
RSprat    = 1161.96;
RSpmax    = 1173.7;
RSp1 = linspace(RSpmin,RSprat,20);
RSp2 = linspace(RSpmax,1400,20);
k_LSS     = 0.5*rho*pi*(R*cos(Precone))^5*Cpmax/TSRo^3;
Rgn2K     = k_LSS*(pi/30)^2*(1/N)^3;
VSspeeds  = [0, 670, RSp1,            RSp2];
VStorques = [0,   0, Rgn2K*RSp1.^2, Prat./(RSp2*pi/30)];
%%%%%%%%%  regionII                regionIII
return
% -----------------------------------------------------------------------
% structural model blades and tower (land-based)

Kb  = 232119*1.63;          %stiffnes blades (N/m)
Kt  = 2721400*2.0;         %stiffness tower (N/m)

wb  = 0.6993;          %first bending natural frequency of a blade (Hz)
wt  = 0.324;            %first bending natural frequency of tower (Hz)
```

```
mb  = 12024;          %blade mass (kg)
mt  = 656330;         %tower mass (kg)

epsb= 0.477465/100;
epst= 1/100;

Bb  = 504.1;          %damping blades (Nm*s/r)
Bt  = 26736;          %damping tower (Nm*s)

rb  = 30.64;          %blade radius (m)
Nb  = 3;              %number of blades

M   = [(mt+(Nb*mb)) (Nb*mb*rb);(Nb*mb*rb) (mb*rb*rb)]; %mass matrix for onshore
B   = [Bt 0;0 (Bb*rb*rb)];        %damping matrix for onshore
K   = [Kt 0;0 (Kb*rb*rb)];        %stiffness matrix for onshore
Q   = [Nb;rb];                    %applied force for onshore
% ------------------------------------------------------------------------
clearvars
load('NTMTWRPTF_NOCTRL.mat')
initial

%% ------------------------------------------------------------------------
%tower & platform models for OC3-Hywind FOWT
mt  = 2.49718E+05;          %tower mass in CM
mp  = 7.46633E+06;          %platform mass in CM
Tnp = 53.5;
w_np= 2*pi/Tnp;             %first bending natural frequency of platform (rad/s)
w_nt= 2.3436;               %first bending natural frequency of tower (rad/s)
epsp= 0.027;                %damping ratio coefficient for the pitch platform displacement
epst= 0.09;                 %damping ratio coefficient for the FA tower displacement

o_p = epsp*w_np;
o_t = epst*w_nt;
wp  = w_np*(1-(epsp)^2)^0.5;
wt  = w_nt*(1-(epst)^2)^0.5;

ht  = 90;
g   = 9.81;                 %gravity acceleration
lt  = 47-10;                %distance from the hinge to the CM
lp  = 89.92+10;             %distance from the hinge to the CM
rt  = (6.5+3.87)/2;         %average radius of tower

It  = (mt*(lt)^2)/3;           %tower inertia [kg*m^2]
Ip  = 4.22923E+09;          %platform inertia for pitch movement [kg*m^2]
```

```
dt  = 2*epst*wt*It;                    %tower damping coefficient
dp  = 2*epsp*wp*Ip;                 %platform damping coefficient

kt  = wt^2*It;                          %stiffness coefficient for the tower
kp  = wp^2*Ip;                        %stiffness coefficient for the platform (includes also the mooring lines and the buoyancy)

Ft0 = 4.16E+05;                     %final thrust force applied to the system [Nm]

I   = diag([1/Ip 1/It]);                              %inertia matrix
D   = [(-dt-dp) dt;dt (-dt)];                        %damping matrix
K   = [(-kp-mp*g*lp-kt) kt;kt (mt*g*lt-kt)];      %spring matrix
Q   = [0 lt];                                       %force coefficient matrix

A   = [zeros(2) eye(2);I*K I*D];
B   = [zeros(2,1);I*[0;1]];
C   = [eye(2), zeros(2)];
sys = ss(A,B,[eye(2), zeros(2)],0);

Ad  = [-o_p wp 0 0;-wp -o_p 0 0;0 0 -o_t wt;0 0 -wt -o_t];
Bd  = [-1 1 -1 1]';

%% Cd matrix coefficients: c1, c2, c3
y0p = 1.56;                    %mean value of Pitch displacement (steady-state value)
y0t = 0.205;                   %mean value of FA displacement (steady-state value)
y0t = 0.220;                   %mean value of FA displacement (steady-state value)
Ft0 = 4.16E+05;              %thrust force at steady-state
Y0  = [y0p;y0t];

Adi = inv(Ad);
Z   = [1 1 0 0]*(Ad\Bd);%(Adi(1,1)+Adi(1,2)+Adi(2,1)+Adi(2,2));
c1  = (-y0p/Ft0)/Z

a   = 0.018;
W   = [a a 1-a 1-a]*(Ad\Bd);%(Adi(3,3)+Adi(3,4)+Adi(4,3)+Adi(4,4));
c23 = -(y0t/Ft0)/W
c2  = a*c23;
c3  = (1-a)*c23;

%% Finish evaluating the state-space system
Cd1 = [c1 c1 0 0;c2 c2 c3 c3];
Cd  = [Cd1;Cd1*Ad];
Dd  = [0;0;Cd1*Bd];
```

```
% verify that the steady-state values are correct
y0  = -Cd1/Ad*Bd*Ft0

sim('provaSSptf.slx')

%% ------------------------------------------------------------------------
% Baseline control for Hywind spar buoy model
%
% sampling time
Ts      = 0.0125;
s       = tf([1 0],1);
%
% speed filter
CornerFreq =   1.570796;              % corner frequency of generator speed filter
alpha      = exp(-Ts*CornerFreq);
%
% control GS-PI: rotational speed
PC_KI      =   0.0008965149;     % FOR HYWIND Integral gain for pitch controller at rated %pitch (zero), (-).
PC_KK      =   0.1099965;        % Pitch angle were the the derivative of the aerodynamic %power w.r.t.
PC_KP      =   0.006275604;     % FOR HYWIND Proportional gain for pitch controller at %rated pitch (zero), sec.

%% ------------------------------------------------------------------------
% run FAST model
% make sure the FASTv8\bin directory is in the MATLAB path (relative path names are not % recommended in addpath()):
% addpath('C:\Users\bjonkman\Documents\CAETools\FASTv8\bin');

initial
CertTest_Dir = '..\..\CertTest';

CertTest_TMax=[20, 20, 20, 70, 30, ...
            35, 70, 20, 40, 25, ...
            20, 20, 40,  0, 20, ...
            20, 70, 60, 60, 60, ...
            60, 60, 60, 200, 60, ...
            120                ];

 for iTest = 24   %[1:13 15:26]

       %------------------------------------------------------------------
       % Set up and run the Simulink OpenLoop model
       %------------------------------------------------------------------

    FileRoot   = sprintf( 'Test%02.0f', iTest );
```

```
  disp('**********************************************');
  disp( ['FAST_SFunc certification test for ' FileRoot] );
  disp('**********************************************');

  FAST_InputFileName = [CertTest_Dir filesep FileRoot '.fst'];
  TMax            = CertTest_TMax(iTest);

  sim('FAST2m.slx',[0,TMax]);

end
      %% ------------------------------------------------------------------------
```

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Silvia Polverini