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EFFICIENCY AND FUNCTIONALITY OF A CONTRA-ROTATING WIND TURBINE

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Goal of this study was to evaluate in terms of efficiency and functionality a newly modelled contra-rotating wind turbine. This new wind turbine was examined in order to find more ecological and econmical technologies in the wind energy sector. Betz Limit will be proofed for single rotor wind turbines and the higher possible energy extraction coefficient for double rotor wind turbines will be explained. Main source for the experimental set-up and validation of the found results is P. Santhana Kumar's et al study of ”Computational and Experimental analysis of a Counter-Rotating Wind Turbine system” (2013). The study has shown that contra-rotating wind turbines are able to have a 26-36% higher power output. Taking into account the higher construction costs leaves the CRWT to be ~5% more efficient than a comparable SWRT. CRWTs are an effective way to boost the renewable energy sector and make wind energy more reliable. With further thinking going into this technology and first real-life attempts CRWTs can support the change of the world to become more environmentally friendly.

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INTRODUCTION

We need to bring sustainable energy to every corner of the globe with technologies like solar energy mini-grids, solar powered lights, and wind turbines.
Ban Ki-moon, UN Secretary General, 08. Nov. 2011[1]

Times of ever accelerating growth of human population and an immense demand for energy to ensure its viability, call for a sustainable, feasible and clean way of producing tomorrow's energy. It is not only that greenhouse-gas emissions need to be lowered, but also that energy needs to be available unremittingly at all times. Furthermore, future technologies in the energy sector ensuring the mentioned aspects need to be achievable and available in all countries.

In the last couple of decades renewable energies have played a leading role in accomplishing those goals. Of all the newly installed European power capacity in 2014 almost 80% was renewable, and thereof more than 55% was wind energy capacity[2]. However, one major problem associated with the deployment of renewable energy technologies to secure continuous energy provision is the consistency of sufficient energy output: solar radiation cannot be collected permanently and the wind does not blow constantly. Another problem with this kind of energy production is the fact that up until now, it has not been possible to sufficiently store or accumulate power generated by renewable energy sources so as to link up supply and demand of energy. Therefore, it is essential to boost current technologies, make them more efficient and develop more sophisticated energy storage systems in order to be able to use the energy produced at times when there is no or little supply.

In an attempt to further previous research, the current thesis introduces a new design of a wind turbine that is intended to be more efficient than conventional HAWTs (Horizontal Axis Wind Turbines). The wind turbine presented below is modelled with the help of a 3D-printer and the CAD program 'Autodesk Inventor'. Progress of the design and building process can

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[1] United Nations News Services Section 2011
[2] Iván Pineda 2015

be found in the appendix. In particular, the focus of this paper is placed on differences in efficiency and functionality, and a possible implementation of the new wind turbine in the current market situation. Thus, measurements of efficiency and effects of various wind speeds on the new design are performed and evaluated and will be presented as the major part of this work.

In order to provide a sound basis for the study, relevant theory of flight and aerodynamics is presented briefly, and the most important aspects are applied to the practical use of power generation from wind. Afterwards the terminology of wind turbine technology is illustrated to provide a common background. Subsequently, a short overview of the different kinds of wind turbines and state of the art technology is given, which is complemented by a discussion of both problems and potentialities for future development. Following this, the newly modelled wind turbine is introduced, and functionality as well as design features are demonstrated. In connection with a presentation of the methods and approaches used to determine the efficiency, the actual measurements are shown and discussed. These measurements are put into relation with those of conventional wind turbines. Finally, this work discusses the new- found results with regard to possibilities for future development and improvements in relation to this kind of wind turbine.

1 THEORY OF FLIGHT AND AERODYNAMICS

The blades of a wind turbine can be compared to the wings of an airplane and work under the same principles. The only difference is that the blades of a wind turbine are all connected to one point at the grounded center, and are all designed in exactly the same way with regard to design direction which makes them rotate.

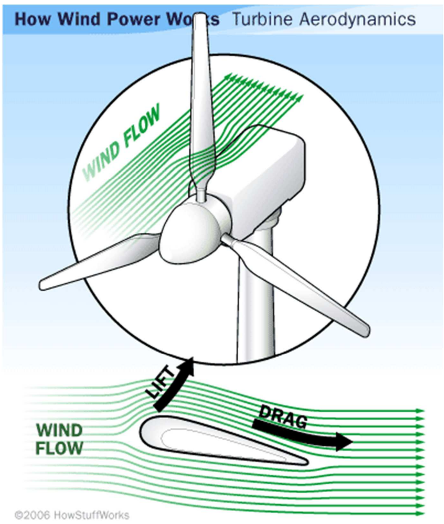

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Figure 1.1 Illustration of wind flow over wind turbine blades and airplane wings

The two wings of an airplane are mirrored at the horizontal axis of the plane body which makes them both move in the same direction. As it can be seen in Figure 1.2 The four forces acting on an airplane wingfour forces have to be taken care of for an airplane to be able to fly:

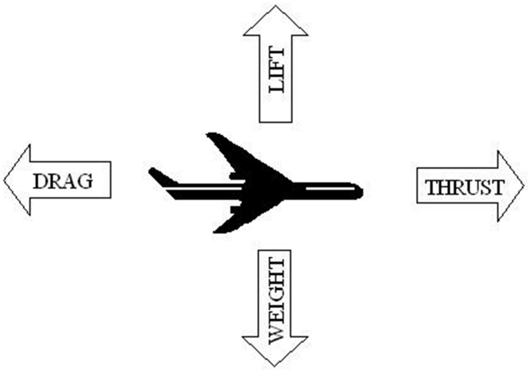

Figure 1.2 The four forces acting on an airplane wing

In order for it to rise up into the sky, a lift force acting on the wings has to be created that exceeds the weight force of the airplane. This is achieved by making the air flow extremely fast over the wings by speeding up the airplane.

1.1 Short Introduction to Aerodynamics

For a better understanding of the principles in flight theory and aerodynamic effects on the efficiency and functionality of wind turbines the following paragraph will briefly introduce the fundamental concepts of aerodynamics. The study of relative flow of air past an object of interest and the forces and moments acting on it is related to aerodynamics. Mach number and Reynolds number are the two main dimensions for determining aerodynamics forces. Mach number is the ratio of relative air velocity and speed of sound through air and the Reynolds number is the ratio of inertia force and viscous force.[3] Two main forces appear when air is flowing past an object, pressure and stress. Aerodynamics observes those forces and tries to optimize pressure and stress distribution over the object’s surface to obtain desired flight characteristics. Pressure acts normal on the object and as mentioned earlier creates the lift whereas stress acts tangential to the object and in flow direction which leads to a decrease of the relative flow between the body and the fluid which has the effect that the relative flow straight at the object’s surface stalls. Engineers are constantly trying to develop better material for wind turbine blades and to design them more streamlined to create the maximum lift with simultaneously minimum drag. After giving a short overview of the main principles that affect a blade the next paragraph is about the main terminology related to wind turbines to create the necessary background for the following power generation calculation from wind and the overview of the state of the art wind energy technology.

The theory of flight and the principle related to converting kinetic energy of wind into useful power are tied to three fundamentals: conservation of mass, conservation of energy, and conservation of momentum.[4] For the

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[3] Arnab Roy 2012

[4] T. Al-Shemmeri 2010

purpose of understanding how flowing air creates a lifting force that helps harvesting energy from the wind, two essential equations, the continuity equation and the Bernoulli equation, are explained in the following.

1.2 Continuity equation

Conservation of mass applied to fluid flow is described by the continuity equation.

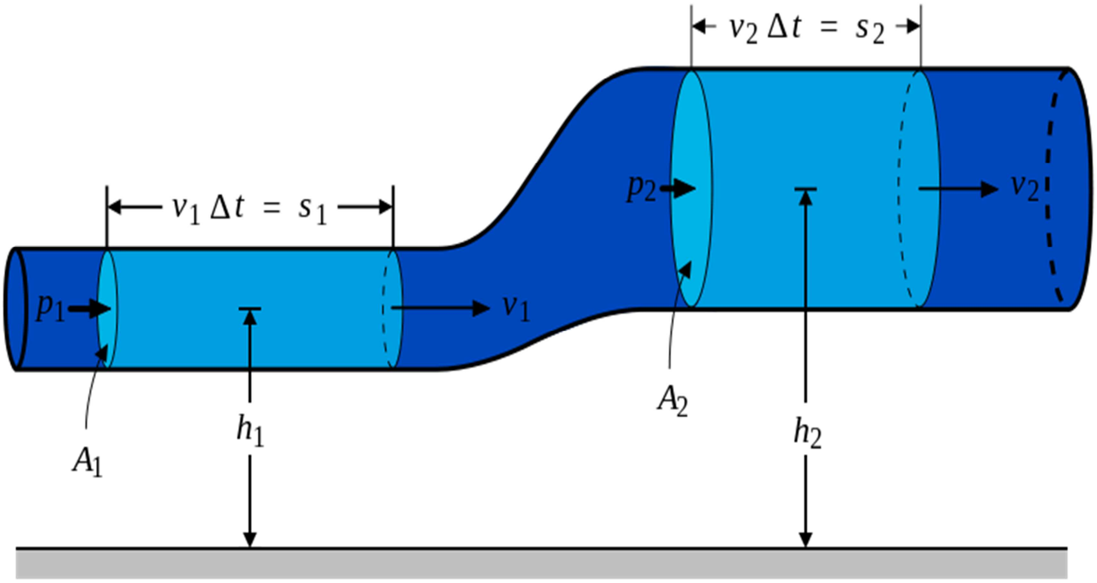

Figure 1.3 Illustration of the derivation of Bernoulli's law

If the flow within the tube is steady (neither accumulation nor decrease of fluid within the control volume) the conservation of mass states that the rate of fluid flow at entry must be equal to the rate of fluid flow at exit. With A_1 being the cross sectional area of the tube's entry and v_1 being the fluid flow velocity the volume flow rate at entry V_{f1} can be written as: $V_{f1}[\frac{m^3}{s}] = A_1[m^2] * v_1[\frac{m}{s}]$

The volume flow rate at exit V_{f2} is calculated analogously: $V_{f2}\left[\frac{m^3}{s}\right] = A_2[m^2] * v_2[\frac{m}{s}]$

Multiplication of the volume flow rate with the specific density of the fluid ρ produces the mass flow rate, and since the two flow rates at entry and exit have to be equal, the continuity equation can be written as:

$$\rho\left[\frac{kg}{m^3}\right] * A_1[m^2] * v_1\left[\frac{m}{s}\right] = \rho\left[\frac{kg}{m^3}\right] * A_2[m^2] * v_2[\frac{m}{s}] \qquad [1]$$

1.3 Bernoulli equation

The Bernoulli equation is derived from the conservation of energy. There are three non-thermal forms of energy tied to a flowing fluid; kinetic, potential and pressure energy.[5] Since the energies at entry and exit of the pipe are equal the following equation can be written as:

$$P_1 + \frac{1}{2}\rho {v_1}^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho {v_2}^2 + \rho g h_2 \qquad [2]$$

where P is the pressure energy, $\frac{1}{2}\rho v^2$ is the kinetic energy and $\rho g h$ is the potential energy.

A wind turbine blade is designed in such a way that one side has a greater surface area than the other.

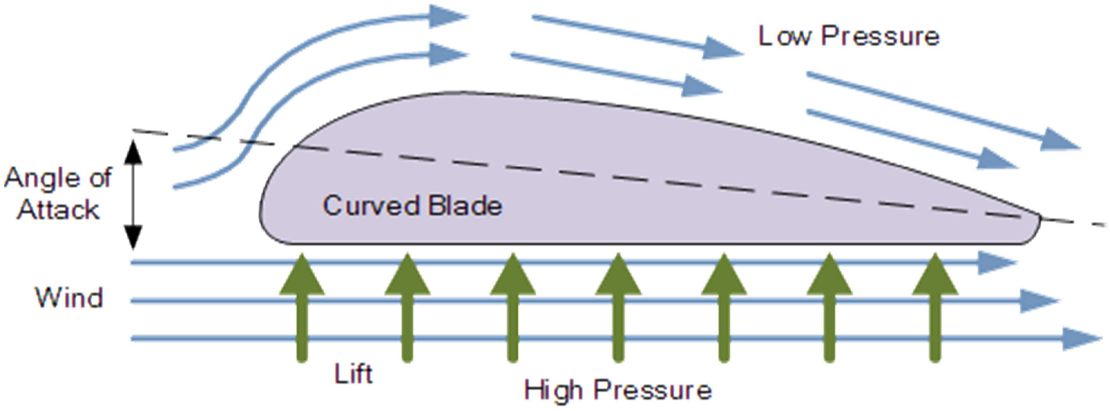

Figure 1.4 Flow over a blade creating high and low pressure fields

As displayed in Figure 1.4 the air has to travel over a greater surface area at the top than the air at the bottom. In order for the continuity equation [1] to be valid the speed at the top has to increase, which in turn leads to a decrease in pressure at the top to maintain Bernoulli's equation [2]. The difference in pressure above and below the blade creates a lift that forces the blade to

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[5] T. Al-Shemmeri 2010

move up. In this case, as it is mentioned before, the blade of a wind turbine will rotate, since it is fixed at one end. To briefly complete the explications required in order to understand what follows in this paper, the mathematical formula of lift force is presented as:

$$lift = C_L * \left(\frac{1}{2}\rho V^2\right) * A \qquad [3]$$

where C_L is the lift coefficient and A the wing area.[6] In order for the wing/blade to rise/rotate it has to overcome the weight force:

$$weight = m * g \qquad [4]$$

where m is the mass and g the gravitational acceleration.

$$lift = C_L * \left(\frac{1}{2}\rho V^2\right) * A \geq m * g = weightforce$$

Just to mention it briefly, the formula above is deduced from the Kutta-Joukowsko-theorem, but a detailed presentation of the formula's derivation is left out at this point, since it would go beyond the scope and purpose of this paper.

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[6] Sablan 1997

2 TERMINOLOGY

In the following, the most important terms related to wind energy are described, and connections to practical use with suitable illustrations are explained.

- An airfoil is the cross section profile of a turbine blade, designed in such a way to provide maximum lift and minimum drag.
- The angle of attack is the angle of relative air flow to a wind turbine's blade.

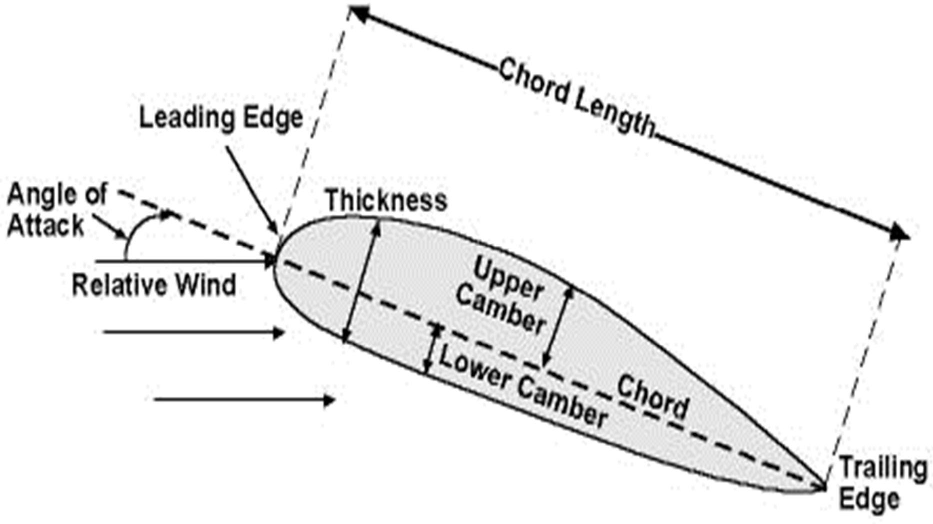

Figure 2.1 Characteristics of an airfoil

- The availability factor describes the time that a wind turbine is operating and not shut down due to maintenance or problems.
- The capacity factor gives the ratio of actual power produced over a given period of time and the power that would have been produced if the turbine had operated at maximum capacity.
- The average wind speed is the mean wind speed over a given period of time.

- The Betz Coefficient describes the theoretical maximum efficiency at which a wind turbine can work (59.3%). This value will be proved in a later chapter concerning wind energy power calculation.
- The chord is the width of a wind turbine blade at a specified location over the blade length.
- The cut-in speed is the wind speed at which the blades start to rotate and produce power.
- The cut-out speed is the wind speed at which turbines automatically stop the blades from rotating to avoid damage.
- Furling defines the process of a wind turbine turning itself out of the wind direction to avoid too high wind speeds.
- Horizontal Axis Wind Turbines or HAWTs are turbines with a horizontal axis of rotation and blades that are perpendicular to the ground.

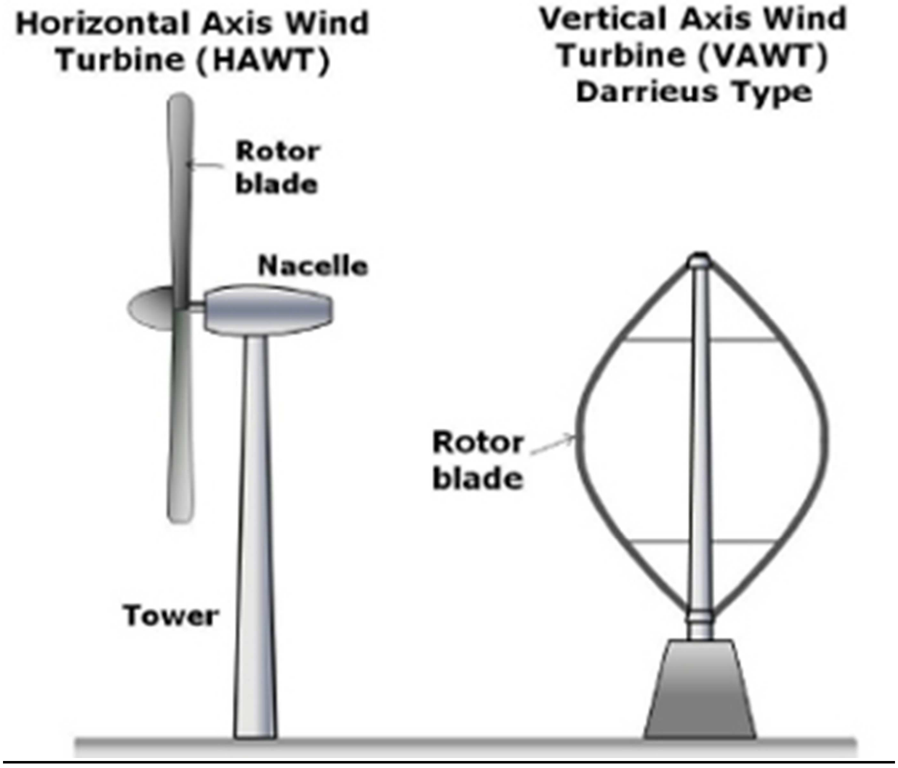

Figure 2.2 Illustration of the basic set-up of a HAWT and a VAWT

- The hub is the central part of the wind turbine which connects the blade to the low-speed rotor shaft inside the nacelle.

- The nacelle is the body just behind the turbine blades which houses the major components including the gearbox and the generator.
- Payback time is the time needed for the investment costs to be covered by the savings resulting from operating the system.
- The peak wind speed is the maximum instantaneous wind speed that occurs in a specific time interval.
- The rated wind speed is the wind speed at which the turbine generates the power it is rated for. Almost always that is the wind speed which is prevalent in the region where the wind turbine is installed.
- The start-up speed is the wind speed at which the blades start to rotate although they do not necessarily produce power until they reach the cut-in wind speed.
- The tip speed ratio is the relationship between blade velocity and relative oncoming wind velocity. Although the efficiencies of a turbine can be increased with higher tip speeds, noise, aerodynamic and centrifugal stress will also increase. A blade that is designed for high tip speed ratios has a low torque at lower speeds, which makes it more difficult to start and results in higher cut in speeds. The general formula for calculating the TSR is: $\lambda = \frac{\Omega * r}{v}$, where Ω is the rotational velocity of the blade [rad/s], r the swept radius and v the relative wind speed.[7]
- The twist in a turbine blade creates a difference in pitch between the blade root and blade tip. There is more pitch at the blade root for easier start-up and less at the blade tip for better high-speed performance.
- A vane is a piece of material that aligns the rotor and blades correctly into the wind and is usually vertically mounted on the back of the nacelle.
- A variable pitch turbine can adjust the angle of attack of the blades according to the occurring wind.
- A vertical axis wind turbine or VAWT has a rotating axis perpendicular to the ground.

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[7] Schubel, Crossley 2012

- A wind rose is a circular plot that describes wind characteristics at a certain location.
- The wind shear is a calculation which describes how wind speed increases with height above the surface of a given terrain.
- Yaw is the rotation of a HAWT about its vertical axis (tower).[8]

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[8] U.S Department of Energy 2015

3 POWER CALCULATION & BETZ LIMIT

To compare the wind turbine that I have developed as part of this thesis with conventional ones, the main focus is placed on efficiency. Therefore, the power generated by both a conventional, and my newly modelled wind turbine is calculated and examined. In order to do so, the following equation is used and, for the sake of completeness proved subsequently.

$$P = C_p * \frac{1}{2}\rho * A * v^3 \qquad [5]$$

Where

C_p is the power coefficient
ρ is the density of flowing air
A is the swept area of the rotor and blades
v is the velocity of the flowing air

Looking at the equation [5], it can be deducted that wind velocity has the biggest impact on the power output, while the generated power increases with wind speed cubed. This means that every doubling of wind speed results in a power increase of eight folds. Therefore, the location of a wind turbine is one of the most essential criteria.[9]

For deriving the following equation, the kinetic energy of a moving mass is the starting point.

$$E = \frac{1}{2}mv^2 \qquad [6]$$

Assuming that wind flowing through the swept area of a wind turbine is nothing less than many little masses moving through a plane of area A. For that matter the rate of change of energy [*J*] over time [*s*] is power [*J/s*] by definition, and thus

$$P = \frac{\Delta E}{\Delta t} = \frac{1}{2} * \frac{\Delta m}{\Delta t} * v^2 \qquad [7]$$

Left to change is the expression $\frac{\Delta m}{\Delta t}$, to get an equation for easily calculating the generated power. The rate of change of mass over time means that the little masses moved a certain length L in a given time period. Hence the vol-

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[9] T. Al-Shemmeri 2010

ume of air that has moved through the swept area A can be calculated with

$V = A * L$ *[8]*

Knowing the density of air gives

$V = \frac{m}{\rho} = A * L$

$\rightarrow m = \rho * A * L$ *[9]*

This conversion can then be substituted for the rate of change of mass in eq. [7] and leads to

$\frac{\Delta m}{\Delta t} = \rho * A * \frac{\Delta L}{\Delta t} = \rho * A * v$ *[10]*

with $\frac{\Delta L}{\Delta t}$ being velocity v by definition. Substituting eq. [10] into eq. [7] results in the equation:

$P = \frac{1}{2} * \rho * A * v^3$ *[11]*

Capturing a fraction C_p of that energy available in wind gives the final equation:

$P = C_p * \frac{1}{2} * \rho * A * v^3$ *[12]*

The C_p fraction of available energy that is possible to convert is limited to a theoretical maximum of 59.3%, also called the *Betz Limit*.

In addition to this, the efficiency of a wind turbine is also influenced by the gearbox and generator losses.[10] The following chapter is intended to help to understand the *Betz Limit* and to prove its existence. It is relatively easy to understand that there is a theoretical limit of energy that can be harvested from wind. In order to use the energy of wind, the turbine slows down oncoming air. To actually use all 100% of the oncoming energy in the air, the turbine would have to bring the wind to a complete stop; this would however stop the rotating blades and therefore hinder the turbine from producing energy.[11]

Starting point for the derivation of the Betz Limit is the equation of the force acting on the wind turbine, substituting eq. [10][12]:

$F = m * a$

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[10] Tyree 2008

[11] T. Al-Shemmeri 2010

[12] Magdi Ragheb, Adam M. Ragheb 2011

$= m * \frac{\Delta v}{\Delta t}$

$= \dot{m} * \Delta v$

$= \rho * A * v * (v_1 - v_2)$ *[13]*

In which Δv is the difference in wind speed before and after the rotor. The change in energy or work can be noted as:

$\Delta E = F * \Delta s$ *[14]*

Again, the power can be expressed as the energy rate over time:

$P = \frac{\Delta E}{\Delta t} = F * \frac{\Delta s}{\Delta t} = F * v$ *[15]*

Inserting eq. [13] into eq. [15], the power available in wind can be written as:

$P = \rho * A * v^2 * (v_1 - v_2)$ *[16]*

Another way of expressing extractable power of wind is the use of the rate of change in kinetic energy:

$P = \frac{\Delta E}{\Delta t}$

$= \frac{\frac{1}{2} * m * v_1^2 - \frac{1}{2} * m * v_2^2}{\Delta t}$

$= \frac{1}{2} * \dot{m} * (v_1^2 - v_2^2)$ *[17]*

Substituting eq. [10] again and equating the two expressions for power eq. [16] and [17] leads to:

$P = \frac{1}{2} * \rho * A * v * (v_1^2 - v_2^2) = \rho * A * v^2 * (v_1 - v_2)$

$\rightarrow \frac{1}{2} * (v_1^2 - v_2^2) = v * (v_1 - v_2)$

$\rightarrow \frac{1}{2} * (v_1 - v_2) * (v_1 + v_2) = v * (v_1 - v_2)$

$\rightarrow \forall\, v_1 \neq v_2 : \frac{1}{2} * (v_1 + v_2) = v$ *[18]*

Eq. [18] implies that the velocity v at the rotor is the average of wind speed before and after the rotor. With that in mind, force F and power P can be noted as:

$F = \rho * A * v(v_1 - v_2)$

$= \frac{1}{2} \rho * A * ({v_1}^2 - {v_2}^2)$ *[19]*

$P = \rho * A * v^2 * (v_1 - v_2)$

$= \frac{1}{4} * \rho * A * (v_1 + v_2)^2 * (v_1 - v_2)$

$= \frac{1}{4} * \rho * A * (v_1^2 - v_2^2) * (v_1 + v_2)$ *[20]*

The interference factor b is the ratio of v_2 to v_1, and hence the ratio of the downstream velocity to the upstream velocity:

$$b = \frac{v_2}{v_1} \qquad [21]$$

Substituting the interference factor into eq. [20] leads to:

$$P = \frac{1}{4} * \rho * A * v_1^3 * (1 - b^2) * (1 + b) \qquad [22]$$

With $C_p = \frac{P}{W}$ being the coefficient of performance and W being the available power in the oncoming wind as expressed in eq. [11] can be written as:

$$C_p = \frac{\frac{1}{4} * \rho * A * v_1^3 * (1 - b^2) * (1 + b)}{\frac{1}{2} * \rho * A * v^3}$$

$$= \frac{1}{2} * (1 - b^2) * (1 + b) \quad ^{13} \qquad [23]$$

For getting the maximum C_p the derivative of eq. [23] has to be set to zero:

$$\frac{dC_p}{db} = \frac{1}{2} * \frac{d}{db}[(1 - b^2) * (1 + b)]$$

$$= \frac{1}{2} * [-2b * (1 + b) + (1 - b^2) * 1]$$

$$= \frac{1}{2} * (-3b^2 - 2b + 1)$$

$$= \frac{1}{2} * (1 - 3b) * (1 + b) = 0 \qquad [24]$$

Equation [24] has two solutions:

Solution 1:

$1 + b = 0$

$\rightarrow b = -1$,which implies: $v_2 = -v_1$ and hence no practical sense.

Solution 2:

$1 - 3b = 0$

$\rightarrow b = \frac{1}{3}$ and thus, for the optimum coefficient of performance

$v_2 = \frac{1}{3} v_1$ has to be valid.[14]

Substituting $b = \frac{1}{3}$ into eq. [23]:

$$C_p = \frac{1}{2} * \left(1 - \frac{1}{3}^{2}\right) * \left(1 + \frac{1}{3}\right)$$

$$= \frac{1}{2} * \frac{8}{9} * \frac{4}{3} = \frac{32}{54} = \frac{16}{27}$$

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[13] Magdi Ragheb, Adam M. Ragheb 2011

[14] Magdi Ragheb, Adam M. Ragheb 2011

$$= 0.5926$$
$$= 59.26\%$$

This means that the theoretical maximum percentage of energy that can be extracted from the available wind energy is 59.26%. However modern wind turbines achieve peak values for C_p only in the range of 0.45 to 0.5 and this does not take any other efficiency losses into account.[15]

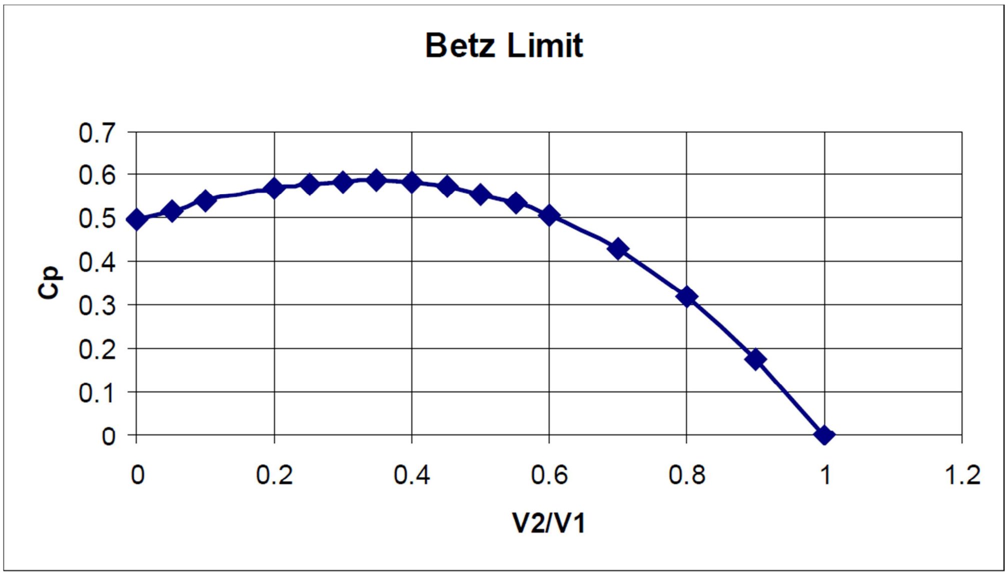

Figure 3.1 Diagram of Betz Limit

However, it is reported that the maximum efficiency obtained by counter-rotors having the same swept area is increased to 64%.[16] This is a major advantage and a huge possibility to further harvest the potential efficiency yield.

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[15] ENERCON GmbH 2010

[16] Santhana Kumar, P. et al 2013

4 CURRENT STATUS

The following chapter gives a small overview of existing differences of currently leading wind energy technologies and their features. Also, the wind energy world market is introduced and the main factors influencing it are explained.

4.1 Wind Turbine Types

All wind turbines that are currently available on the market can be divided into either horizontal axis or vertical axis wind turbines. This section focuses on the main differences between the two varieties and analyzes their usability and efficiency.

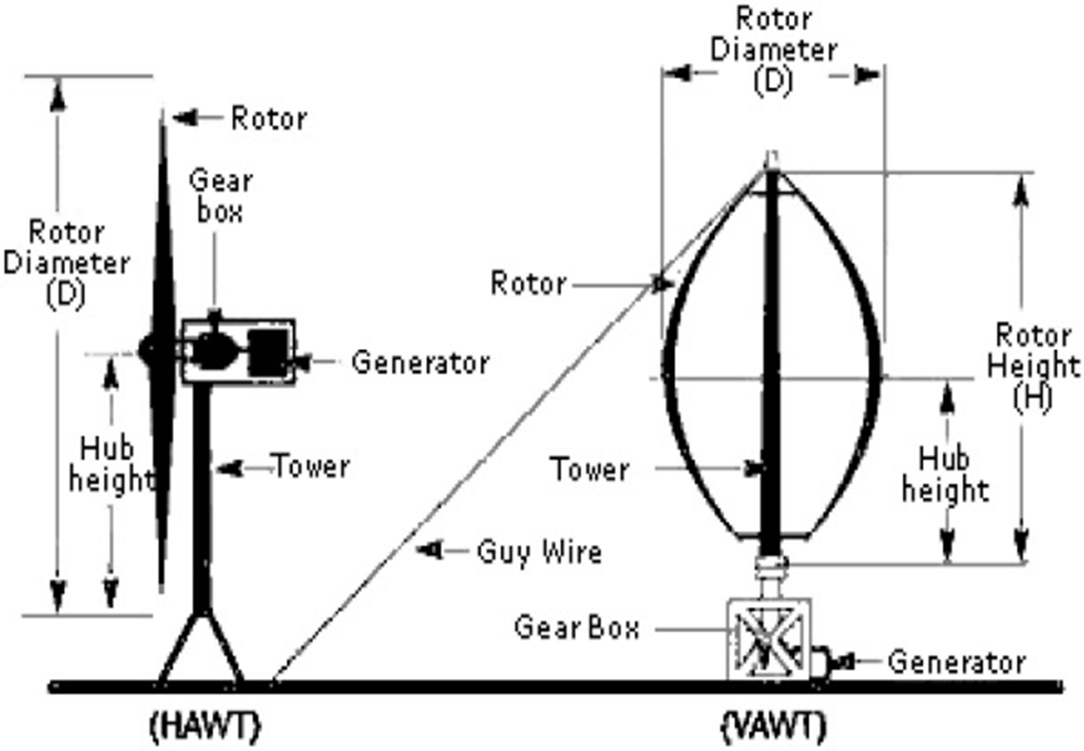

Figure 4.1 Characteristics of HAWT and VAWT

Figure 4.1 depicts visible differences between a HAWT and a VAWT. The main and also name-giving difference is the rotating axis that is either horizontal or vertical. A huge advantage of the VAWT is that noadditional mechanisms are needed to turn the turbine in such a way that is faces the wind, since here wind can attack from any angle and is still able to rotate the blades. On the contrary, a HAWT has to face wind frontally and move with it.

Another fact in favor of VAWTs is that the gearbox and heave generator equipment can be mounted on the ground, and are, therefore, easily accessible for maintenance. However, the low tip speed ratio and difficulties in self-starting have hindered further development of VAWTs. Nevertheless, a novel V-shaped VAWT rotor design is being examined at the moment, and is hoped to be a milestone in future development.[17] The ability to regulate the rotor through pitch and yaw control is the essential feature that makes HAWTs so popular.[18] When it comes to efficiency, HAWTs have a big advantage on their side. As wind blows over the blades of a HAWT all of them contribute to generate electricity. However, with VAWTs only parts of the blades generate torque while the remaining parts just move along, which results in a reduced efficiency in power generation.[19] At the moment the biggest onshore wind energy turbine has a rated power output of 7.5 MW.

4.2 Global Wind Energy Market

In 2014, the wind industry has set a new record with installing more than 51 GW during a single year, and thereby increasing the global total to about 370 GW.[20] Of those 51 GW China alone installed more than 45%. In general Asia has achieved to lead the regional markets and pass Europe in terms of cumulative installed capacity. Over the last 18 years the globally installed wind capacity per year increased from 1,530 MW in 1997 up to 51,473 in 2014, which results in a global cumulative installed wind capacity of 369,597 MW after 2014.

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[17] Stuart Nathan 2010
[18] Schubel, Crossley 2012
[19] Merecicky 2014
[20] GWEC 2014

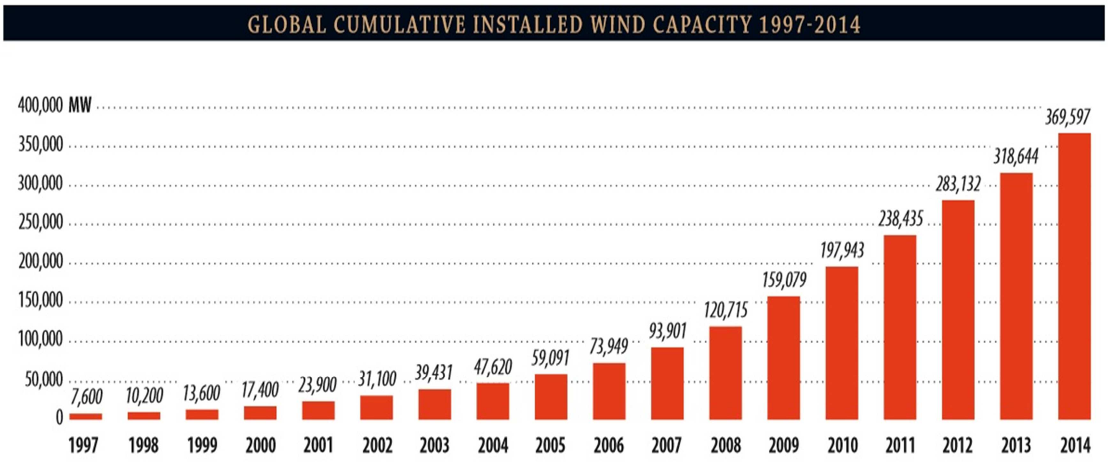

Figure 4.2 Global cumulative installed wind capacity 1997-2014

The top three countries that have installed the most wind power capacity are China with 115,000 MW, the USA with 66,000 MW and Germany with 39,000 MW. Although Denmark is not under the top 10 it has by far the highest wind power capacity per capita with 751 MW per million people.[21]

In 2014, the annual market has grown by 44% and is one of the fastest growing industries within the renewable energies. Looking ahead 2015 is likely to be another good year. The fact that Europe has committed to its 2020 targets ensures a stability in growth, and also Africa and Latin America are expected to grow further. North America's market has steadily grown in 2014. After 2015 however, a policy uncertainty in North America could

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[21] Zachary Shahan 2013

cause a downturn there, and perhaps affect other regional markets as well.[22]

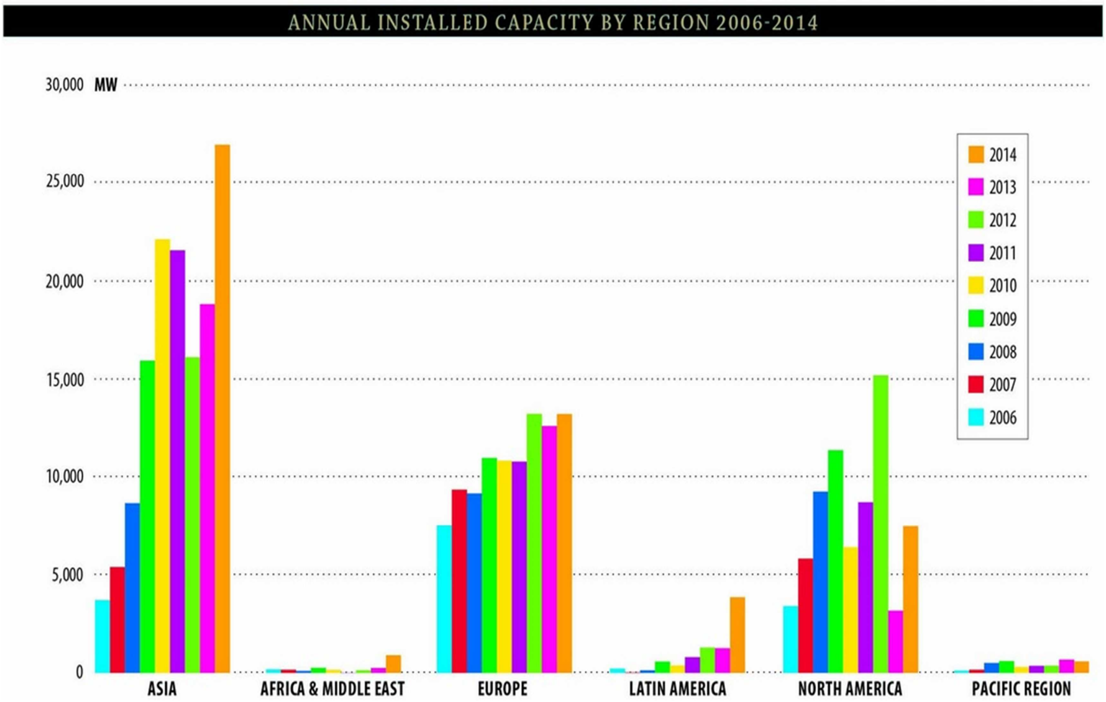

Figure 4.3 Annually installed capacity by region 2006-2014

After a review of the basic theory of flight, a discussion of the efficiency of different types of wind turbines, and a presentation of the current global market, the following part of this work focuses on the newly modelled wind turbine, its efficiency and functionality issues, as well as its integration into the modern renewable energy sector.

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[22] GWEC 2014

5 CONTRA-ROTATING WIND TURBINE (CRWT)

The main motivation behind writing this thesis and developing a new kind of wind turbine is the objective to create an even more efficient HAWT with the least possible intervention in the already existing modern art of wind turbine technology. The basic question to be answered here is, how can a generator produce more electricity?

One possible solution is that wind needs to blow faster and increase the shaft's rotational speed. However, since it is difficult to influence the wind speed, another idea was born. The same wind speed could be also used on a second rotor connected to a generator to pivot it in the opposite direction of the first rotor, which would result in a relative increase in the shaft's rotational speed and generate more electricity. More specifically, the front rotor is mounted with two bearings within the back rotor, which is again mounted to the nacelle with another two bearings. This secures an independent rotation of both rotors. As previously mentioned, the front rotor is connected to a shaft that drives a generator as in any other conventional WTG.

For test purposes and a more practicable setup as part of this paper, the idea is to run experiments without a gearbox. Since this would have no effect on the efficiency or functionality of the double rotor, no further modification as to install one later would have to be done.

The generator is mounted inside the rod and connected to the back rotor. In total, six blades were designed and printed, out of which three blades were intended for the front rotor and another three blades for the back rotor. In particular the back rotor blades were installed in such a way that they mirrored and pitched exactly opposite to the blades of the front rotor. This set-up leads to the fact that now, when wind flows over the blades, it makes the front rotor turn into one direction and the back rotor turn into the other, which causes a relative velocity difference between the generator and its shaft.

However, a problem detected during initial trials is concerned with the rotating generator itself, since the connecting wires started to twist and eventually broke. Therefore, as it can be seen in Figure 5.1, a sliding contact needed to be installed at the end of the rod of the back rotor, in order to maintain a stable wire connection.

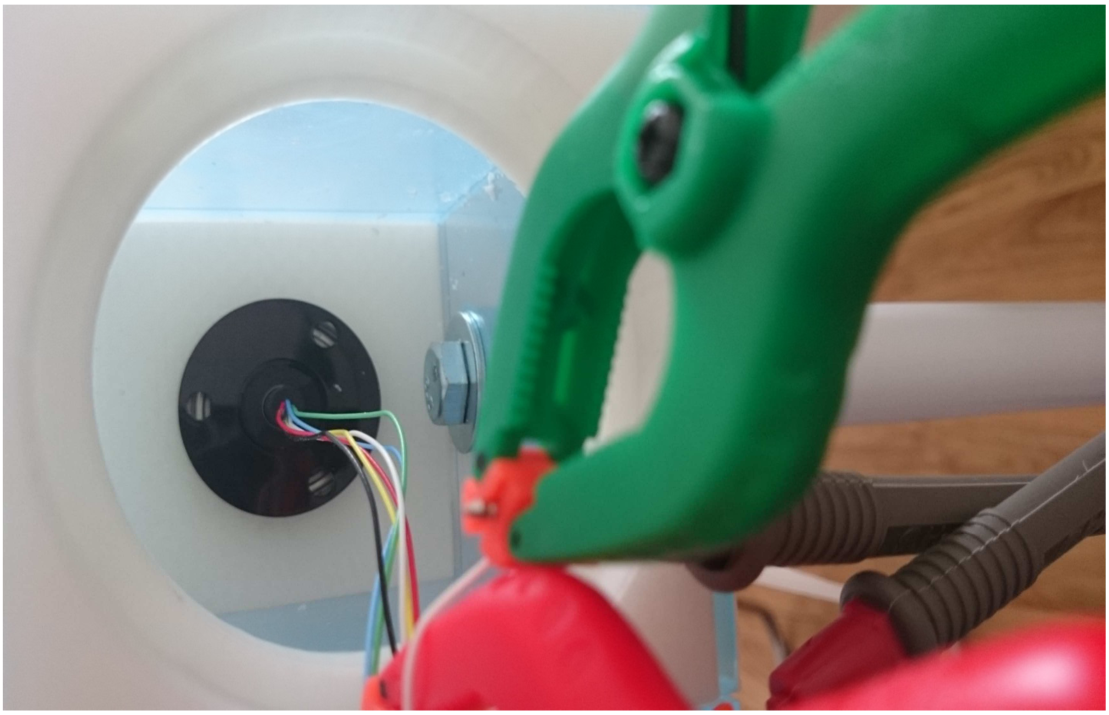

Figure 5.1 View onto sliding contact in nacelle

5.1 Methodology

A fan with blades larger than those of the CRWT was placed at a distance of about one meter apart from the test turbine to function as a wind generator. The fan's rotor and the double rotor were centered and a tube-like structure was placed onto the fan, in order to create a wind tunnel, and to make it easier to measure the wind velocity. Through holes in the tube an anemometer was placed with the purpose to measure the wind velocity constantly.

Furthermore, a resistor able to vary from 1kΩ to 1MΩ was connected in between the wires coming from the generator so as to close the electric circuit and make it possible to measure current and voltage. In order to do so, a volt meter was connected parallel to the load and an ampere meter connected in series. Finally, both meters were linked to a computer to control the data series online.

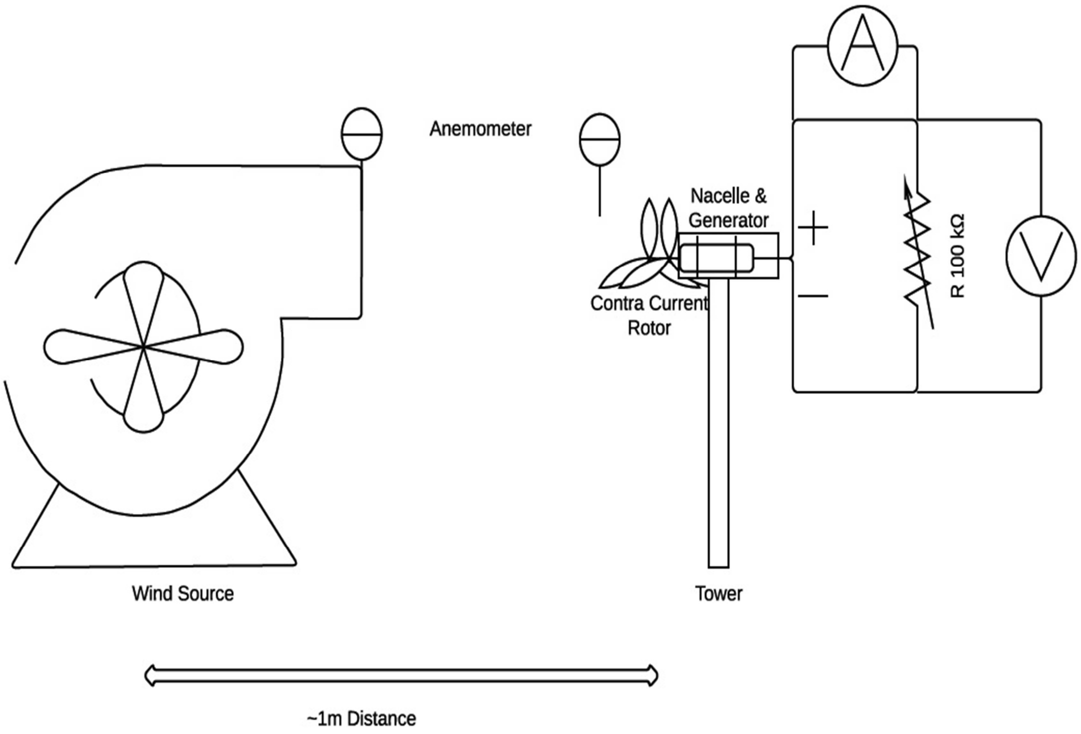

Figure 5.2 Experimental setup of fan and CRWT

In total two different tests were run, each test with two different fan speeds. The first test was run with the contra current rotor and the second test was run, using the same setup, with the single rotor. Each test was run three times and led to a total of 12 data sets (six sets with voltage and six sets with current). Voltage, current and wind velocity measures were captured using the software *Microsoft Excel (2010)* and the resulting power output was calculated with the program's help. Afterwards, tables and diagrams are created, in order to bring wind velocity and power output of both single and double rotor turbines in relation, and to compare the power output of the single rotor turbine to that of the double rotor turbine.

5.2 Results

The following paragraph introduces the results gained from the experiments' measurements in form of diagrams and a complementary short description.

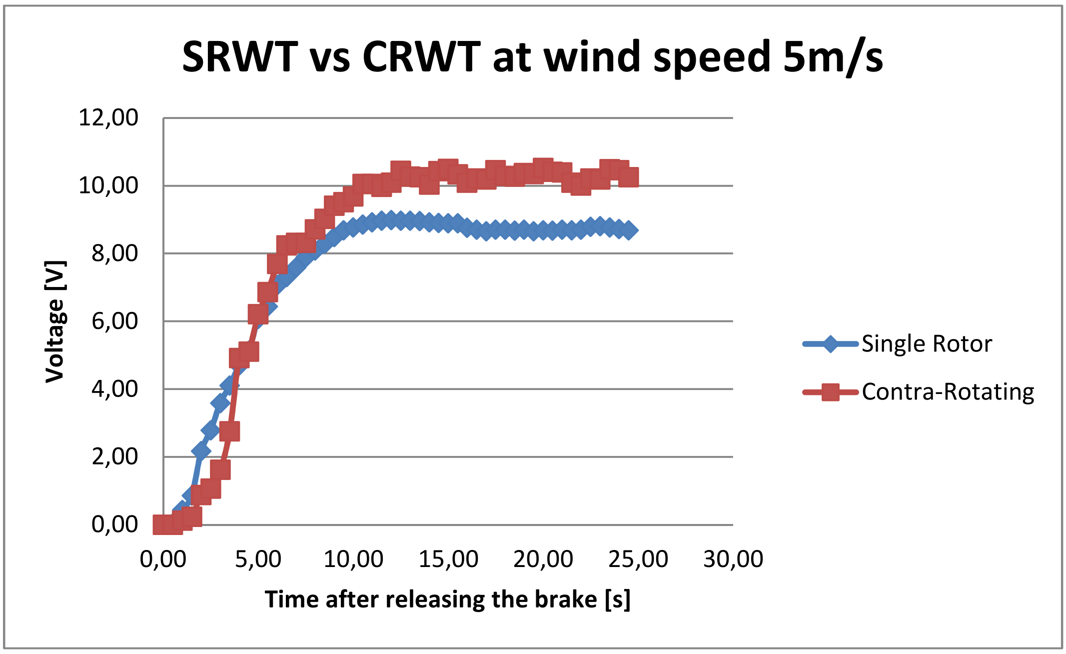

Figure 5.3 Voltage build-up at 5 m/s

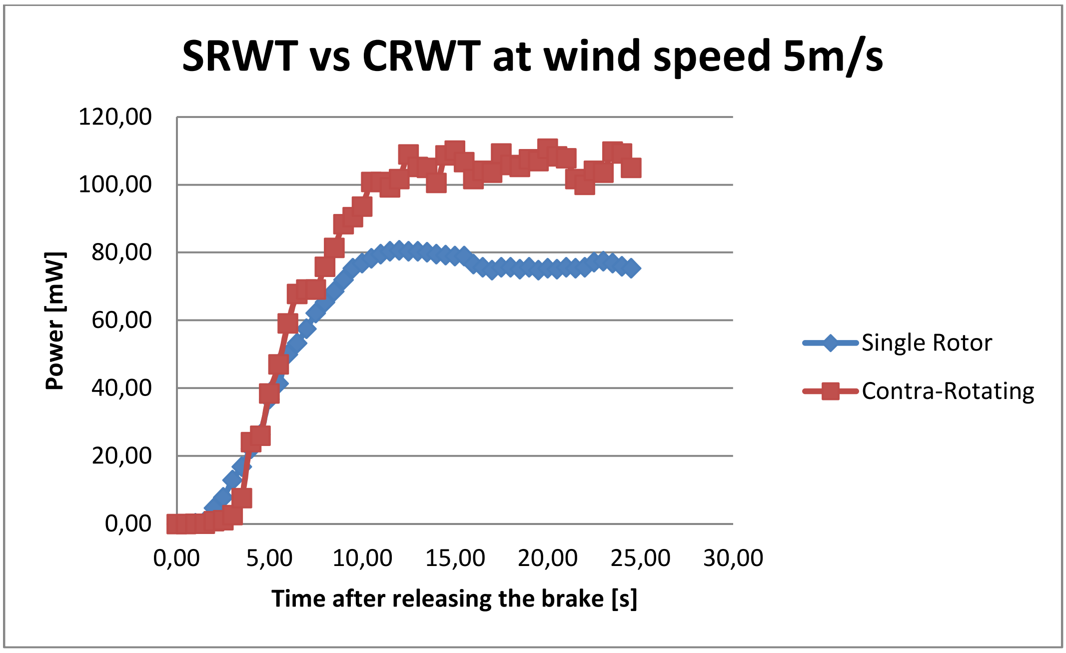

Figure 5.4 Power build-up at 5 m/s

The contra-rotating wind turbine starts building up the voltage one to two seconds later than the single rotor, and then increases steeper resulting in greater voltage after about five seconds after the start (Figure 5.3). Both turbines settle at their maximum voltage (SRWT=8.5-9.0V; CRWT=10.0-11.0V) at about 13 seconds after releasing the rotor break. The power working on the 1kΩ resistor is displayed in Figure 5.4. Here, the power curve proceeds exactly like the voltage curve.

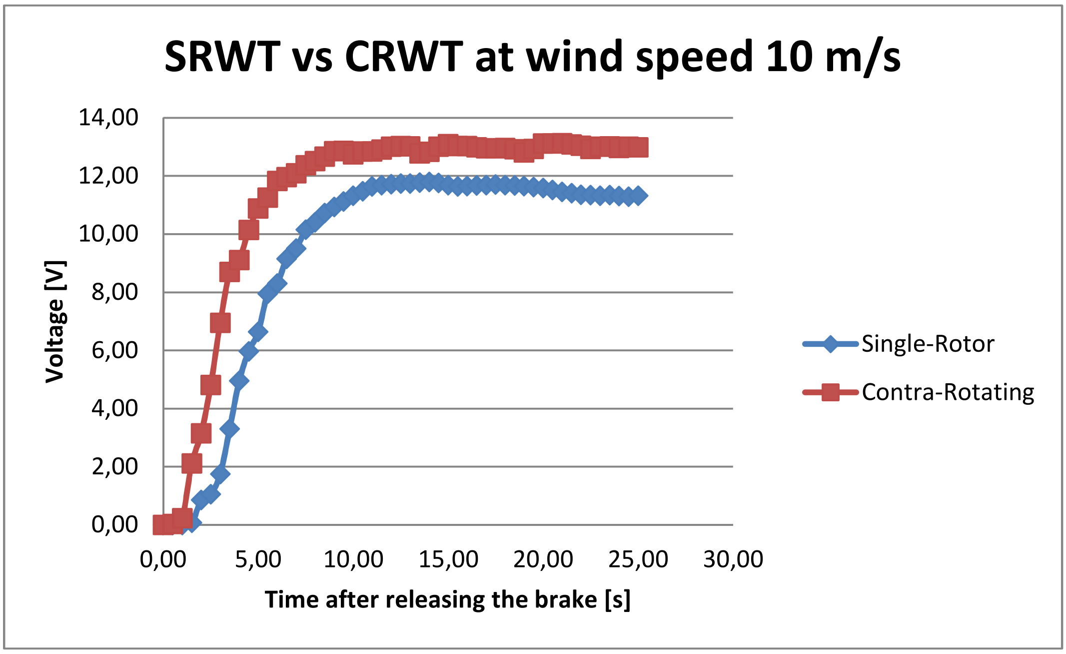

Figure 5.5 Voltage build-up at 10 m/s

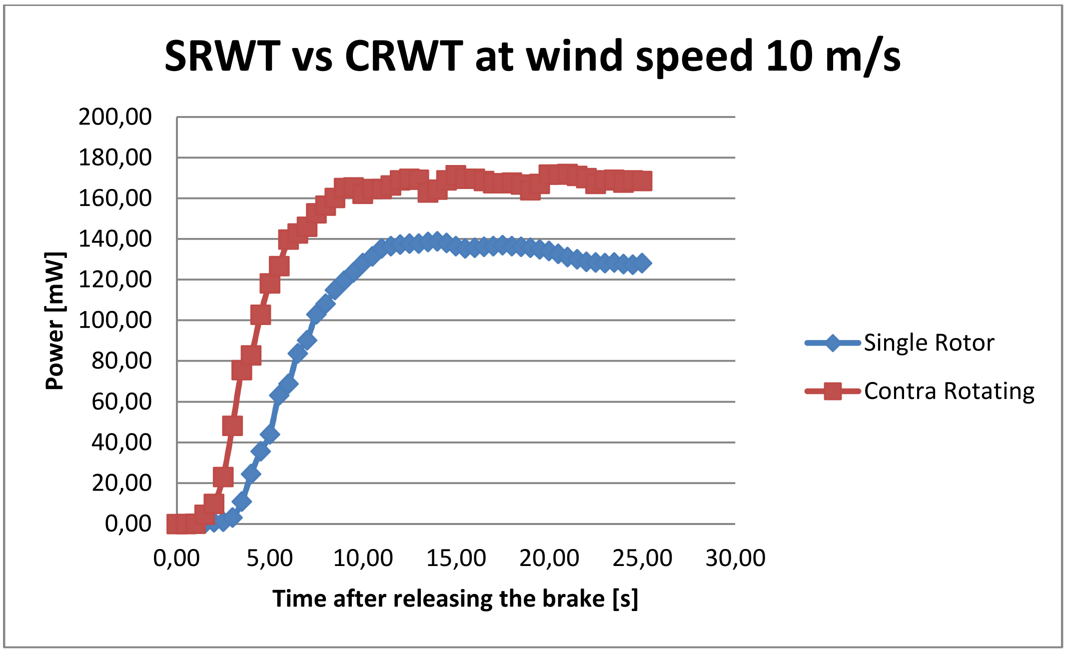

Figure 5.6 Power build-up at 10 m/s

The CRWT builds up its voltage approximately one second earlier than the SRWT, specifically at one second after the start (Figure 5.5).The voltage climbs up evenly until the CRWT reaches its maximum voltage of 13V three to four seconds earlier than the SRWT, which reaches its maximum voltage of 11.5V at nine respectively 12 seconds after the start.

5.3 Discussion

The results of this study reveal several issues that have major positive effects on the efficiency and functionality of a CRWT. The most obvious one is the difference in power output between the SRWT and the CRWT directly resulting in a higher efficiency.

Furthermore, the data shows that the CRWT builds up its power faster than the SRWT at higher wind speeds which could mean a greater torque for the CRWT to make use of the wind more quickly. In addition to the findings of the present study, results of the study by Santhana Kumar (2013) are also discussed and set into relation in the following.

A comparison of the power outputs of both the SRWT and the CRWT reveals an energy yield at 5 m/s wind speed that was 36% higher for the CRWT, as well as an energy yield at 10 m/s that was 26% higher than that of the SRWT. The above mentioned results do not only confirm that the CRWT is more efficient than the SRWT, but that it also exceeds the efficiency difference of 20-30% that Santhana Kumar (2013) has found in his study.[23] Whether 26-36% of higher efficiency is worth the investment costs of both a second rotor as well as required supporting structures will be discussed later on.

Interestingly at lower wind speeds the difference in power output between the two turbines is even greater than at high wind speeds. This can be explained by a higher torque value of the CRWT. The torque of the CRWT is approximately twice as big as the torque of the SRWT at 5 m/s due to presence of a secondary rotor in the wake.[24] As explained earlier torque is the force that enables the rotor to start spinning, which means that the bigger the torque on a rotor, the earlier it starts to rotate. However, a blade that is designed for high tip speed ratios has a low torque at lower speeds and the other way around. Therefore, the CRWT has an advantage at low wind speeds over the SRWT because of its higher torque. At higher wind speeds the greater torque is not such a big advantage anymore and the difference in power output slightly decreases.

Another parameter that was observed during the experiments is the importance of the correct axial distance between the two rotors of the CRWT. Obviously, the rotors should not be too close, since the second rotor is then in the wake of the first and thus, barely if at all rotates. However, if the second rotor is moved away from the first beyond a specific point on the axis, the rotational energy decreases again. It appears that the back rotor profits from the front rotor and produces more energy than without a rotor in front of it.

Additionally, the relation between the two rotor diameters is an essential ratio that has to be taken into consideration. Intuitively, the first rotor has to be smaller in diameter as wind is pushed outwards behind the swept

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[23] Santhana Kumar, P. et al 2013

[24] Santhana Kumar, P. et al 2013

area and a larger second rotor needs to be able to harness it. In the following Figure 5.7, a complete wind velocity profile of a CRWT can be seen. The grey dotted lines show the boundaries of the wind-area that is influenced by the two rotors. The two red vertical lines symbolize the two rotors, which are 0.65 times the diameter of the first rotor apart. The blue lines with the grey arrows show the wind direction and according to the length of the arrows the wind velocity.

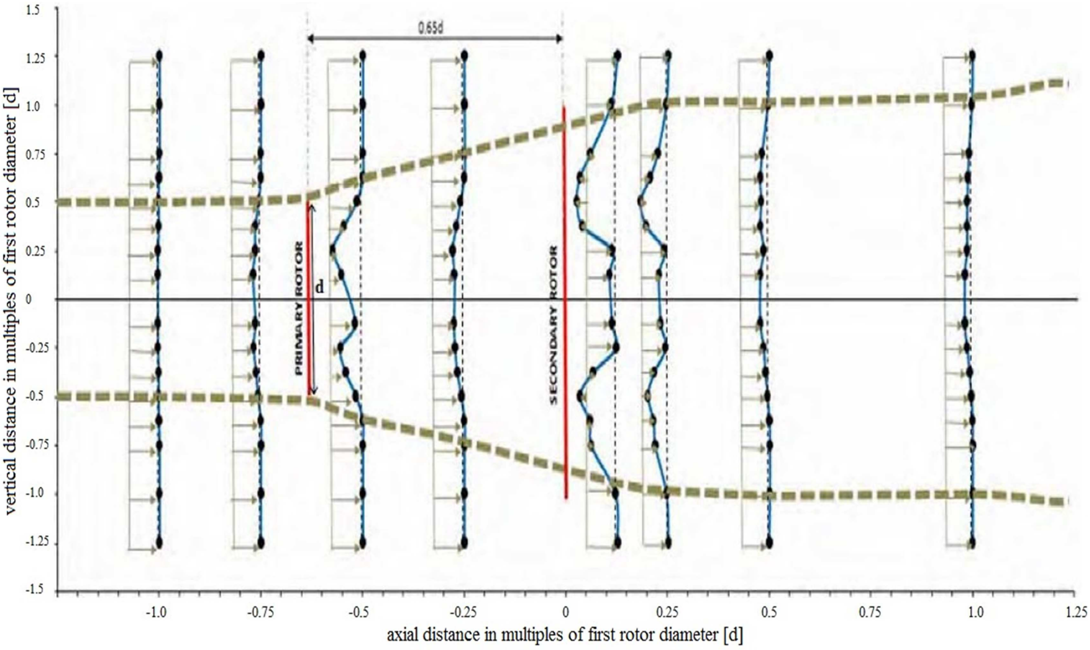

Figure 5.7 Complete wind velocity profile of a CRWT

When a wind flow approaches the first rotor at -0.75d, the wind velocity decelerates within the swept area and accelerates behind it (from -0.5d to -0.25d), just before the flow reaches the second rotor (Figure 5.7). Kumar et al (2013) have found that the primary to secondary rotor diameter ratio for maximum energy output is 1:2. The study has been carried out for axial distances of 0.25d, 0.5d, 0.65d and 0.75d.[25] As shown in Figure 5.8, the power increase in percentage was illustrated over the axial distance. The maximum increase in power output of 9.67% was observed at an axial distance of 0.65d, compared to 8.9% at 0.5d and 7.8% at 0.75d. The reason for the de-

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[25] Santhana Kumar, P. et al 2013

crease after 0.65d is the energy extraction from the wake of the primary rotor[26].

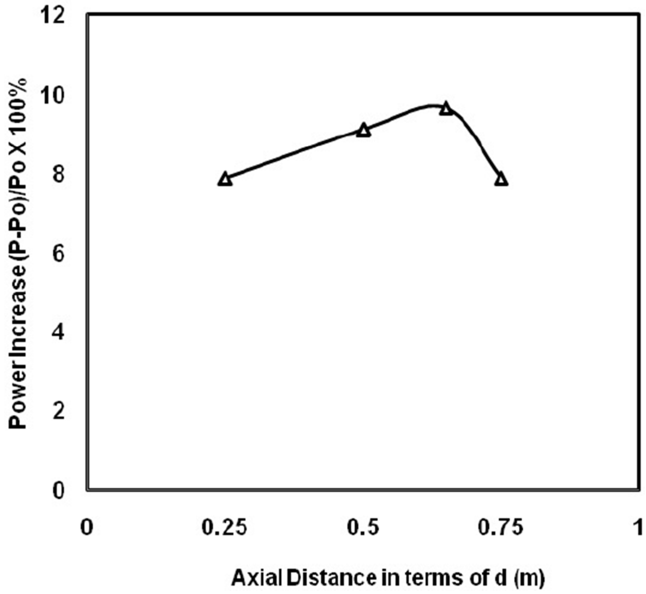

Figure 5.8 Power increase depending on the axial distance

Lastly, another positive effect that was observed during the study was the near-zero net torque in the whole system. Both rotors generate almost the same torque. However, due to their anti-directional rotation, the two forces are oppositely oriented, and thus nearly cancel each other out. This phenomenon leads to no or very small stress caused by torque on the turbine structure and could simplify the building and design of the support structure.

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[26] Santhana Kumar, P. et al 2013

6 CONCLUSION

The present study has shown that contra-rotating turbines have indeed a higher efficiency and are able to harness the wind energy more effectively than single rotor turbines. The costs for enhanced support structures and for the necessary systems, which come along with the installation of a second rotor, are difficult to estimate because at the moment no real size contra-current wind turbine is available on the market. Estimating that the rotor makes up to 15-20% of the total costs of a WTG and additional supporting structure and changes on the generator make up another 10-15% leaves the CRWT to be around 5% more efficient than conventional WTG. In small scale WTGs the efficiency gain will be a lot more and is therefore the proper application sector. The axial distance needed between the two rotors allows mounting one rotor onto each end of the nacelle, and hence not only balancing the tower but also reducing the demand for high resilient joints to keep both rotors in line with the horizontal axis.

Additionally, the near-zero net torque that appears causes less stress on both the structure and all mechanical parts, resulting in low maintenance costs and a longer lifespan. Results indicating that CRWTs are especially capable of using low wind speeds and that their efficiency difference compared to SRWTs is highest in those conditions, makes this alternative design of a wind turbine extremely valuable for onshore installations and regions where low wind speeds are present most of the time during a year. Also, regions where conditions that would make high structures impossible prevail, or where laws exist that restrict buildings to a certain height are interesting sites for CRWTs, since they do not necessary need high wind speeds, which are dominant in greater heights. All those aspects make CRWTs an easily accessible and, in case of siting flexible renewable energy source.

However, all of the studies mentioned here have been conducted in laboratories and under experimental conditions. So far there have been no studies with originally sized contra-rotating turbines. Thus the real-life conditions and problems that might occur have never been observed let alone analyzed. Therefore, this study can only provide a basic understanding of

CRWTs and their behavior. Considering the results of this study and their impact on the development of wind energy technologies, it should be interesting to further investigate CRWTs under real-life conditions.

This leads me back to the introduction and the demand for energy sources that are available for all countries. Taking the explications above into consideration, the contra-rotating technology could really boost the wind energy sector and make every kilowatt-hour produced with wind energy even more economically and ecologically viable. Of course, the big problem of energy storage remains and issues around the field of wind energy technology are left to be solved. However, if it is possible to find solutions that help to produce energy more efficiently and effectively (even if the wind is not blowing at a constantly high level) it might also be possible to achieve a change away from fossil fuels to renewable energy sources.

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