Operation of a small scale urban wind turbine placed on a building

SKOUNTZOS IOANNIS
ID: 3302130009

SCHOOL OF SCIENCE & TECHNOLOGY
A thesis submitted for the degree of
Master of Science (MSc) in Energy Systems

NOVEMBER 2014
THESSALONIKI – GREECE
Operation of a small scale urban wind turbine placed on a building

SKOUNTZOS IOANNIS
ID: 3302130009

Supervisor: Prof. Georgios Giannakidis
Supervising Committee Members:
Assoc. Prof.
Assist. Prof.

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

NOVEMBER 2014
THESSALONIKI – GREECE
Abstract

This dissertation focuses on a small scale wind turbine placed on a building. The aim of this thesis is to study the effects on the urban areas on the electricity production.

The initial investigation put emphasis on the performance of the wind turbine which was calculated by using software, called QBlade, along with the assistance of some different assumptions (conclusions) for the effects of the urban area and buildings regarding the velocity profile.

Finally, I want to thank my supervisor Professor Georgios Giannakidis for his guidance, his patience and his time.

Skountzos V. Ioannis
12/11/14
Contents

ABSTRACT ............................................................................................................................................3

CONTENTS ........................................................................................................................................4

LIST OF FIGURES..............................................................................................................................6

LIST OF TABLES ...............................................................................................................................9

GLOSSARY ........................................................................................................................................10

INTRODUCTION ...............................................................................................................................12

CHAPTER 1: GENERAL FACTS ABOUT WIND TURBINES..............................................................15

  1.1 WIND TURBINES IN HISTORY ............................................................................................15

  1.2 TYPES OF WIND TURBINES ...............................................................................................21

       1.2.1 Vertical axis wind turbines (VAWT) ..........................................................................21

       1.2.2 Horizontal axis wind turbine ...................................................................................25

CHAPTER 2: SMALL SCALE WIND TURBINES.................................................................................28

  2.1 GENERAL FACTS ...................................................................................................................28

  2.2 ADVANTAGES AND DISADVANTAGES OF SMALL SCALE WIND TURBINES ...............30

  2.3 TOWERS ................................................................................................................................30

CHAPTER 3: SMALL SCALE WIND TURBINE ON A BUILDING (STUDY AND PERFORMANCE OF WIND TURBINES) ............................................................................................................34

  3.1 OPTIMAL POSITION OF A WIND TURBINE ON A ROOF OF A BUILDING ......................34

  3.2 VIBRATIONS .........................................................................................................................35

  3.3 MATHEMATICAL ANALYSIS OF THE PERFORMANCE ......................................................36

  3.4 WEIBULL DISTRIBUTION – REYLEIGH DISTRIBUTION .................................................40

  3.5 THE PERFORMANCE CURVES ............................................................................................43

CHAPTER 4: WIND CHARACTERISTICS ............................................................................................47

  4.1 WIND STATISTICS ................................................................................................................51
CHAPTER 5: CONSTRUCTING SMALL SCALE URBAN WIND TURBINES
ON A BUILDING..................................................................................................................55

5.1 BLADES .......................................................................................................................55
5.2 ROTOR BLADE ...........................................................................................................56
5.3 NUMBER OF BLADES ..............................................................................................59
5.4 MATERIALS ................................................................................................................60
5.5 NACELLE ......................................................................................................................62
5.6 YAW CONTROL ............................................................................................................62
5.7 GENERATOR ..............................................................................................................63
5.8 LOADS AND VIBRATIONS .......................................................................................64

CHAPTER 6: CONTRIBUTION..............................................................................................66

CHAPTER 7: RESULTS........................................................................................................85

CONCLUSIONS..................................................................................................................87

BIBLIOGRAPHY...................................................................................................................89

APPENDIX A......................................................................................................................92

APPENDIX B......................................................................................................................95

APPENDIX C.....................................................................................................................102

APPENDIX D.....................................................................................................................103

APPENDIX E.....................................................................................................................104
List of Figures

Figure 1.1: Different sizes of wind turbines [4] ..........................................................12
Figure 1.2: The Smith – Putnam WT (http://www.integener.com/SABTSKMANUSCRIPT/CHAPTER06.HTM) ...........16
Figure 1.3: The Gedser turbine (http://mstudiobackboard.tudelft.nl/DUWIND/WIND%20ENERGY%20ONLINE%20READER/STATIC_PAGES/WIND_PIONEERS.HTM) ........................................17
Figure 1.4: A wind turbine back in 70s (http://www.nasa.gov/centers/glen/ABOUT/HISTORY/70S_ENERGY.HTML).18
Figure 1.5: A wind turbine in 80s (http://barnardonwind.com/2014/02/18/OFFSHORE-VAWTS-DEBUNK/) ........19
Figure 1.6: Wind turbine at Vindeby 1991 (http://popularlogistics.com/2012/04/DO-WE-NEED-NUCLEAR-POWER-PART-2/) 19
Figure 1.7: The Kappel (Denmark) wind farm 2002 (http://mstudiobackboard.tudelft.nl/DUWIND/WIND%20ENERGY%20ONLINE%20READER/STATIC_PAGES/LANDSCAPE.HTM) ...............................................20
Figure 1.8: The variety of size power and rating over the years [5] ..........21
Figure 1.9: Forces and velocities acting in a VAWT (winturbine-analyis.com) ...........................................................................................................23
Figure 1.10: Savonius rotor (http://www.buch-der-synergie.de/c_neu_html/c_08_08_WINDENERGIE_SENKRECHTACHSER.HTM)24
Figure 1.11: Darrieus rotor (http://schwarmkraft.at/ERNEUERBARE-ENERGIE/WINDKRAFT/WINDKRAFT-UNKONVENTIONELL/) ........................................24
Figure 1.12: H-rotor and cycloturbine (http://www.wind-works.org/cms/index.php?id=500) .................................................................25
Figure 1.13: Various types of HAWT [3] ........................................................................26
Figure 1.14 Horizontal axis wind turbine (http://science.howstuffworks.com/environmental/green-science/wind-power2.HTM) ........................................................................................................27
Figure 5.6: Rubber shims for vibration [40] .................................................65
Figure 6.1: The curves CL-CD, CL-A, CM-A, CD-A [45] ............................70
Figure 6.2: The curves CL-CD, CL-A, CM-A, CD-A, for \( \alpha = 7.5 \), \( \text{Re} = 200000 \) [45] 71
Figure 6.3: c-r/R and gT0-r/R curves ..........................................................74
Figure 6.4: The airfoil for NACA0012 [46] ....................................................74
Figure 6.5: The CP-x curve and the airfoil at \( \alpha = 7.5 \) [46].......................75
Figure 6.3: CL-A, CD-A curves with 3600 view [46] ..................................76
Figure 6.6: The input values and the design products [46] ..........................78
Figure 6.7: The curves: CP-TSR, Ct-TSR, a-pos, for wind speed 2.5 m/s [46] 80
Figure 6.7: The curves P-V, P-\( \lambda \), T-\( \lambda \) and P-1/\( \lambda \), for \( \lambda = 7 \) and \( \alpha = 7.5 \) [46] ....81
Figure 6.8: The curves P-V, S-V and A/A-x, for \( \lambda = 7 \) and \( \alpha = 7.5 \) [46]........83
Figure 7.1: The curves P-V, S-V [46] .........................................................86
Figure A1: Weibull probability density function for different shape factors [3] ..........................................................................................................................93
Figure A2: Weibull cumulative distribution function for different shape factors [3] ..................................................................................................................93
Figure A3: CP-\( \lambda \) performance curve with losses [3] .............................94
Figure A4: The effect of changing solidity [3] ..............................................94
Figure B1: Wind direction distribution in January [34] ...............................95
Figure B2: Wind direction distribution in February [34] .............................96
Figure B3: Wind direction distribution in March [34] .................................96
Figure B4: Wind direction distribution in April [34] ....................................97
Figure B5: Wind direction distribution in May [34] ....................................97
Figure B6: Wind direction distribution in June [34] ...................................98
Figure B7: Wind direction distribution in July [34] ....................................98
Figure B8: Wind direction distribution in August [34] ..............................99
Figure B9: Wind direction distribution in September [34] .......................99
Figure B10: Wind direction distribution in October [34] ..........................100
Figure B11: Wind direction distribution in November [34] ......................100
Figure B12: Wind direction distribution in December [34] .......................101
Figure C1: The Ginlong generator (0.5 and 1.0 kW) [51] .........................102
Figure D1: Power and RPM for various speeds of the wind [38] .........103
List of Tables

TABLE 5.1: STRENGTH AND STIFFNESS PARAMETERS OF MATERIALS IN PRINCIPLE AVAILABLE FOR ROTOR BLADES [37].................................................................61
TABLE 6.1: NCRIT VALUES [45] ........................................................................69
TABLE 6.2: CHORD AND TWIST ANGLE VALUES...........................................73
TABLE E.1: DIFFERENT VALUES OF $C_L$ AND $C_D$ [45] .........................104
# Glossary

<table>
<thead>
<tr>
<th>SYMBOLS</th>
<th>A/A</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>WIND SPEED</td>
<td>M/S</td>
</tr>
<tr>
<td>P</td>
<td>AIR DENSITY</td>
<td>KG/M³</td>
</tr>
<tr>
<td>P</td>
<td>POWER OUTPUT</td>
<td>WT.</td>
</tr>
<tr>
<td>A</td>
<td>AREA SWEPT BY THE ROTOR BLADES</td>
<td>M²</td>
</tr>
<tr>
<td>D</td>
<td>TURBINE’S DIAMETER</td>
<td>M</td>
</tr>
<tr>
<td>C_P</td>
<td>POWER COEFFICIENT</td>
<td>%</td>
</tr>
<tr>
<td>M</td>
<td>MASS</td>
<td>KG</td>
</tr>
<tr>
<td>Λ</td>
<td>TIP SPEED RATIO</td>
<td>-</td>
</tr>
<tr>
<td>Ω</td>
<td>ANGULAR ROTATION VELOCITY</td>
<td>DEG/S</td>
</tr>
<tr>
<td>R</td>
<td>TURBINE’S RADIANCE</td>
<td>M</td>
</tr>
<tr>
<td>AOA</td>
<td>ANGLE OF ATTACK</td>
<td>DEG</td>
</tr>
<tr>
<td>VAWT</td>
<td>VERTICAL AXIS WIND TURBINES</td>
<td>-</td>
</tr>
<tr>
<td>HAWT</td>
<td>HORIZONTAL AXIS WIND TURBINES</td>
<td>-</td>
</tr>
<tr>
<td>U_∞</td>
<td>UPSTREAM WIND VELOCITY AT THE ENTRANCE ON THE ROTOR BLADES</td>
<td>M/S</td>
</tr>
<tr>
<td>U_E</td>
<td>DOWNSTREAM WIND VELOCITY AT THE EXIT OF THE ROTOR BLADES</td>
<td>M/S</td>
</tr>
<tr>
<td>PMG</td>
<td>PERMANENT MAGNET GENERATORS</td>
<td>-</td>
</tr>
<tr>
<td>RPM</td>
<td>REVOLUTIONS PER MINUTE</td>
<td>-</td>
</tr>
<tr>
<td>DC</td>
<td>DIRECT CURRENT</td>
<td>VOLT</td>
</tr>
<tr>
<td>AC</td>
<td>ALTERNATING CURRENT</td>
<td>VOLT</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------</td>
<td>------</td>
</tr>
<tr>
<td>C</td>
<td>BLADE CHORD</td>
<td>M</td>
</tr>
<tr>
<td>$C_L$</td>
<td>COEFFICIENT OF LIFT</td>
<td>%</td>
</tr>
<tr>
<td>$C_D$</td>
<td>COEFFICIENT OF DRAG</td>
<td>%</td>
</tr>
<tr>
<td>$C_T$</td>
<td>COEFFICIENT OF THRUST</td>
<td>%</td>
</tr>
<tr>
<td>K</td>
<td>WEIBULL DISTRIBUTION FACTOR</td>
<td>-</td>
</tr>
<tr>
<td>$A'$</td>
<td>WAKE ROTATION</td>
<td>DEG</td>
</tr>
</tbody>
</table>
Introduction

Kyoto protocol forced many countries to reduce greenhouse gas emissions (GHG) up to 20% by 2020 in order to mitigate climate change. About 30-40% of electrical energy, for many countries, will need to come from renewables and wind energy will play a vital role in order to succeed this target.

The use of wind energy is becoming increasingly more important. Each year, more and more large industries manufacture and install wind turbines with thousands of MWs of new capacity.

This thesis shall provide a study of small scale wind turbines in an urban area and more specifically on a building. The study and deployment of a wind turbine in an urban area is more complicated than in rural, open spaces. Thus, there are some major issues which can be identified: The wind characterization around buildings, the specific design requirements of the wind turbines in an urban area and finally the deployment of the WT on a building.

![Different sizes of wind turbines](image.png)

Figure I.1: Different sizes of wind turbines [4]
Chapter 1 introduces the general facts about wind turbines. In this chapter the historical development, the different types of wind turbines and different heights as it shows at figure 1, which are used nowadays is presented.

Chapter 2 sets out the basis of this thesis. Small scale wind turbines are introduced in this chapter. The types of small wind turbines and their advantages and disadvantages are also discussed in this chapter.

Chapter 3 provides some general information about horizontal axis wind turbines. In this chapter the main issue is the performance of a HAWT $C_p$-$\lambda$, $C_Q$-$\lambda$ and $C_T$-$\lambda$ performance curves, and a description of their main parts.

Chapter 4 discusses how wind velocity affects the performance of a wind turbine on a building. There are many wind velocity parameters which must be taken into consideration in order to clarify how the wind affects the performance of a wind turbine. This chapter also concentrates on the historical data and the geographical analysis of the wind’s velocity in the city of Thessaloniki, which is the area that this thesis examines. Finally, this chapter also refers to the energy potential of the wind on a building.

Chapter 5 provides the constructing analysis of a wind turbine placed on a building in an urban area. The aerodynamic analysis via Reynolds number, rotor blades, airfoil and load, materials which are used, the insulation which is necessary and the power generation are examined in details in this chapter. Last but not least is the examination of the loads on the wind turbine and how damage can be avoided.

Chapter 6 presents the Qblade program. It is important to understand the procedure that has been followed and the reason that this program has been used. There are three parameters which have been used for this program. First of all, the building’s height and its effect on the other buildings in the neighborhood. Secondly, the height of the small scale horizontal axis wind turbine in order to produce the maximum power and not to have problems with its stability, noise, weight.

Chapter 7 and Conclusions present the results from the program and the main conclusions of the work.
Finally, although non-technical barriers such as regulations and economics are very important for successful installation of WT in the urban area, these will not be analysed in the present work.
Chapter 1: General facts about wind turbines

1.1 Wind turbines in history [5, 6]

The first attempt

Human attempt to generate electricity from the wind power is traced back to the nineteenth century with the use of a windmill (the first wind turbine) with a 12 kW DC (direct current). This first try was constructed by an American, Charles Brush.

However, for many years the interest in using the wind energy for generating electricity was minor. The main interest was for battery charging for the distant residences. Fortunately, these systems were stopped when the access to the grid of electricity became available.

Figure 1.1: The first try (Righter, Robert W. (1996)
The 30’s
In 1931 a 100kW with a 30 meters diameter was constructed in the USSR (today Russia).

The 40’s
Later in 1941, Smith - Putnam who developed a 1250kW wind turbine in the USA. This extraordinary turbine had a 53 meters steel rotor. Even though, the machine failed in 1945 (only ran for 1100 hours), it remained the largest wind turbine for the next 40-50 years.

The 50’s
In the early 50s Andrea Enfield designed a 100kW wind turbine with a 24 diameter pneumatic design in the UK. The main difference of this turbine is that for the first time hollow blades were used, which were open at the tip, in order to draw air up through the tower and then to the generator with the help of another turbine.

In 1956 in Denmark, 24 meters Gedser turbine was constructed producing 200kW.
The 60’s
In 1963, Electricite de France tested a turbine which had 35 meters diameter and produced 1.1 MW power.

The 70’s
The increase in oil prices in 1973 was the main factor that UK, among other countries, turned to other sources for energy production such as solar energy, wind energy etc. This led the governments, especially the USA, to fund new programs of research. The results were impressive as a new type of turbines were constructed starting with 100kW power and 38 meters diameter up to 97.5 meters diameter with 2.5 MW in 1987. The same strategy was followed by other countries as well, such as in Canada (4MW vertical axis Darrieus wind turbine), in the UK (straight blades for a vertical axis design for a 500 kW prototype constructed), in Denmark (3 bladed, upwind stall wind turbine regulated rotor and a fixed speed induction generator drive train with a 60 meters diameter and power up to 1.5MW).
The 80’s
In USA, in 1981, a 3MW horizontal axis wind turbine, which used a hydraulic transmission and the entire structure, was orientated into the wind. The optimal number of blades was not specified for a long time, but for large scale horizontal axis turbines the usual number was one, two or in most cases three blades.

Between 1981 and 1990, a 20 to 350kW wind turbines, installed in California, gave over 1,700 MW and produced over 3.000.000 MWh of electricity which was enough to give power to a city with 300.000 people.
The 90’s
The market turned to Europe and Asia after 1990, with high utility power rates wind turbines (which) had installation of 50kW up to 1,5MW mainly in Germany, Denmark and the Netherlands.

The first offshore wind farm, consisting of 11 wind turbines with 450kW power constructed at Vindeby in 1991.
After the 90s the main scope for using wind turbines was to decrease the CO₂ emissions, and the high potential of the wind energy to generate power.

The first attempt to use an offshore substation, which aimed to increase the power collection voltage from 30kV up to 150KV for transmission to shore, was a 160kW wind farm and was constructed in Denmark in 2002.

In 2010, a wind offshore wind farm with a 500MW was built in England, whereas new projects with 1000MW are under construction.

After the Kyoto protocol (20% of all energy should be from renewable sources by 2020) the need for a swift from oil to renewable sources in electricity production makes it imperative for increasing interest in wind energy.

Figure 1.7: The Kappel (Denmark) wind farm 2002
### 1.2 Types of wind turbines

There are two types of wind turbines nowadays. The vertical-axis wind turbines (VAWT) and the most commonly used/seen, horizontal-axis wind turbines (HAWT).

#### 1.2.1 Vertical axis wind turbines (VAWT)

The main rotor shaft is set vertically. At the base of the turbine the main components are located. There are two types of VAWT: drag and lift VAWTs. Their main difference is that the lift VAWTs are more sensitive to turbulence.

**Advantages and Disadvantages of VAWTs**

The main advantage of this type of wind turbine is that it can accept the wind from any direction, so it doesn’t need to be pointed into the wind. Another advantage is that the gearbox and the generator are located close to the ground facilitating repair and service. Finally, it doesn’t create vibrations and noises [6, 7]

On the other hand, one of the main disadvantages is that the rotor is closer to the ground, and there is cyclic variation of power on every revolution of the rotor. Another disadvantage is that the blades are prone to fatigue due to the variety of the applied forces during rotation. [7,8]
Aerodynamics of VAWTs

The amount of power that can be absorbed by the WT is [9]:

\[ P = \frac{1}{2} C_p \rho A u^3 \]

Where \( \rho \)=air density, \( A \)=swept area, \( u \)=the wind velocity and \( C_p \)=power coefficient

The angle of attack and the resultant airspeed flow are calculated as [10]:

\[ a = \tan^{-1}\left(\frac{\sin \theta}{\cos \theta + \lambda}\right) \]

\[ W = U \sqrt{1 + 2 \lambda \cos \theta + \lambda^2} \]

Where, \( \lambda = \frac{\omega R}{U} \), tip speed ratio

The resultant aerodynamic force is divided into drag and lift components (D, L) or tangential and normal (T, N). The forces and velocities acting in a VAWT are:
There is a variety of shapes and sizes. The most common designs are:

- Savonius rotor
  It can be found as a ventilator in delivery vans or railway carriages. It is a drag type turbine having two or three scoops. A two scoop machine looks like “S” letter. The differential drag is the reason that the turbine spins [1, 11].
• Darrieus rotor

Is a vertical axis wind turbine which has a number of curved aerofoil blades rotating vertical of the surface line. The airfoils moving forward in a circular path due to the rotor’s spinning. An angle of attack is created to the blade due to the oncoming airflow which is added to the wind generating force. This force with the help of the positive torque to the shaft rotates it [1, 12, and 13].
• Giromill [1, 14]
  Is almost the same as the Darrieus turbine. It uses vertical airfoils which is the main difference of the Darrieus rotor. Another giromill is the cycloturbine which has a blade that rotates around its own vertical axis.

Figure 1.12: H-rotor and cycloturbine

1.2.2 Horizontal axis wind turbine

Horizontal axis wind turbine (HAWT) has a shaft which is mounted parallel to the ground, horizontally. It must be always aligned with the wind using a mechanism adjustment called yaw. It is a system that is consisted of gearboxes and electric motors, which move the entire rotor right or left in small increments. This process can happen with an electronic controller which “reads” the wind speed and direction and adjusts the position of the rotor in order to capture the most available wind energy. [3, 5]

Horizontal axis wind turbines are usually used in wind farms for electric power production. Furthermore, they can be used for residential needs, in smaller scale. [1]
Advantages and disadvantages of the HAWTs [15]
The main advantage for using HAWT is the high efficiency as the blades always move perpendicular to the wind. The high height assists for stronger wind thus, generates more energy. Finally, the optimum angle of attack ($\alpha$) is succeeded to the turbines blade from the variable blade pitch. Optimum angle of attack is remotely adjusted and thus, gives greater control so the HAWT can collect the max amount of wind energy.

However, using HAWTs has also disadvantages. The taller the tower is, the more difficult and more expensive to transport and install their parts can get. High height wind turbine is aesthetically unpleasant and creates many problems such as signal cutter (affecting the side lobes of radar installations). Finally, when the tower construction is strong, the gearbox, the generator and the blades get heavier.

Operation of the wind turbine
With the help of rotor blades, the wind turbine captures the energy of the wind and converts it to rotational energy. This energy is transferred into generator by shaft and there the rotational energy of shaft becomes electricity.
Figure 1.14 Horizontal axis wind turbine
Chapter 2: Small scale wind turbines

2.1 General facts

Small scale wind turbines may be considered to be “mini” versions of the large scale wind turbines. But there are many differences between the two of them. The main difference is the economic issue. Energy from large grid connected turbines costs less than from small scale wind turbine because small scale wind turbines generate less electricity per initial investment costs than larger wind turbines. [19]

Another difference is the installation requirements. For small scale wind turbines in most cases (diameter less than 2m and not attached to the property) do not need either building permits or bureaucratic processes. Finally, large turbines reach much higher from the ground so can utilize better conditions of the wind.

Figure 2.1: Small scale vs Large scale wind turbine [20]
Small scale wind turbines are used mainly for residential use for example individual homes, schools, businesses, farms. They produce electricity up to (in some cases) 100kW. In order to allow sensitivity to low wind speeds, some units of the turbine have been constructed to be very lightweight. [4, 18]

Small scale wind turbine can be used on and off grid. 
For on-grid (cottage, business, farm or home): small wind can help to be independent on the local electricity utility by supplying the owner’s grid.
For off-grid (cottage, business, farm, home, a boat, a remote station or community): small wind provides electricity to remote locations for the whole year.
For isolated grids, which the system is not connected to the national electrical grid: small wind reduces the use of fuels, reducing pollution and saving fuel costs.

A small scale wind turbine can be installed on a building. Thus, some issues must be resolved such as vibration of the turbine, turbulence caused by the ledge (this problem leads to generate small amounts of power) and mainly the strength of the roof. [17]

It is usually preferred to have Horizontal axis wind turbines but every year more and more vertical axis wind turbines are used.
They usually consist of 2 or blades made from fiber-reinforced plastic. They have no brakes and the rotor turns out of the wind in case of over-speed protection. They also have a tail which helps the blades aim into the wind. [16]

Three phase generators are usually used with alternating current (AC). In order to convert direct current (DC) output to alternating current, power inverters and battery charging is used.

2.2 Advantages and disadvantages of small scale wind turbines [18].

Advantages:

- Reliability and high durability
- Reduce CO\textsubscript{2} emissions
- Easy installation in insolated locations
- All existing land uses may continue to any other use without obstacles (small scale wind turbines use only a small percentage, about 2% of the land)

Disadvantages

- Require a relatively high initial investment and require some maintenance because they have moving parts
- There is a concern about the noise generated by the blades of the electric motor
- The opinions on the aesthetic (visual) impact are split.

2.3 Towers

There are four types of small scale wind turbines towers:

**Guyed tower** (for residential use) [21]:

Is up to 24 meters height and applies for small scale wind turbines up to 5kW. It is simple structure with low cost and easy to install. The tower body consists of a steel tube
with 4 to 8 wires. Although there is noticed that some vibration is generated because of the small size of the tower.

![Figure 2.3: Guyed Tower [21]](image)

**Tilt-up Tower [21]**

It is from 1kW to 5kW. The main advantage of this type of tower is that can lay down without a hydraulic rotor or crane. This will protect the turbine from strong winds and reduce the maintenance costs.
Self-Supporting tower [21]
It is from 5kW up to 10kW. It has small footprint but higher costs than the others. They are typically four (sometimes three) sided lattice type structures made from pipe, angle or solid rod. They can be transferred and installed easily.
Monopole tower [22]
It is from 5kW up to 10kW. It has the smallest footprint of all types of towers and it
doesn’t need any wires. It is easy and quick to install with the help of a crane and is aes-
thetically pleasing. The only disadvantage is the higher costs.
Chapter 3: Small scale wind turbine on a building (Study and performance of wind turbines)

Built-environment wind turbines which are located in an urban environment. They are usually small scale wind turbines of a capacity of 100kW or less. Many wind turbines were not designed for built environment with lower average wind speed, numerous changes in wind direction and with high turbulence but for rural areas. [24]

But recent research shows that there are promising opportunities for wind energy in urban areas. However, it is important for the developers to pay attention to the local wind conditions as the efficiency of the turbine is very sensitive to the instantaneous variations in wind conditions which happen in urban environment. Other difficulties for the wind turbines in an urban area are loads to a building structure, noise, structural failures and vibrations. [23, 24]

3.1 Optimal position of a wind turbine on a roof of a building.

The optimal position of a wind turbine on a roof of a building is to be placed it above the turbulence layer. The wind turbine must be placed as closer as to the edge of the roof for the prevailing wind. The height plays important role as a lower height is a major advantage for a WT placed near the roof’s edge and also from the prospective of height restrictions and costs. [23]
This only happens if the wind blows from the prevailing direction rather than other directions.

### 3.2 Vibrations

One of the biggest disadvantages is that the vibrations which are created by the wind turbines and transmitted to the building.

Wind turbulence is created by roof tops and interferes with the operation of the turbine. Wind turbulence reduces the power production of the turbine even if sophisticated vibration dampening systems are added to the wind turbine in order to help the isolation of it from the building. This leads to the damage of the turbine. A solution to that problem is to increase the height of the turbine (turbine’s tower) up to avoid the turbulence. However, this solution leads to higher costs, reducing its safety and finally, adding to the complexity of the installation. [24]

One solution to that problem is the reinforced concrete. With the use of it on roofs may be able to absorb a part of the wind turbine’s loads.
Another important consideration for the built-environment wind turbine is vibration and resonance. When resonance frequency of the mast’s combination and roof falls within the operating frequency is between a range of the wind turbines such as 1-10 Hz.

Then, wind turbines may produce vibrations into the building. In order to prevent any unwanted effect due to these phenomena, the resonance frequency’s mast type turbine is designed to be below 1 Hz.

The system’s mass determines the width of the support structure’s and building’s potential vibration.

### 3.3 Mathematical analysis of the performance

The wind turbine is a rotor machine which transforms the kinetic energy (from the wind) to mechanical. Then, the mechanical energy is converted to electrical power (electricity).

A kinetic energy is calculated from:

$$ KE = \frac{1}{2} m u^2 = E $$

With the air’s volumetric flow rate through the turbine is $Au$ and the air’s mass flow rate is $\rho Au$ in kg/s, the P (power output) will be:

$$ P = \frac{1}{2} (\rho Au) u^2 = \frac{1}{2} \rho Au^3 $$

With A (swept area by the rotor blades):

$$ A = \frac{\pi}{4} D^2 $$
The power extracted from the wind is given by:

\[ P = \frac{1}{2} \rho A u_{\infty}^2 (u_{\infty}^2 - u_e^2) \]

So the mass flow rate will be:

\[ \rho A \frac{u_{\infty}^2 - u_e^2}{2} \]

And with some modifications the power coefficient of the rotor \((C_p)\):

\[ C_p = \frac{(1 + \frac{u_e}{u_{\infty}}) [1 - (\frac{u_e}{u_{\infty}})^2]}{2} \]

\(C_p\) peaks at the Betz limit which is \(C_p = 16/27\) or \(C_p = 0.59\) so the ideal case is \(\frac{u_e}{u_{\infty}} = 1/3\)

The Betz limit or efficiency implies that the maximum power that can be produced by the wind cannot be over 0.59 or 59%.

Figure 3.2: Betz Limit [3]
This efficiency can only be achieved when the velocity of the air behind the wind turbine is 1/3 of the velocity of the air before the turbine. In real cases, the efficiency of the rotor reaches 0.5 or 50% and usually is ranged from 20% to 40%.

Therefore:

\[ P_0 = \frac{1}{2} \rho A u^3 C_p \]

Figure 3.3: A turbine with A area and wind with u velocity [26]

The best way to describe the performance of wind turbine is the power curve which specifies the power output (in kW) in terms of wind speed (in m/s). This curve gives the turbine efficiency. [27]
The rated speed is the minimum wind turbine’s speed has to produce at rated output. [4]

The lowest speed of the wind that generates power is known as cut-in-speed. [4, 27]

When the wind speed increases and the cut-in-speed starting to rise to the rated speed, the output power rises up to the rated output. [4]

![Power curve of a wind turbine](image)

**Figure 3.4: Power curve of a wind turbine [27]**

Finally, in the third region wind speed are over the rated speed of the wind and the power output remains constant at the rated value.

There are two ways to achieve this regulation of power: through natural stalling of the flows over the blades or through the control of the angles of the blade pitch. When the wind speed exceeds (after region three) the cut-in-speed value and the turbine must safely shut down. [28]
3.4 Weibull Distribution – Reyleigh Distribution

Weibull distribution

Weibull distribution is a traditional method for expressing the probability density of velocities of the wind. The graph below shows a typical site which the median wind speed is about 6.7 m/s (indicated by the vertical line). The areas below the curve are equal on every side.
Figure 3.6: Weibull’s distribution graph [29]

The Weibull distribution is given by:

$$h(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{(k-1)}e^{-\left(\frac{u}{c}\right)^k}$$

For $0<u<\infty$ where $k>0$ and $c>0$

And finally $h = \frac{\text{fraction of time wind speed is between } u \text{ and } (u+\Delta u)}{\Delta u}$

The below graph shows the Weibull’s probability function with scale parameter $c=10$ and shape parameter $k=1, 2, 3$
Figure 3.7: Graph of \( h \) and \( u \) with various \( k \) [25]

- The energy distribution is given by:

\[
e = \frac{kWh \text{ contribution in the year by the wind between } u \text{ and } (u) + \Delta u}{\Delta u}
\]

Thus, for the Rayleigh equation the distribution look like the shaded curve in the below figure:

\[
k=1, \ h = \lambda e^{-\lambda u}, \text{ where } \lambda = 1/c
\]

\[
k=2, \ h = 2\lambda e^{2}ue^{-(\lambda u)^{2}}
\]

\( k>3 \), makes it approach a normal bell shape distribution.
Figure 3.8: Wind speed and energy density frequencies for various wind speeds

Rayleigh distribution

It is a simplified situation of the Weibull distribution function in which the k (which is the shape parameter) is approximated as 2. [25]

3.5 The performance curves

The wind turbine’s performance can be characterized by three indicators which are: [3]

- Power: which shows the amount of energy captured by the rotor,
- Thrust: it is important for the structural design of the tower.
- Torque: determines the gear box’s size and must be matched by any generator is being driven by the rotor.
The $C_p$-$\lambda$ curve of performance

At the above performance curve the maximum $C_p$ value is 0.47 at speed ration of seven. This is less than the Betz limit for that $\lambda$ and is caused by drag, tip losses and also the stall which reduce the $C_p$ at low values of the $\lambda$. However, without these losses the maximum value of $C_p$ won’t also reach the Betz limit as the blades are not perfect.

Another considerable parameter is the solidity. Solidity is the total blade area disunited by the swept area. Changing the number of blades or the blade chord the solidity could change readily. [3]
It is important to examine the change of the solidity as:

- High solidity makes the turbine very sensitive to $\lambda$ changes and there will be a relatively low $C_p$ maximum value if the solidity is too high which is caused by stall losses.
- Low solidity (flat, broad curve) means that the $C_p$ will remain almost unchanged over a wide $\lambda$ range. However the maximum value of $C_p$ is low because the high drag losses.
- Optimum solidity (achieved with 3 blades) but can also be achieved with 2 blades even if the lower $C_p$ maximum value which may lead in a larger energy capture.

*The $C_Q$-$\lambda$ curve of performance*

The $C_Q$-$\lambda$ curve of performance shows the torque coefficient which is derived from the power coefficient diving by the $\lambda$. The torque assessment when the rotor is connected to a generator and a gear box is the main use of $C_Q$-$\lambda$ curve.

![Figure 3.11: $C_Q$-$\lambda$ with the effect of solidity [3]](image)
The $C_T$-$\lambda$ curve of performance shows the rotor’s thrust force which is applied to the supporting tower so considerably affects the tower’s structural design. Finally, if the rotor’s thrust increases the solidity will increase too.

Figure 3.12: $C_T$-$\lambda$ with the effect of solidity [3]
Chapter 4: Wind characteristics

Figure 1 shows the wind resources at 80 meters above ground level for the European Union countries published in 2012. Northern countries have the highest amount of wind speed (up to 12-13 m/s). The coasts around Europe have high amount of wind speed (up to 10-11 m/s). However, in the European mainland the wind speed differs from 3-4 m/s up to 5-6 m/s.

![Figure 4.1: Wind resources, 80metres above ground level, Europe](image)

The following figure (3.2) shows that in Greece, the areas with high wind velocity (up to 10 m/s) are mainly the Aegean islands and the mountainous northern Greece because of the high mountains.
The wind’s velocity profile is very complex especially in an urban area as it shown in figure 4.3.
These figures provide the modification of the velocity profile as the wind flows from a free space to an urban area (over buildings). The main facts that reduce the mean wind speed are the buildings’ height and the distance into the urban environment.
It is important to identify the Internal Boundary Layer (IBL) as to predict the roof’s speed of the wind of a certain building.

It is assumed that the wind comes from the left side. Then with roughness length $z_{0,ref}$ and creates a step from the roughness length to a built environment’s roughness $z_0$. This downwind new step creates a new boundary layer called IBL. Above this layer the wind speed is undisturbed and equal to the wind speed upwind of the change of the roughness. [32]

For the height calculation Garret shows that:

$$h_k(x) = 0.28 z_{0,max} \left( \frac{x}{z_{0,max}} \right)^{0.8}$$

Thus the wind speed profile inside the IBL will be:
The velocity of the wind vector at the roof of a building is not parallel with the roof but creates an angle with it. This angle is the skew angle (figure 4.4) and depends on the building’s shape, surrounding roughness and the position at the roof.

The performance of a horizontal axis wind turbine depends on the skew angle and with Glauert momentum theory for yawed flow shows a power decrease by a misalignment factor.

\[ m_h = \cos^3 \gamma \]

The yaw angle can be interchanged with the skew angle thus the skewed flow decreases the power of the HAWT. And this is because of the symmetry of the rotor.

Figure 4.4: Skew and yaw angle [32]
4.1 Wind Statistics

The scope of this dissertation is to examine the wind and the wind turbine in a urban area. In order to do so it is necessary to examine the speed and the direction of the wind monthly and annually.

The statistics are taken from windfinder.gr which is an internet site specializing in wind reports and recordings. For better results the reports are from Kalamaria’s station which is an area located east from the center of Thessaloniki with elevation 41m.
Figure 4.6: Kalamaria’s weather station [34]

The figure below shows the wind direction throughout the year from Kalamaria’s weather station. The monthly wind direction reports are shown at the Appendix B at the end of the dissertation.

*Wind direction*
From the figure above the wind direction is from northwest up to southwest.

- There is a 12.3% of the wind distribution for the WNW (northwest direction mostly west) yearly.
- There is an 11.1% of the wind distribution for the W (west) yearly.
- There is a 10.6% of the wind distribution for the WSW (southwest direction mostly west) yearly.
- There is an 11% of the wind distribution for the SW (southwest) yearly.
- There is an 11.4% of the wind distribution for the SSW (southwest direction mostly south) yearly.

Wind statistics

The weather statistics are taken from Kalamaria’s weather station during the past year and more specific form 01/2013 – 01/2014 daily from 7am to 7pm local time.
The graph above shows the monthly average wind speed (m/s) at Kalamaria, the dominant wind direction, the wind probability for equal or over 4 Beaufort and the average air temperature.
Chapter 5: Constructing small scale urban wind turbines on a building

5.1 Blades

In order to succeed in creating a successful blade design there are some objectives to have in mind:

Maximise the energy yield (per year) for the specified wind speed distribution
Avoid resonances
Limit max power output
Minimise costs and weights
Resist fatigue and extreme loads
Restrict tip deflections in order to avoid blade collisions,

To design the blade properly there are two stages.
First of all for the aerodynamic design the maximum power output must be limited and the annual energy yield must be maximized. The aerodynamic design focuses in selecting the optimum geometry of the blade (aerofoil family, twist, thickness and chord distributions).

Secondly, for the structural design the objectives 2, 4 and 6 must be satisfied. It focuses in selecting the blade material and in determining the structural cross section.

In order to find the optimal chord of the blades the tip speed ratio is needed. The tip speed ratio also known as $\lambda$ has been mentioned above at chapter 3. The optimum chord is given by this equation with the help of $\lambda$, the number of blades, blade radius and the sectional blade radius: [3]
A new approach at the blade design is the swept tip blades. It is shown that this type of blades can reduce the blade tip noise as they can reduce the interaction of the blade trailing edge with the tip vortex. They are also more aesthetic than the un-swept blade. The major disadvantage for this scenario is that the swept tip blades require higher manufacture cost so they are optional. A good solution is the use of interchangeable blades so the users can choose the type which fits to their needs. [36]

5.2 Rotor blade

The rotor blade theory describes the forces (lift or drag) on the elements (with length $\delta r$ and radial $r$) of the several blades liable for the rate of change of momentum (angular or axial) of the air which passes through the annulus swept by the elements of the blades. [3]

The drop of the pressure causes the force on these elements. This drop on the pressure is related with the rotational velocity ($\omega$) in the wake.

The Blade Element Momentum Theory or BEM Theory suggests that there is no aerodynamic interaction between the elements meaning that there is no radial flow. The forces on the blade can be calculated by the angle of attack which is determined from the incident resultant velocity ($u$) in the cross-sectional plane of the element. [3]
The axial relative wind velocity is calculated by:

\[ U(1 - a) \]

And the rotational relative wind velocity by:

\[ \Omega r + \frac{\omega}{2r} = \Omega r(1 + a') \]

Taking a look from the blade tip (as it is shown at the figure 5.3) the blade twist angle \( \theta_T \) is calculated relatively to the blade tip:

\[ \theta_T = \theta_p - \theta_{p,0} \]

And the angle of the relative wind by:

\[ \phi = \alpha + \theta_p \]
The lift force is calculated by:

\[
dF_L = \frac{1}{2} C_l \rho C u_{rel}^2 dr
\]

The drag force is calculated by:

\[
dF_D = \frac{1}{2} C_D \rho C u_{rel}^2 dr
\]

For B blades the total normal force is calculated by:
\[
dF_N = B \frac{1}{2} \rho U_{rel}^2 (C_l \cos \varphi + C_D \sin \varphi) \, cdr
\]

And this is because

\[
dF_N = dF_L \cos \varphi + dF_D \sin \varphi
\]

The same happen with the tangential force as:

\[
dF_T = dF_L \sin \varphi + dF_D \cos \varphi
\]

Finally, the torque which is calculated through the tangential force is:

\[
dQ = B r dF_T
\]

\[
dQ = B \frac{1}{2} \rho U_{rel}^2 (C_l \sin \varphi - C_D \cos \varphi) \, cdr
\]

In order to find the twist and the chord distribution of a blade, the Betz optimum rotor is been used. So, the wake rotation \( \alpha' = 0 \) the drag coefficient \( C_d = 0 \) and the axial induction factor is \( \alpha = 1/3 \).

### 5.3 Number of blades

An important parameter for the designing of a wind turbine is the number of blades. It determines the cost, performance, aesthetics and weight of the WT. After many researches WT with 3 blades produce much better performance, than those with 2 blades, for the complexity and the added cost. [3]

From the other hand, although a 4 blade wind turbine performs slightly better than the 3 blade WT the performance cannot justify the complexity and the added cost. Thus, the optimal design for the wind turbines is the 3 blade design. [3]
The number of the blades can also be calculated by: [3]

\[ Nc(\mu) \left( \frac{\Omega R}{U_{\infty}} \right)^2 = \frac{16\pi R}{9C_l} \frac{1}{\mu} \]

where \( \mu = r/R \), \( c(\mu) \) the chord length at \( \mu \), \( N \) the number of the blades, \( C_l \) the lift coefficient and \( R \) the rotor radius.

Figure 5.3: The difference of three and two bladed turbines [3]

5.4 Materials

Using the correct materials is a major point for the construction of a wind turbine. After many years of experience in constructing wind turbines the most suitable materials are the following:

- Titanium,
- Steel,
• Aluminum,
• Wood,
• Fibre composite material, such as carbon, glass and aramide fibres.

The most important properties for these materials are:

• specific weight (g/cm³)
• strength limit (N/mm²)
• modulus of elasticity (kN/m²)
• breaking strength related to the specific weight, the so-called breaking length (km)
• modulus of elasticity related to the specific weight, (10³ km)
• Allowable fatigue strength after 10⁷ to 10⁸ load cycles (N/mm²).

Table 5.1: Strength and stiffness parameters of materials in principle available for rotor blades [37]
5.5 Nacelle

A closed nacelle is used for the housing the mechanical components and electric generator of a wind turbine. In some cases though, a small scale wind turbine does not need any nacelle. However, in case of complete integration of the components a completely closing housing could be useless.

5.6 Yaw control [2, 3]

Yaw control or yaw drive is the mechanism which rotates the nacelle according to the tower on its slewing bearing. It is necessary in order the turbine to keep facing the wind and to help cables and unwind power not to become overly twisted.

It usually has one or sometimes more hydraulic or electric motors which are on the nacelle each of which drives a pinion (which engages with gear teeth on the fixed slewing ring bolted to the tower) mounted on a vertical shaft through a reducing gearbox.

The gear teeth (depending on the bearing arrangement) can be on the outside or on the inside of the tower, but they usually can be found on the outside on smaller machines so that the gear does not present a safety hazard in the space which is for personnel access.

Yaw brakes are used (after a completed yawing operation) in order to avoid the situation of the drive motors having to absorb the yawing moment. Unless there is a special yaw drive with integrated breaking function, a yaw brake is needed. If not, it would not be easily guaranteed the life span of the upstream gears or of the drive units. Finally, in smaller scale wind turbines it is common to be created with yaw damping in the yaw bearing or azimuth bearing.
Figure 5.4: Typical yaw drive, yaw brake and yaw bearing [3]

5.7 Generator

The generator consists of a rotor which is carrying a field winding in order a set of windings named as stator produces a rotating magnetic field.

Usually, with the help of a gearbox the blades spin a shaft which is connected with the generator. The gearbox converts the blades’ turning speed as fast as the generator needs to produce electricity. [37]

Nowadays small scale wind turbines usually use a three phase direct drive permanent magnet generator (PMG), which does not require a gear box in order to increase the shaft revolution per minute (Appendix D) until it reaches the traditional DC motor revolution per minute. This PMG operating revolution per minutes is characterized by the number of poles which are on the generators rotor. [38]

A direct drive PMG in order to convert the AC to DC power for charging the battery uses a rectifier. A sample of a generator with figures is shown in Appendix C.
Hub and the PMG are connected through the bearing housing to the yaw shaft. The bearing housing is used in order to hold the PMG with the extension of the shaft in-line with the hub utilizing one bearing on the forward side of the yaw shaft. The PMG also has the help of 2 U-bolts, which strength the PMG against the bearing housing. [38, 39]

The blades are attached to the forward side of the bearing housing using the aft mounted hub plate and the forward mounted hub plate. Finally, the PMG adjacent to the aft side of the bearing housing when in the same time the rotor hub adjacent to the shaft extension. [39]

The bending load is taken by the bearing and the PMG gives the thrust load to the yaw shaft.

![Figure 5.5: Hub and motor disassembled](image)

### 5.8 Loads and vibrations

The major problems for a Building adjacent wind turbine are the loads at the building structure and the vibrations.
**Loads**

Usually a new building structure can hold the loads for a small wind turbine. An issue could be the compatibility with an exterior material. Special mounting techniques may-be required for the siding and other non-structural materials as bricks and mason would not present any problem. [40]

In order to understand it better for a building with siding, for example, the siding into the structure might be penetrated by a special mount which allows the bracket to hover above the siding, in order not to pinch the siding against the structure and cause damage. Thus, pre-drilled holes are used to avoid the material crumbling and falling off the building’s wall. [40]

**Vibrations**

It is already known that vibrations which are caused from the high speeds of the wind or the bad structure of the turbine can cause issues.

Many small scale wind turbines had to stop due to excess of vibration and noise being transferred to the structure.

Thus, one of the ideas to eliminate this problem was the use of rubber mounting shims. These shims must be placed between the mounting hardware and mounting arm which helps to isolate the building and the load path of the WT by putting a damper between the two. To achieve the desired level of vibration the number of shims can be increased (figure 5.6). [40]

![Figure 5.6: Rubber shims for vibration](image-url)
Chapter 6: Contribution

Airfoil cross-sections are used for the creation of modern wind turbine blades. QBlade program is introducing a two or three dimensional design and simulation of the blade of a wind turbine. With QBlade, blade profiles are constructed and presented.

The main principle of this program is the Blade Element Momentum theory (BEM). This theory is used to calculate the chord length and the twist angle for a given rotational speed and cross-section at finite number of blade positions along the span.

A wind turbine’s aerodynamics are very influenced by the up and downstream from the rotor. Also they depend on the turbulent which has small scale flow conditions all around the blades. For all these a large simulated domain with a fine spatial resolution is needed. The use of CFD (Computational Fluid Dynamics) which can fulfill these requirements is very time consuming and very expensive. Alternative simulations are vortex methods, with limitations since they are supported on potential flow theory.

The only design which can have the tools to do this is the BEM method, which is used to predict the efficiency of HAWT. Compared to CFD, BEM model has computational time significantly less and is very cost efficient.

BEM model helps to develop and test different designs of rotors to each other, making small changes and test them again.

BEM theory examines each cross-section of the blade as an independent airfoil. This airfoil experiences wind with a direction and speed that is the vector sum of the velocity generated by rotation and the velocity of the oncoming wind. This relative velocity changes along the span in magnitude and direction and so different airfoil cross-section have to be used in order to optimize the behavior of the wind turbine. [44]

In this dissertation, the QBlade V8.0 software has been used. QBlade provides a calculation software to the user that is seamlessly integrated into analysis tool, an airfoil de-
sign and XFOIL, in order to design a one solution software for the aerodynamical com-
putation and design of the blades of a wind turbine. The XFOIL’s integration allows the
user to design custom airfoils, extrapolate the polar data to a 360° range, compute their
polars and finally integrate them directly into a simulation of a wind turbine. This step
of importing and exporting foil and geometry data between programs is overlooked. A
huge advantage of this program is that is accessible to a large number of interested peo-
ple skipping the usual command line interface tools. And this is because of the integra-
tion of the DMS code and BEM code into XFOIL’s sophisticated GUI (Graphical User
Interface) [47].

The program teaches easily the user all the useful and fundamental relationships be-
tween chord, twist, type and control of the turbine and the power curve. The GUI helps
for a post processor spot to understand better all the conducted rotor simulations and
gives a deep insight to all rotor and blade variables which are relevant for verification,
to compare with other rotor configurations.

To sum up the program is friendly to the user and very flexible for wind turbine blade
design. Finally, the QBlade program can act as a modular system which can be used for
future implementations which can exploit the possibilities that a combination of para-
metric and manual airfoil analysis and design coupled with a simulation tool and blade
design offers.

The first parameter for calculation is the NACA number. It is an airfoil number which
developed by the National Advisory Committee for Aeronautics (NACA). The NACA
parameters are used into equations to generate the cross-section of an airfoil and calcu-
late their properties. [41]

At this thesis a 4-digit NACA airfoil is used as the five-digit is for more complex air-
foils.

The first digit in the NACA nomenclature is describing the maximum camber (in %) of
the chord. The second digit is describing the distance of the maximum camber from the
leading edge of an airfoil (in %) multiplied by 10. Finally, the third and fourth digit de-
scribing the airfoil’s thickness, at its maximum level, as percent of the chord. [42]
For example a NACA 1424 airfoil has: 1% of maximum camber, 40% from the leading edge and finally 24% of maximum thickness of the chord.

If $m$ is the maximum camber and $p$ is the location of it, in order to calculate the mean camber line: [43]

$$y_c = \begin{cases} 
\frac{m}{p^2} \left(2p - \frac{x}{c}\right), & 0 \leq x \leq pc \\
\frac{c}{(1-p)^2} \left(1 + \frac{x}{c} - 2p\right), & pc \leq x \leq c 
\end{cases}$$

In order to calculate the thickness the coordinates $(x_L, y_L)$ and $(x_U, y_U)$ which are the lower and upper airfoil surface are needed:

$$x_U = x - y_t \sin \theta, \quad y_U = y_c + y_t \cos \theta,$$
$$x_L = x + y_t \sin \theta, \quad y_L = y_c - y_t \cos \theta,$$

With,

$$\theta = \arctan \left( \frac{dy_c}{dx} \right),$$

$$\frac{dy_c}{dx} = \begin{cases} 
\frac{2m}{p^2} \left(p - \frac{x}{c}\right), & 0 \leq x \leq pc \\
\frac{2m}{(1-p)^2} \left(p - \frac{x}{c}\right), & pc \leq x \leq c 
\end{cases}$$

At this thesis a symmetric airfoil NACA0012 has been chosen. Also the Reynolds number, which is a dimensionless value that depends on the velocity, wing chord and fluid, is calculated by:
The velocity of the fluid (air at this example) is 2.5 m/s, the kinematic viscosity of the fluid is \(1.5111 \times 10^{-5}\) m\(^2\)/s for 20\(^\circ\)C and the chord width is 1m.

Thus the Reynolds number is estimated at 200000.

The \(N_{\text{crit}}\) value is a value which is used to model of the fluid’s turbulence or airfoil’s roughness. From the table below the most suitable \(N_{\text{crit}}\) value is 9.

**Table 6.1: \(N_{\text{crit}}\) values [45]**

<table>
<thead>
<tr>
<th>SITUATION</th>
<th>(N_{\text{crit}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAILPLANE</td>
<td>12 TO 14</td>
</tr>
<tr>
<td>MOTORGLIDER</td>
<td>11 TO 13</td>
</tr>
<tr>
<td>CLEAN WIND TUNNEL</td>
<td>10 TO 12</td>
</tr>
<tr>
<td>AVERAGE WIND TUNNEL</td>
<td>9</td>
</tr>
<tr>
<td>DIRTY WIND TUNNEL</td>
<td>4 TO 8</td>
</tr>
</tbody>
</table>

The Mach number is zero (0).

For Reynolds number 50000 up to 1000000 the curves \(C_L-C_D\), \(C_L-\alpha\), \(C_m-\alpha\), \(C_D-\alpha\) will be:
Figure 6.1: The curves $C_L$-$C_D$, $C_L$-$\alpha$, $C_m$-$\alpha$, $C_D$-$\alpha$ [45]
In order to find the optimum $\alpha (^\circ)$ for the calculation of $C_L$ and $C_D$, with the help of the above table the maximum $C_L/C_D$ for Reynolds number 200000, and $N_{crit}=9$ is 41.5 for $\alpha=7.5$.

So the curves $C_L-C_D$, $C_L-\alpha$, $C_m-\alpha$, $C_D-\alpha$ will be:

![Curves CL/Cd, CL/alpha, Cm/alpha, Cd/alpha](image)

Figure 6.2: The curves $C_L-C_D$, $C_L-\alpha$, $C_m-\alpha$, $C_D-\alpha$, for $\alpha=7.5$, $Re=200000$ [45]

And with these numbers the optimum $C_L$ and $C_D$ will be 0.8286, 0.01997 respectively. (Taken from the table in appendix E).
In order to design the wind turbine the following procedure is used.
Choosing B=3 blades turbine with radius R=1m, AoA $\alpha=7.5$, tip speed ratio $\lambda=7$ and the above $C_L$ and $C_D$ factors and knowing that the chord and twist angle distributions are:

$$c(r) = \frac{8\pi r \sin(\varphi)}{3BC_L\lambda \frac{r}{R}}$$

And

$$\theta_{r0} = \theta_{p0} - \theta_{ptip}$$

respectively.

$\theta_{p0}$ is the section pitch and is calculated by:

$$\theta_{p0} = \varphi - \alpha$$

$\varphi$ is the relative wind angle and is calculated by:

$$\varphi = \tan^{-1}\left(\frac{2}{3\lambda \frac{r}{R}}\right)$$

The following table show the calculated chord length and twist angle for different values of the radial position $r$ along the blade span.
Table 6.2: Chord and twist angle values.

<table>
<thead>
<tr>
<th>r/R</th>
<th>c</th>
<th>Twist angle θ_T (°)</th>
<th>Relative wind angle φ (°)</th>
<th>Section pitch θ_p (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.332</td>
<td>38.2</td>
<td>43.6</td>
<td>36.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.207</td>
<td>20.0</td>
<td>25.5</td>
<td>18.0</td>
</tr>
<tr>
<td>0.3</td>
<td>0.146</td>
<td>12.2</td>
<td>17.6</td>
<td>10.1</td>
</tr>
<tr>
<td>0.4</td>
<td>0.112</td>
<td>8.0</td>
<td>13.4</td>
<td>5.9</td>
</tr>
<tr>
<td>0.5</td>
<td>0.090</td>
<td>5.3</td>
<td>10.8</td>
<td>3.3</td>
</tr>
<tr>
<td>0.6</td>
<td>0.075</td>
<td>3.6</td>
<td>9.0</td>
<td>1.5</td>
</tr>
<tr>
<td>0.7</td>
<td>0.065</td>
<td>2.3</td>
<td>7.7</td>
<td>0.2</td>
</tr>
<tr>
<td>0.8</td>
<td>0.057</td>
<td>1.3</td>
<td>6.8</td>
<td>-0.7</td>
</tr>
<tr>
<td>0.9</td>
<td>0.051</td>
<td>0.6</td>
<td>6.0</td>
<td>-1.5</td>
</tr>
<tr>
<td>1</td>
<td>0.046</td>
<td>0.0</td>
<td>5.4</td>
<td>-2.060</td>
</tr>
</tbody>
</table>

With these chord and twist angle values are formed two graphs c-r/R and θ_T-r/R:
These values will be used at the QBlade program.

Opening the QBlade program and with the help of its guidelines the first thing to do is the selection of the airfoil. From the airfoil design choose the NACA foil. At this example is chosen NACA0012.

After that using the Xfoil direct analysis setting the Reynolds number and defining a range of AoA from -5° up to +25°, the flow around the chosen airfoil is simulated to create a polar.
At this point the curves $C_L$-$C_D$, $C_L$-$\alpha$, $C_m$-$\alpha$, $C_D$-$\alpha$ are transformed. There is also a curve of $C_p$-$x$ and the simulation of the airfoil for different AoA. The figure below shows the $C_p$-$x$ curve for the airfoil, at which the pressure arrows are been shown, at a given AoA.

![Figure 6.5: The $C_p$-$x$ curve and the airfoil at $\alpha=7.5$][46]

In order to simulate a Wind Turbine, the polar’s AoA range has to be extrapolated to $360^\circ$.

This happens with the polar extrapolation to $360^\circ$ button. In order to simulate a rotor or a turbine the data must be extrapolated polar data.

As the figure below shows with this way two new curves are created ($C_L$-$\alpha$, $C_D$-$\alpha$)
The two curves above shows that at variable $\alpha$ different values of $C_L$ and $C_D$ are created. The maximum $C_L$ value is 1.12 for $\alpha=12$ and the minimum value is -0.82 for $\alpha=-5$.

The maximum value for $C_D$ is when $\alpha=-80$ and $\alpha=80$ and it is $C_D=1.7$ while the minimum value is 0 for $\alpha=0$.

When the 360° polar has been created, a new blade can be designed.

The HAWT rotorblade design allows the user to create a new blade. At this example a three blade wind turbine with hub radius 0.2m and the diameter of the rotor 1m had been designed. The QBlade program gives the possibility to design a new blade by filling the table below with the chord and twist values from table 6.2 above.
<table>
<thead>
<tr>
<th>Pos (m)</th>
<th>Chord (m)</th>
<th>Twist</th>
<th>Foil</th>
<th>Polar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0,2</td>
<td>38,2</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>2</td>
<td>0,1</td>
<td>0,332</td>
<td>38,2</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>3</td>
<td>0,2</td>
<td>0,207</td>
<td>20</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>4</td>
<td>0,3</td>
<td>0,146</td>
<td>12,2</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>5</td>
<td>0,4</td>
<td>0,112</td>
<td>8</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>6</td>
<td>0,5</td>
<td>0,09</td>
<td>5,3</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>7</td>
<td>0,6</td>
<td>0,075</td>
<td>3,6</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>8</td>
<td>0,7</td>
<td>0,065</td>
<td>2,3</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>9</td>
<td>0,8</td>
<td>0,057</td>
<td>1,3</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>10</td>
<td>0,9</td>
<td>0,051</td>
<td>0,6</td>
<td>NACA 0012</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>0,046</td>
<td>0</td>
<td>NACA 0012</td>
</tr>
</tbody>
</table>
The most important part of this program is the BEM simulation. In other words BEM simulation is a rotor simulation submodule where over a range of tip speed ratios ($\lambda$),
rotor blade simulations are performed. A rotor simulation always comes out dimensionless. The rotor radius is normalized for the computation and the freestream velocity is (usually) unity. This means that during the rotor simulation no load curves or power curve can be computed.

The three curves (power coefficient-Tip Speed Ratio, thrust coefficient- Tip Speed Ratio and axial induction factor- radial position) show the simulation results for different values of $\lambda$. 
From the graphs above for tip speed ratio 7 the Cp (power) coefficient is almost 0.35 and Ct (thrust) coefficient is 5.1. The Betz limit which is the theoretical maximum power coefficient is 0.59 or 59%. Thus, at this example the maximum power coefficient of the wind turbine is lower than the Betz limit so the turbine does not work at its maximum efficiency.

In the next step, the multi parameter simulation carries out simulations over a range of wind speeds, pitch angles and finally, rotational speeds.

The multi parameter simulation is very helpful in order to design pitch controlled WT rotors or/ and custom control strategies for variable rotational speed.
For an average wind speed of 2.5 m/s and a rotational speed 100 rpm in order to get the maximum power the pitch angle must be 0°. The maximum power at this wind speed value is only 14.2 W and the maximum rotor torque is 1.3 Nm for \( \lambda = 7 \).

At the turbine BEM simulation the type of the WT is defined. At this example a stall regulated turbine is chosen.

This type of turbine has no pitch control and that means the power output is limited at the rotor when the stall occurs. An iterative approach is needed when a stall turbine is designed that limits its power at the desired wind speed to the desired output.
Another input for the design of the turbine is the transmission at which a single transmission turbine has been selected as only one rotational speed is needed in which the turbine operates.

The V cut-in and V cut-out are the speeds of the wind that the turbine starts to operate and stops the operation. For this example a V cut-in 1 m/s and V cut-out 5 m/s has been selected.

By defining the Weibull distribution factors $k$ and $A$ the program gives the annual yield. At this example the annual yield is 13 kWh for $k=1$ and $A=1$. 
At the graph Power – wind speed, the turbine is producing power when the wind speed is over 1.1 m/s, when the wind speed is 2.5 m/s (which is the mean average wind speed of this example’s area) the WT producing 14 W and finally when the wind speed is 2.8 m/s the turbine produces at its maximum (almost 17 W). After that the turbine is producing less than 17 W.

For the second graph, Thrust- wind speed, the turbine has the maximum of the thrust (9.2 N) when the wind speed is 2.8 m/s and when the wind speed is 2.5 m/s (which is the mean average wind speed of this example’s area) the thrust is just over 8 N.

The information for the overall rotor performance is given by the Cp over λ curve. A BEM computation is represented by every point of this curve for wind speed or one tip speed ratio.

From the other hand, by adding up the forces which are acting on the elements the trust is calculated. The blade variables like α, give information from the conditions at the blade. A BEM computation is represented by every curve of a blade variable for wind speed or one tip speed ratio.

For the construction of the wind field which is necessary in order to create the fast simulation which concludes the program, some variables are needed. For the geometry parameters, the rotor radius is 1.0 m (from specifications of small wind turbines) and
the hub height is 3.0 m which is a mean height for wind turbines placed on a building. [48, 49, 50]

For the wind parameters, the mean wind speed (as it is referred before) is 2.54 m/s and the turbulence intensity is about 10%.

\[
\left( \frac{u}{u_r} \right) = \left( \frac{Z}{Z_r} \right)^a
\]

With \(a=1/7\) or 0.143, \(u_r= 2.5\) m/s and \(z_r=41\) m and \(z=41+14=55\) m. So the wind speed at a height of 55 m is 2.54 m/s.

The measurement is estimated about 14 m as Kalamaria has many four store apartment buildings. Finally, the roughness length \(z_0\) is 0.1.
Chapter 7: Results

The major problem of this example was that the designed wind turbine had not the efficient wind speed in order to produce enough power for anything. A mean power of 14 W (17 W maximum), when the wind speed is 2.5 m/s, is not enough to generate a lighting bulb.

Thus, in order to test the designed wind turbine in depth, a new site is selected with higher wind speed than the Kalamaria’s station. The scope of this chapter is to compare and test the same wind turbine at new wind velocity much higher than the first one to see how much more power can give.

The new site which had been chosen is Tinos Island which is located at the Aegean Sea. The average wind speed at this location is much higher than the Kalamaria’s station. The average wind speed (with elevation height of 1 m) is 9.5 m/s.

Thus for a 4 storey building the new wind speed for a height of 15 m is 14.1 m/s (the same calculation method from chapter 6 had been used here). For new pitch angle (14 deg) and rotational speed 200 rpm the curves of power- wind speed and thrust – wind speed will be:
Figure 7.1: The curves P–v, S–v [46]

So for these values the maximum power is for 14 degrees of pitch angle. And for the calculated wind speed the maximum power is 350 W a lot higher than the power generated at 2.5 m/s. The same huge difference it is shown with the thrust which is calculated 80 N for 14.1 m/s.

Finally the annual yield is calculated 754 kWh for Weibull’s k factor equal to 1.
Conclusions

This thesis illustrates how a small wind turbine works when it is placed on a building in a building environment. To understand better the operation of this wind turbine a real example is taken.

Assuming that the turbine is placed in a four-storey apartment building at the center of Kalamaria the wind speed, taking into consideration, the turbulence of the wind at the building area is calculated as 2.6 m/s. The wind velocity is calculated in the built environment so there was no need for further calculations (it was important to understand that if the wind speed was calculated at a rural area different calculation method had to be used).

The results were not the optimal as the wind turbine generated very low power (14 W). So the next step was to compare different wind speeds from different locations (especially in Greece) so to see if the wind turbine that was designed can generate enough power for a four storey apartment building.

In order to test this wind turbine at higher wind levels a new location had been chosen. There was a difference at the power which was generated from the turbine and it was 350 W (at 14.1 m/s wind speed). However the power is not enough for a four storey apartment building to operate which was the purpose of this dissertation.

A bigger wind turbine with larger rotor radius and blade length is suggested at the new location in order to succeed a better power coefficient and higher power generation as the wind’s potential is optimal for high power generation.

The roof’s wind velocity in average is larger than the wind speed which is undisturbed in the build environment. Although, the wind speed above the roof is still very small in addition to the wind speed at a wind turbine placed in open surroundings on a tall tower. So high buildings are necessary in order to have the maximum available wind speed in the built environment and produce an acceptable energy yield.
The testing standards by the manufacturers for small scale wind turbines are still under development, the local government (for this example Greek) installation regulations face difficulties and finally, public perception of small scale wind turbines, or systems in general, is in its infancy.

The developing market of small wind systems still faces many challenges. The future is bright though. And this is because the manufacturers and the designers improve their technology and the public becomes more informed in order to make the small wind turbines more viable than the solar photovoltaic are today.
Bibliography

5. Illustrated history of wind power development by Darrell M. Dodge, Littleton, Colorado
20. Small scale wind energy: Policy insights and practical guidance, Carbon Trust
23. Wind turbine in the Urban Environment, M. Ragheb, 3/10/12
29. www.windpower.org
30. R. Erickson, S. Angkititrakul, and K. Almazeedi, a new Family of Multilevel Matrix Converters for Wind Power Applications: Final Report. Published December 2006 by University of Colorado
31. www.cres.gr
34. http://www.windfinder.com
41. E.N. Jacobs, K.E. Ward, & R.M. Pinkerton.NACA Report No. 460, "The characteristics of 78 related airfoil sections from tests in the variable-density wind tunnel". NACA, 1933.
45. www.airfoiltools.com
46. QBlade program
47. QBlade instructions
Appendix A

The scope of this appendix is to have a better look at tables and figures of different Weibull’s shape factors (k), the performance curve and finally the solidity curve as it is important to see for how many blades will have better performance.

<table>
<thead>
<tr>
<th>c</th>
<th>k</th>
<th>Mode Speed</th>
<th>Mean Speed</th>
<th>RMC Speed</th>
<th>Pmode (W/m²)</th>
<th>Pmean (W/m²)</th>
<th>Prmc (W/m²)</th>
<th>Ermc (KWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.5</td>
<td>3.81</td>
<td>9.03</td>
<td>12.60</td>
<td>68</td>
<td>451</td>
<td>1225</td>
<td>5366</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>7.07</td>
<td>8.86</td>
<td>11.00</td>
<td>216</td>
<td>426</td>
<td>814</td>
<td>3565</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>8.15</td>
<td>8.87</td>
<td>10.33</td>
<td>331</td>
<td>428</td>
<td>675</td>
<td>2957</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>8.74</td>
<td>8.93</td>
<td>10.00</td>
<td>409</td>
<td>436</td>
<td>613</td>
<td>2685</td>
</tr>
<tr>
<td>15</td>
<td>1.5</td>
<td>7.21</td>
<td>13.54</td>
<td>18.90</td>
<td>230</td>
<td>1521</td>
<td>4134</td>
<td>18107</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>10.61</td>
<td>13.29</td>
<td>16.49</td>
<td>731</td>
<td>1439</td>
<td>2748</td>
<td>12036</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>12.23</td>
<td>13.31</td>
<td>15.49</td>
<td>1120</td>
<td>1444</td>
<td>2278</td>
<td>9978</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>13.10</td>
<td>13.39</td>
<td>15.00</td>
<td>1377</td>
<td>1472</td>
<td>2067</td>
<td>9053</td>
</tr>
<tr>
<td>20</td>
<td>1.5</td>
<td>9.61</td>
<td>18.05</td>
<td>25.19</td>
<td>544</td>
<td>3604</td>
<td>9790</td>
<td>42880</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>13.14</td>
<td>17.72</td>
<td>22.00</td>
<td>1731</td>
<td>3410</td>
<td>6514</td>
<td>28531</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>16.30</td>
<td>17.75</td>
<td>20.66</td>
<td>2652</td>
<td>3423</td>
<td>5999</td>
<td>23648</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>17.47</td>
<td>17.86</td>
<td>20.00</td>
<td>3266</td>
<td>3489</td>
<td>4900</td>
<td>21462</td>
</tr>
</tbody>
</table>

Note: $P =$ upstream wind power density in watts per square meter of the blade-swept area $= 0.5 \rho V^2$, where $\rho = 1.225$ kg/m³; the last column is the energy potential of the site in kWh per year per m² of the blade area, assuming a rotor efficiency $C_r$ of 50% (i.e., the maximum power that can be converted into electric power is $0.25 \rho V^2$).
Figure A1: Weibull probability density function for different shape factors [3]

Figure A2: Weibull cumulative distribution function for different shape factors [3]
A good solution would be that a wind turbine to have a large number of small individual solidity blades but with a second thought this will increase production costs and blades’ results which are very flexible and structurally weak. [3]
Appendix B

The scope of this appendix is to see the wind direction distribution in % for every and each month separately, in order to understand from which direction the designed wind turbine has the orientation direction of the wind with the highest speed for longer time. [34]

Figure B1: Wind Direction distribution in January [34]
Figure B2: Wind Direction distribution in February [34]

Figure B3: Wind Direction distribution in March [34]
Figure B4: Wind Direction distribution in April [34]

Figure B5: Wind Direction distribution in May [34]
Figure B6: Wind Direction distribution in June [34]

Figure B7: Wind Direction distribution in July [34]
Figure B8: Wind Direction distribution in August [34]

Figure B9: Wind Direction distribution in September [34]
Figure B10: Wind Direction distribution in October [34]

Figure B11: Wind Direction distribution in November [34]
Figure B12: Wind Direction distribution in December [34]
Appendix C

A good example of a generator is the PMG which is manufactured by Ginlong (a Chinese manufacturer). The PMG comes in 2 models: [51]

- The first rated at 0.5 kW and
- The other at 1.0 kW.

Both of them have the same diameter thus can be used to the same baseline WT design. So, the user can select either 0.5 kW rated PMG or 1.0 kW rated PMG for a lower or higher wind speed location respectively.

Figure C1: The Ginlong generator (0.5 and 1.0 kW) [51]
Appendix D

RPM

The RPM is a variable to allow for peak power tracking. This tracking is used, for a given wind speed, to vary the RPM so that the optimum tip speed ratio can be conserved. [38]

Figure D1: Power and RPM for various speeds of the wind [38]
Appendix E

In order to define better the $C_L$ and $C_D$ factors a NACA0012 foil has been chosen. For NACA0012 and with Re number 200000 the above table shows every value for $C_L$ and $C_D$ for a different values of $\alpha$. These values are calculated with the help of Xfoil. [45]

Table E.1: Different values of $C_L$ and $C_D$ [45]

<table>
<thead>
<tr>
<th>XFOIL</th>
<th>Version 6.96</th>
</tr>
</thead>
</table>

Calculated polar for: NACA0012H for VAWT from Sandia report SAND80-211

1 1 Reynolds number fixed          Mach number fixed

xtrf = 1.000 (top)     1.000 (bottom)
Mach = 0.000       Re = 0.200 e 6       Ncrit = 9.000

<table>
<thead>
<tr>
<th>alpha</th>
<th>CL</th>
<th>CD</th>
<th>CDp</th>
<th>CM</th>
<th>Top_Xtr</th>
<th>Bot_Xtr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-14.750</td>
<td>-1.0665</td>
<td>0.07558</td>
<td>0.07090</td>
<td>-0.0293</td>
<td>1.0000</td>
<td>0.0686</td>
</tr>
<tr>
<td>-14.500</td>
<td>-1.1225</td>
<td>0.06442</td>
<td>0.05942</td>
<td>-0.0367</td>
<td>1.0000</td>
<td>0.0683</td>
</tr>
<tr>
<td>-14.250</td>
<td>-1.1604</td>
<td>0.05754</td>
<td>0.05224</td>
<td>-0.0396</td>
<td>1.0000</td>
<td>0.0683</td>
</tr>
<tr>
<td>-14.000</td>
<td>-1.1894</td>
<td>0.05272</td>
<td>0.04711</td>
<td>-0.0399</td>
<td>1.0000</td>
<td>0.0686</td>
</tr>
<tr>
<td>-13.750</td>
<td>-1.2125</td>
<td>0.04920</td>
<td>0.04328</td>
<td>-0.0382</td>
<td>1.0000</td>
<td>0.0689</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>-8.000</td>
<td>-0.8721</td>
<td>0.02130</td>
<td>0.01313</td>
<td>-0.0077</td>
<td>1.0000</td>
<td>0.1214</td>
</tr>
<tr>
<td>-7.750</td>
<td>-0.8506</td>
<td>0.02086</td>
<td>0.01250</td>
<td>-0.0064</td>
<td>1.0000</td>
<td>0.1253</td>
</tr>
<tr>
<td>-7.500</td>
<td>-0.8286</td>
<td>0.01997</td>
<td>0.01175</td>
<td>-0.0055</td>
<td>1.0000</td>
<td>0.1297</td>
</tr>
<tr>
<td>-7.250</td>
<td>-0.8068</td>
<td>0.01955</td>
<td>0.01134</td>
<td>-0.0044</td>
<td>1.0000</td>
<td>0.1344</td>
</tr>
<tr>
<td>-7.000</td>
<td>-0.7851</td>
<td>0.01919</td>
<td>0.01081</td>
<td>-0.0031</td>
<td>1.0000</td>
<td>0.1391</td>
</tr>
<tr>
<td>-6.750</td>
<td>-0.7633</td>
<td>0.01845</td>
<td>0.01021</td>
<td>-0.0020</td>
<td>1.0000</td>
<td>0.1441</td>
</tr>
<tr>
<td>-6.500</td>
<td>-0.7414</td>
<td>0.01809</td>
<td>0.00984</td>
<td>-0.0008</td>
<td>1.0000</td>
<td>0.1497</td>
</tr>
<tr>
<td>-6.250</td>
<td>-0.7195</td>
<td>0.01763</td>
<td>0.00932</td>
<td>0.0004</td>
<td>1.0000</td>
<td>0.1552</td>
</tr>
<tr>
<td>-6.000</td>
<td>-0.6980</td>
<td>0.01715</td>
<td>0.00894</td>
<td>0.0016</td>
<td>1.0000</td>
<td>0.1609</td>
</tr>
<tr>
<td>-5.750</td>
<td>-0.6762</td>
<td>0.01686</td>
<td>0.00860</td>
<td>0.0028</td>
<td>1.0000</td>
<td>0.1674</td>
</tr>
<tr>
<td>-5.500</td>
<td>-0.6547</td>
<td>0.01636</td>
<td>0.00816</td>
<td>0.0040</td>
<td>1.0000</td>
<td>0.1737</td>
</tr>
<tr>
<td>-5.250</td>
<td>-0.6331</td>
<td>0.01607</td>
<td>0.00789</td>
<td>0.0052</td>
<td>1.0000</td>
<td>0.1806</td>
</tr>
<tr>
<td>-5.000</td>
<td>-0.6114</td>
<td>0.01569</td>
<td>0.00752</td>
<td>0.0064</td>
<td>1.0000</td>
<td>0.1879</td>
</tr>
<tr>
<td>-4.750</td>
<td>-0.5899</td>
<td>0.01540</td>
<td>0.00730</td>
<td>0.0076</td>
<td>1.0000</td>
<td>0.1955</td>
</tr>
<tr>
<td>-4.500</td>
<td>-0.5682</td>
<td>0.01510</td>
<td>0.00699</td>
<td>0.0088</td>
<td>1.0000</td>
<td>0.2037</td>
</tr>
<tr>
<td>-4.250</td>
<td>-0.5466</td>
<td>0.01483</td>
<td>0.00681</td>
<td>0.0099</td>
<td>1.0000</td>
<td>0.2123</td>
</tr>
<tr>
<td>-4.000</td>
<td>-0.5247</td>
<td>0.01456</td>
<td>0.00657</td>
<td>0.0110</td>
<td>1.0000</td>
<td>0.2214</td>
</tr>
<tr>
<td>-3.750</td>
<td>-0.5029</td>
<td>0.01437</td>
<td>0.00642</td>
<td>0.0121</td>
<td>1.0000</td>
<td>0.2312</td>
</tr>
<tr>
<td>-3.500</td>
<td>-0.4810</td>
<td>0.01411</td>
<td>0.00625</td>
<td>0.0131</td>
<td>1.0000</td>
<td>0.2413</td>
</tr>
<tr>
<td>-3.250</td>
<td>-0.4586</td>
<td>0.01400</td>
<td>0.00613</td>
<td>0.0140</td>
<td>1.0000</td>
<td>0.2526</td>
</tr>
<tr>
<td>-3.000</td>
<td>-0.4362</td>
<td>0.01378</td>
<td>0.00603</td>
<td>0.0148</td>
<td>1.0000</td>
<td>0.2641</td>
</tr>
<tr>
<td>-2.750</td>
<td>-0.4138</td>
<td>0.01360</td>
<td>0.00594</td>
<td>0.0156</td>
<td>1.0000</td>
<td>0.2766</td>
</tr>
<tr>
<td>x</td>
<td>y</td>
<td>z</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>-2.500</td>
<td>-0.3718</td>
<td>0.01334</td>
<td>0.00579</td>
<td>0.0125</td>
<td>0.9948</td>
<td>0.2946</td>
</tr>
<tr>
<td>-2.250</td>
<td>-0.3262</td>
<td>0.01297</td>
<td>0.00557</td>
<td>0.0088</td>
<td>0.9872</td>
<td>0.3167</td>
</tr>
<tr>
<td>-2.000</td>
<td>-0.2801</td>
<td>0.01249</td>
<td>0.00536</td>
<td>0.0049</td>
<td>0.9804</td>
<td>0.3452</td>
</tr>
<tr>
<td>-1.750</td>
<td>-0.2385</td>
<td>0.01191</td>
<td>0.00516</td>
<td>0.0020</td>
<td>0.9711</td>
<td>0.3956</td>
</tr>
<tr>
<td>-1.500</td>
<td>-0.1995</td>
<td>0.01111</td>
<td>0.00502</td>
<td>-0.0002</td>
<td>0.9611</td>
<td>0.5169</td>
</tr>
<tr>
<td>-1.250</td>
<td>-0.1568</td>
<td>0.01046</td>
<td>0.00499</td>
<td>-0.0026</td>
<td>0.9537</td>
<td>0.6470</td>
</tr>
<tr>
<td>-1.000</td>
<td>-0.1233</td>
<td>0.01012</td>
<td>0.00497</td>
<td>-0.0028</td>
<td>0.9406</td>
<td>0.7210</td>
</tr>
<tr>
<td>-0.750</td>
<td>-0.0902</td>
<td>0.00988</td>
<td>0.00493</td>
<td>-0.0026</td>
<td>0.9259</td>
<td>0.7727</td>
</tr>
<tr>
<td>-0.500</td>
<td>-0.0589</td>
<td>0.00973</td>
<td>0.00490</td>
<td>-0.0020</td>
<td>0.9093</td>
<td>0.8120</td>
</tr>
<tr>
<td>-0.250</td>
<td>-0.0289</td>
<td>0.00965</td>
<td>0.00489</td>
<td>-0.0011</td>
<td>0.8909</td>
<td>0.8428</td>
</tr>
<tr>
<td>0.000</td>
<td>0.0000</td>
<td>0.00961</td>
<td>0.00486</td>
<td>0.0000</td>
<td>0.8696</td>
<td>0.8696</td>
</tr>
<tr>
<td>0.250</td>
<td>0.0289</td>
<td>0.00965</td>
<td>0.00489</td>
<td>0.0011</td>
<td>0.8428</td>
<td>0.8909</td>
</tr>
<tr>
<td>0.500</td>
<td>0.0590</td>
<td>0.00973</td>
<td>0.00490</td>
<td>0.0020</td>
<td>0.8120</td>
<td>0.9093</td>
</tr>
<tr>
<td>0.750</td>
<td>0.0902</td>
<td>0.00988</td>
<td>0.00493</td>
<td>0.0026</td>
<td>0.7728</td>
<td>0.9259</td>
</tr>
<tr>
<td>1.000</td>
<td>0.1233</td>
<td>0.01012</td>
<td>0.00497</td>
<td>0.0028</td>
<td>0.7210</td>
<td>0.9406</td>
</tr>
<tr>
<td>1.250</td>
<td>0.1568</td>
<td>0.01046</td>
<td>0.00499</td>
<td>0.0026</td>
<td>0.6471</td>
<td>0.9537</td>
</tr>
<tr>
<td>1.500</td>
<td>0.1995</td>
<td>0.01111</td>
<td>0.00502</td>
<td>0.0002</td>
<td>0.5168</td>
<td>0.9611</td>
</tr>
<tr>
<td>1.750</td>
<td>0.2385</td>
<td>0.01191</td>
<td>0.00516</td>
<td>-0.0020</td>
<td>0.3956</td>
<td>0.9711</td>
</tr>
<tr>
<td>2.000</td>
<td>0.2801</td>
<td>0.01249</td>
<td>0.00536</td>
<td>-0.0049</td>
<td>0.3452</td>
<td>0.9804</td>
</tr>
<tr>
<td>2.250</td>
<td>0.3262</td>
<td>0.01297</td>
<td>0.00557</td>
<td>-0.0088</td>
<td>0.3167</td>
<td>0.9872</td>
</tr>
<tr>
<td>2.500</td>
<td>0.3718</td>
<td>0.01334</td>
<td>0.00579</td>
<td>-0.0125</td>
<td>0.2946</td>
<td>0.9948</td>
</tr>
<tr>
<td>2.750</td>
<td>0.4137</td>
<td>0.01360</td>
<td>0.00594</td>
<td>-0.0156</td>
<td>0.2766</td>
<td>1.0000</td>
</tr>
<tr>
<td>Value</td>
<td>Parameter 1</td>
<td>Parameter 2</td>
<td>Parameter 3</td>
<td>Parameter 4</td>
<td>Parameter 5</td>
<td>Parameter 6</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>3.000</td>
<td>0.4361</td>
<td>0.01378</td>
<td>0.00603</td>
<td>-0.0148</td>
<td>0.2641</td>
<td>1.0000</td>
</tr>
<tr>
<td>3.250</td>
<td>0.4585</td>
<td>0.01400</td>
<td>0.00613</td>
<td>-0.0140</td>
<td>0.2526</td>
<td>1.0000</td>
</tr>
<tr>
<td>3.500</td>
<td>0.4809</td>
<td>0.01411</td>
<td>0.00624</td>
<td>-0.0131</td>
<td>0.2413</td>
<td>1.0000</td>
</tr>
<tr>
<td>3.750</td>
<td>0.5028</td>
<td>0.01436</td>
<td>0.00642</td>
<td>-0.0121</td>
<td>0.2312</td>
<td>1.0000</td>
</tr>
<tr>
<td>4.000</td>
<td>0.5246</td>
<td>0.01456</td>
<td>0.00657</td>
<td>-0.0110</td>
<td>0.2214</td>
<td>1.0000</td>
</tr>
<tr>
<td>4.250</td>
<td>0.5465</td>
<td>0.01483</td>
<td>0.00681</td>
<td>-0.0099</td>
<td>0.2123</td>
<td>1.0000</td>
</tr>
<tr>
<td>4.500</td>
<td>0.5680</td>
<td>0.01510</td>
<td>0.00699</td>
<td>-0.0088</td>
<td>0.2038</td>
<td>1.0000</td>
</tr>
<tr>
<td>4.750</td>
<td>0.5898</td>
<td>0.01540</td>
<td>0.00730</td>
<td>-0.0076</td>
<td>0.1955</td>
<td>1.0000</td>
</tr>
<tr>
<td>5.000</td>
<td>0.6113</td>
<td>0.01569</td>
<td>0.00752</td>
<td>-0.0064</td>
<td>0.1880</td>
<td>1.0000</td>
</tr>
<tr>
<td>5.250</td>
<td>0.6330</td>
<td>0.01607</td>
<td>0.00789</td>
<td>-0.0052</td>
<td>0.1806</td>
<td>1.0000</td>
</tr>
<tr>
<td>5.500</td>
<td>0.6546</td>
<td>0.01635</td>
<td>0.00816</td>
<td>-0.0040</td>
<td>0.1737</td>
<td>1.0000</td>
</tr>
<tr>
<td>5.750</td>
<td>0.6761</td>
<td>0.01686</td>
<td>0.00860</td>
<td>-0.0028</td>
<td>0.1674</td>
<td>1.0000</td>
</tr>
<tr>
<td>6.000</td>
<td>0.6979</td>
<td>0.01715</td>
<td>0.00894</td>
<td>-0.0015</td>
<td>0.1609</td>
<td>1.0000</td>
</tr>
<tr>
<td>6.250</td>
<td>0.7194</td>
<td>0.01763</td>
<td>0.00931</td>
<td>-0.0004</td>
<td>0.1552</td>
<td>1.0000</td>
</tr>
<tr>
<td>6.500</td>
<td>0.7413</td>
<td>0.01808</td>
<td>0.00984</td>
<td>0.0009</td>
<td>0.1497</td>
<td>1.0000</td>
</tr>
<tr>
<td>6.750</td>
<td>0.7632</td>
<td>0.01845</td>
<td>0.01020</td>
<td>0.0021</td>
<td>0.1441</td>
<td>1.0000</td>
</tr>
<tr>
<td>7.000</td>
<td>0.7850</td>
<td>0.01919</td>
<td>0.01081</td>
<td>0.0031</td>
<td>0.1391</td>
<td>1.0000</td>
</tr>
<tr>
<td>7.250</td>
<td>0.8067</td>
<td>0.01955</td>
<td>0.01133</td>
<td>0.0044</td>
<td>0.1344</td>
<td>1.0000</td>
</tr>
<tr>
<td>7.500</td>
<td>0.8286</td>
<td>0.01997</td>
<td>0.01175</td>
<td>0.0055</td>
<td>0.1297</td>
<td>1.0000</td>
</tr>
<tr>
<td>7.750</td>
<td>0.8506</td>
<td>0.02086</td>
<td>0.01250</td>
<td>0.0064</td>
<td>0.1253</td>
<td>1.0000</td>
</tr>
<tr>
<td>8.000</td>
<td>0.8720</td>
<td>0.02130</td>
<td>0.01313</td>
<td>0.0077</td>
<td>0.1214</td>
<td>1.0000</td>
</tr>
<tr>
<td>8.250</td>
<td>0.8939</td>
<td>0.02180</td>
<td>0.01368</td>
<td>0.0088</td>
<td>0.1173</td>
<td>1.0000</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td>0.9162</td>
<td>0.9376</td>
<td>0.9588</td>
<td>0.9807</td>
<td>1.0029</td>
<td>1.0225</td>
</tr>
<tr>
<td></td>
<td>0.02241</td>
<td>0.02334</td>
<td>0.02399</td>
<td>0.02457</td>
<td>0.02554</td>
<td>0.02651</td>
</tr>
<tr>
<td></td>
<td>0.01421</td>
<td>0.01524</td>
<td>0.01603</td>
<td>0.01662</td>
<td>0.01749</td>
<td>0.01868</td>
</tr>
<tr>
<td></td>
<td>0.0097</td>
<td>0.0108</td>
<td>0.0119</td>
<td>0.0129</td>
<td>0.0136</td>
<td>0.0148</td>
</tr>
<tr>
<td></td>
<td>0.1137</td>
<td>0.1102</td>
<td>0.1067</td>
<td>0.1035</td>
<td>0.1004</td>
<td>0.0977</td>
</tr>
<tr>
<td></td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>14.000</td>
<td>1.1899</td>
<td>0.05276</td>
<td>0.04715</td>
<td>0.0397</td>
<td>0.0686</td>
<td>1.0000</td>
</tr>
<tr>
<td>14.250</td>
<td>1.1609</td>
<td>0.05761</td>
<td>0.05231</td>
<td>0.0394</td>
<td>0.0683</td>
<td>1.0000</td>
</tr>
<tr>
<td>14.500</td>
<td>1.1228</td>
<td>0.06455</td>
<td>0.05956</td>
<td>0.0364</td>
<td>0.0683</td>
<td>1.0000</td>
</tr>
<tr>
<td>14.750</td>
<td>1.0662</td>
<td>0.07587</td>
<td>0.07120</td>
<td>0.0288</td>
<td>0.0686</td>
<td>1.0000</td>
</tr>
</tbody>
</table>