Master Thesis

Degree in Energy and Nuclear Engineering

Dynamic modelling of a vertical axis wind turbine

******

Supervisor(s):

Prof. Bracco Giovanni

Prof. Mattiazzo Giuliana

Candidate:

Peyrot Simone s278949

Politecnico di Torino

2022

Declaration

I hereby declare that the contents and organization of this work constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

* This work is presented in partial fulfillment of the requirements for **MSc degree** in the Politecnico di Torino

Abstract

Offshore wind power is becoming a profitable way to produce vast quantities of electrical power because of the high availability of the resource and progressive decrease of the design and installation costs. The most widespread technology is nowadays bottom-fixed offshore turbines, but studies are being carried to go in deep water, where floating systems are needed. This causes unprecedented challenges in integrated system design, and still a definitive optimal configuration is not present. So different designs, also concerning the turbine, are being studied. One of them is vertical axis wind turbines, because of their lower centre of gravity and upscaling properties.

The aim of this thesis is to model and simulate a vertical axis wind turbine system in onshore conditions, to determine its behaviour for a future integration on a floating system.

To do that, initially a short review about vertical axis turbines technology was done, together with a comparison of aerodynamic models. Then, a steady-state aerodynamic model is built on MATLAB to find principal solicitations and machine performances. Many turbines were tested on this model, and then 2 of them were chosen to be studied more deeply. To do a proper dynamical simulation, also a control system on 2 variables (torque and pitch) was implemented to improve both performance and safety of the system.

In the following chapters the aerodynamic code was validated, first against QBLADE, then, with a refinement, against literature data. Then the real model on SIMSCAPE Multibody was built, starting from obtained aerodynamic data and CAD models of the machines. The output of this model was confronted with the literature data. With this model, a productivity analysis was done. This simulation was done in turbulent wind conditions in the location of Carloforte, in the southwest of Sardinia, and in a dedicated part simulation conditions were described. The choice of the location influenced the occurrence of the windspeed values, and so the productivity of the system. It was found to be lower than the one of standard wind turbines, but some of its features could be promising for open-sea deployment.

In the end, some considerations were done about productivity and possible improvements of the model.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Global energy problem and offshore renewables.

To face the increase of global energy demand limiting environmental disasters, renewable energy systems are being studied, implemented, and deployed. But they face an important intrinsic problem: the power density in terms of power over land use (W/m2) of the renewable energy systems (solar, wind, hydroelectric, biomass and so on) is 3 or more orders of magnitude lower with respect to conventional plants, even more with respect to nuclear power. It means that these plants will need much more land use to produce the same amount of power with respect to conventional or nuclear power plants.

Since there is not enough land that can be safely converted to renewable energy uses without causing too many environmental and social disasters, a plan is to try exploiting the energy in sea or oceanic regions. Many concepts of renewable energy systems for marine environment are being developed and, in some cases, deployed. Some examples are wave energy converters, tidal turbines, and offshore wind turbines. The latter is the most diffused technology and some plants of industrial scale have already been installed in some areas of the world.

They all are renewable based, because they are one of many ways in trying to endure the climate crisis and mitigate its effects.

1.2 Introduction about offshore wind

In this document the focus will be on offshore wind because it is the only renewable energy technology that has already been deployed in enough quantity to be considered at a global level. But at the same time most of the potential is still untapped because of some main technological challenges.

1.2.1 Opportunities of offshore wind plants

Offshore wind is an interesting technology to increase energy production without increasing the land use for many reasons. It has an environmental impact which must be evaluated and limited, mainly in construction and decommissioning phases due to the recycling and/or disposal of the material (large quantities of composite/fiberglass, metals, concrete, and rare earths). But many problems that occur in other energy systems are not present (greenhouse gases and pollutants emission during operation).

First, offshore wind speeds are usually higher at sea than on ground. This is important because little increases in wind speed have important effects in energy performance: a turbine in a 15-m/s wind is able to provide around two times the energy with respect to the same machine in a 12 m/s wind. Faster wind speed offshore means a lot more energy to be exploited. Then, offshore wind tends to be less variable than onshore, with less variations in both space and time. A more constant wind supply means a more reliable resource, with an increase in annual energy production and so profitability of the plants.

It must be also considered that many coastal zones have high energy needs. For example, around half of the United States' population lives in zones near the coast, in particular in the more important coastal cities. So, offshore wind farms in these zones can be useful to satisfy this energy demand from nearby resources.

So, offshore wind power generation is becoming in some countries an interesting and profitable way to produce electrical energy. Offshore wind plants still are not very diffused in the world: they produce just the 0.3% of total global electricity. Nevertheless, the potential energy extraction is very high, and the installed power is increasing rapidly in some places in the world. The installation rate is quite high every year, and it is projected to grow in the next years.

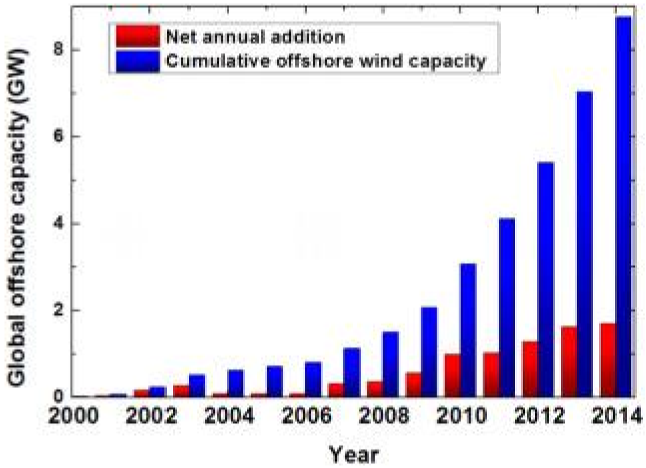

Figure 1: cumulative offshore wind capacity

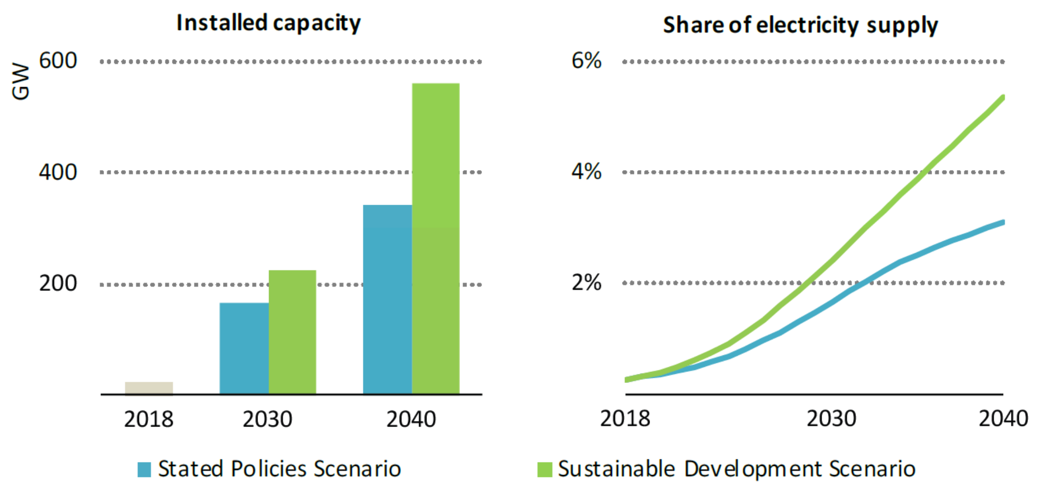

Figure 2: future trends for offshore wind

Moreover, the average predicted capacity factor for an offshore wind installation is more favourable than the onshore case (around 35% vs 25%) (International Energy Agency, 2019).

Europe, in the North Atlantic zone, is the place where the development is higher. Most of these installations are fixed offshore systems, so they benefit from the North Sea characteristics:

- Low seabed (around 50 m on average).
- High availability of the resource.

Another benefit in Europe is linked to the hydrogen strategy: the plan to produce green hydrogen for industrial uses will need power to gas plants to exploit the electricity surplus production. In fact, the cost of green hydrogen production is strictly dependent on the levelized cost of electricity. Offshore installation also means no land use on the ground. This aspect will become crucial to preserve fertile soil and reduce both impact on other activities or ecosystems and reduce the growing opposition to these kind of plants from the local people (NIMBY and NIMTO syndromes).

Then, even if wind can have gusts, high turbulence and variation in speed and direction, its variations are usually less steep than irradiance variations. They can have ±20% of ramp from the mean value in an hour. It is a fast and important variation, but anyway better than the irradiance ramps for PV, which can reach ±40% in one hour.(International Energy Agency, 2019) Because of lower ramps and higher capacity factors with respect to different other renewables, they can be used as a “non-programmable baseload” in electricity networks. This aspect will become very important when more conventional plants will be shut down to meet climate change targets, removing more flexible plants from the energy mix.(Genovese, 2019)

1.2.2 Offshore wind plants: problems

There are some main challenges to solve to accelerate development of this technology. These challenges are due to economic, environmental, and technical aspects.

First, these are installations that require great capital investments. Nowadays the installation cost of an offshore wind farm is around 4000 €/kW, much higher than other technologies (PV costs around 1500-2000 €/kW for small plants, even lower for big installations). Then, the most promising plants are the ones in the deep sea, where fixed installation is not possible, and floaters are needed. Here another issue arises: since floating turbines still are not much exploited, still there is not a good integration of supply chain between the producers of the various components. Turbine, floater, moorings, electrical cabling, and other components are often provided by different producers without an integrated design. This means that each component is optimized on its own, without considering the behaviour of the rest of the plant. This causes integration problems when the system must be assembled, makes installation more difficult (Collu & Borg, 2016) and could make the plant utilization and control complicated.

Then, electrical networks must be adapted to manage these plants, that have high installed power while being far (or very far) from the consumption places. So long high voltage lines are needed, in some case even HVDC. Most networks are not equipped for this kind of installations, and some of them are obsolete also now in some parts of Europe. This new nonprogrammable plant is inserted into the electrical grid, and so its impact must be considered in the grid management. This is a crucial problem: electrical networks will experience growing stresses in the following years because of the increase of non-programmable energy production(Genovese, 2019). These stresses can cause curtailment of the produced power, reducing the profitability of the plants, or in the worst cases also outages, failures, or other problems. This can be an important problem for new technologies, when unforeseen issues are common because of limited experience.

Third, the environmental impact on the sea life of this technology still is not known. Some studies are being carried on, but still there is nothing conclusive.

Offshore wind turbines still are not a mature technology. Even if for horizontal axis wind turbine there is a standard configuration (3 blades, variable speed, upwind, variable pitch, and yaw), there are many possible solutions for the base of fixed offshore turbines and even more for the floaters. Still there is not an optimal winning concept on the others, so there are and will be further study and experimentations.

There is also a returning interest for vertical axis wind turbines. In fact, even if less efficient, some of their characteristics, like the lower centre of mass, are more suited to floating offshore systems.

1.2.3 Offshore wind plants: installations

There are already some installations both for the case of fixed offshore turbines and for floating ones. Fixed wind turbines are already deployed in some big offshore farms, especially in the North Sea (for example the Hornsea wind farm, with installed power of 1.2 GW). On the other hand, only some pilot plant for the floating wind turbines has been built up to now.

All these considerations are valid for horizontal axis wind turbines: up to date, there is only one floating vertical axis wind turbines pilot plant. It was built by the seatwirl company, and it is composed by a straight-bladed vertical axis wind turbine with a nominal power of 30 kW. It is already grid-connected.

Figure 3. SeaTwirl pilot plant

1.3 Vertical axis wind turbines history

Even if the interest in vertical axis wind turbines is now re-emerging for offshore applications, the first patents were at the beginning of the XX century. They were 2 main kinds of devices, from which all the others emerged: drag-type turbines (Savonius) and lift-type turbines (Darrieus, H-rotors). Only the latter were found to be suitable for upscaling and power production. Nearly no research was done until the 1970s, when events such as the 1973 Arab oil embargo gave to western countries an incentive to assess their reliance on foreign energy sources and try new ways to produce energy. The Darrieus concept, which was little known outside of France, was reintroduced in the mid-1960s at the National Research Council of Canada (CNRC). A large portion of the Canadian wind turbine development was focused toward VAWTs, and several projects were initiated, lasting until the1990s. In the early 1970s, also Sandia National Laboratories (Sandia) was assigned by the US Department of Energy (DOE) to investigate alternative energy resources and quickly learned about the Canadian VAWT research. The VAWT concept subsequently became the focus of Sandia's renewable energy research. These 2 laboratories were the first to study, project and build vertical axis wind turbines with nominal power higher than 100 kW. (Möllerström et al., 2019)

After that, many other turbines were built in 1980s and 1990s: the biggest was called EOLE, a curved blade Darrieus turbine with a nominal power of 3.8 MW. At that time, in fact, still there was not a winning concept of wind turbine: many shapes and principles were tested contemporarily.

The causes for the adoption of a standard horizontal axis concept, instead of a vertical one, are not universally agreed. One motivation was that many of the vertical axis devices suffered different failures, mostly due to fatigue on the blades or errors in manufacturing. This happened since the aerodynamics was more complex and less studied with respect to the one of “standard” turbines, so the loads on the blades and structure were not always properly assessed. Because of that many of the turbines shut down before the planned end or even suffered failures during operation and the abandoning of the project. Then, the Danish industry, which was the main wind turbine producer in 1990s, was setting as standard the 3 bladed horizontal axis configuration. This further concentrated the studies on one kind of machine not considering the other.

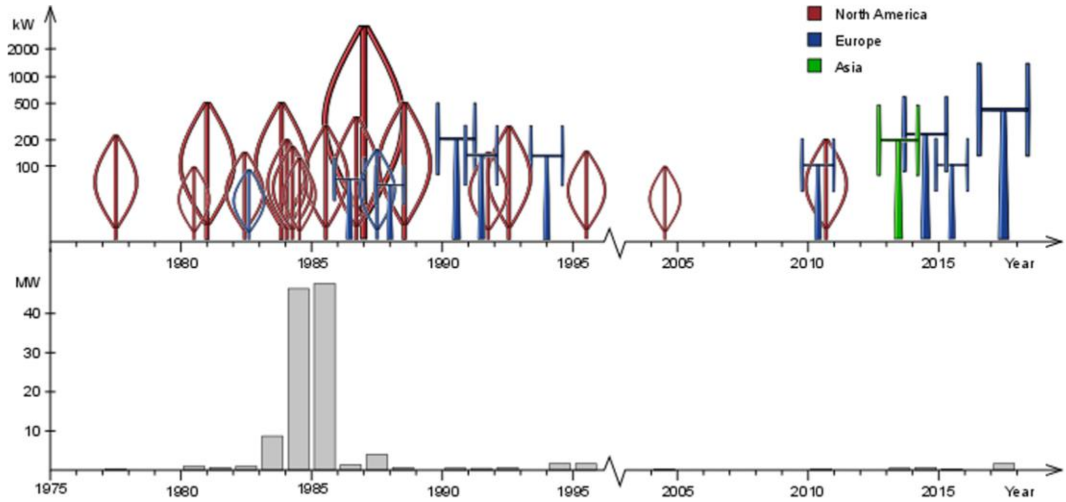

Figure 4: vertical axis wind turbine history

Anyway, some studies were carried out also afterwards, but without changing the whole picture. Now there is a growing interest in vertical axis wind turbines. The offshore wind turbines are still a new concept, and it is not sure if the standard machine is the best wind turbine to be mounted on a floater for far offshore applications, because of the height of its centre of mass, variety and complexity of solicitations that occur.

Chapter 2

Vertical axis wind turbines technology

2.1 Technical characteristics (Strength – Weaknesses - Opportunities - Threats analysis)

Vertical axis wind turbines still are not a mature technology, since radically different configurations are still being proposed and tested in terms of geometry, modelling, and construction. In fact, in this case there are still some different configurations which are studied: there is not an only optimal design. This kind of turbines can be divided in 2 main categories, with reference to their principle of operation:

- Drag-type turbines, like Savonius turbines. They exploit the resistance of a semi-circular plate with respect to the wind to extract power. They are easy to build, because they do not employ an airfoil shape and have a very simple design. In any case they have very low efficiency (<20%) without many margins of improvement. So, they are not suitable for upscaling or industrial deployment.(Manwell et al., 2010)
- Lift type turbines. They are of 3 main kinds, according to the blade shape, and are in general more complex to build with respect to the Savonius turbines.(Hand et al., 2021)
    a. Straight blades, also called H-rotors.
    b. Curved blades (Darrieus, modified Darrieus).
    c. Helical blades (Gorlov turbines).

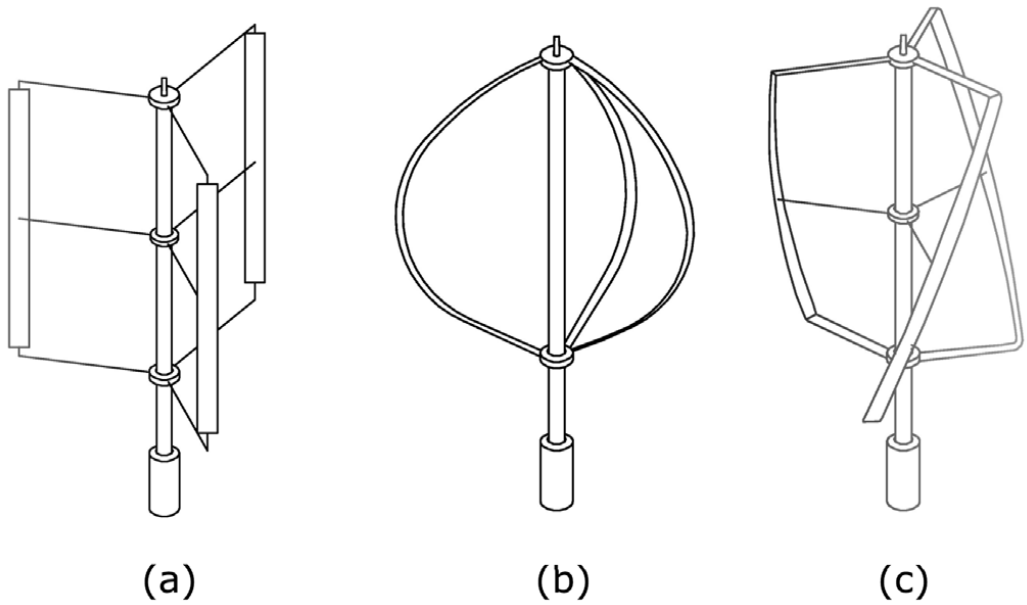

Figure 5: turbine tipologies

Straight-bladed turbines are the simplest and cheapest to manufacture, since they have straight blades, usually with constant pitch and with the same airfoil all around its length. There is often a narrowing at both ends to reduce the entity of tip losses. They grant good aerodynamic efficiency (35-40%), do not need guy cables and have a good stall control, which automatically reduces overspeed. On the other hand, they are subjected to high, fast cyclical loads and torque ripple which are relevant in term of fatigue of the components and need support struts which reduce aerodynamic efficiency.

Curved blades turbines often have blades in the shape of a troposkine curve, which is the shape a spinning rope assumes without gravity if blocked at the 2 ends. Also parabolic, catenary, or modified troposkine are used because of their simpler shape. With respect to the straight blades, they experience lower structural stresses, since their shape is optimized to minimize bending moments: struts aren't always needed. Then, since they have no free blade tips, losses from tip vortices are avoided. They have, nevertheless, need for guy cables to stabilize the rotor, which can interfere with the air flow. Then, these turbines usually have poor stall behaviour since their variable radius can cause early stall near the ends. Another very important aspect is that curved blades are longer per power unit with respect to the straight ones and are more expensive to manufacture and build.

In helical-bladed turbines, the geometry of the blade is swept along the turbine's circumference of rotation. This is done to eliminate the torque ripple, which is harmful for the life of the turbine. It has also quite good self-starting characteristics with respect to the other kinds of vertical axis wind turbines, that do not self-start quickly. This happens at the expense of the peak efficiency and dynamic stall, which occurs at lower tip speed ratios with respect to the other kinds of turbines. Manufacturing of the blades is very expensive for 2 main causes: the shape, which is complicated, and the low tolerances allowed.

The first deployment of lift-based vertical axis wind turbines which were built in the 1970s-1980s and had curved blades. This happened because they were designed to resist both very high centrifugal stresses at high rotation speed and to minimize bending moments. They were mainly pilot plants, built to test the on-field behaviour of the technology. The biggest vertical axis turbine was the EOLE deployed in Quebec in 1987, with a rated power output of 2.5 MW, even if most turbines were around 200-300 kW of power output. Straight bladed turbines also are quite diffused, because of the ease of manufacturing, good performances, and stall behaviour. Anyway, they have much smaller deployment and size with respect to standard horizontal axis wind turbines. Most of the commercialized ones were used in urban environment, since they have good yield in when there is low or turbulent wind due to their omnidirectional nature: they have, anyway, very small size (up to some kW). (Sutherland et al., 2012)

2.1.1 Main issues of the technology

The causes of the limited deployment and scale of vertical axis wind turbines were due to an important intrinsic limit in past years: the fatigue behaviour. When the first blades were built, there was not complete understanding of fatigue behaviour of materials. This was made worse from the fact that a 2-bladed turbine experienced at every cycle a torque variation from zero to the maximum value in these environmental conditions. So, there was an early failure of blades, and the project was abandoned. Further studies faced and greatly reduced this problem. In fact, there is no proof that a well-designed vertical axis rotor has worse fatigue behaviour with respect to an horizonal axis one. Moreover, cyclic loading depends strongly on the rotation speed: large turbines have lower rotation speed so slower load variations, and so less fatigue problems.(Hand et al., 2021; Manwell et al., 2010)

Anyway, still some main problems remain:

1. Vertical axis wind turbines need longer blades with respect to a standard rotor having the same swept area. A Darrieus turbine, for example, has blades that are long twice with respect to the horizontal axis blades. This causes higher costs of the blades and need of very careful structural design.

2. Aerodynamics is more complicated with respect to the horizontal axis rotors. In fact, angles of attack in this kind of turbines experience an important variation around one cycle, both in value and in sign. This means blades work in stall or deep stall condition in a significant part of the time. So, the aerodynamic simulation must consider the stall conditions. Then, the turbine intersects its wake in the downward part of the stream, adding turbulence and reducing power extraction. This happens also because the aerodynamic design and analysis of vertical axis wind turbines has received very limited attention thus far, despite the benefits of this technology being well-established in the literature. Up to now the optimal design is not universally defined. It is emphasised that further investigation is needed as the VAWT is starting from an inferior technological position to the HAWT due to the lack of development especially over the past two decades.
3. Lower efficiency with respect to horizontal axis design. Also lift type turbines, which have good efficiency, reach a maximum power factor Cp around 40% while commercial multi-MW horizontal axis turbines reach 50%. (Manwell et al., 2010)

These important aspects have, up to now, impeded a mass construction of vertical axis wind turbines.

2.1.2 New opportunities

This kind of turbine represented a very popular option for urban environment, due to its superior performance in highly unstable flows, with low noise emissions (a consequence to its operation at low TSRs). Furthermore, they have a resurgence in interest for a large-scale offshore floating environment: they have some important features that could make them competitive with more established designs. There are some main reasons. All of them are referred to lift-type turbines, drag turbines were not considered:

1. ***Design simplicity:*** One of the primary incentives for using this technology is to attain a higher level of reliability reducing mechanical complexity and optimising robustness for the harsh offshore environment. They can be equipped with blades of uniform and untwisted cross-section allowing simple manufacture and low cost (horizontal axis wind turbines have twisted blade profiles which vary along their span). They have an omni-directional nature, making it insensitive to wind direction and allowing a simpler mechanical design as a yaw mechanism is not needed. This is

beneficial for offshore systems, as the yawing system is one of the primary sources of failure in the horizontal axis turbines' mechanical system. Moreover, the floating yaw control system will also have to consider the platform hydrodynamic motions and therefore will be a lot more complex compared to bottom-fixed ones. High reliability is imperative for an offshore environment, owing to the additional difficulties for access and maintenance compared with onshore turbines. By employing a direct-drive generator (no gearbox), the complex speed increasing multistage gearbox is eliminated together with all associated potential failures. The direct coupling of the driveshaft to the generator also ensures the energy loss during the mechanical to electrical energy conversion is minimal. A direct drive generator is larger and heavier than a conventional geared generator, but this is not a major obstacle, since the generator is positioned at the base of the turbine. This VAWT allows greater design freedom for the generator to be optimised with a focus on cost and robustness constraint rather than on the low mass constraint.

2. ***Offshore floating suitability:*** In an offshore HAWT array, the wake created by upstream turbines worsens the performance of downstream turbines through a velocity deficit and an increase in freestream turbulence. It is clear downstream HAWTs operate less efficiently than in isolation due to the turbulent wake produced by upstream turbines. Consequently, a very large HAWT spacing in the order of twenty turbine diameters D is required to allow the flow to reenergise sufficiently for downstream turbines to achieve performance levels comparable to those in isolation. Despite this, a trade-off is usually taken between the wind farm efficiency and its footprint, whereby HAWTs are positioned 6–10D in the streamwise direction and 3–5D in cross-streamwise direction.

Wind farm power density in W/m2 of counter rotating VAWTs has the potential to be an order of magnitude higher than that of an equivalent HAWT array and thus demand less stringent spacing of offshore turbines. Field experiments show the energy deficit in the VAWT wake can recover in only 4–6D.

Figure 6: rendering of offshore vertical axis turbines

3. ***Scalability:*** One of the primary advantages of moving offshore, is the potential to scale the wind turbine to a large rated power. There is a growing trend towards the development of large-scale offshore wind turbines as the system becomes more cost-effective with increasing scale. This happens since installation cost scales more rapidly with turbine number with respect to turbine size. Horizontal axis turbines suffer from blade cyclically reversing gravitational loads. On the other hand, the vertical axis turbines experiences varying aerodynamic forces, which have a more favourable scaling behaviour than gravitational loads: in fact, aerodynamic forces scale with the square of the blade length (with the swept area), while gravitational forces scale with the cube of the blade length. (Hand et al., 2021).

Chapter 3

Objectives and model parts

3.1 Model objectives

The aim of this work is to analyse the dynamic modelling of a vertical axis wind turbine. To do that, a Simscape Multibody model will be implemented to consider the main aspects of the system. This model will be composed of:

- Vertical axis wind turbine, including pitch and torque control systems.
- External variable wind input.

A dynamic model was implemented on MATLAB SIMULINK, on its extension SIMSCAPE MULTIBODY. This application was chosen because of its versatility. The model was implemented putting together models and experiments from different papers and reports "welding" the most useful parts. The simulink model was built anew even if the simulations in papers were present. This choice was forced for many reasons:

a. Many aerodynamic simulations were carried out using computational fluid dynamics, which used dedicated software and had high computational cost. Finally, they were often steady-state and/or were valid only in some conditions (only certain values of tip speed ratio).

b. Other papers which indagated the aerodynamic aspect did not implement a model for force estimation: they had the physical object and started everything from measurements. This was a problem since experiments were often done with very small turbines (so low Reynolds numbers) in a controlled environment.

c. Many of the "full system" studies, which considered in a more complete way dynamic effects, analysed only electrical drives and converters. The turbine dynamic behaviour was just represented by an efficiency map, where the efficiency was plotted with respect to the tip speed ratio. Often this curve came from measurements. Here is an example(Rossander M, 2017):

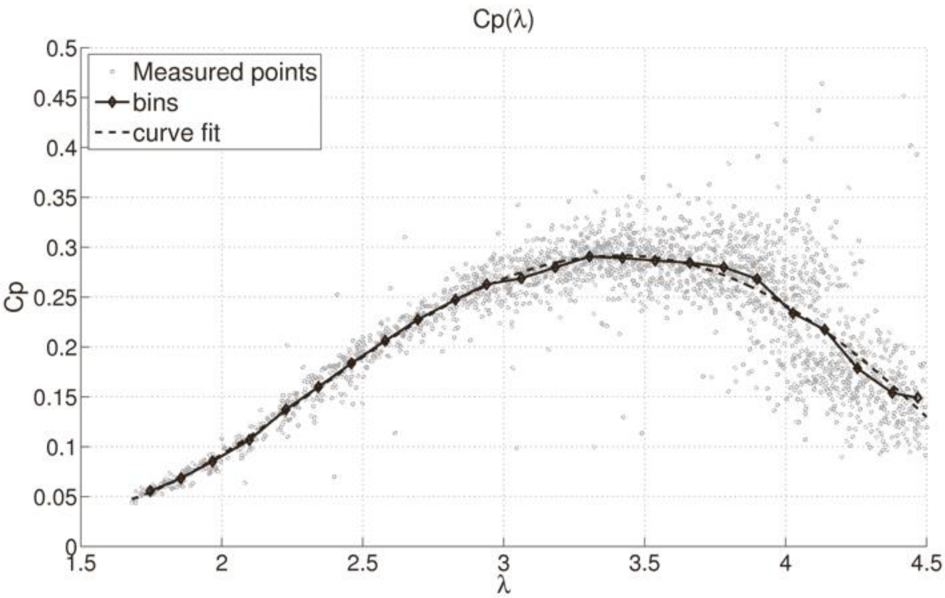

Figure 7: experimental power coefficients' interpolation

Since in this thesis there was not a real turbine, it was not possible to do a model validation on a physical object. So, experiment results on smaller turbines were used, while for bigger machines the only way to validate this model was to check if the behaviour was similar to the one present in the literature in simulation codes. At first an aerodynamic code was developed on MATLAB to reduce the dependence from experimental data which can be difficult and expensive to obtain. This was done in order to have a flexible tool which could be easily adapted.

To validate the results, the software QBLADE was used. It is an open-source software developed by the TU Berlin (Teknische Universität), which is used for pre-design of the system to have a first overview of the turbine performances in different conditions. Its main strengths are the fact that it is very simple to create a turbine and implement a simulation, and it has a very intuitive and user-friendly interface. The simplicity of the simulation also causes an important drawback. In fact, QBLADE does only have a quite simple implementation which neglects some aerodynamic effects, like dynamic stall, drag from the blade struts.

After the validation, the results of the MATLAB code and QBLADE simulations were compacted into data structures to be loaded into the Simscape environment to carry on the simulations.

3.2 Considered turbines for analysis

In this work, many models of turbines were considered. The main applications for this kind of devices are in urban areas with turbulent winds, so with very small size and simple fabrication. Since one of the main advantages of offshore systems is the possibility of using big machines, very small systems are not much of interest for many motivations. First, in wind power the cost of installation of a wind farm grows much faster with the turbine number than with the turbine size: it is cheaper to build one 1 MW turbine than 2 of 500 kW each. Then, similitude laws lose accuracy when the turbine scaling factors becomes very important. While doubling the rotor dimensions introduces a manageable error, a scaling bigger than 10 can lead to important errors since performance depends on the aerodynamic coefficients, which in turn are found experimentally for a fixed size of the blade. So, plants with a minimum size of 10 kW are considered.

Here arises a problem: very few working plants were built for systems with rated power >10 kW, and some of them were for research purpose and not commercial turbines. Some tests were done, but many failures happened.(Möllerström et al., 2019). 5 machines wile considered here:

1. 12 kW H-rotor built by Uppsala university.(Rossander M, 2017)
2. 200 kW H-rotor built by Uppsala university in collaboration with VertiWind Gmbh(Kjellin, 2012; Rossander M, 2017)
3. 500 kW Darrieus rotor built by Sandia national laboratory. It was the first extensive campaign about a vertical axis wind turbine with a 1:1 prototype.(Sutherland et al., 2012)
4. 5 MW modified Darrieus rotor studied in the DeepWind project by Sintef. This is only a very detailed numerical model with a 1 kW prototype, since the real device was never built because it needed some more studies and testing on crucial aspects.(Svendsen H. & Merz Karl O., 2012)
5. 6 MW modified straight rotor with floater studied in the DeepWind project by TUDelft. This is only a numerical model, since the real device was never built because that was not the aim of the study(Vlasveld et al., 2018), and important capital expenses are needed for these kinds of plants, even more if they are first-of-a-kind.

3.2.1 Uppsala H-rotors

They are three bladed H-rotor VAWT with fixed blades. The driveline is a directly driven design with the generator at ground level, which gives design freedom for the generator. It simplifies implementation of a large multi-pole permanent magnet synchronous generator (PMSG). The placement of the generator gives the turbine a low centre of gravity, which is beneficial for floating offshore applications. The power extraction from the wind is controlled by adjusting the rotational speed, which in turn is controlled by the electric power drawn from the generator. The power extraction above nominal is reduced with passive stall of the turbine by forcing the rotational speed down.

Wind turbines with fixed blade pitch must adjust the rotational speed to the wind speed to maximize wind energy absorption. A directly driven PMSG has high efficiency, but it has some problems. Here the voltage and frequency in output vary with the rotational speed, and so the electric voltage generated by a PMSG cannot be directly connected to the grid. A common solution, even in many modern horizontal axis wind turbines, is to rectify the generator voltage to DC which is then inverted back to an AC voltage suitable for the grid, by a power converter. The power electronics is also very important in this system because it allows to modify the rotational speed of the generator, and the torque by consequence. In fact, since the turbine is directly driven, without gearbox, there is no other way to control the power output.

This concept has no yaw, pitch, or gearbox and one of the power converters is replaced by diodes. The concept therefore has a potential to reduce downtime and failure rate of wind power, since there were not some troublesome components, the gearbox, or the yawing system.

In both turbines blades are straight, with the same airfoil on the whole length, constant pitch, and a limited narrowing on the tips to reduce tip effects.

2 devices were built: a test device with 12 kW of rated power and a first – of – a – kind machine with 200 kW of rated power.

Figure 8: 12 kW prototype

Figure 9: 200kW prototype by Uppsala University

Properties of the 2 turbines (Kjellin, 2012):

NOMINAL DATA			
Operational and performance data			
Rated power	[kW]	12	200
Rated rotational speed	[rpm]	127	30
	[rad/s]	13.3	3.14
Rated wind speed	[m/s]	12	12
Cut-in wind speed	[m/s]	4	4
Cut-out wind speed	[m/s]	25	25
Geometry			
Rotor radius	[m]	3.25	13
Total height	[m]	6	40
Rotor height	[m]	5	25
Blade chord	[m]	Tip 0.15, bulk 0.25	Tip 0.42, bulk 0.7
Solidity	[-]	0.23	0.16
Swept area	[m2]	32.5	624
Blade profiles		NACA0021	NACA0021
Masses and inertias			
Rotor inertia	[kgm2]	525	TBC
Generator inertia	[kgm2]	16.9	TBC

Table 1: Uppsala turbines' data

3.2.2 Sandia Darrieus rotor

The Sandia 34-Meter Test Bed Turbine was a Darrieus VAWT, with a diameter of 34-m. It was designed and then constructed by Sandia National Laboratories to provide a testbed for the research on a full-scale turbine. The machine was a turbine operating at variable speed from 28 to 38 rpm. It was not designed for commercial deployment. So, the used philosophy was of a conservative design; optimizations for a commercial design were not implemented. In fact the main objective of the project was to validate the codes to do the design. Because of that the turbine was modular, so that many parts, could be changed.

The design still had to be verified: the machine was built to endure and be able to withstand a great variety of loads, not to be commercially competitive. The Test Bed was used for research until its decommissioning in the late spring of 1998. This was because the foundation suffered a failure, with cracks forming on its surface, due to fatigue from cyclical loading.(Möllerström et al., 2019)

The rotor used for the Test Bed was equipped with two blades and height-diameter ratio of 1.25. The rotor was kept stable using some sets of fixed guy cables. The aluminium blades were built using aerofoils that were shaped into a troposkine shape to reduce bending moments. The final design used sections constructed using aerofoils with chords of 1.22 m, 1.07 m, and 0.91 m. The widest section used a NACA 0021 profile, and the other two used a tailor – made SAND 0018/50 profile. The solidity of the rotor was 0.107.

The turbine was equipped with a variable-speed, constant frequency generator system with a PLC. The generator was dimensioned to operate the rotor at its nominal power of 500 kW even though its peak power rating was of 625 kW. The generator’s torque, and thus speed, was controlled by a specialized electrical drive, called Load commutated inverter (LCI). This drive created the connection from the rotor to the system which was used as grid /load simulator. It happened by converting the variable voltage and frequency of the generator to the constant voltage and frequency which were required.(Sutherland et al., 2012):

NOMINAL DATA		
Operational and performance data		
Rated power	[kW]	500
Rated rotational speed	[rpm]	37.5
	[rad/s]	3.93
Rated wind speed	[m/s]	12.5
Cut-in wind speed	[m/s]	4
Cut-out wind speed	[m/s]	25
Geometry		
Rotor radius	[m]	17
Total height	[m]	45
Rotor height	[m]	42.5
Blade chord	[m]	1.2/1.07/0.91
Solidity	[-]	0.107
Swept area	[m2]	955
Blade profiles		NACA0021, SNL0018/50
Masses and inertias		
Rotor inertia	[kgm2]	5.22E+06
Generator inertia	[kgm2]	5E+04

Table 2: SNL turbine data

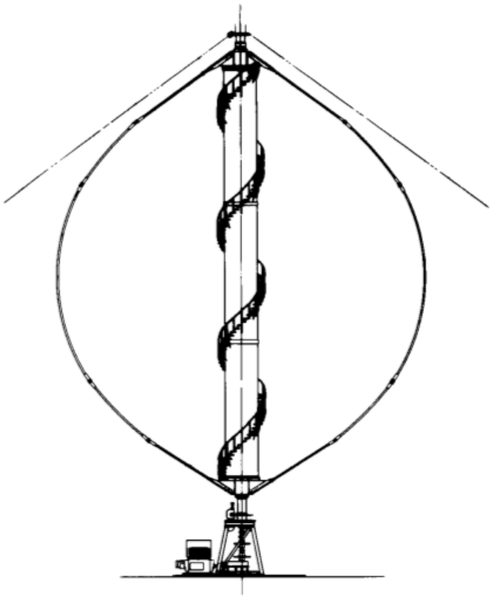

Figure 10: 500 kW Test Bed from Sandia National Laboratories

3.2.3 DeepWind rotor

Another design which was considered was the DeepWind design, which was the conceptual project of a floating vertical axis wind turbine with a modified Darrieus shape. Of this model it was initially considered only the turbine part for onshore evaluation, without considering the floater and its hydrodynamics. The original design combined a Darrieus rotor and a floating spar rotating in its entire length. Towards the seabed at the end of the rotating platform a bottom fixed generator converts the power, and a torque absorption system distributes the loads to the seabed. DeepWind presents a simple design with few components (without nacelle) and with good balancing properties, omnidirectional operation with respect to wind direction, light weight rotor and O&M potentials.

The rotor shape was a modified Troposkien shape with NACA0018 profile at the equatorial section, and at the root sections NACA0025 to ensure that the blade root sections can withstand the bending moments that occur in such large structure. This way, the center sections of the blades can remain slender resulting in a lighter structure with reduced drag losses. (Svendsen H. & Merz Karl O., 2012)

In Table 3 main dimensions and operation data are given.

NOMINAL DATA		
Operational and performance data		
Rated power	[MW]	5
Rated rotational speed	[rpm]	5.25
	[rad/s]	0.55
Rated wind speed	[m/s]	14
Cut-in wind speed	[m/s]	4
Cut-out wind speed	[m/s]	25
Geometry		
Rotor radius	[m]	60.49
Total height	[m]	143
Rotor height	[m]	130
Blade chord	[m]	5
Solidity	[-]	0.1653
Swept area	[m2]	11996
Blade profiles		NACA0018, NACA0025
Masses and inertias		
Rotor inertia	[kgm2]	2.37E+08
Generator inertia	[kgm2]	5.00e+05

Table 3: 5MW DeepWind concept data

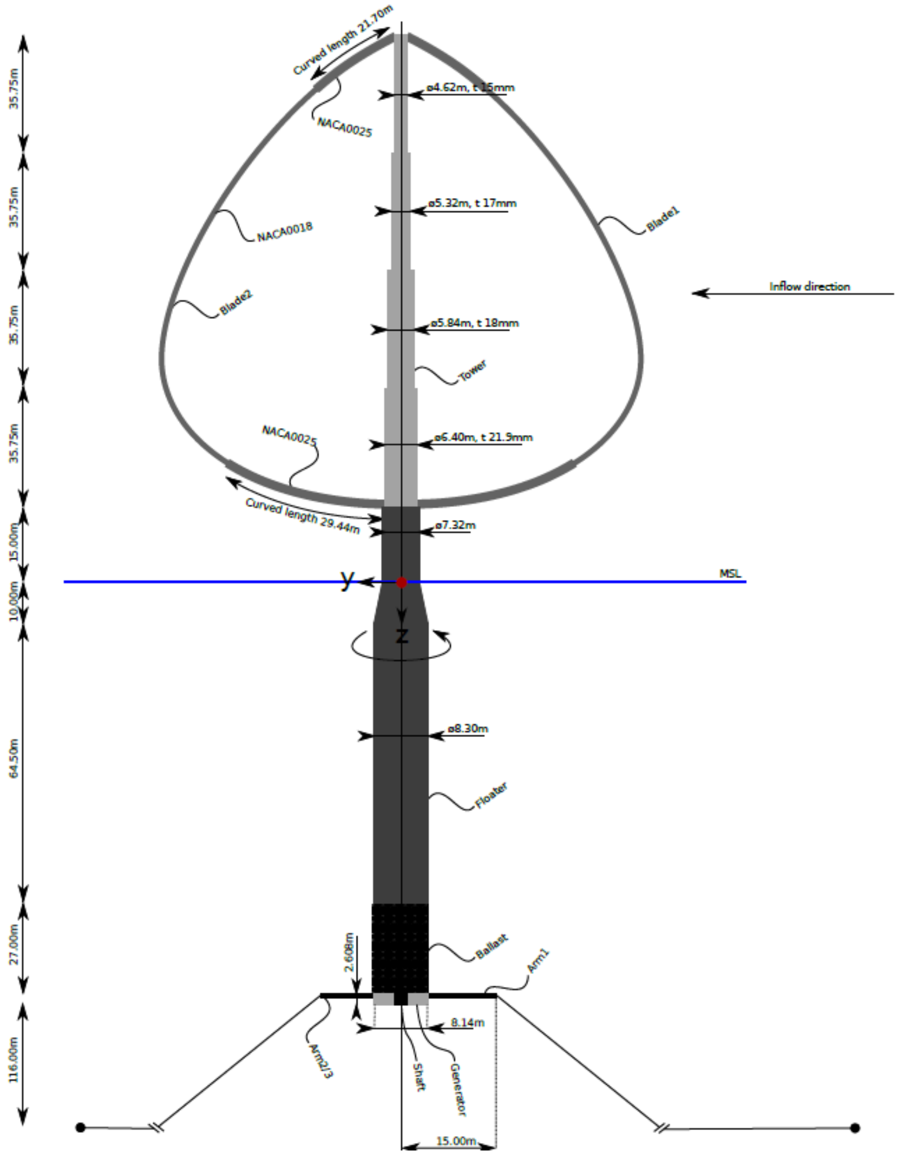

Figure 11: 5MW DeepWind concept by SINTEF

3.2.4 Delft rotor

Another design which was considered was the design proposed by the Delft University, which was the conceptual project of a floating vertical axis wind turbine with a straight bladed shape. Of this model it was considered only the turbine part for aerodynamics evaluation, without considering floater and hydrodynamics. The original design combined a straight, inclined blades rotor and a semisubmersible floater with the trifloater shape. It had simple design with few components (without nacelle) and good balancing properties, omnidirectional operation with respect to wind, light weight rotor and O&M potentials. The 3 blades design is important to have a reduced torque ripple. An important feature of this turbine model is the active pitch control, useful at high windspeed to reduce the thrust on the system when the windspeed exceeds the nominal one.(Vlasveld et al., 2018)

The rotor shape was a modified straight bladed shape with an aerofoil which was custom-made (TUD-0124) but had similar characteristics with respect to a simple NACA0024 aerofoil. The blade inclination (larger upwards, as shown in the figure) is fundamental to achieve higher energy power output exploiting zones with higher windspeed. This is a conceptual design: the actual machine was never built.

NOMINAL DATA		
Operational and performance data		
Rated power	[MW]	6.2
Rated rotational speed	[rpm]	8.46
	[rad/s]	0.89
Rated wind speed	[m/s]	11
Cut-in wind speed	[m/s]	4
Cut-out wind speed	[m/s]	25
Geometry		
Rotor maximum radius	[m]	70
Total height	[m]	140
Rotor height	[m]	140
Blade chord	[m]	5
Solidity	[-]	0.21
Swept area	[m2]	17700
Blade profiles		TUD0124 (Similar to NACA0024)
Masses and inertias		
Rotor inertia	[kgm2]	1.99E+08
Generator inertia	[kgm2]	5.00e+05

Table 4: TU Delft 6 MW turbine data

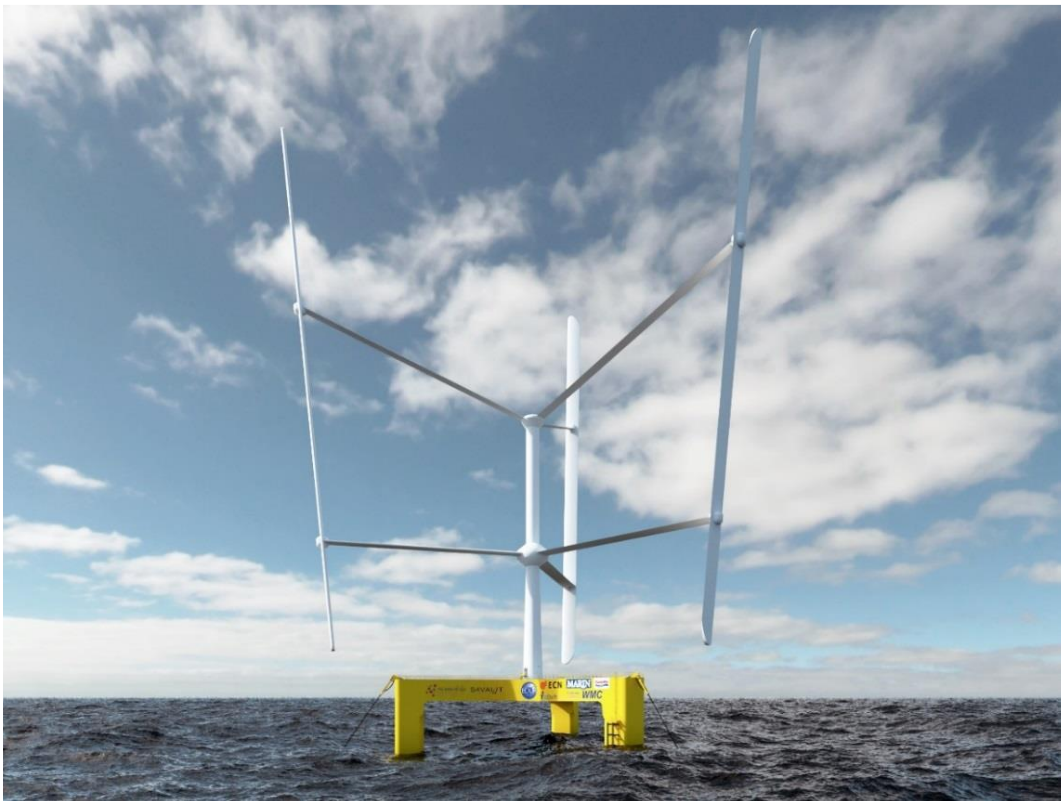

Figure 12: 6 MW concept by TUDelft

3.3 Variable wind speed data

The wind speed distribution is heavily influenced from the geostrophic wind distribution, terrain characteristics of roughness, Coriolis force and thermal influences.

In this model 2 main effects were considered to evaluate the windspeed:

- Wind shear
- Turbulence

Wind shear is a boundary layer effect that causes the variation of the wind speed on a short vertical distance. It is due to the interaction with the soil and with obstacles at soil level. The wind-speed profile can often be simulated using a logarithmic or power law profile.

$$V(z) = V(z_0) * \left(\frac{z}{z_0}\right)^{\alpha}$$

Equation 1

$$V(z) = V(z_0) * \frac{\ln\left(\frac{z}{z_{rif}}\right)}{\ln\left(\frac{z_0}{z_{rif}}\right)}$$

Equation 2

In this equation, α is the shear exponent, which considers the ground roughness, z0 is the height at which the anemometer is put, and zrif has the same meaning of α. Starting from the IEC 61400-3, the shear coefficient was imposed to be equal to α=0.14.

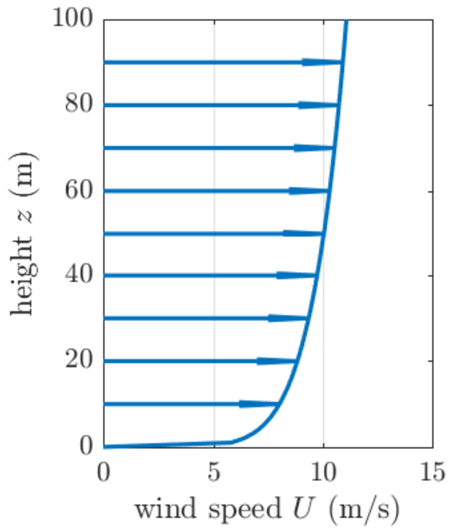

Figure 13: wind shear representation

On the other hand, turbulence is the sum of short-term fluctuations in the windspeed, both in module and in direction. Since it is not possible to model in a deterministic way the turbulence, some statistical properties are defined. The most significant is the turbulence intensity, which is the standard deviation of the windspeed normalized with respect to the average wind speed:

$$I_{turb} = \frac{\sigma}{V_{wind}}$$

Equation 3

Also in this case, IEC 61400-3 provides a few normalized values, ranging from I=0.12 to I=0.16.

In the model the turbulent wind was generated by means of the open-source program TurbSIM.

TurbSIM is a program able to generate a turbulent wind starting from some input parameters, that are:

- The turbulence model that will be used (Kaimal, Von Kármán: here Kaimal was used)
- The wind class (1,2 or 3: here class 3 was imposed)
- The turbulence intensity (A, B or C: here C was selected to simulate high turbulence)
- Wind shear exponent
- Grid size: it corresponds roughly to the rotor dimensions.
- Reference height for wind measurement
- Average wind speed.

Other, more technical features were left in default conditions. This is the result with average speed of 8 m/s:

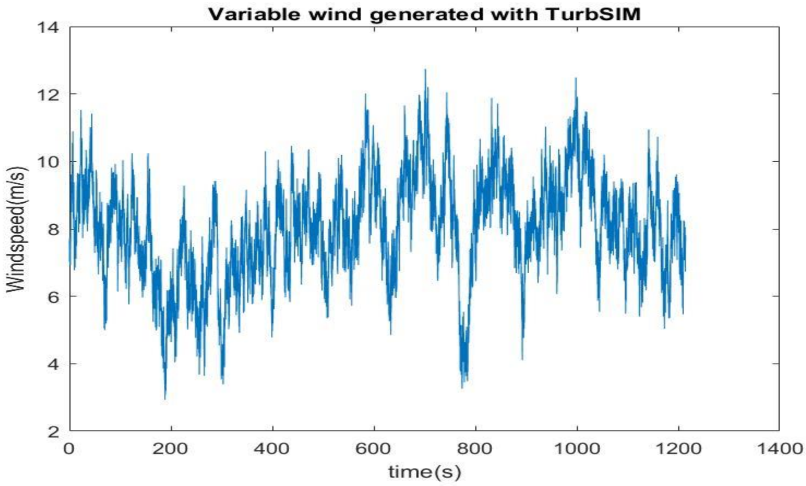

Figure 14: example of turbulent wind evolution with average speed of 8m/s

Chapter 4

Aerodynamics of vertical axis wind turbines

4.1 Aerodynamic modelling of vertical axis wind turbines

Vertical axis wind turbine aerodynamics is quite a complex field. Since not so many plants exist, there is not a standard way to predesign or assess system performances. Many ways were tested of different degrees of complexity, and various levels for quality of results. The aerodynamic model is fundamental: it is used not only to calculate the average system productivity, but also of the solicitations it must face.

The first difficulty that must be faced is that the phenomena occur in very different conditions with respect to horizontal axis wind turbines. First, the blade meets the wind with a variety of angles of attack, that are not always included in aerofoil data. This causes the airflow to be very different between upstream half-cycle and downstream half-cycle of the turbine, causing important oscillations in the loads on the rotor at every revolution.

Here some of the most used models are considered, apart from CFD. Computational Fluid Dynamics is not considered here since it is very expensive in terms of computational effort, and often the simulations cannot be conducted on a simple personal computer. The major aerodynamic modelling approaches used for VAWTs are the Blade Element Momentum (BEM) model, Cascade models, Vortex models and panel methods. Methods such as Reynolds–averaged Navier-Stokes (RANS) and computational fluid dynamics (CFD) require a too high computational effort to be useful for the initial assessment of turbine performances.

4.1.1 Blade element momentum models

This model is based on equating the momentum change across the turbine to the forces acting on the turbine blades. The double-multiple streamtube (DMST) model is the most elaborate variant and has the best agreement with experimental results for momentum models. Besides having multiple streamtubes, this model performs the momentum calculations separately for the upwind and downwind half-cycles of the rotor. This enabled the analysis of more complex shapes without a loss in numerical accuracy. In a DMST model, at each time increment, the process involved calculating the relative velocity and angle of attack at each collocation point. With these in hand the aerofoil lift and drag characteristics are obtained from a database. These forces are then updated to consider dynamic stall and/or other three-dimensional effects. Finally, the momentum loss over the upwind and downwind cycles is calculated, and the blade loads are integrated. This model gave an adequate correspondence with experimental measurements of the overall performance for light-loaded, low-solidity rotors, but it suffers both numerically and in accuracy when the rotor has a high solidity, is heavily loaded and/or is operating at high tip-speed ratios.

A variant of the DMST model is the actuator cylinder model. There, instead of considering the momentum balance within streamtubes, an energy balance approach is considered for the swept surface of a VAWT rotor. It provides better accuracy but can be troublesome in considering 3D effects (Ayati et al., 2019; Borg et al., 2014; Vallverdù D & Rempfer D, 2014).

Advantages: most used in open-source software, quite easy to implement, fast convergence.

Disadvantages: the basic version overestimates turbine efficiency with respect to real cases, not very suitable for high tip speed ratios and high solidities.

4.1.2 Cascade models

These models are based on cascade theory used in turbomachinery design. In this procedure, the blades of the rotor are assumed to be positioned on a plane surface, known as a cascade, with the spacing between adjacent blades equal to the rotor circumference divided by the number of blades. First, the relationship between wake and free – stream velocity is obtained using Bernoulli equation, the induced velocity comes from a semi – empirical formulation. Aerodynamic properties of each blade element come from the double multiple streamtube. After that, the turbine is split into a cascade configuration, where the cascade is a plane normal to the turbine axis, as shown in figure 15.

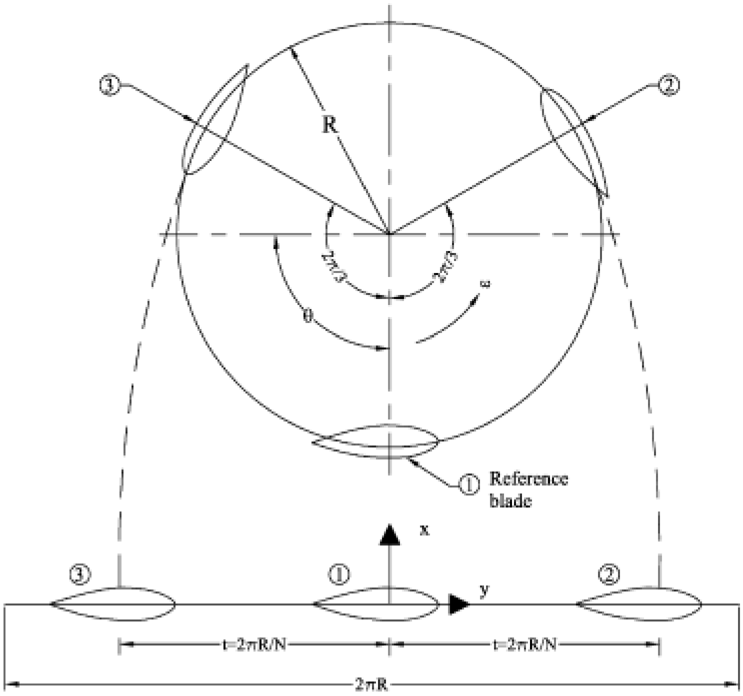

Figure 15: Cascade model scheme

To find the induced velocity, a relationship between the wake velocity and the induced velocity is introduced, and then used to calculate the average torque.
The Cascade model is adequate for predicting the overall values of both low and high solidity turbine systems. It is slower than blade element momentum models, but still has a low cost in terms of computation. It does not have convergence issues when tip speed ratios and/or solidities are high. The theory also can incorporate the effect of the Reynolds number variation with the azimuth (orbital position), zero-lift-drag coefficients, finite aspect ratios and the flow curvature effect.
To make better the performance of this method, the phenomena of dynamic stall and flow curvature with blade pitching must be considered. The calculated values of the wake velocities after these modifications become comparable with those obtained with complex dynamic models.

This model provides accurate overall values and does not suffer convergence problems at high solidities and high tip speed ratios but requires more computational time than the blade element momentum model. Another important drawback of this model is that it is not implemented in many usable aerodynamic codes.

4.1.3 Vortex models

Vortex models assume potential flow. This means that they basically assume irrotational and inviscid flow. Blades split and every segment is represented by vortices, that can be bound or lifting-line type. Vortex strength is calculated with coefficients depending on the angle of attack. With each timestep vortices are shed and these influence the induced velocity of the blade. Two-dimensional vortex models for VAWT made several assumptions such as: high tip-speed ratios, lightly loaded rotor, small angles of attack to ignore stall. Further improvements included dynamic effects, such as dynamic stall. The ability of vortex models to accurately predict the velocities and evolution of the near wake, allow for more precise simulations of the wake-rotor interactions. These interactions may prove to be an important factor, as they may significantly affect the aerodynamic performance of a floating turbine. (Borg et al., 2014).

More specifically, in these models, fluid velocity at every point of the flow field is the sum of the undisturbed and induced wind velocity. Definition of the induced velocity comes from the definition of circulation provided by the Kutta-Zhukovskij theorem:

$$\Gamma = \frac{1}{2} c C_L V_{rel}^2$$

Equation 4

Starting from this equation, together with the Biot-Savart law, it was possible to obtain the velocity field of the blades at different span values. This method can include very well dynamic effects, like dynamic stall or added mass, and is the simplest one able to consider correctly the wake effects. This method is more accurate than blade element momentum method for predicting blade loads but has the same accuracy when it comes to power calculation.

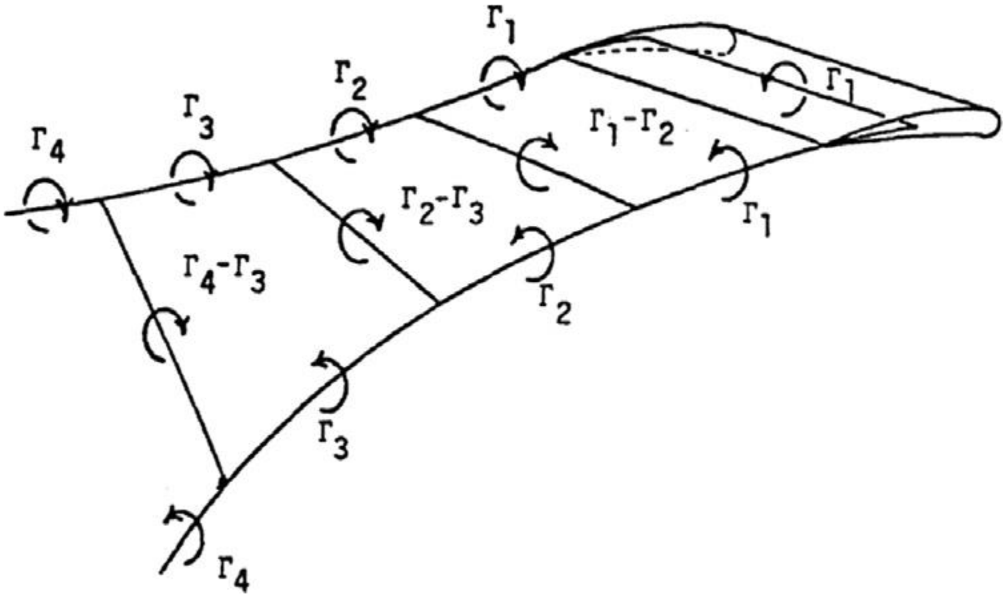

Figure 16: Vortex definition

On the other hand, this method is computationally very slow with respect to other systems, and heavily relies on some assumptions, like:

1. Inviscid flow
2. 2-D flow: it is difficult to consider spanwise effects using this procedure.

To include those aspects, some semi – empirical correlations should be inserted, that further slow the convergence of the calculations.

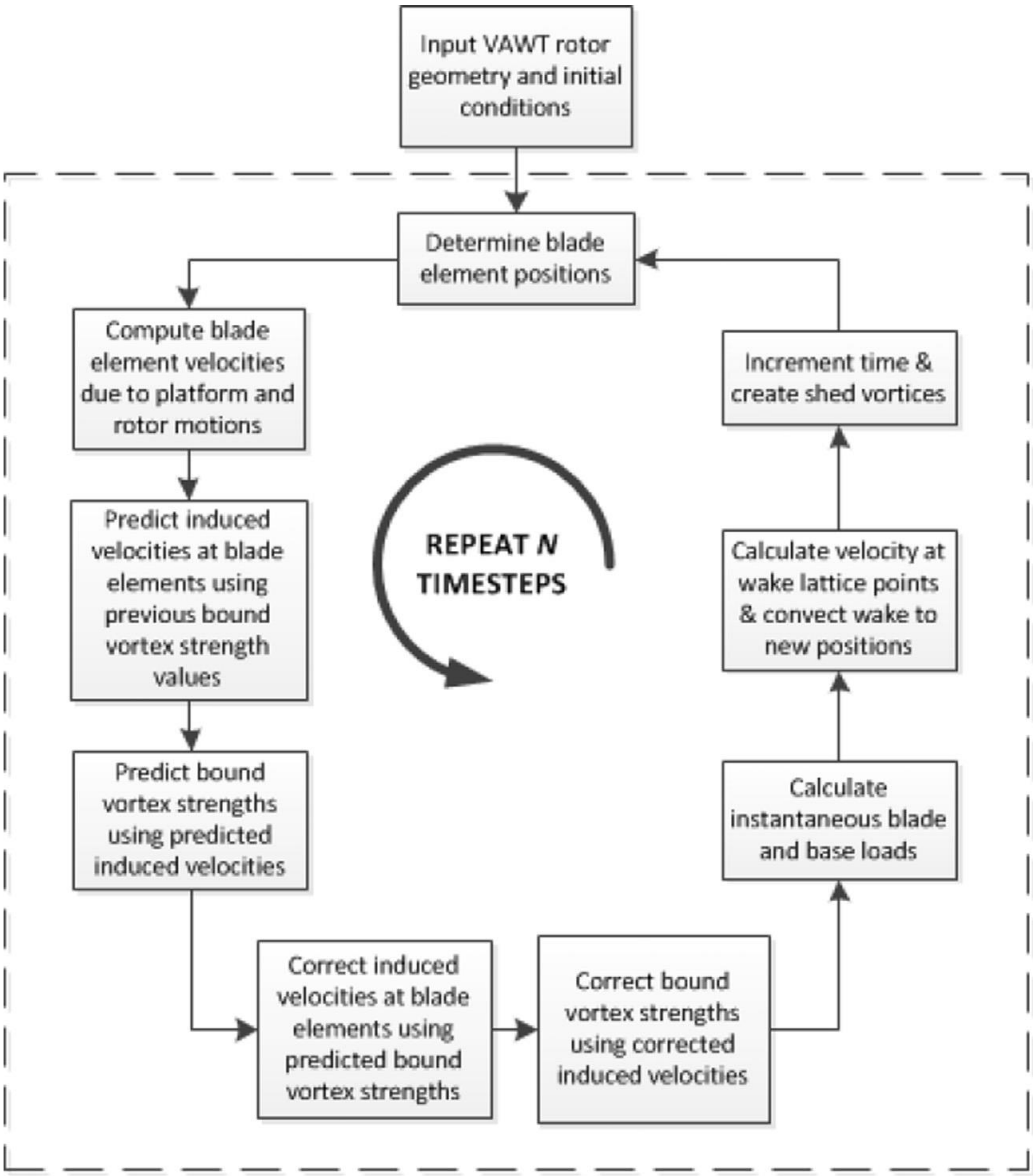

Figure 17: Vortex model scheme

They have adequate performance but are complex to implement and expensive from a computational point of view. Nevertheless, some programs, like QBLADE or CACTUS (open source), implement this method. QBLADE can use a method called Lifting Line Free Vortex Wake (LLFVW) to evaluate the turbine performances, but it is not well optimized.

4.1.4 Panel models

This approach is based upon discretising the 3D surface of the rotor into a number of panels and assuming a potential flow regime, as shown in figure 18 below.

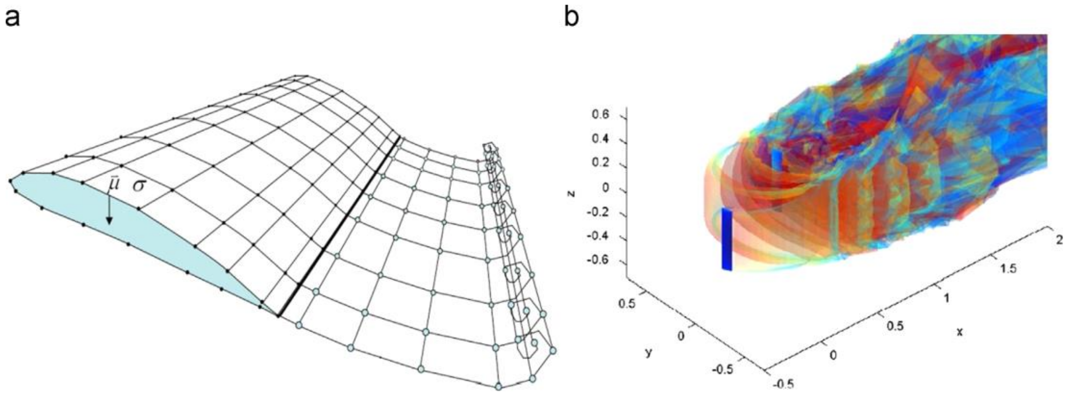

Figure 18: Panel method

Here on each panel an ideal flow element is placed with a prescribed strength and the Laplace equation is subsequently solved for the inviscid and incompressible flow. Panel models can be considered as an extension to vortex models that can consider 3D effects in a more accurate way. The relatively fast computational time in comparison to using higher-fidelity CFD simulations is one of the main benefits of this method. Another major benefit of panel method is that any geometry can be modelled. This method does not rely on the interpolation/extrapolation of two-dimensional aerofoil data obtained through experiment or CFD.(Borg et al., 2014)This is very useful when considering new geometries, or aerofoils where not all data are available or even present.

Even if faster than CFD simulations, the panel models remain very complex to implement and requires an important computational effort.

4.2 Chosen method: Double Multiple Streamtube Theory (DMST)

The theory which was chosen and employed here was the double multiple streamtube model (DMST), which belongs to the more general family of the Blade Element Momentum (BEM) models. The choice of this method was mainly due to 2 causes. First, it is the simplest to implement on a MATLAB code, because it is quite intuitive and does not need too much computational power. The second, more important cause, is the fact that the QBLADE software, which was used as reference, worked with the same principle, but it had not some of the features that were needed to do a full analysis in different configurations. Moreover, nowadays most of the studies on this kind of devices are conducted with a corrected and enriched version of this algorithm.

This theory considers the turbine as a succession of 2 actuator disks, as shown in the figure, considering the different phenomena which occur in the upstream part and downstream part. Differently from a horizontal axis wind turbine, in this kind of turbine the blades experience a lower wind velocity in the downstream half of the cycle. This happens because downstream the wind has already met the blades and it has already transferred some of its energy to the turbine. Because of this aspect it is possible to consider together upstream and downstream part (Manwell et al., 2010).

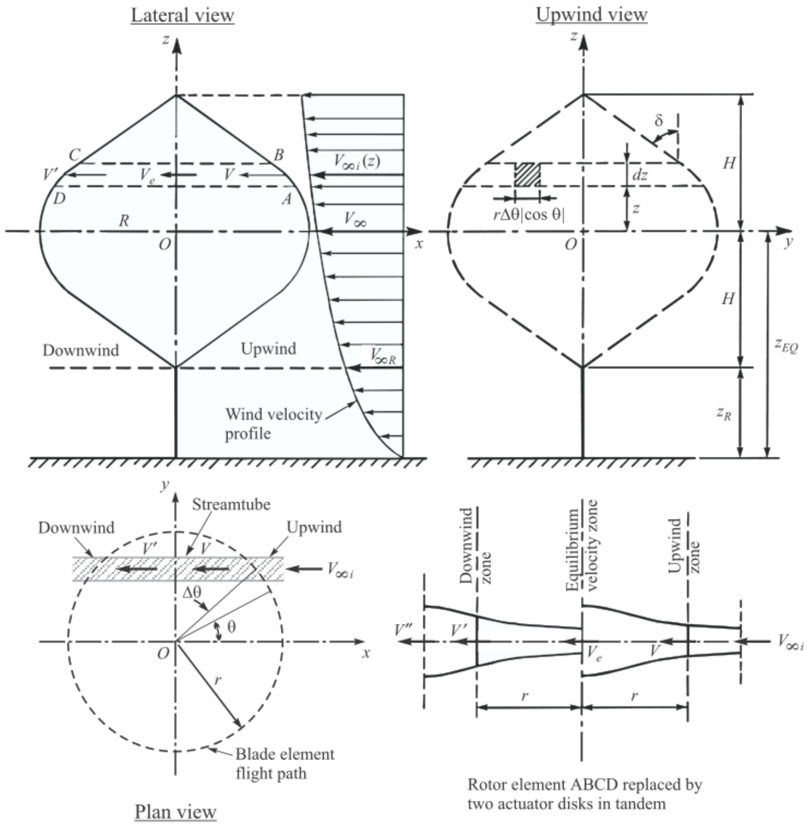

Figure 19: DMST illustration

The whole turbine is divided in streamtubes. To create the streamtubes the turbine circumference is divided in sectors with the same angular width and each sector of the upstream part is coupled with one of the downstream parts. The volume delimited by these sectors and the turbine bases is a streamtube. On every streamtube the wind progressively decelerates. On it some important points are considered, where velocity values are taken:

1. Far before the turbine: free wind velocity, V_{wind}
2. On the upstream sector: Upwind velocity, $V_{up} = \left(1 - a_{up}\right) * V_{wind}$

Equation 5

3. At the rotor half: Equilibrium velocity, $V_{eq} = \left(1 - 2a_{up}\right) * V_{wind}$

Equation 6

4. On the downstream sector: Downwind velocity, $V_{down} = \left(1 - 2a_{up}\right) * (1 - a_{down}) * V_{wind}$

Equation 7

5. Far after the turbine: Wake velocity, $V_{eq} = \left(1 - 2a_{up}\right) * (1 - 2a_{down}) * V_{wind}$

Equation 8

All these values depend from the local induction factor of the streamtube (aup,adown).

The induction factor is a coefficient which quantifies the energy extraction from the air flow by the turbine as a deceleration of the stream itself. The angle of attack is needed to find drag and lift coefficients, which can be used to calculate the forces involved.

Blades are divided into small elements represented by aerofoils which are only subject to local physical events (blade element model); this means that all blade sections are independent and any spanwise evolution is neglected. The rotor volume is divided into disks of thickness dz; in each disk there are N (N is the blade number) blade elements of length dz. The forces contribution from all disks are summed along the span of the blade to calculate the total loads on the rotor.

Double multiple streamtube is an iterative procedure since it has to solve some nonlinear equations. The procedure is done for every streamtube, first upstream and then downstream, at a given angle. As first, an initial value for the induction factor is chosen (usually 0). From that, the relative velocity of the wind is calculated for a single streamtube. From that, the angle of attack was obtained to evaluate drag and lift on the blade element. These coefficients were obtained from literature or software (QBLADE) data. They describe the behaviour of the system, since it is a lift-based turbine:

$$D = \frac{1}{2}\rho c l C_D(\alpha) V_{rel}^2$$

Equation 9

$$L = \frac{1}{2}\rho c l C_L(\alpha) V_{rel}^2$$

Equation 10

$$M = \frac{1}{2}\rho c^2 l C_m(\alpha) V_{rel}^2$$

Equation 11

$$\alpha = \varphi - \gamma = \text{atan}\left[\frac{cos(\theta)}{-sin(\theta) + \frac{\omega r}{V_{INF}(1-a)}}\right] - \gamma$$

Equation 12

Equation (12) describes how the angle of attack is calculated in the upstream half; equation (13) is for the downstream part:

$$\alpha = \varphi + \gamma = \text{atan}\left[\frac{cos(\theta)}{-sin(\theta) + \frac{\omega r}{V_{INF}(1-a)}}\right] + \gamma$$

Equation 13

Where γ is the pitch angle.

$$C_n = C_l \cos(\varphi) + C_d \sin(\varphi)\,, C_t = C_l \sin(\varphi) - C_d \cos(\varphi)$$

Equation 14

$$a(i) = \frac{n_{blades}c}{8\pi r}\left(\frac{U_{rel}}{V_{wind}}\right)^2 (C_n \cos(\theta) + C_t \sin(\theta)) + a(i-1)^2$$

Equation 15

This model was verified calculating the average power with the calculated coefficients when the turbine is in rated conditions. There was not an exact match, but this must consider that many phenomena were ignored, like struts’ drag.

$$P_{AVG} = M_{AVG}\omega = \frac{\omega N_{blades} RL\rho c}{4\pi} \int_0^{2\pi} c_T U_r^2 d\theta$$

Equation 16

$$c_T = C_L sin\alpha - C_D cos\alpha$$

Equation 17

The integral was calculated by means of the trapezoidal method.

Starting from the induction factor, angle of attack, thrust coefficient and mechanical instantaneous torque are evaluated. This calculation can be alternatively done for all the streamtubes at the same time. As total torque at every timestep can be used the integral average of the torque on every streamtube

$$T_{average} = \frac{\Delta\theta}{2\pi} \sum_{i=1}^{N_{streamtubes}} \left(T_{up}(\theta_i) + T_{down}(\theta_i + \pi)\right)$$

Equation 18

and it gives in output the instantaneous power when multiplied by the rotational speed. This works for both straight and curved blades.

An interesting consideration was done on the number of blades. Most vertical axis systems have 2 or 3 blades, and their behaviour change. With this simulation, the power output in both cases was the same, but with very different loading conditions. In fact, with 3 blades torque variations on the shaft are much smaller than with the case with 2 blades. This is very important, because high cyclical loads are very dangerous, because they induce fatigue in the components and reduce their technical life. Anyway, a 3 blades turbine is more expensive to build because of the higher cost of the material and heavier.

There are important oscillations because this is the instantaneous power at the blades, not the one transferred to the rotor.

On the blade airfoils, forces are calculated starting from drag and lift:

$$N = Lcos\alpha + Dsin\alpha, T = Lsin\alpha - Dcos\alpha$$

Equation 19

It was defined that:

$$F_{ax} = T, F_{ay} = N, M_{rz} = \frac{1}{2}\rho c^2 l C_m V_{rel}^2$$

Equation 20

In a vertical axis wind turbine, the force acting on the z axis is constant and equal to the rotor weight, so there is a limited interest in its value during the simulation. The moments on the x and y axis are defined as the bending moment on the blade, that is important for the analysis of the loads but not for the system dynamics. It was not investigated here, since the main focus for the dynamics.

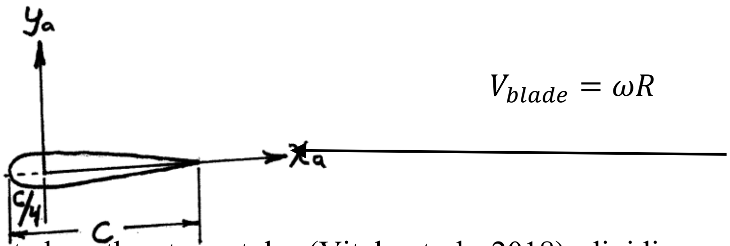

Figure 20: blade reference system

Torque is directly evaluated on the streamtubes(Vitale et al., 2018), dividing upstream and downstream cases:

$$T_{up}(\theta) = \frac{c\rho l}{2}\left[V_{rel,up}^2 * \left(C_{t,up} * r\right)\right], -\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2}$$

Equation 21

$$T_{down}(\theta) = \frac{c\rho l}{2}\left[V_{rel,down}^2 * \left(C_{t,down} * r\right)\right], \frac{\pi}{2} < \theta < \frac{3}{2}\pi$$

Equation 22

4.2.1 Aerodynamic coefficients determination

CL and CD (lift and drag coefficients) depend on the chosen profile and on angle of attack by means of tables. They were taken by the QBLADE software, as explained later in the QBLADE chapter. Another parameter which was evaluated was the pitching moment of the blade, which is the moment produced by the aerodynamic force on the aerofoil if that aerodynamic force is applied not at the centre of pressure, but at the aerodynamic centre of the aerofoil. This coefficient was taken from literature or database (a good one is provided by the website airfoiltools.com) with small angles of attack (from -20° to 20°), and in stall region using an analytical approximation (Merz, 2011), with some hypotheses:

From those coefficients the new induction factor is calculated using this relation. The output value is used to evaluate again the relative speed and the procedure is repeated until convergence is reached. Drag and lift coefficients are obtained from the angle of attack, with some hypotheses:

1. Nose and tail angles of the aerofoil equal to its leading edge and trailing edge angles: $\varphi_{nose} = 71.73°, \varphi_{tail} = 15.22°$ for NACA0024, $\varphi_{nose} = 61.35°, \varphi_{tail} = 13.08°$ for NACA0021.
2. Nose radius to chord radius (rnose/c) is roughly equal to 0.07 for the considered profiles NACA0021 and NACA0024.

which is calculated as:

$$C_M = -C_N \left[x_{cp} - 0.16 \left(1 - \frac{2\alpha}{\pi} \right) - 0.25 \right]$$

Equation 23

$$x_{cp} = 0.5 - 0.35 \left[0.3\varphi_{tail}(0.2 + 0.08\varphi_{tail}) + \left(0.3 - \varphi_{nose}(0.2 + 0.08\varphi_{nose})\right) \left(1 - 1.8\sqrt{\frac{r_{nose}}{c}} \right) \right]$$

Equation 24

The parameter c, instead, is the chord length of the profile.

In the case of the Uppsala turbine, at nominal operation, this is the situation:

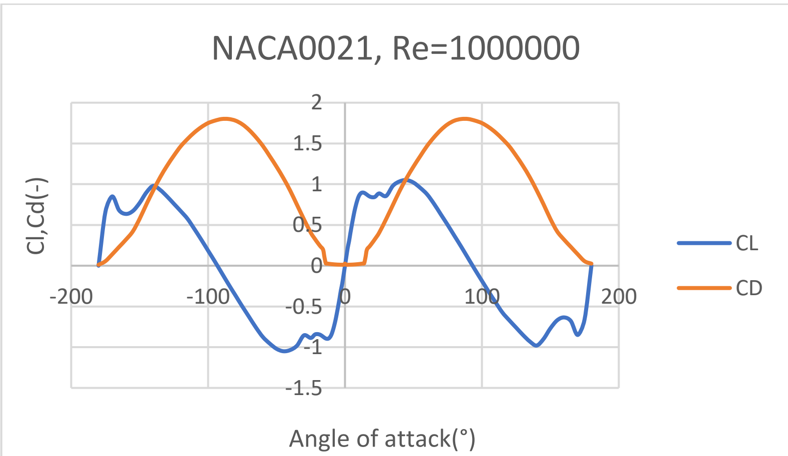

Figure 21: aerofoil coefficient extrapolation

4.2.2 Add-ins: Calculation of induction factor-curved blades

This procedure is not completely valid for turbines with curved blades. There the radius changes and the coefficient must be evaluated at different values of the radius, which correspond to different heights. The idea is to divide the curved blade in many small straight bladed intervals, to evaluate the induction factor at every radius. Another important factor, in this case, is the local blade inclination angle with respect to the ground (it varies around z coordinate).

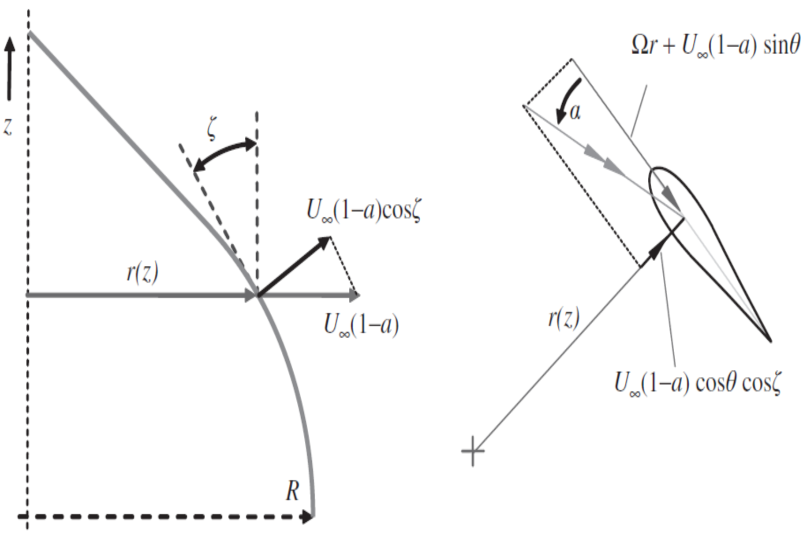

Figure 22: curved blades angle convention

So, the relations become:

$$V_{rel}(\theta) = \sqrt{[(\omega R - V_{IN}(1-a)\sin(\theta))^2 + V_{IN}^2(1-a)^2\cos^2(\theta)\cos^2(\zeta)]}$$

Equation 25

$$\alpha = \text{atan}\left[\frac{cos(\theta)\,cos(\zeta)}{-sin(\theta) + \frac{\omega r}{V_{INF}(1-a)}}\right] \pm \gamma$$

Equation 26

$$a(i) = \frac{n_{blades}c}{8\pi r}\left(\frac{U_{rel}}{V_{wind}}\right)^2 \frac{C_n\cos(\theta) + C_t\sin(\theta)}{\cos(\zeta)} + a(i-1)^2$$

Equation 27

Where $\underline{\boldsymbol{a}}$ is the induction factor.

Coefficients are calculated in the same manner of the straight blades case.

4.2.3 Add-ins: Calculation of tip losses

An important effect which was included was to consider the tip vortices of the blades. This is important because it allows to consider the fact that the blade is finite. This correction was used using the Willmer-Prandtl method (Marten & Wendler, 2013; Sanvito et al., 2021). To do this, a corrective coefficient FPrandtl was evaluated, that varies along the span of the blade. An auxiliary variable z is defined along the span of the blade, with z=0 at the blade centre:

$$s = \frac{\pi V_e}{N_{blade}\Omega}, where\ V_e = \left(1 - 2a_{up}\right)V_{wind}$$

Equation 28

$$z = \frac{Zcoordinate}{2 * L_{blade}}, a_{tip} = 0.5L_{blade} - \left|\frac{zL_{blade}}{2}\right|$$

Equation 29

$$F_{Prandtl} = \frac{\arccos\left(\exp\left(-\frac{\pi a_{tip}}{s}\right)\right)}{\arccos\left(exp\left(-\frac{\pi L_{blade}}{2s}\right)\right)}$$

Equation 30

This coefficient is then used to calculate the relative speed and the angle of attack:

$$V_{rel} = \sqrt{[(\omega R - V_{IN}(1-a)\sin(\theta))^2 + F_{Pr}^2 V_{IN}^2 (1-a)^2 \cos^2(\theta)\cos^2(\zeta)]}$$

Equation 31

$$\alpha = \mathrm{atan}\left[\frac{F_{Prandtl}\, cos(\theta)\, cos(\zeta)}{-sin(\theta) + \frac{\omega r}{V_{INF}(1-a)}}\right] \pm \gamma$$

Equation 32

4.2.4 Add-ins: Calculation of tower shadow

This is an important effect, that considers the fact that the rotation of the shaft of the turbine gives some aerodynamic friction. It was considered only as an average effect on the whole average torque. To do that the equilibrium speed of the turbine (averaged on the revolution) and the drag of a rotating cylinder were considered. The drag coefficient was taken equal to 1 because of high Reynolds numbers (>1000000)):

$$T_{tower} = \frac{1}{2}\int_0^{H_{tower}} \rho C_{D,cyl} r_{tower} D_{tower} V_{eq,average}^2 dz$$

Equation 33

Other effects, like dynamic stall, were not considered. Dynamic stall was not considered because it is an hysteresis effect, and could not be used in the lookup tables present into the SIMSCAPE models. Other effects that were not considered were the curvature of the airflow after the turbine and wake interactions, because they needed more elaborate models with respect to the blade element momentum ones, with higher computational time.

4.3 The QBLADE software

This procedure is implemented by the open-source program QBLADE, developed by the DTU of Berlin. It allows to build a model of a wind turbine and can carry a wide range of simulations in different conditions. It is a fast, user-friendly tool that can be quite versatile.

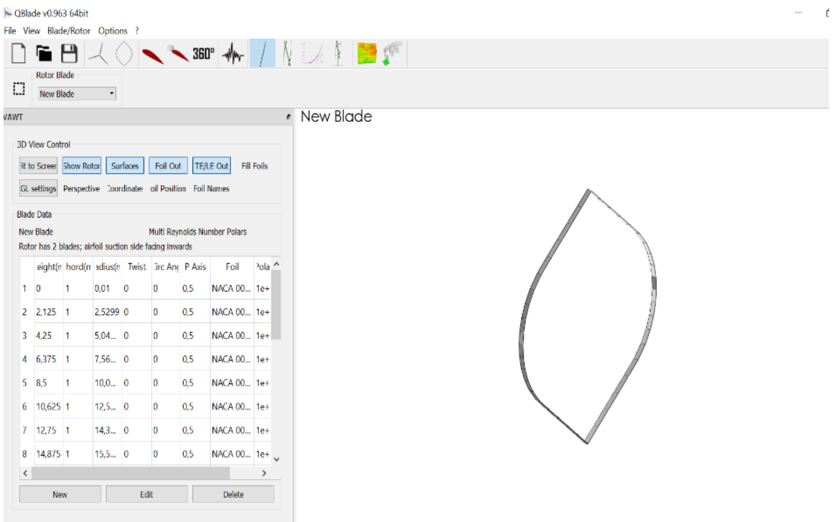

Figure 23: blade creation page in QBLADE

An important aspect of QBLADE is that it incorporates a module to calculate aerodynamic coefficients of the profiles. This is very important, because the whole turbine behaviour is very sensible to these parameters. The steps to carry on a simulation of a vertical axis wind turbine are:

1. Definition of the airfoil: it can be either imported from outside or chosen from a library.
2. Polar calculation: the calculation of drag and lift coefficients to do the simulations. These coefficients can be then extrapolated to cover the whole range of angles of attack. This calculation is done in 2 parts: first, in the usual range of the angle of attack (indicatively between -20° and 20° of angle of attack) the coefficients are calculated. Then, an extrapolation is done using either the Montgomerie or the Viterna-Corrigan method to have the coefficients for every angle of attack.
3. Blade definition: the dimensions, shape and number of the blades were defined.
4. Setting of the simulation parameters: rotation speed, wind speed and pitch angle are set.
5. Multi-parameter Simulation, carried out with the double multiple streamtube algorithm explained before.(Marten & Wendler, 2013)

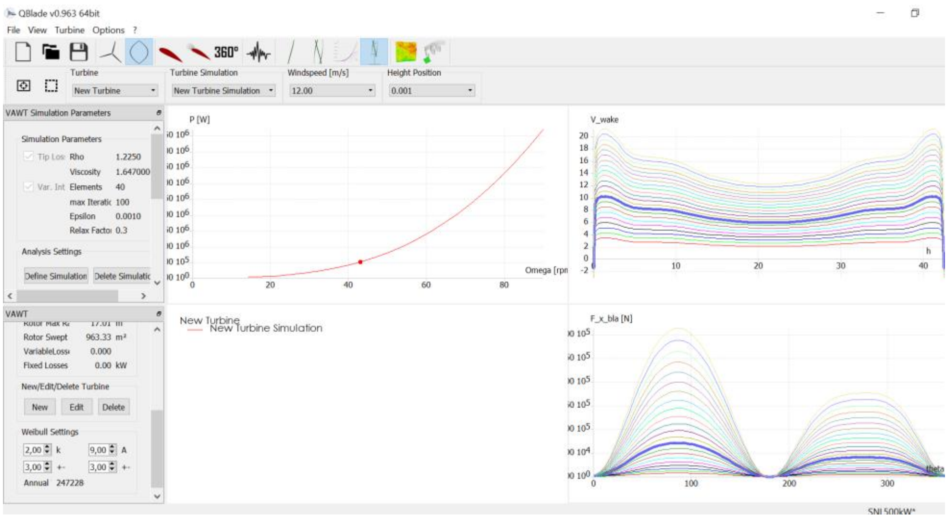

Figure 24: turbine simulation page in QBLADE

The simulation results were then confronted with a matlab code which was developed in house. This code was necessary because QBLADE did not provide an adequate flexibility to evaluate all parameters combinations and was used as proof for the validation.

Even if in the end the MATLAB code was used to find blade loads, QBLADE data were anyway used. Qblade gave the STL files to create the blades for the multibody simulation, which would have been very difficult to build from scratch. Then the aerodynamic lift and drag coefficients at different Reynolds numbers were taken from this application to be put into the simulations.

4.4 Code scheme

Putting the previous pieces of information together, a flow-chart and then a MATLAB code was developed to find forces and torques on the turbine rotor:

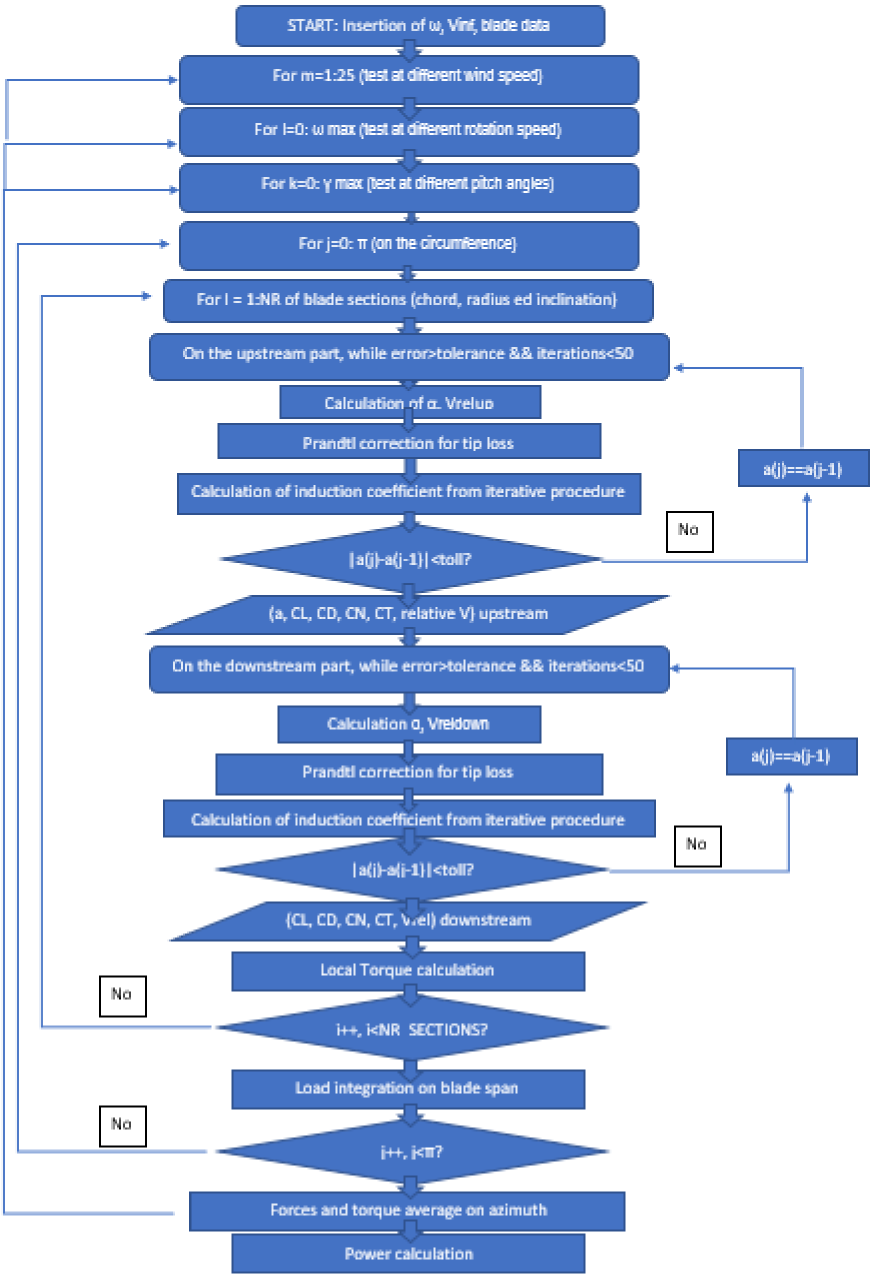

Figure 25: MATLAB code structure

Chapter 5

Control system

This chapter is divided in 2 parts: torque control and pitch control. The controls on the turbine are needed to be able to extract the maximum power from the turbine in a safe way, to limit stresses and cope with turbulent wind or dynamic situations. All vertical axis turbines have a torque control that works in a similar way to the one of horizontal axis turbines, even if other, more elaborate systems can be employed. In plants from small to medium size a pitch control is not used, since loads on small blades are not excessive.

This pitch control system is quite simple, since it has only a safety function, to reduce loads at high rotational speed, like horizontal axis systems presented in NREL reports. Some more advanced strategies were studied to maximize power production, like individual pitch with variations on every revolution, but they are more difficult to implement and suffer of frequent failures (Hand et al., 2021)

5.1 Pitch Control system

5.1.1 Pitch control

Pitch control is a debated issue in vertical axis wind turbines' control. In fact, it is a complex mechanism which requires a great deal of study and accurate measurements. Then, its complexity causes the mechanism to be difficult to maintain and failures in experimental devices are not uncommon. On the other hand, it can have an important impact on the productivity (+10% on the annual energy production) for any kind of turbine. Of the considered turbines, only the 6 MW one had a pitch control system, while all the others were assumed to be fixed-pitch machines.

Nevertheless pitch control would probably become crucial for a floating, multi – MW vertical axis wind turbine(Huijs et al., 2018), where thrust loads become very important and must be reduced to safeguard the structures and avoid catastrophic failures. This is because stresses become very important and, with fixed pitch, there is no upper limit for the thrust on the turbine.

The pitch control considered here will be a collective pitch control (same for the 3 blades), with a behavior like the one for horizontal axis wind turbines. The pitch angle depended only on the windspeed and had 2 objectives:

- If windspeed was lower than nominal speed, it was used to reach higher power output.
- Otherwise, it was used to keep a constant power output not to have too high aerodynamic loads.

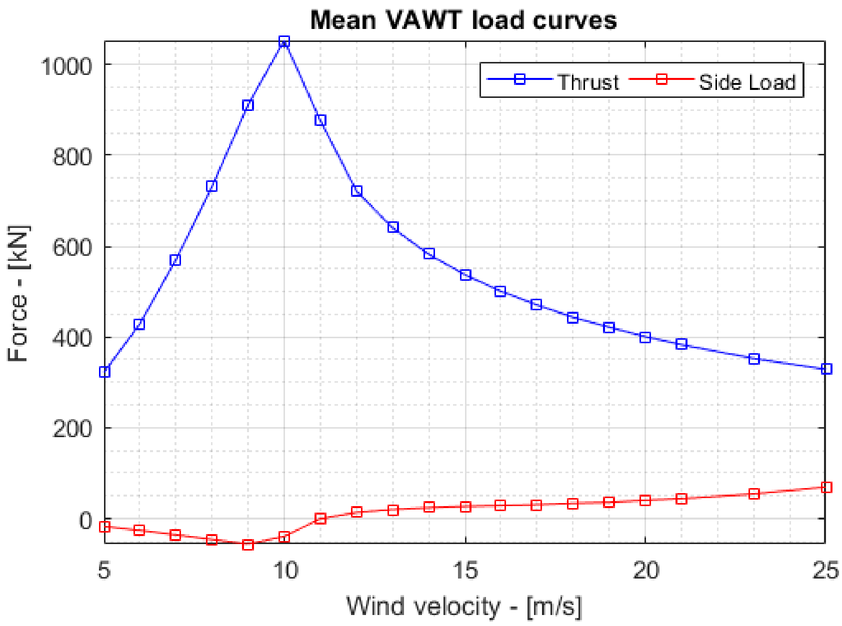

Figure 26: loads with pitch regulation

In absence of a pitch control, the turbine would be designed with respect to the survival conditions. This aspect would be detrimental for the system efficiency because the main problem would become its survivability. In this case the thrust would have a monotonous increase with the windspeed. This is the thrust forecast for the DeepWind 5 MW fixed pitch turbine, with respect to windspeed:

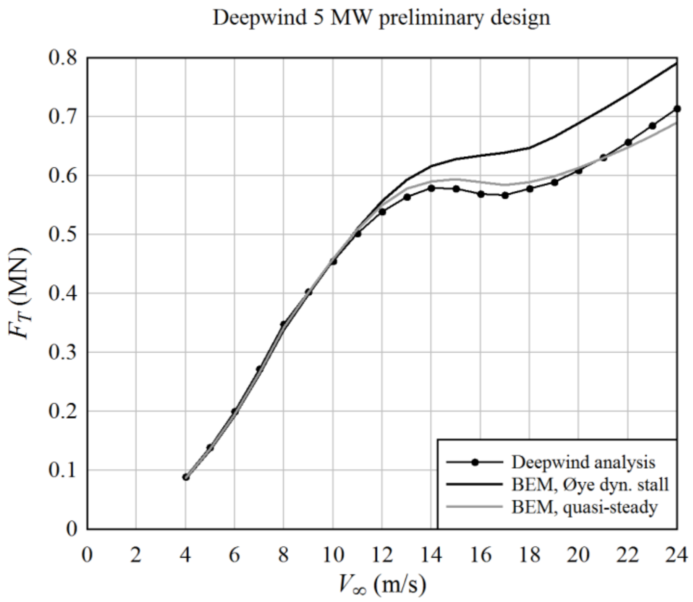

Figure 27: thrust of fixed-pitch turbine

This system was implemented into the Simscape model. Ideally, it follows a pattern like the one presented in the reference 15 MW offshore wind turbine(Gaertner et al., 2020):

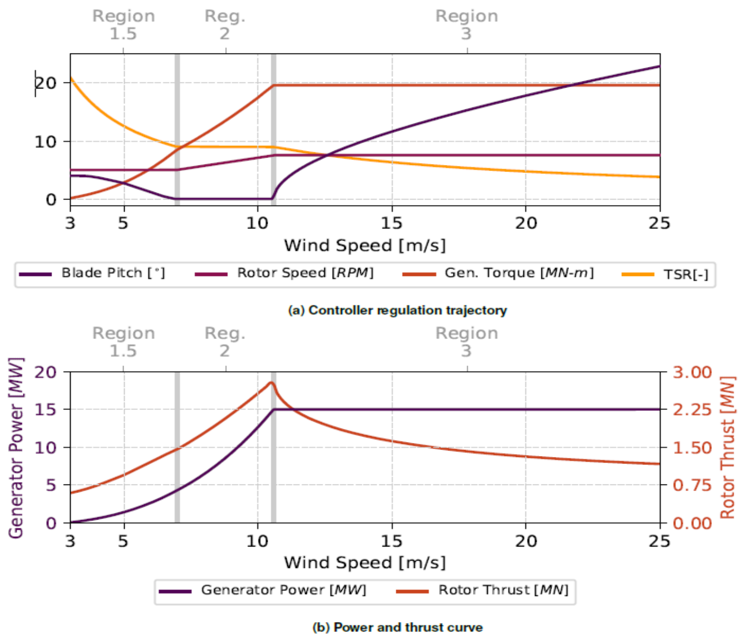

Figure 28: resume of control objectives

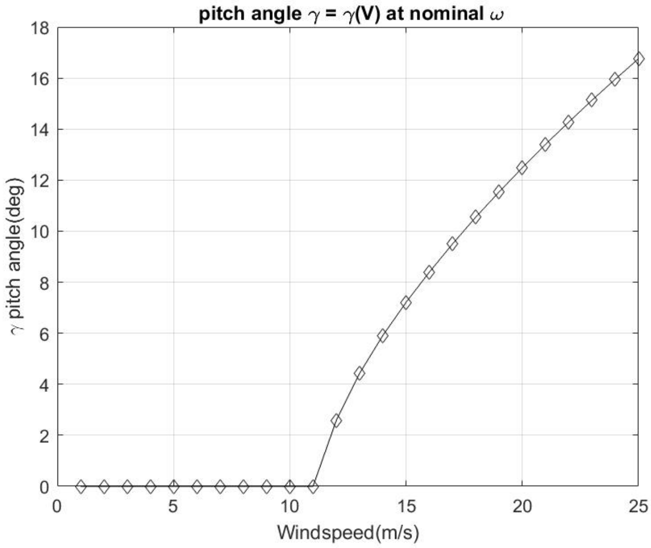

Figure 29: optimal pitch angle at different windspeeds

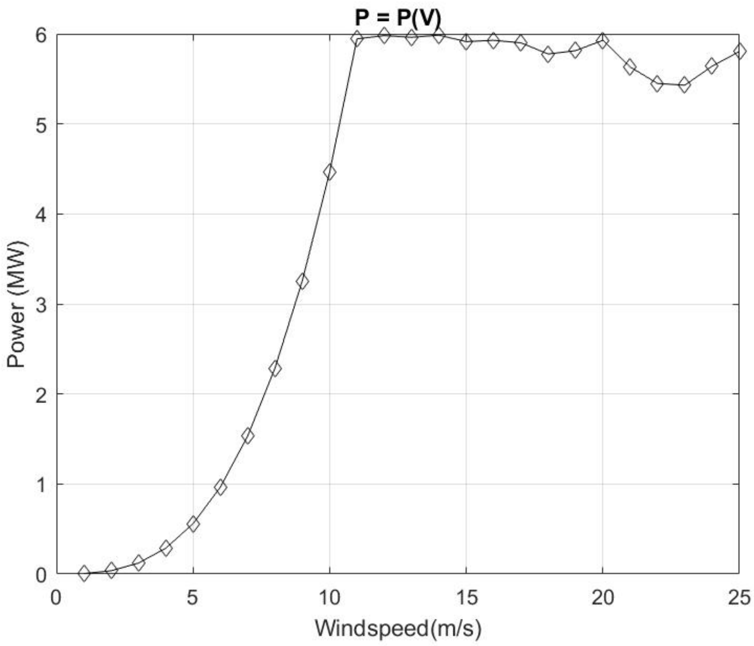

Figure 30: power output-controlled turbine

Nevertheless, the Simscape implementation was not just a lookup table, but it was structured as a PI (proportional-integral) control.

5.1.2 Pitch control implementation

First, the pitch values in steady-state conditions were found. The revolution-averaged power output depended on 3 variables (rotational speed, pitch angle, windspeed), so to find the angle's value at every windspeed a logic was imposed:

$$\gamma = \begin{cases} 0 \; if \; \omega \leq \omega_{nom} \\ \gamma|_{P=P_{nom}} \; if \; \omega \geq \omega_{nom} \end{cases}$$

Equation 34

This happens because the aim of this control is to maintain nominal power at higher windspeed. The pitch angle was found starting from the power matrix, that depended also on the wind and rotational speed. In the power matrix at $V_{wind}>V_{nom}$, at rated rotational speed, the correct pitch was the one that gave the most similar power output with respect to the nominal one.

The reasoning started from a model of the wind turbine employing only one degree of freedom. The aim of this kind of blade-pitch control was to moderate the generator speed, which is the degree of freedom of this system. This was structured as a proportional – integral PI control system. To calculate the required control parameters Kp and Ki, it was necessary to work on the constitutive equation of the rotor. Starting from the forces' diagram of the rotor drivetrain, the constitutive equation was found as:

$$T_{aero}(\theta, \omega, V, \gamma) - T_{mecc}(\omega, \gamma) = J\frac{d\omega}{dt}$$

Equation 35

From this equation, some considerations can be done assuming that at nominal rotor speed the torque is approximately constant with respect to rotor speed, so a Taylor expansion is possible:

$$T_{aero} \cong \frac{P_{nom}}{\omega_{nom}} + \frac{1}{\omega_{nom}}\left(\frac{\partial P}{\partial \gamma}\right)\Delta\gamma$$

Equation 36

Where Δγ was defined as a small perturbation of the blade-pitch With proportional-integral (PI) control, this value is related to the rotor speed perturbations by:

$$\Delta\gamma = K_p\Delta\omega + K_i\int_0^T \Delta\omega dt$$

Equation 37

This kind of control was chosen because it was simpler to implement and good for concentrated parameters' model. Starting from Taylor expansion of the aerodynamic torque the parameters Kp and Ki can be evaluated from its rearrangement:

$$K_P = \frac{2J_{drivetrain}\omega_{nom}\zeta\omega_{nat}}{-\frac{\partial P}{\partial \gamma}}, K_I = \frac{2J_{drivetrain}\omega_{nom}\omega_{nat}^2}{-\frac{\partial P}{\partial \gamma}}$$

Equation 38

The natural speed, a free parameter, was taken equal to 0.8, while the damping coefficient is imposed as 0.7. The drivetrain inertia was taken to be equal to the sum of blades' inertia, struts inertia and rotating shaft inertia.

The denominator was the value of the power sensibility with respect to the pitch angle, it was found considering nominal power conditions at nominal rotational speed for every windspeed. This derivative was not constant: it was found that it depended linearly on the windspeed, as showed in the following figure:

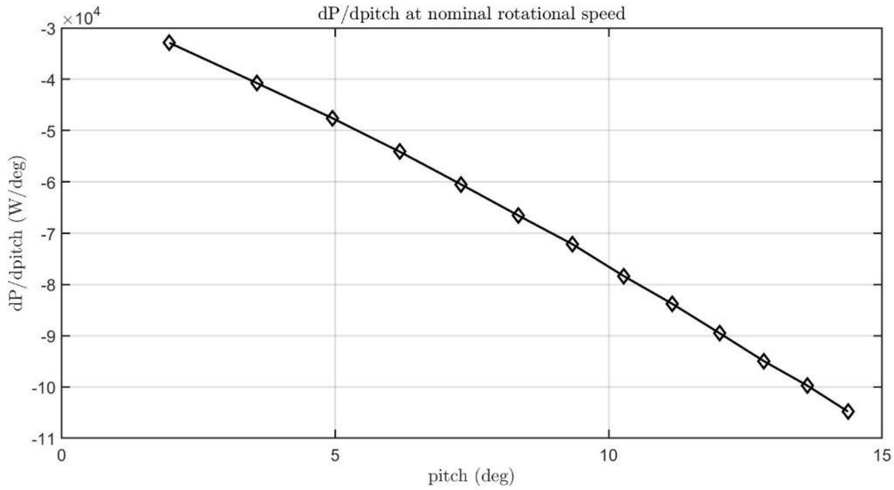

Figure 31: Power variations vs pitch

From there the PI block was built on Simscape:

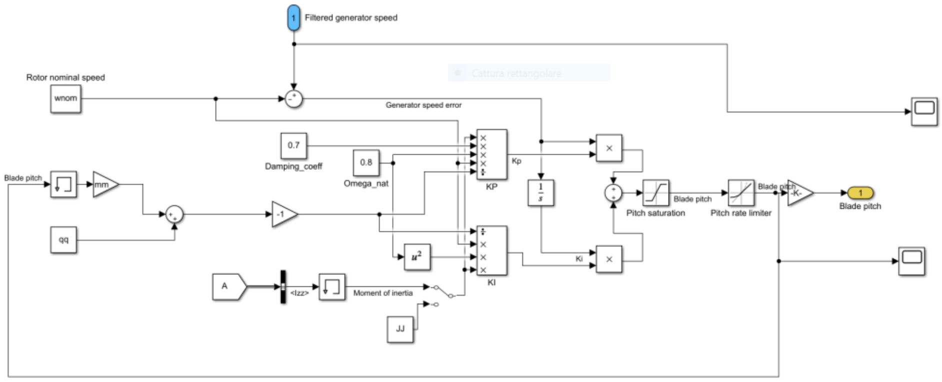

Figure 32: Simulink-control system overview

In the block some discontinuities were added to consider the systems' stiffness. So, a rate limiter was added. The rate limiter captures the fact that the actuation of the system isn't instantaneous, but happens in some time, especially for large turbines, and this effect is very important.

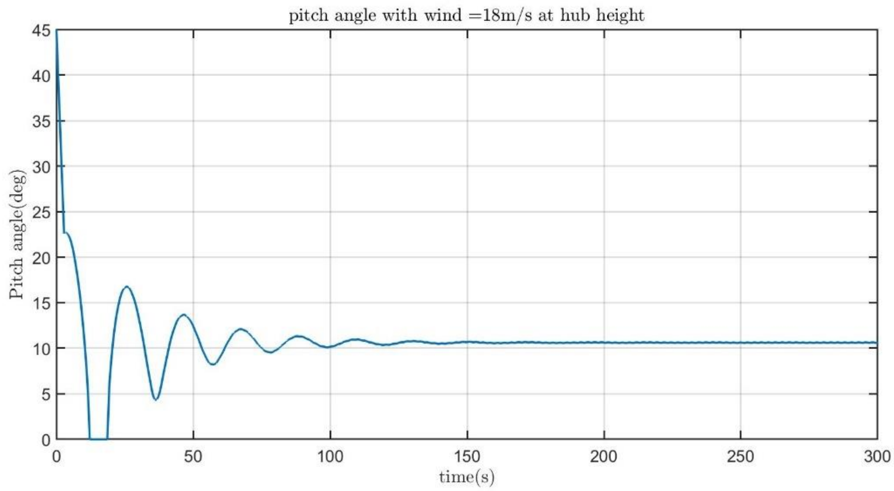

Figure 33: pitch behaviour with fixed windspeed

These graphs are relative to the 6 MW system, for the smaller machine the procedure was the same, only with different numbers.

5.2 Torque Control system

5.2.1 Torque control

It is fundamental on every kind of turbine. It modulates the electrical resistant torque to ensure both optimal power extraction and operational safety. It is the basic control system that ensures the optimal operation of the system even with fixed pitch.(Hand et al., 2021) This system intervenes on the internal torque provided by the electrical generator, which is supposed to have a constant efficiency during the operation. The generator torque is dependent on the current inside, from the equation:

$$T_{elt} = k_{mag} I_{stator}$$

Equation 39

Where k and I depend on the generator characteristics. The electric behaviour can be modulated by means of electronic converters with various strategies (Andriollo et al., 2008). In this work the electrical part was not considered, since it had a faster dynamic with respect to the mechanical phenomena, and its effects could be considered with a lookup table.

The torque control system was roughly divided in 3 parts:

1. When the rotational speed was too low (usually when windspeed was <=4m/s), no power was extracted by the electrical generator, in order to let the turbine accelerate as much as possible, since it must not stop.
2. When the rotational speed is between cut-in and nominal speed, the generator works to keep the efficiency as near as possible to the rated value.
3. When the rotational speed is bigger than the rated value, the generator keeps constant power absorption in order not to overload.

These pieces of information are resumed in a lookup table, very similar to the one used on a standard horizontal axis wind turbine.

$$T_{mecc}(\omega) = \begin{cases} 0 \; if \; \omega \leq \omega_{cut-in} \\ k_1\omega^2 + k_2\omega + k_3 \; if \; \omega_{cut-in} \leq \omega \leq \omega_{nom} \\ P_{nom}/\omega \; if \; \omega \geq \omega_{nom} \end{cases}$$

Equation 40

The coefficients k1, k2 and k3 are obtained by the interpolation of the torque curves at different wind speed.

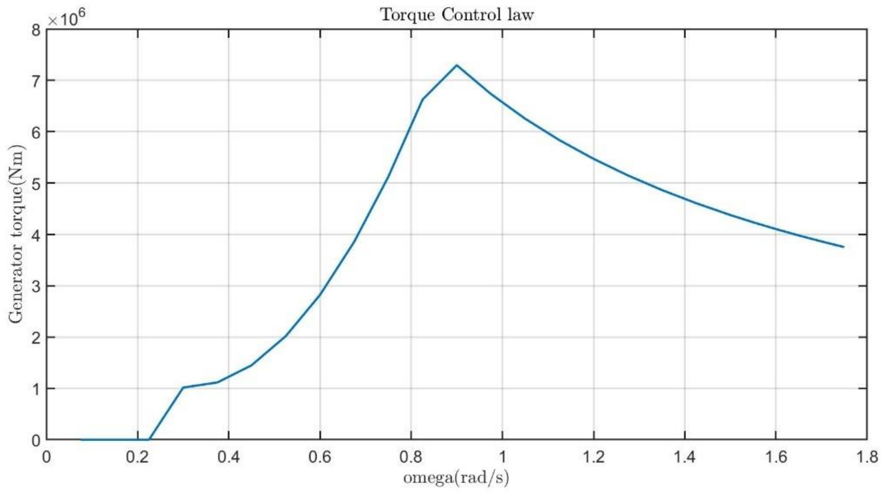

Figure 34: Torque control law

This can be improved by means of a simple PI (proportional-integral) architecture, where also the windspeed is considered.

One important feature of these control systems is that they do not depend directly on the windspeed, so the machine does not need an anemometer. This is a very good feature, since the anemometer is often a complex and expensive component to be installed, also considering that there is no yawing mechanism.

Another input of this torque control is the pitch angle. In this system, the pitch angle is passed as second input to the control system. In this case pitch motion happens only at high windspeed to reduce blade loads, but in the beginning of the simulation it has great oscillations in torque, speed, and power output, before remaining in a small range. This is not good for high windspeed, because it causes large, fast varying stresses on the structure. To reduce this phenomenon and accelerate stabilization, a condition was added in the torque control: whenever the pitch angle became higher than 1°, the electrical torque was imposed equal to the nominal one. To avoid too fast variations in torque output, a limit in torque rate was imposed. For the 6 MW machine it was imposed to be equal to the one used in the NREL 5 MW reference wind turbine (Jonkman et al., 2009), while for the other machine the same value was scaled together with the nominal power.

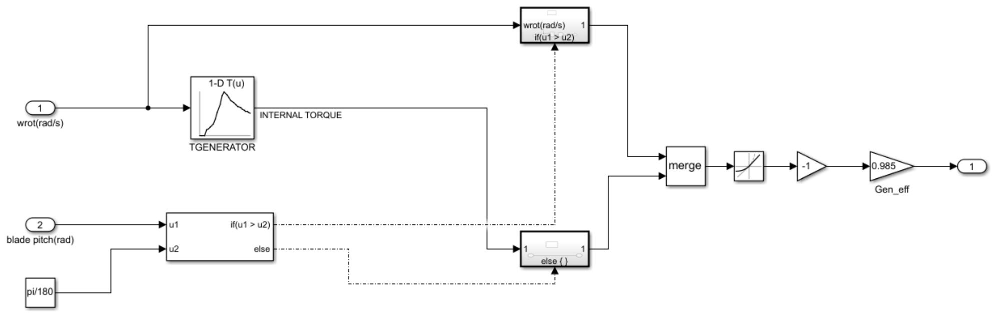

Figure 35: Torque control Subsystem with rate limiter

Chapter 6

Validation of aerodynamic code

There was a necessity to validate the code and then the model, to understand its accuracy. The code validation was done considering just the MATLAB code used to generate aerodynamic data for the Simscape model. It was confronted with the QBLADE software. In fact, QBLADE alone could not give the blade load data with respect to the azimuth position at all the useful tip speed ratios. These data were necessary to evaluate the dynamic behaviour of the turbine, properties only revolution-averaged data were not able to evaluate.

The validation was done running the simulation in steady state on QBLADE and on the simplified version of the MATLAB code in the same conditions, with same aerofoil coefficients. The significant results (average torque, power, rated rotational speed) were confronted to evaluate the difference. The results in nominal conditions were confronted also with literature data. The error was taken as the average of the errors on every considered situation of wind and rotational speed:

$$\Delta\bar{X} = \frac{1}{N}\sum_{i=1}^{N}\frac{|X_{i,MATLAB} - X_{i,QBLADE}|}{|X_{i,QBLADE}|}$$

Equation 41

There was a good agreement between the simplified code and QBLADE simulations for all the turbines.

CONSIDERED TURBINE	ERROR BETWEEN MATLAB (SIMPLIFIED CODE) AND QBLADE			
NAME	ΔT average	σΔT	ΔP average	σΔP
H-rotor 12 kW	3.64%	3.4%	3.39%	3.4%
H-rotor 200 kW	5.13%	2.5%	6.40%	3.6%
Darrieus 500 kW	6.67%	3.9%	6.62%	4.1%
Modified Darrieus 5 MW	7.87%	2.6%	7.48%	2.6%
Inclined blades 6 MW	5.94%	2.78%	6.02%	2.91%

Table 5: Errors in validation of MATLAB code

On the other hand, there was not a good agreement between the nominal performances foreseen by the QBLADE with the literature data. Some reasons for this situation were:

1. Literature data are sparse, and very few for the considered plant sizes. They are more abundant for microturbines (<=1 kW).

2. There is no standard aerodynamic model. As shown in the table below, every turbine was simulated in a different way on a different software, in many cases empirical corrections were taken because a 1:1 machine was available. Anyway, the most diffused algorithm was the double multiple streamtube for aerodynamics.

3. QBLADE, and more in general double multiple streamtube theory, does not work well with blades of complex geometry. This happens mostly on the 5 MW modified Darrieus DeepWind.

This is an example of the turbines that were considered:

CONSIDERED TURBINE	AERODYNAMIC MODEL	EXPERIMENTAL TESTS
12 kW H-rotor	Double multiple streamtube + free vortex	On field with atmospheric wind.
200 kW H-rotor	Double multiple streamtube + free vortex	On field with atmospheric wind.
500 kW Darrieus	Double multiple streamtube	Aerodynamic testing in wind tunnel, fatigue testing on field.
5 MW modified Darrieus	Actuator cylinder	None at full scale: only the prototype was tested.
6 MW inclined straight blades	Lifting line free vortex wake	None

Table 6: literature aerodynamic method review

Better agreement between the MATLAB code and literature data were reached with a refinement of the code, adding some effects, as tower drag and wind shear in logarithmic formulation. Windshear becomes more important with multi-MW turbines.

The final MATLAB code that was used to create the structures for Simulink was a bit different from the one used for the validation with QBLADE. In fact, the validation code was built to be as like QBLADE as possible, so very simplified. On the other hand, some aerodynamic effects were needed to improve the accuracy of the results. The additional effects were:

- Wind shear.
- Aerodynamic pitching moment on the blade.

They allowed to obtain results that were more like the ones in literature. For example, the QBLADE result for the TU Delft turbine was a nominal power of 7.6 MW, while with the improved MATLAB code the nominal power was found 6.8 MW, much nearer to the one foreseen on the paper (6 MW). The same happened with the 200-kW system, where QBLADE foresaw 300 kW of peak power, while the improved code obtained 250 kW. This refined code was used to generate MATLAB structures. These are the results for the improved MATLAB code:

CONSIDERED TURBINE	NOMINAL ROTATIONAL SPEED FROM QBLADE/ AERODYNAMIC CODE	NOMINAL POWER FROM QBLADE	NOMINAL POWER FROM AERODYNAMIC CODE	NOMINAL ROTATIONAL SPEED FROM LITERATURE	NOMINAL POWER FROM LITERATURE
NAME					
H-rotor 12 kW	ωnom=14.8 rad/s	Pnom=15.4 kW	Pnom=14.3 kW	ωnom=13.3 rad/s	Pnom=12 kW
H-rotor 200 kW	ωnom=4.62 rad/s	Pnom=305 kW	Pnom=257 kW	ωnom=3.14 rad/s	Pnom=200 kW
Darrieus 500 kW	ωnom=4.42 rad/s	Pnom=430 kW	Pnom=450 kW	ωnom=3.75 rad/s	Pnom=500 kW
Modified Darrieus 5 MW	ωnom=1.36 rad/s	Pnom=8.6 MW	Pnom=9.5 MW	ωnom=0.62 rad/s	Pnom=5 MW
Inclined blades 6 MW	ωnom=0.79 rad/s	Pnom=7.6 MW	Pnom=6.8 MW	ωnom=0.66 rad/s	Pnom=6 MW

Table 7: Confrontation with literature data

There are, as mentioned before, significant differences between QBLADE, the in-house model and the literature data, but the elaboration of the MATLAB model allowed to reduce them significantly. The confrontation was done with respect to QBLADE and with respect to the nominal operating conditions foreseen by the literature. Only a spot comparison, shown in the table, was possible with the literature: it did not provide performance curves. In fact, were not found performance curves for this kind of turbines in literature, since most of the studies only gave output power in function of windspeed and integrated already with control strategies (Merz, 2011; Sutherland et al., 2012; Vlasveld et al., 2018). This happens mostly because BEM methods were often coupled with unsteady aerodynamical simulations, that did not allow to find this kind of curves, that are taken in steady state. The theoretical literature performance curve is shown in the figure 38 for the 200-kW turbine. A comparison on the performance curves was possible in an analytical way only with QBLADE results:

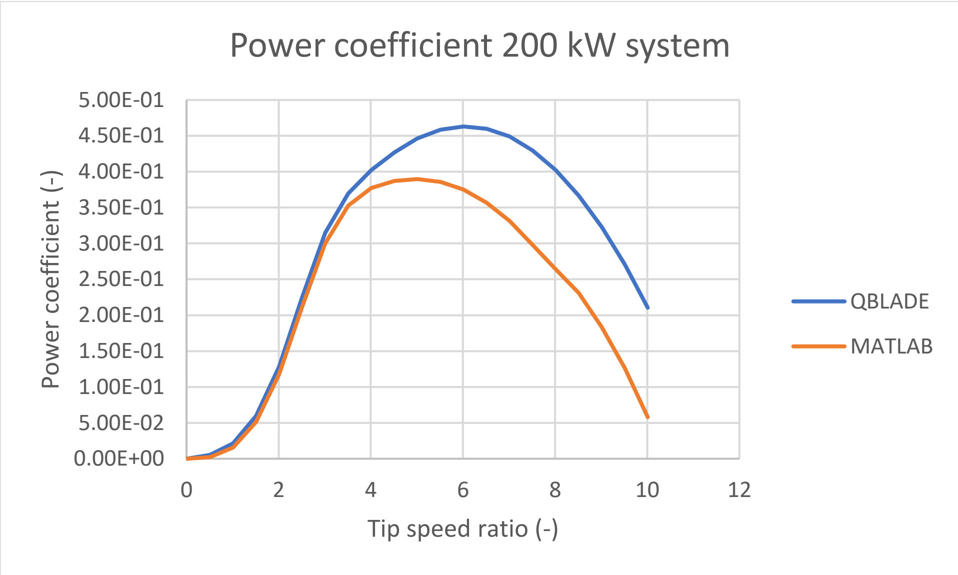

Figure 36: Power coefficients-QBLADE vs MATLAB

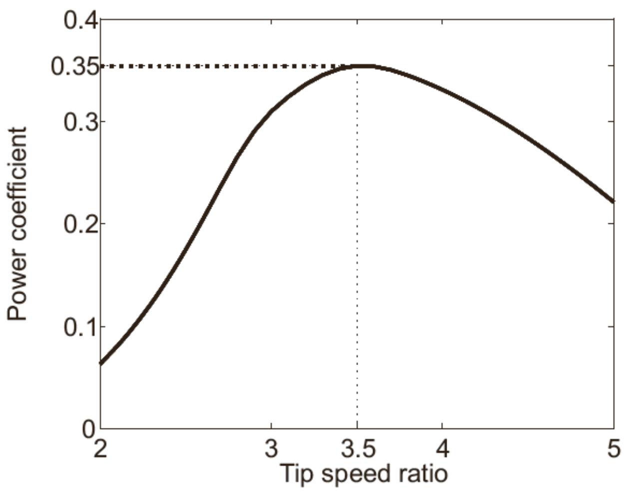

Figure 37: Power coefficient 200 kW system

It is important to notice that, even if the behaviour was very similar with respect to the literature, the MATLAB code found the maximum power at a higher tip speed ratio. This can be explained by the fact MATLAB did not consider hysteresis effects like dynamic stall or wake effects, that are more important at low tip speed ratios and can move the optimal operation point. From these considerations, it is possible to state that the in-house code has an adequate validity.

After the validation, the Simulink/Simscape was then built with the 2 turbines that were the most suitable for a pitch control, because of the straight blades: the Uppsala 200 kW rotor and the TU Delft 6 MW rotor were chosen. Those had also an adequate agreement with paper data (Kjellin, 2012; Vlasveld et al., 2018). From here it is possible to notice that Qblade can give a good guess to find the working point of the turbines but must be improved and integrated to have more precise and adequate results.

Chapter 7

Simscape Multibody model

The model was implemented on Simscape Multibody, which is a toolbox developed in Simulink environment to be used in case of mechanical design. Its main advantage with respect to a normal block diagram implemented in Simulink is the ability to evaluate rigid bodies, and so local loads. This is very useful, because otherwise the simulation environment is structured to work with concentrated parameters and can consider rigid bodies only in an aggregated way. Its blocks can interface with the standard Simulink blocks.

The equation which expresses the dynamics of the system is the standard turbogenerator equation:

$$T_{wind}(\omega, V, \theta, \gamma) - T_{mech}(\omega, \gamma) = J\frac{d\omega}{dt}$$

Equation 42

Where Twind is the torque provided by the wind, which depends on:

- Rotational speed ω
- Wind speed V
- Azimuth angle of the blade θ
- Pitch angle γ

Tmecc is the torque extracted by the generator, which depends on its input control variables:

- Rotational speed ω
- Pitch angle γ

J is the total moment of inertia of the drivetrain.

All these variables can vary and/or evolve in time.

Because of the possibility to evaluate rigid bodies, the necessity to know which are the bodies involved is crucial. Unfortunately, the reference papers for the 6 MW turbine were mostly focused on the aerodynamic and control aspects of the turbine. Since there was not even a components' description, a reasonable guess, starting from the papers and some home-made CAD models, was done. For the shaft a simple fatigue dimensioning was done using Von Mises formula, assuming safety factor SF=3 and maximum admissible stress σ_{am}=200MPa (cemented steel):

$$d \geq \sqrt[3]{\frac{16}{\pi \sigma_{am}} \sqrt{3M_t^2}} \; supposing \; M_f = 0$$

Equation 43

Moments of inertia were calculated directly using a function in Simscape Multibody. This is the component list for the straight-bladed turbines:

COMPONENTS OF 200 kW TURBINE			
NAME	NUMBER	MASS	MOMENTS OF INERTIA [Ixx Iyy Izz]
Blade	3	1.5 t	[57466.8, 57502, 38.5257] kgm2
Nacelle + struts	1	5 t	[82801.3, 82795.5, 137987] kgm2
Shaft	1	8 t	[750039, 750039, 78.125] kgm2
Tower	1	8.6 t	[997414, 997414, 11136.3] kgm2
COMPONENTS OF 6 MW TURBINE			
NAME	NUMBER	MASS	MOMENTS OF INERTIA
Blade	3	43 t	[6.95e+07,6.95e+07,568995] kgm2
Nacelle + struts	1	240 t	[1.55e+08,1.55e+08,1.99e+08] kgm2
Shaft	1	160 t	[7.40e+07,7.40e+07, 9568.55] kgm2
Tower	1	80 t	[3.27e+07,3.27e+07,485331] kgm2

Table 8: inertia properties of turbine components

The tower does not intervene in the system dynamics. The model is divided in some main important blocks:

- Blade aerodynamics blocks
- Angular position block: it is necessary to find the angular speed to be used in the MATLAB structure. It is important to notice that the angles must be inserted in the lookup tables in the range $-\frac{\pi}{2} \leq \theta \leq \frac{3}{2}\pi$, because of the tables' code structure.

- Parameters' evaluation: in this block, the important blade parameters, together with windspeed and rotational speed are put together in order to carry on the simulation.
- Control block.
- Revolution joint: it is the Simscape Multibody block that solves the momentum and motion equations. In this system, the revolution joint receives the resistant (generator) torque as input and gives in output the cinematics of the rotor (rotational speed and acceleration). It is important, for the revolution joint, the setting of the state target of rotation speed: it must respect the wind conditions, otherwise the turbine arrests. This is important because it means that a good guess of the windspeed is needed, also in case of turbulent wind.
- Windspeed block.

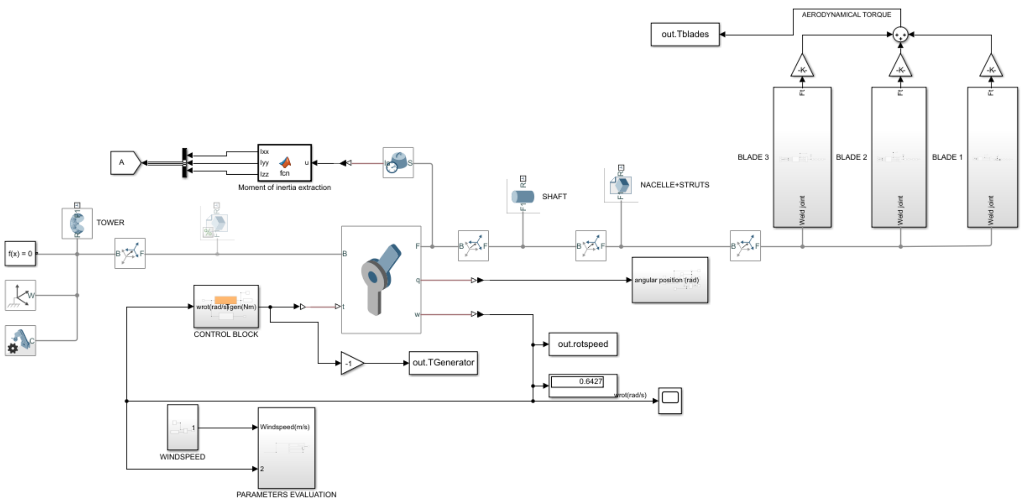

Figure 38: Simscape model overview

In the model, the windspeed block enters in the parameter generation block and it is sent to the blades together with the main blade parameters (chord, span, local radius etc).

7.1 Blades subsystem

The aerodynamic data from the MATLAB code were inserted into the blade blocks. In every blade block, there were some lookup tables to insert the three principal forces present on the blades (Ft=Fx, Fn=Fy, Mz). These forces and moments were calculated in the blade reference system, and the change of coordinates was included in the multibody implementation. They were 4-D tables, where the output (Ft=Fx, Fn=Fy, Mz) depended on azimuth angle, tip speed ratio, pitch angle and windspeed. The spanwise effects were included in a different way. The blade was divided in pieces all with the same length on the z axis (same span for straight blades) and for every point the forces were calculated. Then, the integral value was evaluated.

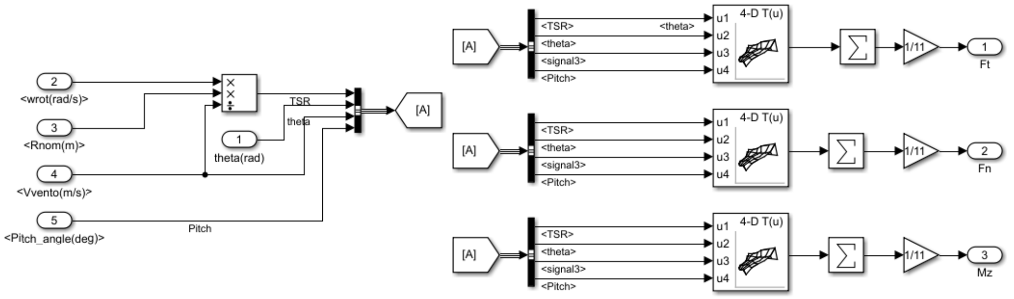

Figure 39: Simulink-blade loads tables

These results from the lookup tables were inserted into the Simscape blocks and then to the blades, that were welded to the rotor blocks. Weld joint is very important because it allows to measure forces and torques on Simscape elements.

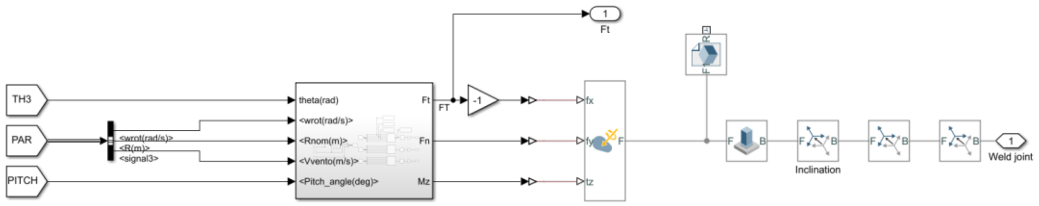

Figure 40:Simscape-blade blocks

In blade blocks the input data are used to calculate solicitations of the system, which are inserted in the “external force and torque” block of Simscape Multibody. This was necessary to translate the Simulink signals in signals that could be used into the revolution joint. These forces make the external torque that acts on the revolution joint, that calculates the rotational speed.

7.2 Controller subsystem

In the control block blade pitch and internal torque are evaluated. Pitch control needs only the rotational speed, while torque control also needs the pitch angle. Rotational speed goes into torque lookup table and into PI pitch control to react to external conditions. In the PI control, a saturator and a rate limiter are needed because otherwise the controlled pitch had too high oscillations and the angle reached unrealistic values. This is a problem since the lookup tables cover only a limited range of pitch angles, which are imposed positive (toe-out) as in figure:

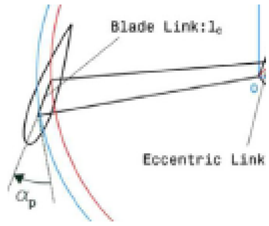

Figure 41: pitch angle mechanism

COMPONENTS		
NAME	NUMBER	UNIT
Max pitch angle rate	5	deg
Pitch angle range saturation (min)	0	deg
Pitch angle range saturation (max)	45	deg

Table 9: pitch system components

This subsystem has the fundamental function of maintaining both torque and speed at the nominal values when the windspeed becomes too high.

To properly integrate the control system into a simulation into a variable windspeed, a lowpass filter was inserted to avoid high frequency components to interfere into the PI system. The time constant of the lowpass filter was taken at a low value to exclude high frequency noise which can affect the sensibility of the control.

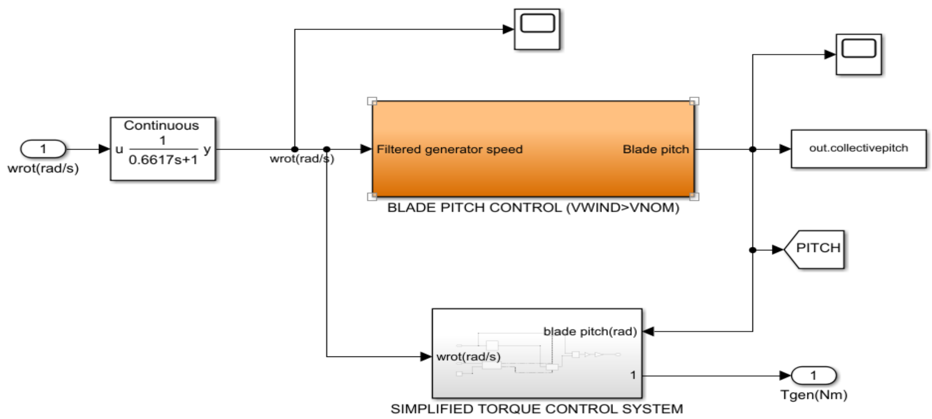

Figure 42: Simulink-control system blocks

Chapter 8

Multibody model validation

To validate the Simscape model a precise reference test was not found, since the literature sources(Apelfröjd et al., 2016; Vlasveld et al., 2018) did provide only graphs, without giving additional information, like the numerical values of average power at different windspeed. Anyway, a check on the performances of the system in dynamic conditions was needed to see if the dynamics of the system was well represented. In literature, the results were present only for the full simulation, with the refined model in dynamic conditions, or as spot measurements of the actual machine.

In our case, the validation was done running the simulations in turbulent conditions at different wind speed values. Turbulent conditions were obtained using the TurbSIM software. For every windspeed value, the average power of the simulation time was calculated, neglecting the first 30s, when the system still is not stabilized. The values were then put on a plot together with the average windspeed at hub height, and confronted with literature data, where present.

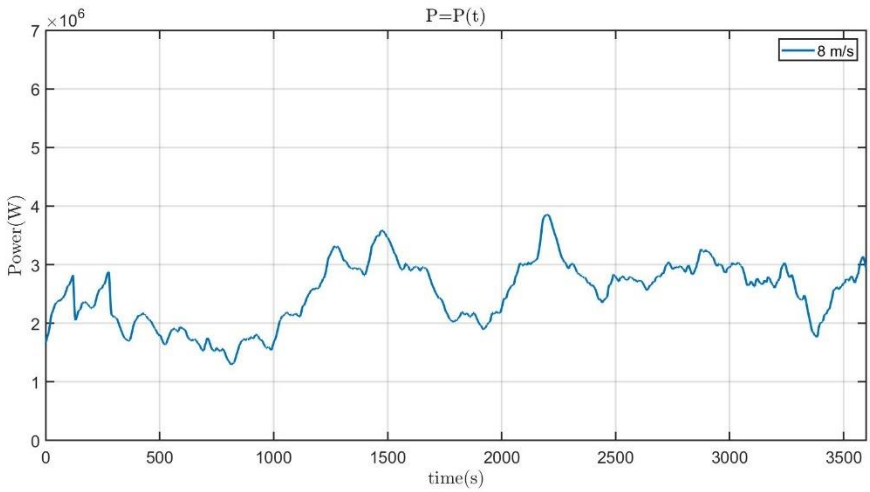

Figure 43: Delft turbine Power production (below rated windspeed)

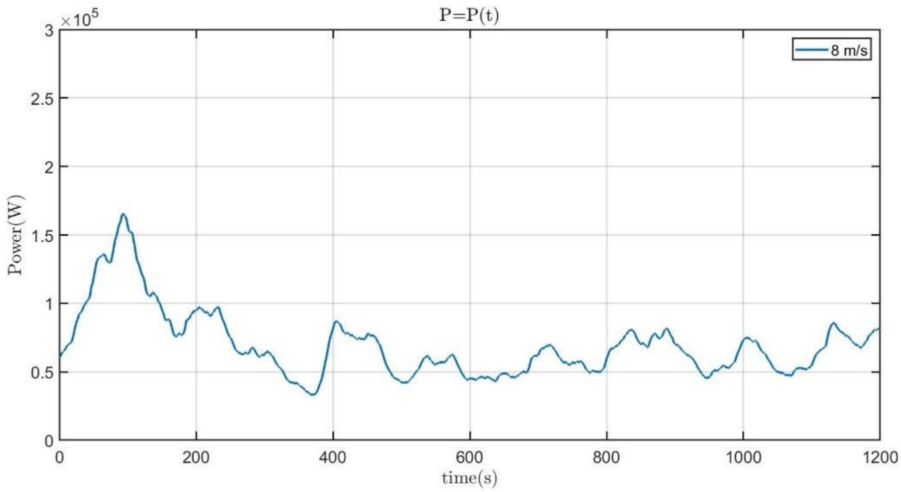

Figure 44: Uppsala turbine power production (below rated windspeed)

From the graphs are evident important oscillations in the produced power with variable windspeed. This phenomenon is probably increased because there is no inclusion of the hysteresis effects in the aerodynamic tables, that act as an "added mass" and increase the rotor inertia**,** reducing oscillations and improving power extraction.

These oscillations reduce the power output, which happens to be lower than the steady-state case with both turbines. The comparation was done taking the power production in steady-state (here called DMST) and the average power output from the SIMSCAPE simulation along the whole simulation time. It is clearly shown in the following figures. This effect becomes more important around nominal windspeed, because sometimes pitch control starts at power level lower than the nominal one. This is good because it makes the simulation results more accurate, nearer to the values which were foreseen in the papers. This applies particularly for the TUDelft 6 MW system, where it is possible to appreciate that in dynamic conditions there is a very good correspondence between the paper and the Simscape model, both at low and high windspeed.

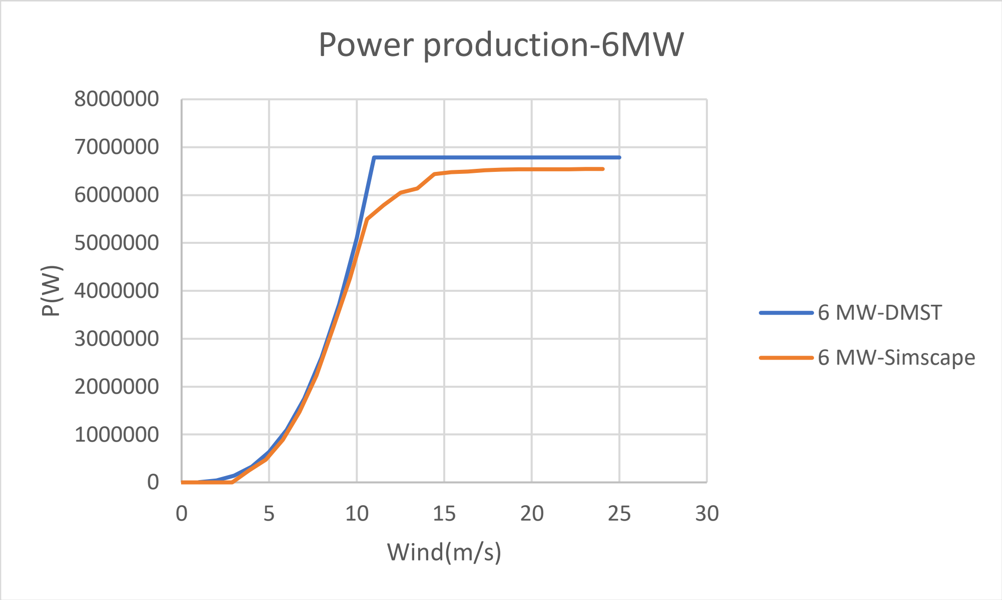

Figure 45: Steady state vs average power in simulation

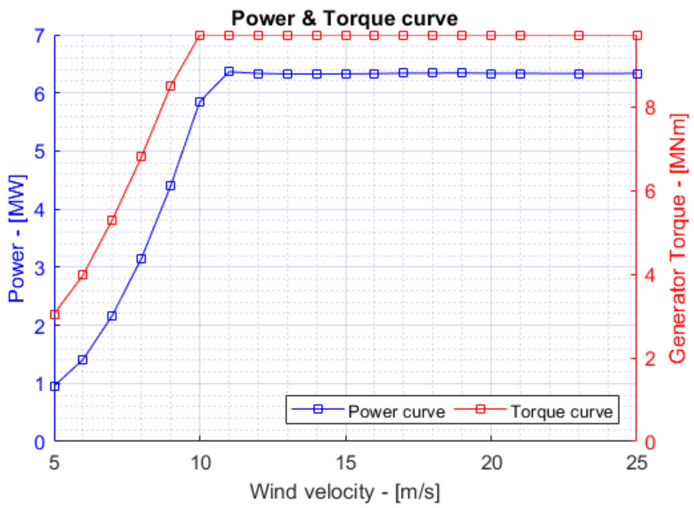

Figure 46: TUDelft - Simulation output from literature

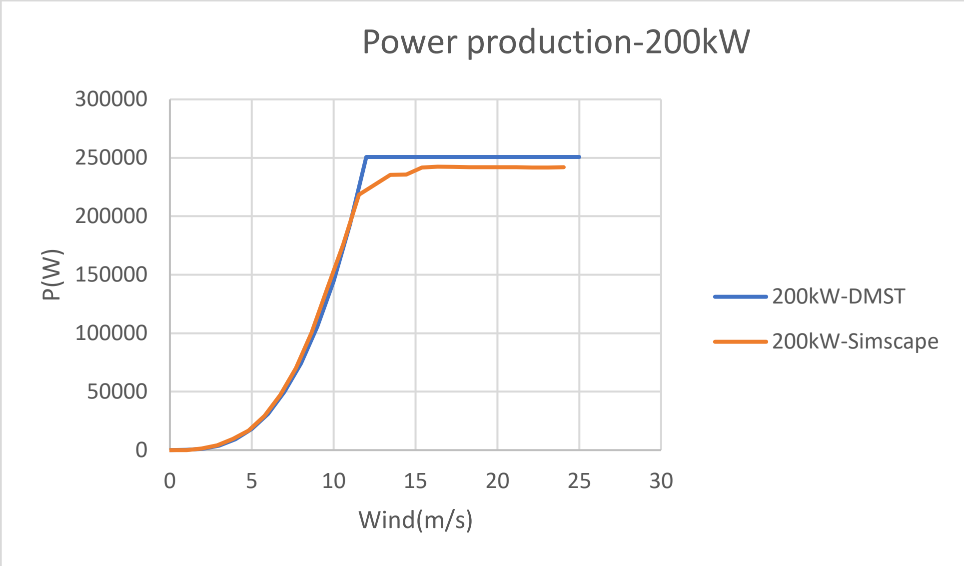

Figure 47: steady-state vs mean simulation value

Differences between models arise, as explained before, from the fact that the simulations were carried with different methodologies.

On the other hand, oscillations were found in an analogous simulation using the NREL reference horizontal axis wind turbine (Cottura et al., 2021).

Chapter 9

Productivity analysis

The last part of the work is the productivity analysis, to assess, in an onshore case, how much energy the turbine can produce "on-field". These data can be confronted with the productivity of a horizontal axis wind turbine in the same conditions.

A further step would be to arrive to calculate the profitability, in these conditions, of this technology, in form of CF and equivalent hours.

9.1 Meteorological data for plant simulation

The first step of the analysis was to choose a suitable location for the analysis. It was chosen to be near Carloforte in Sardinia (Italy). This choice was motivated by the fact that it is a site with good average windspeed and without too many issues in finding a suitable terrain for the installation.

After that, the meteorological data were retrieved. They were found on the database Copernicus, that allowed to find a great variety of meteorological data at a chosen location. From this amount of data, only wind data were searched, at 2 different heights: 10 m from the ground, to use them for small to medium size turbines, 100 m from the ground, if a multi-MW system was analysed. The data were taken with a 0.5°*0.5° resolution with 2 level of height. The database also provided indications for a wind rose, but since this kind of turbine is indifferent with respect to the wind direction only the modulus of the vector was taken. Of the data grid inside, the values used for the wind were the mean values on the map, since the aim is not to fund a suitable place for the installation but only to have a preliminary assessment of the annual energy production and of the capacity factor.

The chosen location was near Carloforte (coordinates 39.1°-39.2°N,8.2°-8.3°E), taking an area of 1° of latitude by 1° of longitude. The choice of this area size is given by the fact that a smaller area would have been too near to the mesh size of ERA5.

From the downloaded data, the average annual windspeed was extracted to have a rough idea of the location performance. It is not a representative parameter for energy production, since with small velocity increment there are relevant power differences. Then, from the timeseries, the probability density curve is built. An important aspect is that, since the turbine is omnidirectional, the wind direction was not considered, even if the database ERA5 provided it. Windspeed was only taken as the resultant of its 2 components, at every timestep:

$$V_{wind}(t) = \sqrt{V_x^2 + V_y^2}$$

Equation 44

To assess the productivity, it is necessary to find the probability of occurrence of a certain windspeed during the year. To do that, the data were divided into classes, each one of size Δv = 1 m/s, and the occurrences' graph was found below:

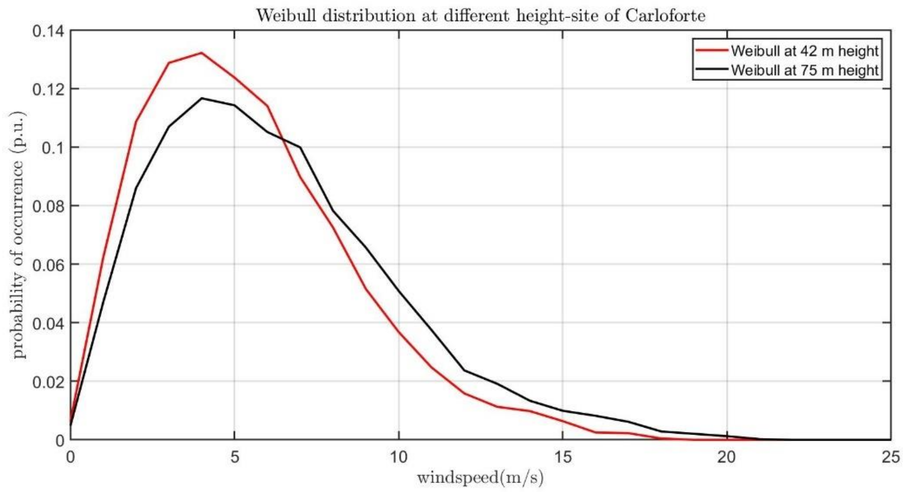

Figure 48: Windspeed occurences in Carloforte

From this elaboration it is found that the wind occurrence is quite like the Weibull distribution. This is good because it guarantees the good quality of the forecast, meaning the error. There are 2 profiles at 42 m and 75 m height. The windspeed values were found starting from the dataset at 100 m height, then the values were corrected using the wind shear equation to find the speed at the correct hub height, respectively 42 and 75 m for the 200 kW and 6 MW turbine. Only one database was used since the 10-m height dataset and the 100-m dataset were coherent only "on average", not punctually, so it was decided to use only the furthest one from the ground.

The aerodynamical loads were calculated considering wind at hub height, which is at half blade length.

9.2 Simulation path

After the occurrence of the windspeed was found, the simulations started. For every wind "class", a turbSIM profile was created to insert variable windspeed into the model. The power law exponent was roughly deduced from the dataset, since it is a land-based simulation it was not possible to use a priori the standard power law exponent.

These were the specifics imposed in turbSIM:

1. Turbulence model: IECKAI ("Kaimal model");
2. Roughness length: Z0=0.8 m. This was found starting from data found on global wind atlas, and averaging on a small surface;
3. Power law exponent left as default from TurbSIM;
4. Timestep: Δt=0.05s;
5. Simulation length: t=1200s;

Then, the simulation was executed for every windspeed, with turbulent input, to better assess the performances. During the simulation the energy production was calculated as:

$$E(t_i) = \int P(t)dt$$

Equation 45

These data were then stored, weighted for the occurrence of the input windspeed, and summed together to evaluate the annual energy performance, capacity factor and equivalent working hours, defined as

$$CF = \frac{AEP(kWh)}{P_{nom} * 8760h}$$

Equation 46

$$h_{eq} = CF * 8760$$

Equation 47

9.3 Performance results

The simulation was carried out for the 2 turbines for every windspeed from 1 to 25 m/s with a step of 1 m/s.

The 6-MW machine, more suited to offshore operation, gave as a result a capacity factor of 29.6% for the locality of Carloforte. This result is like the results for a standard turbine in a favourable onshore site, which is evaluated slightly over 25% (International Energy Agency, 2019). This can be explained with the fact that the site is one of the windiest in Italy, and that some losses were not considered. Another important aspect is that in turbulent situation the efficiency and produced power remain constant. This last aspect was not foreseen, but it is important to notice this is an averaged effect, because of the occurring oscillations in windspeed, that are very important.

The oscillations in power production are linked to the turbulent wind oscillations shown before.

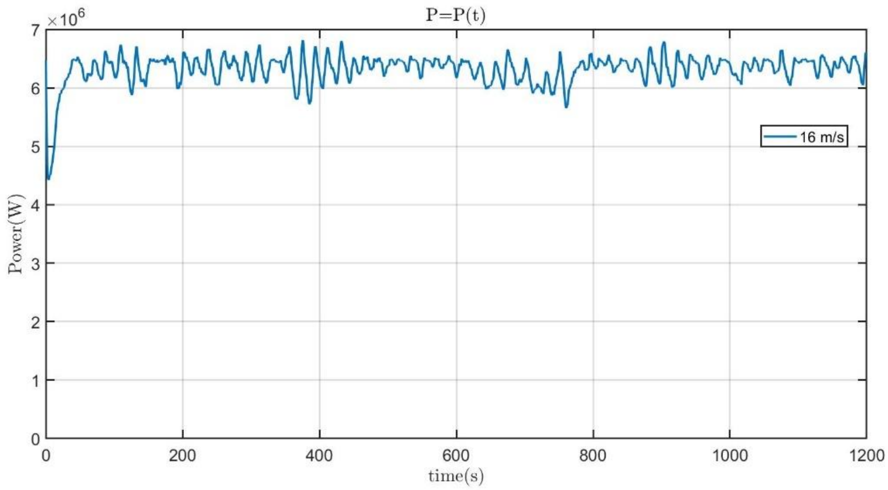

Figure 49: 6 MW power production (above nominal windspeed)

The pitch control is able, in this case, to stabilize power at high windspeed to safeguard structure integrity and allow safe operation. The “valleys” in the graph are due to the simplicity of the control, to the fact it does not include a filter for rotational speed at the input of the PI part. Moreover, it reduces the power oscillations, causing a smoother operation and lower load variations.

Annual performance	
5.60003E+13	AEP(J)
15555638.97	AEP(kWh)
0.295959646	CF
2592.606495	Heq(h/year)

Table 10: AEP 6 MW turbine onshore

The 200-kW machine, which is more suited to onshore operation, gave as a result a capacity factor of 20.8% for the locality of Carloforte. This result is significant because the location of the real machine, in the west coast of Sweden, had similar annual average wind speed with respect to Carloforte. There they obtained a capacity factor of 11.25% in a test campaign (Apelfröjd et al., 2016). This is significantly smaller than the results obtained in the simulation, but there are some explanations:

1. Measurements were done during a test campaign. This was a moment when the main objective was to test the system and validate simulations, more than maximize energy production. So, it is extremely likely that during that campaign test periods were alternated to periods when the machine was parked, even if the wind resource was available with adequate windspeed.

2. The turbine was always operated at lower speed than nominal because the structure was subjected to low frequency vibrations which became very dangerous at high windspeed, also because the prototype worked at fixed pitch. The machine never reached full power output in this campaign: the maximum power output that was allowed was around 80 kW before a dissipative disc brake intervened(Apelfröjd et al., 2016; Möllerström et al., 2019). This causes an important drop in energy production since it does leave untapped the higher windspeed.

The lower capacity factor is also due to the smaller size of this turbine, which cannot catch the same high-height wind of the standard multi-MW turbine. In fact, the hub height of the considered turbine is only 42 m, not 87.6 m like the reference 5 MW machine built by NREL: windspeed difference given by windshear becomes very important, especially in onshore simulations. Then, putting together the fact this technology is less performing than the standard turbines and has not any kind of optimization, this causes a lower power output. The results showed are consistent with the literature data.

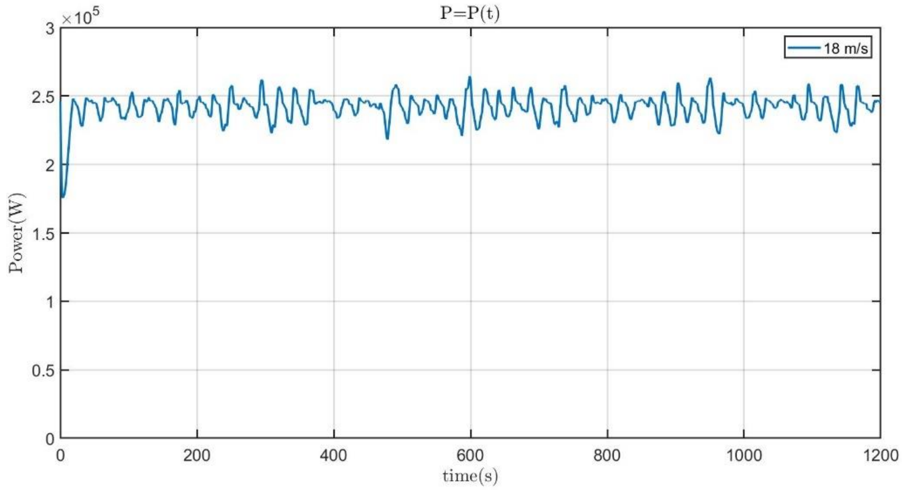

Figure 50: 200 kW Power production (above nominal windspeed)

It is shown on this figure that the pitch control, even if simple, can adequately limit the power production, keeping the turbine into a safe operating zone. Moreover, it reduces the power oscillations, causing a smoother operation and lower load variations.

Annual performance	
AEP(J)	1.31E+12
AEP(kWh)	364393.9
CF	0.207987
Heq (h/year)	1821.969

Table 11: AEP 200kW onshore

The results for the capacity factor are between 20 and 29%. These results mean that the annual energy performance of a vertical axis turbine with variable pitch is comparable, also in terms of productivity, to that of a horizontal one. These results were evaluated as consistent with the aerodynamic behaviour of the system since there were very few references in literature about productivity of these turbines because of their limited diffusion, and nearly none for MW-size machines.

Chapter 10

Future developments

These in-house codes and model are only the first step of a work about vertical axis wind turbines. This model was built starting from another Simulink-Simscape model of a horizontal axis wind turbine, that had different properties and very different behaviour. This Simscape model did not have a reference for validation, so literature data in nominal conditions were used as a comparation together with the QBLADE software for the aerodynamic code for the steady state. Some improvements are anyway needed:

1. The most important improvement needed is a better, unsteady aerodynamics model to reduce the oscillations during the simulation and provide better results. Lifting-line methods are promising improvements for this kind of plants because they work better in unsteady flow with respect to blade element methods. Some open-source codes are available, like CACTUS (Code for Axial and Crossflow TUrbine Simulation) from Sandia National Laboratories, or HAWC2 from DTU. They work in FORTRAN language and could be analysed and integrated in the Simscape model to increase its accuracy. The utilization of a dedicated code instead of an in-house software should increase significatively the accuracy of the result, allowing to consider unsteady effects, like dynamic inflow or stall.
2. Since these machines are mostly employed for offshore applications, a floating substructure needs to be integrated. This could be done using Wec-Sim, a program for floating devices integrated in the MATLAB environment. It could be able to integrate aerodynamics and hydrodynamics. A floating structure, moorings and substructure should be studied, dimensioned, and simulated.
3. The control part needs to be enriched and improved, since it was done in a simplified way to use established practices used for horizontal axis turbines, both on generator and pitch control. This was necessary to have a simple, reliable regulation that could limit the power of the turbine with the minimum number of input parameters. The control systems could be improved to achieve higher efficiency at partial loads both using torque and

pitch control. Torque control could be improved considering the electrical part, also simulating the electrical generator, and working on its working parameters (voltage, current, etc.) as done in some papers (Andriollo et al., 2008; Svendsen H. & Merz Karl O., 2012). Pitch control could be used also to increase performances, also trying simulations with individual pitch systems, or where the angle changes for every blade across each revolution.

These features, once incorporated, should give a significant improvement to the system performances.

Chapter 11

Conclusions

The aim of this thesis was to build a first in-house dynamic model of a vertical axis wind turbine, to simulate its aerodynamic behaviour in turbulent wind conditions.

First, a review of the main technology for this kind of machines was done, to have an overview of the most important deployed systems and, more importantly, the aerodynamic models employed. Starting from that, a double multiple streamtube model was employed because of its simplicity to implement, the possibility to add three-dimensional effects and most importantly the fact that most of the literature used this method.

To do that, initially the open-source code called QBLADE was employed and validated with respect to literature data. It became clear that QBLADE gave significantly different results from literature, could not be used to find instantaneous blade loads in all the conditions needed, a code was developed in-house. This code worked with the same principles of QBLADE (Double multiple StreamTube) and was initially compared to it to assess its stability, then refined. This refinement brought better agreement between literature results and in-house results, allowing us to have all needed degrees of freedom (windspeed, rotational speed, azimuth, pitch). This allowed to control and modify every input variable to what was needed. The turbines which were found to be more representative were the 200 – kW prototype built by the Uppsala university and the 6 – MW concept developed by the University of Delft, since they were more detailed than many other partial studies.

These results were then put into a Simulink-Simscape Multibody model, to integrate the aerodynamic results into a dynamic environment, where it was possible to understand how this system worked with variable windspeed input and how the power output could be regulated.

So, in the Simulink environment a simple control system was built to limit the power output at high windspeed. This was done in 2 ways: pitch and torque control, both analogous to the ones present for a horizontal axis wind turbine. This allowed the power to remain constant at high windspeed, keeping constant torque and increasing pitch angle to limit rotational speed.

This model was built in-house since there was not, in literature or online, a dynamic model of this kind. The use of Simscape allowed to consider more precisely the effects of the rigid bodies composing the turbine, also obtaining an animation useful to have a first impression of the working system. This model had the aim to capture the system behaviour in turbulent wind, to be as close as possible to the real case.

The model was then used to do a productivity analysis, using wind data from the database ERA5 of a location in Italy (Carloforte) to establish the energy production in a real site.

The results on the Simscape model showed important oscillations in the power output and highlighted the fact that an unsteady aerodynamical model could be a better choice for a model refinement, but that a good preliminary guess could be deduced with a stationary formulation like double multiple streamtube, as done here. The control system showed to be rough but effective, and in addition damped very well wind speed oscillations when windspeed was high, reducing cyclical loads and improving fatigue behaviour.

The results, even considering many approximations that were involved, showed a productivity lower than the one of horizontal axis wind turbines, around 21% for the 200 kW system and 29% for the 6 MW system. This is anyway a promising result, because it shows that there is not an excessive productivity gap for large-scale, variable pitch vertical turbine systems. This is interesting for offshore installations, where these devices may offer some advantages with respect to standard turbines, mostly from the point of view of the floating behaviour and interaction with the platform. This could also make the investment competitive with respect to other offshore installations.

References

Andriollo, M., de Bortoli, M., Martinelli, G., Morini, A., & Tortella, A. (2008). Control strategies for a VAWT driven PM synchronous generator. *SPEEDAM 2008 - International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, 804–809. https://doi.org/10.1109/SPEEDHAM.2008.4581124

Apelfröjd, S., Eriksson, S., & Bernhoff, H. (2016). A Review of Research on Large Scale Modern Vertical Axis Wind Turbines at Uppsala University. *Energies*, *9*(7), 570. https://doi.org/10.3390/en9070570

Ayati, A. A., Steiros, K., Miller, A. M., Duvvuri, S., & Hultmark, M. (2019). A double-multiple streamtube model for vertical axis wind turbines of arbitrary rotor loading. *Wind Energy Science*, *4*(4), 653–662. https://doi.org/10.5194/wes-4-653-2019

Borg, M., Shires, A., & Collu, M. (2014). Offshore floating vertical axis wind turbines, dynamics modelling state of the art. part I: Aerodynamics. In *Renewable and Sustainable Energy Reviews* (Vol. 39, pp. 1214–1225). Elsevier Ltd. https://doi.org/10.1016/j.rser.2014.07.096

Collu, M., & Borg, M. (2016). Design of floating offshore wind turbines. In *Offshore Wind Farms: Technologies, Design and Operation* (pp. 359–385). Elsevier Inc. https://doi.org/10.1016/B978-0-08-100779-2.00011-8

Cottura, L., Caradonna, R., Ghigo, A., Novo, R., Bracco, G., & Mattiazzo, G. (2021). Dynamic modeling of an offshore floating wind turbine for application in the mediterranean sea. *Energies*, *14*(1). https://doi.org/10.3390/en14010248

Gaertner, E., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Skrzypinski, W., Scott, G., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C., & Viselli, A. (2020). *Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report*. www.nrel.gov/publications.

Genovese, F. (2019). *Transizione energetica: Sfide nella gestione del sistema elettrico e ruolo dello storage*.

Hand, B., Kelly, G., & Cashman, A. (2021). Aerodynamic design and performance parameters of a lift-type vertical axis wind turbine: A comprehensive review. In *Renewable and Sustainable Energy Reviews* (Vol. 139). Elsevier Ltd. https://doi.org/10.1016/j.rser.2020.110699

Huijs, F., Vlasveld, E., Gormand, M., Savenije, F., Caboni, M., Leblanc, B., Simao Ferreira, C., Lindenburg, K., Gueydon, S., Otto, W., & Paillard, B. (2018). Integrated design of a semi-submersible floating vertical axis wind turbine

(VAWT) with active blade pitch control. *Journal of Physics: Conference Series*, *1104*(1). https://doi.org/10.1088/1742-6596/1104/1/012022

International Energy Agency. (2019). *Offshore Wind Outlook 2019: World Energy Outlook Special Report*. www.iea.org/t&c/

Jonkman, J., Butterfield, S., Musial, W., & Scott, G. (2009). *Definition of a 5-MW Reference Wind Turbine for Offshore System Development*. http://www.osti.gov/bridge

Kjellin, J. (2012). *Vertical Axis Wind Turbines: Electrical System and Experimental Results*. http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-182438

Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind Energy Explained: Theory, Design and Application* (Wiley, Ed.; second edition). www.LearnEngineering.in

Marten, D., & Wendler, J. (2013). *QBlade Guidelines v0.6*.

Merz, K. O. (2011). *A Blade Element Momentum Method for Dynamic Analysis of Vertical Axis Wind Turbines-Rev B*.

Möllerström, E., Gipe, P., Beurskens, J., & Ottermo, F. (2019). A historical review of vertical axis wind turbines rated 100 kW and above. In *Renewable and Sustainable Energy Reviews* (Vol. 105, pp. 1–13). Elsevier Ltd. https://doi.org/10.1016/j.rser.2018.12.022

Rossander M. (2017). *Electromechanics of vertical axis wind turbines*. Acta Universitatis Upsaliensis.

Sanvito, A., Dossena, V., & Persico, G. (2021). Formulation, Validation, and Application of a Novel 3D BEM Tool for Vertical Axis Wind Turbines of General Shape and Size. *Applied Sciences*, *11*(13), 5874. https://doi.org/10.3390/app11135874

Sutherland, H. J., Berg, D. E., & Ashwill, T. D. (2012). *SANDIA REPORT A Retrospective of VAWT Technology*. http://www.ntis.gov/help/ordermethods.asp?loc=7-4-

Svendsen H., & Merz Karl O. (2012). *Description of simplified numerical model relevant for development of control concepts*.

Vallverdù D, & Rempfer D. (2014). *STUDY ON VERTICAL-AXIS WIND TURBINES USING STREAMTUBE AND DYNAMIC STALL MODELS*.

Vitale, A. J., Genchi, S. A., Rossi, A. P., Guillermo, E. D., & di Prátula, H. R. (2018). Aerodynamic Performance of Straight-Bladed Vertical Axis Wind Turbines: A Practical Open Source Implementation. *INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH*, *8*(2).

Vlasveld, E., Huijs, F., Savenije, F., & Paillard Eolfi Paris, B. (2018). *COUPLED DYNAMICS OF A VERTICAL AXIS WIND TURBINE (VAWT) WITH ACTIVE BLADE PITCH CONTROL ON A SEMI-SUBMERSIBLE FLOATER OMAE2018-78058*. http://asmedigitalcollection.asme.org/OMAE/proceedings-pdf/OMAE2018/51319/V010T09A085/2537203/v010t09a085-omae2018-78058.pdf