ISTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

WIND ENERGY TECHNOLOGIES: PRELIMINARY DESIGN CODE DEVELOPMENT

M.Sc. Thesis by
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Programme : Aeronautics and Astronautics Engineering

SEPTEMBER 2007

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Date of submission : 7 September 2007

Date of defence examination: 4 September 2007

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SEPTEMBER 2007

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

RÜZGÂR ENERJİSİ TEKNOLOJİLERİ: ÖN TASARIM KODU GELİŞTİRMESİ

YÜKSEK LİSANS TEZİ

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Tezin Enstitüye Verildiği Tarih : 7 Eylül 2007

Tezin Savunulduğu Tarih : 4 Eylül 2007

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EYLÜL 2007

PREFACE

I would like thank to my supervisor Prof. Dr. Süleyman Tolun, for his encouragement, guidance and endless support with my studies in this beautiful subject.
I would also like to thank to Prof. Dr. A. Rüstem Aslan for permitting me study in such a good environment, ROTAM. Thanks to my dear friends, engineers at ROTAM and academicians at Faculty of Aeronautics and Astronautics, ITU. Special thanks to Hasan, Evren, Erkan, Serhat, Ali, Hakan, Can Ç., Can Z., Zeynep, İlhan and Güniz for their never-ending supports.
And thanks to my family for being with me and their supports during of my life.
For clean and livable Earth with wind energy…

September 2007 **Utku TÜRKYILMAZ**

INDEX

ABBREVIATIONS

GUI	: Graphical User Interface
HAWT	: Horizontal Axis Wind Turbine
RSM	: Response Surface Method
COE	: Cost of Energy
WT	: Wind Turbine
YERT	: Horizontal Axis Wind Turbine (Yatay Eksenli Rüzgar Türbini)
GL	: Germanischer Lloyd
IEC	: International Electrotechnical Commission
BEMT	: Blade Element Momentum Theory
NREL	: National Renewable Energy Laboratory
WERA	: Wind Energy Resource Analysis
DOE	: Design of Experiments
PM	: Permanent-Magnet
WindPACT	: Wind Partnerships for Advanced Component Technology
LWST	: Low Wind Speed Technology
FFD	: Full Factorial Design
CCD	: Central Composite Design
BBD	: Box Behnken Design
EIMSE-optimal	: Expected integrated mean squared error optimal
WAsP	: the Wind Atlas Analysis and Application Program
CFD	: Computational Fluid Dynamics

LIST OF TABLES

LIST OF FIGURES

Page Number

NOMENCLATURE

A	: Rotor disc area [m^2]
a	: Axial induction factor
a'	: Tangential induction factor
AEP	: Annual energy production [kWh]
AP	: Annual payment [$]
B	: Number of blades
$\mathbf{B_A}$	: Benefits over the life of project [$]
c	: Chord length [m]
c	: Weibull scale factor
$\mathbf{C_A}$	: Total cost of operation of project [$]
$\mathbf{C_{AssemblyInstall}}$	: Cost of assembly and installation [$]
$\mathbf{C_{Component}}$	: Component costs [$]
$\mathbf{C_{ControlSystem}}$	: Cost of control system [$]
$\mathbf{C_d}$	: Drag coefficient
$\mathbf{C_D}$	: Drag coefficient for the parked rotor
$\mathbf{C_{ElectricalSystem}}$	: Cost of electrical interface and connections [$]
$\mathbf{C_{EngineeringPermits}}$	: Cost of engineering permits [$]
$\mathbf{C_F}$	: Capacity factor
$\mathbf{C_{Foundation}}$	: Cost of foundation and support structure [$]
$\mathbf{C_{Generator}}$	: Generator cost [$]
$\mathbf{C_I}$	: Total cost (initial investment) [$]
$\mathbf{C_{I,ref}}$	: Reference C_I value [$]
$\mathbf{C_l}$	: Lift coefficient
$\mathbf{C_{l,design}}$	: Design lift coefficient
$\mathbf{C_{matching}}$	: Weight matching factors
$\mathbf{C_n}$	: Normal force coefficient
COE	: Cost of energy [$/kW/h]
$\mathbf{COE_{ref}}$	: Reference COE value [$/kW/h]
$\mathbf{C_{OM}}$	: Operation and maintenance cost [$]
$\mathbf{C_P}$	: Power coefficient
$\mathbf{C_{P,max}}$	: Maximum power coefficient
$\mathbf{C_{RoadsCivilWork}}$	: Cost of roads and civil work [$]
$\mathbf{C_{service}}$	: Weight service design drives
$\mathbf{C_t}$	: Tangential force coefficient
$\mathbf{C_T}$	: Thrust coefficient
$\mathbf{C_{Transportation}}$	: Cost of transportation [$]
D	: Drag force [N]
e	: Escalation rate
$\mathbf{e_a}$	: Apparent escalation rate
$\mathbf{E_{IR}}$	: Generated energy between cut-in speed and rated speed [kWh]
$\mathbf{E_{RO}}$	: Generated energy between rated speed and cut-out speed [kWh]
$\mathbf{E_T}$	: Total energy generated [kWh]
$\mathbf{E_{T,ref}}$	: Reference $E_{T,ref}$ value [kWh]

$\mathbf{F}$: Loss factor
$\mathbf{f}$: Probability function
$\mathbf{F_A}$: Blade airfoil weight factor
$\mathbf{F_{CL}}$: Cyclic load factor
$\mathbf{F_{hub}}$: Hub loss factor
$\mathbf{F_N}$: Normal force [N]
$\mathbf{F_{objective}}$: Objective function
$\mathbf{F_{RC}}$: Rotor control factor
$\mathbf{F_{RF}}$: Root flange factor
$\mathbf{F_T}$: Tangential force [N]
$\mathbf{F_{tip}}$: Tip loss factor
$\mathbf{H_{hub,initial}}$: Initial guess value for hub height [m]
$\mathbf{H_{hub,max}}$: Maximum value for hub height [m]
$\mathbf{H_{hub,min}}$: Minimum value for hub height [m]
$\mathbf{H_{optimum}}$: Optimum value for hub height [m]
$\mathbf{i}$: Nominal interest rate
$\mathbf{I}$: Rate of interest
$\mathbf{k}$: Weibull shape factor [m/s]
$\mathbf{k_{CI}}$: C_I priority for cost function
$\mathbf{k_{COE}}$: COE priority for cost function
$\mathbf{K_{Cost}}$: Specific costs [$/kg or $/kW]
$\mathbf{K_{ElectricalSystem}}$: Electrical interface and connections cost factor [$/kW]
$\mathbf{K_{EngineeringPermits}}$: Engineering permits cost factor [$/kW]
$\mathbf{k_{ET}}$: $E_{T,ref}$ priority for cost function
$\mathbf{k_{nPayBack}}$: $n_{PayBack}$ priority for cost function
$\mathbf{K_{RoadsCivilWork}}$: Roads and civil work cost factor [$/kW]
$\mathbf{K_{Transportation}}$: Transportation cost factor [$/kW]
$\mathbf{k_{velocity}}$: Design velocity factor (ratio of design speed to mean speed)
$\mathbf{L}$: Lift force [N]
$\mathbf{L/D}$: Lift-to-drag ratio
$\mathbf{m}$: Ratio of operation and maintenance to initial investment
$\mathbf{n}$: Power curve exponential [m/s]
$\mathbf{n}$: Present value period [years]
$\mathbf{n_{PayBack}}$: Pay back period [years]
$\mathbf{n_{PayBack,ref}}$: Reference $n_{PayBack}$ value [years]
$\mathbf{NPV}$: Net present value
$\mathbf{P}$: Power [W]
$\mathbf{P_{available}}$: Available power [W]
$\mathbf{P_{Curve}}$: Power curve power value [kW]
$\mathbf{P_{rated}}$: Rated power [kW]
$\mathbf{PV}$: Present value
$\mathbf{Q_R}$: Rated torque [Nm]
$\mathbf{r}$: Distance between blade elements along the blade radius [m]
$\mathbf{r}$: Inflation rate
$\mathbf{R}$: Rotor radius [m]
$\mathbf{R^2}$: Adequacy factor
$\mathbf{RC_F}$: Rough capacity factor
$\mathbf{Re}$: Reynolds number
$\mathbf{r_{hub}}$: Rotor hub radius [m]
$\mathbf{R_{initial}}$: Initial guess value for rotor radius [m]

$\mathbf{R_{max}}$	: Maximum value for rotor radius [m]
$\mathbf{R_{min}}$	: Minimum value for rotor radius [m]
$\mathbf{R_{optimum}}$	: Optimum value for rotor radius [m]
$\mathbf{RPM_{rotor}}$	: Rotor angular speed [r/min]
$\mathbf{SS_E}$	: Error or residual sum squares
$\mathbf{S_{yy}}$	: Total sum squares
t	: Blade root thickness [m]
T	: period of time [h]
T	: Period of time [hours]
$\mathbf{T_{ex}}$	: Extreme thrust [N]
V	: Speed [m/s]
$\mathbf{V_{cut-in}}$	: Cut-in speed [m/s]
$\mathbf{V_{cut-out}}$	: Cut-out speed [m/s]
$\mathbf{V_d}$	: Design wind speed [m/s]
$\mathbf{V_{ex}}$	: Extreme wind speed [m/s]
$\mathbf{V_{hub}}$	: Velocity at hub height [m/s]
$\mathbf{V_{mean}}$	: Mean wind speed [m/s]
$\mathbf{V_R}$	: Rated speed [m/s]
$\mathbf{V_{reference}}$	: Velocity at reference height [m/s]
$\mathbf{V_{rel}}$	: Relative velocity on the rotor [m/s]
$\mathbf{V_{tip}}$	: Tip speed [m/s]
$\mathbf{V_{tip}}$	: Tip speed on the rotor [m/s]
$\mathbf{V_{wind}}$	: Wind speed upcoming to the rotor [m/s]
$\mathbf{W_{BA}}$	: Blade airfoil weight [kg]
$\mathbf{W_{BF}}$	: Blade root flange weight [kg]
$\mathbf{W_{Blades}}$	: Weight of all blades [kg]
$\mathbf{W_{Brake}}$	: Mechanical brake weight [kg]
$\mathbf{W_{BS}}$	: Blade spar weight [kg]
$\mathbf{W_{component}}$	: Component weight [kg]
$\mathbf{W_{Component}}$	: Component weights [kg]
$\mathbf{W_{Gear}}$	: Weight of gearbox [kg]
$\mathbf{W_{Gen}}$	: Weight of generator [kg]
$\mathbf{W_{Hub}}$	: Hub weight [kg]
$\mathbf{W_{HydraulicCooling}}$	: Weight of hydraulic and cooling system [kg]
$\mathbf{W_{MainBearings}}$	: Weight of main bearings [kg]
$\mathbf{W_{Mainframe}}$	: Weight of mainframe [kg]
$\mathbf{W_{NacelCover}}$	: Weight of nacelle cover [kg]
$\mathbf{W_{Nosecone}}$	: Weight of nosecone [kg]
$\mathbf{W_{Pitch}}$	: Weight of pitch control system [kg]
$\mathbf{W_{PitchBearings}}$	: Weight of pitch bearings [kg]
$\mathbf{W_{PlatformRailing}}$	: Weight of platform and railings [kg]
$\mathbf{W_{Rotor}}$	: Weight of rotor [kg]
$\mathbf{W_{Shaft}}$	: Weight of low speed shaft [kg]
$\mathbf{W_{Tower}}$	: Weight of tower [kg]
$\mathbf{W_{Towerhead}}$	: Towerhead weight [kg]
$\mathbf{W_{Yaw}}$	: Weight of yaw system [kg]
$\mathbf{x_1, x_2..., x_k}$	: Coded variables
$\mathbf{X_I}$	: Cut-in speed factor
$\mathbf{X_O}$	: Cut-out speed factor
$\mathbf{X_R}$	: Rated speed factor

y	: Response surface function
$\mathbf{z_{hub}}$	: Hub height [m]
$\mathbf{z_{reference}}$	: Reference height [m]
α	: Power law exponent
α	: Angle of attack [degrees]
α_{design}	: Design angle of attack [degrees]
$\beta_1, \beta_2 ..., \beta_k$	: RSM polynomial coefficients
Γ	: Gamma function
ε	: Model error
η	: Generator and transmission efficiency
θ	: Twist angle [degrees]
λ	: Tip speed ratio
λ_r	: Local tip speed ratio
μ_{air}	: Air viscosity [Pa.s]
$\xi_1, \xi_2 ..., \xi_k$	: Independent (natural) variables
ρ	: Density [kg/m^3]
ρ_{air}	: Air density [kg/m^3]
ρ_M	: Blade root density [kg/m^3]
σ	: Rotor solidity
σ_M	: Blade root strength [Pa]
σ_r	: Local rotor solidity
ρ_{SP}	: Blade spar density [kg/m^3]
σ_{SP}	: Blade spar strength [Pa]
ϕ	: Effective relative angle [degrees]
Ω	: Rotational speed of the rotor [rad/s]
ω	: Tangential angular speed of the flow [rad/s]

WIND ENERGY TECHNOLOGIES: PRELIMINARY DESIGN CODE DEVELOPMENT

SUMMARY

A preliminary design code is developed for the wind energy conversion systems. This code is built in MATLAB language with graphical user interface (GUI) involving optimization and analysis processes. Current design and analysis codes are summarized and a specific preliminary design and optimization program 'WIND' is built. Program achieves site specific design with actual observed wind data and optimization involving; wind resource analysis, preliminary design of horizontal axis wind turbine (HAWT), aerodynamics design and analysis, wind energy calculations and economic analysis. For the wind resource analysis Weibull approach is used. In the aerodynamics section blade element momentum theory is used. In the weight and cost analysis, blade weight is calculated with Sunderland weight and cost model. The other components are calculated with statistical and experimental relations. Energy calculations are done with Weibull approach. In the economic analysis present worth approach is used. For the optimization algorithm response surface method (RSM) is used. In the program objective function is consisting of variables cost of energy (COE), pay back period, Wind Turbine (WT) sales price and Annual Energy Production. User defined wind data, generator rated power and other design parameters; site information, design options, aerodynamic, economic, power curve and optimization sections generates necessary inputs. As a result WT rotor radius and hub height is optimized. Results will be a guide for feasibility of wind energy projects.

RÜZGÂR ENERJİSİ TEKNOLOJİLERİ: ÖN TASARIM KODU GELİŞTİRMESİ

ÖZET

Bu çalışmada rüzgâr enerjisi çevrimi sistemlerinin ön tasarımı için bir kod geliştirilmiştir. MATLAB dili ile bu kod yazılmış, görsel kullanıcı arayüz kullanan eniyileme ve çözümlemelerden oluşan bir program oluşturulmuştur. Mevcut tasarım ve çözümleme programları özetlenmiş ve özgün bir ön tasarım ve eniyileme programı 'WIND' geliştirilmiştir. Program seçilen yöreye uygun tasarımı ve eniyilemeyi; yöreden alınan gerçek rüzgâr verileri kullanılarak rüzgâr kaynağı çözümlemesi, yatay eksenli rüzgâr türbini (YERT) kavramsal tasarımı ile ağırlık ve maliyet çözümlemeleri, aerodinamik tasarım ve çözümleme, rüzgâr enerji hesaplamaları ile ekonomik çözümlemeler gerçekleştirmektedir. Rüzgâr Kaynağı çözümlemesi bölümünde Weibull yaklaşımı, aerodinamik bölümünde pala elemanı momentum kuramı kullanılmıştır. Ağırlık ve maliyet kestirimleri bölümünde Sunderland ağırlık ve maliyet modeli ile pala ağırlığı hesaplanmakta diğer bileşen ağırlıkları da istatistiksel ve deneysel bağıntılar yardımıyla hesaplanmaktadır. Enerji hesaplamaları için Weibull yaklaşımı kullanılmıştır. Ekonomik çözümlemelerde şimdiki değer maliyet yaklaşımı kullanılmıştır. Eniyileme algoritması için RSM (Response Surface Method) yöntemi seçilmiştir. Programda eniyileme amaç fonksiyonunda birim enerji üretim maliyetleri, geri dönüşüm zamanı, rüzgâr türbini satış fiyatı ve yıllık enerji üretimi gibi değişkenler kullanılmıştır. Kullanıcının belirlediği rüzgâr verisi, üreteç anma rüzgâr gücü ve diğer tasarım değişkenleri; yöre bilgisi, tasarım seçenekleri, aerodinamik, ekonomi, güç eğrisi ve eniyileme gibi bölümlerde girdiler atanarak, rüzgâr türbini rotor yarıçapı ve rüzgâr türbini göbek yüksekliği değişkenleri eniyilenmiştir. Sonuçlar rüzgâr enerjisi projelerinin uygulanabilirliği açısından bir rehber teşkil etmektedir.

1 INTRODUCTION

Wind resource is unstable as its nature and its theoretical potential is limited by many circumstances. Wind energy conversion depends on the factors that are explained below;

- Technical: WT design, component design, current previous works, situation of the electrical grid, hybrid systems, availability of the wind turbines, etc.
- Geographic and meteorological: topography, terrain, vegetation, atmospheric boundary layer, the wind regime characteristic, etc.
- Economics; laws, politics, permissions, certification and standards, manufacturing, logistics, machine costs, processes, benefits, payback time, etc.
- Social: aesthetics, public acceptance, ecology, land use, etc.

1.1 History of Modern Multi MegaWatt Sized Wind Turbine Design

First electricity generator wind turbine was built by Charles F. Brush, in 1888. In 1930s modern Danish type wind turbines are developed from the pioneers [1]. After 1970s the wind turbine technology followed rapid growth and still continues its growth trend with a rate of 20-40% [2]. Historical growth of turbine sized via power ratings are shown in Figure 1.1.

In recent years, many wind turbine manufacturers progressed their technologies with minimizing COE [cost/kWh] and the wind turbine specific costs [cost/kW] reached level of 1000$/kW [5].

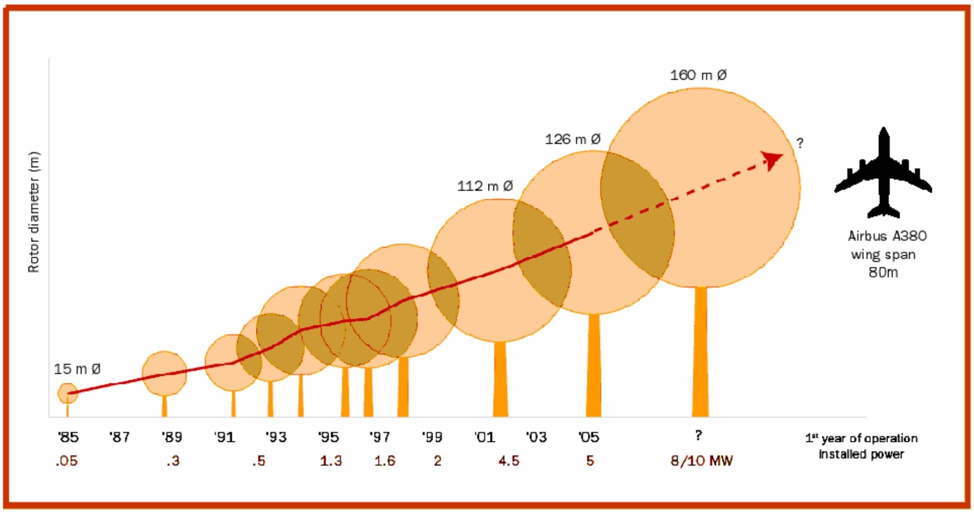
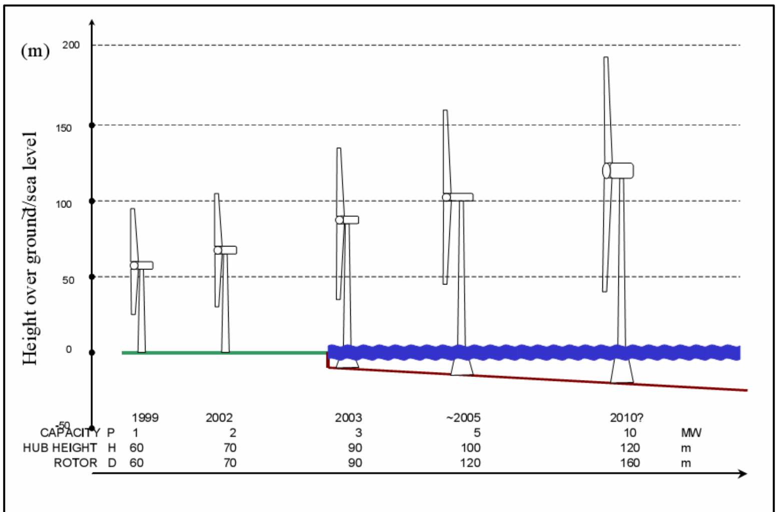


Figure 1.1: Growth of Wind Turbine Technology [3]



The development in unit sizes of wind power plants during period 1999-2010
source: Climtech Programme, VTT

Figure 1.2: Growth of Offshore Turbine technology [4]

1.2 Wind Energy State-Of-The-Art Design Codes and Softwares

Wind energy and its conversion is a multidisciplinary research field. There are many codes developed for wind energy systems in different disciplines in order to minimize overall costs.

Current classification for design tools used by many manufacturers and research institutes are;

- meteorological wind climate (wind potential, wind farming, micrositing)
- state-of-the-art wind turbine design codes

Recommended by McGowan et al. [6], the design tools can be divided into these categories;

- Modeling machine (WT), component & system design
- Data collection and analysis
- Operation and control

Molenaar explains and compares many state-of-the-art wind turbine design codes with his own study, DAWIDUM wind turbine design code [1]. Overview of the design codes are shown in Table 1.1.

Wind Resource analysis programs are summarized in Table 1.2.

Table 1.1: State-of-the-art Wind Turbine Design Codes [1]

Name	Description	Developer; Company / University / Institude
Adams/WT	Automatic Dynamic Analysis of Mechanical Systems - Wind Turbine	Mechanical Dynamics, Inc. (MDI) / National Renewable Energy Laboratory (NREL)
BLADED	Performance and Loading Calculations accepted GL Certification Program	Garrad Hassan & Partners Ltd
DUWECS	Delft University Wind Energy Converter Simulation Program	Institute for Wind Energy / Delft University of Technology
FAST	Fatigue, Aerodynamics, Structures and Turbulence	Oregon State University / Wind Technology Branch of NREL
FLEX5	Dynamic Simulation of Wind Turbines	Technical University of Denmark
FLEXLAST	Flexible Load Analyzing Simulation Tool	Stork Product Engineering
FOCUS	Fatigue Optimization Code Using Simulations	Stork Product Engineering / Institute for Energy / Delft University of Technology
GAROS	General Analysis of Rotating Structures	Energiesysteme GmbH
GAST	General Aerodynamic and Structural Prediction Tool for Wind Turbines	Technical University of Athens
HAWC	Horizontal Axis Wind Turbine Code	Wind Energy Department of RISO National Laboratory
PHATAS-IV	Program for Horizontal Axis Wind Turbine Analysis and Simulation	Dutch Energy Research Foundation (ECN)
TWISTER	Analyzer	FKA
VIDYN	Simulation Program for Static and Dynamic Analysis of HAWT	Teknikgruppen AB
YawDyn	Yaw Dynamics Computer Program	University of Utah / NREL

Table 1.2: Wind Resource Design, Analysis and Modeling Programs

Name	Description	Company / Institude	Web Page
GH WindFarmer	Wind Farm Design Software	Garrad Hassan & Partners Ltd	http://www.garradhassan.com/
meteodyn	CFD tool for the wind assessment, Structure Dynamics	ASCOMP GmbH	http://www.meteodyn.com/
WAsP	Wind Atlas Analysis and Application Program	RISO National Laboratory	http://www.wasp.dk/
WindFarm	WindFarm Wind Energy Software for Designing and Optimising Wind Farms	ReSoft Ltd	http://www.resoft.co.uk/
WindPRO	Design and Planning of Wind Farm Projects	EMD International A/S	http://www.emd.dk/
Windsim	Simulator for Optimizing the Energy Production of WT using CFD	WindSim AS	http://www.windsim.com/

1.3 Motivation

Current codes or softwares are used and certified by the main Germanische Lloyd (GL) of the Regulation for the Certification of Wind Energy Conversion Systems and by International Electrotechnical Commission (IEC) standards [5].

Although there are standards used for the whole system design, there is still need of specific codes or softwares to develop specific analysis and design studies.

Wind turbines and wind farms are designed for the chosen specific site. In special cases, the current standards and current machines are not sufficient to maintain a low cost of electricity production. There are examples of unsuccessful projects because of insufficient feasibility studies.

For a selected site, collection of data is very important for the whole system to achieve a good energy output. According to the data analysis there has to be preliminary design of the wind farm and if needed, there has to be done machine design for the specific sites. Optimization techniques such as genetic algorithms and response surface method can also be included for the optimum results. Consequently, the wind energy conversion will be more efficient having low costs.

1.4 Objective and Scope of the Study

Objective of this study is to build a preliminary design code for the optimum WTs and their projects. The code consists of optimization of design parameters with user defined constraints. Analyses and calculations take place within the current code.

In the current study a MATLAB code is developed with GUI. User defines the program configuration selection and design options as inputs for the calculations. Code is build for optimization algorithm RSM involving wind resource analysis using observed wind data, HAWT aerodynamic analysis, preliminary design of HAWT, cost and weight analysis, energy calculations and economic analysis.

2 WIND ENERGY CONVERSION

2.1 Wind Resource Characteristics

It is important that to determine the wind characteristics of wind resource in site where the wind energy system will be adapted. In order to achieve a feasible project, many observations, analyses and calculations must be done. These works will show the designers, manufacturers and operators that wind energy generation of the system will be different than its expected theoretical potential.

For the wind resource analysis the wind characteristics of the site must be determined. The wind regime of a site is originated from the Sun that produces the global winds, local winds and Earth's Coriolis force effect. The wind characteristics of a site are affected by the atmospheric boundary layer properties [5];

- Lapse rate (temperature, density, pressure variations with height)
- Turbulence
- Vertical wind shear (variation of wind speed with elevation)
- Wind speed variation with height for steady winds
    - Logarithmic profile (log law)
    - Power law profile
- Effect of terrain
- Surface roughness
    - Flat terrain
    - Non-flat terrain or complex terrain

Since the wind has unstable (stochastic) in nature, the variations in time, location and directions effect the wind characteristics. Long term (ten years or annual) winds and short term winds (turbulence effects, gusts) are the important effects in design procedure.

In order to predict wind regime, wind data analysis of the selected site must be done. Some methods for predicting wind regime are;

- Best way for wind data analysis is direct use of data averaged over a short time interval
- Method of bins
- Power distribution curves
- Statistical analysis using summary measures
    - Rayleigh distribution
    - Weibull distribution

2.2 HAWT Aerodynamic Design

Aerodynamic studies have initiated with the Rankine-Froude actuator-disk model. This model is extended by Glauert as Blade Element Momentum Theory (BEMT) which is still used and developed by the modern wind turbine rotor aerodynamic design codes. This theory has become a very powerful way for the aerodynamic design of the wind turbine rotors. This model agrees with the experimental measurements and the actual wind turbine performance data.

2.2.1 Power in the Wind

Theoretically power from the wind is extracted from the air passing through the rotor for HAWT. Power is proportional to the cube of wind speed, density of the air and rotor swept area:

$$P \sim \frac{1}{2}\rho A V^3 \tag{2.1}$$

Rankine-Froude actuator disk model defines a very important design parameter defined as power coefficient. This is a dimensionless parameter that determines whole wind turbine performance:

$$C_p = \frac{2P_{available}}{\rho A V^3} = \frac{2P_{available}}{\rho \pi R^2 V^3} \tag{2.2}$$

Its theoretical maximum is defined as the Lanchester-Betz limit, commonly called as Betz Limit and its value is:

$$C_{p,\max} = \frac{16}{27} \cong 0.59 \tag{2.3}$$

Another important design parameter is tip speed ratio defined as the ratio between the rotor tip tangential velocity and the free stream velocity. It is formulated as:

$$\lambda = \frac{V_{tip}}{V} = \frac{\Omega R}{V} \tag{2.4}$$

2.2.2 BEMT Theory

In BEMT theory the momentum theory and the blade element theories are combined as an extension of Rankine-Froude disk theory.

For more precise results BEMT model is developed with the (semi) empirical relations. As told by Molenaar most common corrections applied to the BEMT are [1]:

- Tip Effects (Prandtl Tip Loss Correction)
- Root effects (Prandtl Hub Loss Correction)
- Turbulent Wake State (Glauert)
- Dynamic Inflow
- Dynamic Stall
- 3-D corrections

Airfoil characteristics have to be determined for the calculations. In airfoil selection Reynolds number is an important factor that influencing the aerodynamic properties of the airfoils. Reynolds number of air passing over an airfoil having chord length ‘c’ is defined as:

$$Re = \frac{\rho_{air} V_{rel} c}{\mu_{air}} \tag{2.5}$$

V_{rel} is the relative velocity on the blades. For a chosen blade geometry (chord distribution along the blade), using the correct airfoils at calculated Reynolds numbers is very important in order to predict airfoil behavior successfully.

The polar information of the airfoils has to be put in the algorithms in order to have better results for prediction of the blade’s performance. Since there is a lack of airfoil information, e.g. for high angle of attack values, the drag and the lift information have not been known, specific methods such as extrapolating with using the experimental airfoil data has been developed. Common aerodynamics codes use these methods.

AeroDyn program uses S809 airfoil at a Reynolds number of 750 million. In the range of angle of attack from -20° to 40° the lift and drag data of this airfoil is generated from wind tunnel test results and the remaining values up to angle attack values of ±180° are calculated with FoilCheck program developed by National Renewable Energy Laboratory (NREL). The sample data is shown in figures.

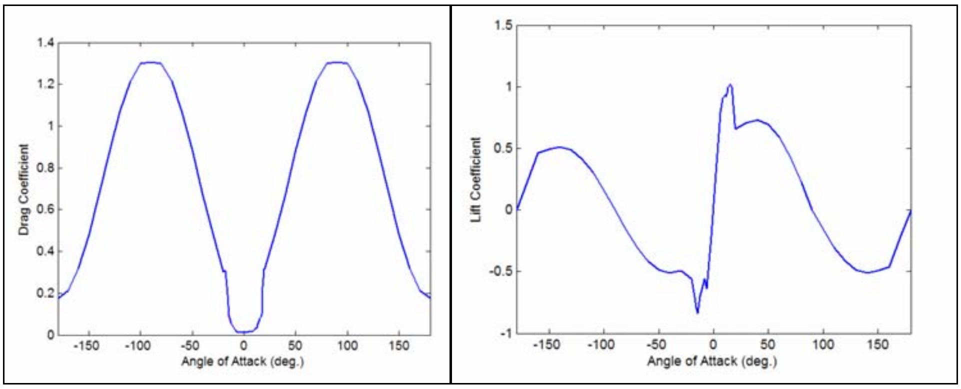


Figure 2.1: Drag and Lift coefficient via angle of attack of s809 airfoil [7]

2.3 Preliminary Design of Horizontal Axis Wind Turbines

Wind turbine and its system design is a multidisciplinary iteration process. In recent studies there are many methodologies are developed for the WT and wind farm design. Some of the studies are detailed in the next sections and adapted to the study.

By Diveux et al. [8], an optimization using genetic algorithms is done for the HAWT system design. Constraints and parameters are determined according to the geographic, wind turbine configuration and other design options specified by wind turbine technology. The objective function of that study is minimization of cost of kWh. Cost and weight models are calculated in different modules for different components of the WT and the different parts of the overall system.

According to McGowan [6] the modeling codes are divided into two parts; turbine system design and machine design. Inputs for the turbine system design part are geographic, meteorological, siting and economic information. They are built in one body resulting as the wind farm layout, energy capture calculations and economics design. In turbine system part the long term wind data is used for predicting behavior and benefits of the system during its lifetime. Inputs for the machine design part wind parameters and also other design options determined in the system design section are used for calculations. In the code, aerodynamic design, component design and overall turbine (machine) design are carried out. Short term wind data is used for predicting the fatigue life of the machine in the machines life analysis.

Addition to these studies, detailed by Harrison et al. [9] the Sunderland cost model of wind turbines focuses on the methodology that calculates the machine component weights and costs. According to the selected design drives (loading conditions such as nominal conditions, extreme conditions) and coefficients by calculations done with statistical methods regressed from actual machine data weights of the components. General formulation for calculations is showed below equation:

$$W_{component} = C_{matching}\,(\text{factors}) \times C_{service}\,(\text{design drivers}) \qquad (2.6)$$

Table 2.1: Weight and Cost Breakdown [10]

Components \ Wind turbine	Medium-sized turbine 750 kW (stall-controlled) Proportion %	Large turbine 1500 kW (variable-speed controlled) Proportion %
Rotor blades	34.0 %	21.0 %
Rotor hub	2.0 %	2.1 %
Blade bearings	—	3.1 %
Hydraulic blade-pitch system	0.8 %	4.0 %
Rotor shaft	2.7 %	2.6 %
Rotor bearings with housings	1.0 %	1.7 %
Gearbox	12.5 %	13.6 %
Load-bearing nacelle structure	8.7 %	4.7 %
Yaw drive (includes. azimuth bearing)	2.4 %	3.4 %
Nacelle fairing	2.0 %	1.6 %
Miscellaneous (rotor brake, generator shaft, clutches, heat exchanger etc.)	5.0 %	3.2 %
Generator (and inverter in the large turbine)	7.5 %	10.9 %
Control system and monitoring equipment	5.0 %	7.4 %
Tower	16.4 %	20.7 %
Component costs	100.0 %	100.0 %
Assembly (in the factory)	5.0 %	5.0 %

Component costs are derived from the weight breakdown of components. Methodology is simple, for each component the specific costs (cost per unit weight) are given by Harrison et al. [9]. For chosen materials defined in design options the component costs can be easily calculated. Finally the cost of the wind turbine itself is determined from these components. Typical wind turbine cost breakdown is shown in table 2.1.

2.4 Wind Energy Calculations and Economics

2.4.1 Performance of the WT Systems

Important performance criterion for the wind energy conversion system is energy output calculations. Energy production of a wind turbine is predicted by monitoring its energy output over long time periods. At the design stage of wind energy system, for energy calculations conventional approaches are followed such as Weibull or Rayleigh. The methodology is explained in many studies. WERA (Wind Energy Resource Analysis) program uses the similar methodology used by the literature that is explained by Mathew [11]. In the calculations prediction of a power curve has an important direct effect on the performance.

For energy production there is an important performance factor is introduced. Capacity factor is defined as the ratio of the actual energy production to energy produced if the machine would have operated at its rated power in a lifetime period. The wind energy projects are evaluated for their capacity factors. The formulation is shown by Equation (2.12).

$$C_F = \frac{Energy\ Generated\ by\ the\ WT}{TP_{rated}} \tag{2.7}$$

The typical values for the C_F are changing between 0.25 and 0.40 [6]. Below 0.25 the system is said to be unfeasible. Values higher that 0.40 represents efficient system. In the formula E_T is the total energy generated by the wind turbine. T is period of time that is determined by the designer. Generally time period is chosen as annual and it is in hours in a year.

If there is not enough information about the site and the project the rough capacity factor is introduced [11]. If the representative power curve is not known the rough capacity factor is calculated as rough capacity factor:

$$RC_F = \frac{P_{\text{at average wind speed}}}{P_{rated}} \tag{2.8}$$

2.4.2 System Economics

The overall system costs involve many concepts. The future of a wind energy project is highly dependent to the costs of many issues. In general WT system economics involves the calculation of the COE.

As detailed by Mathew [11] WT system costs involves manufacture costs of the machine (turbine itself), other investment costs and operation and maintenance costs. For determining the project costs fixed and variable costs are introduced.

Fixed costs are consisting of Initial investment costs including the turbine machine costs. The initial investment components and their percentages are shown in figure 2.1.

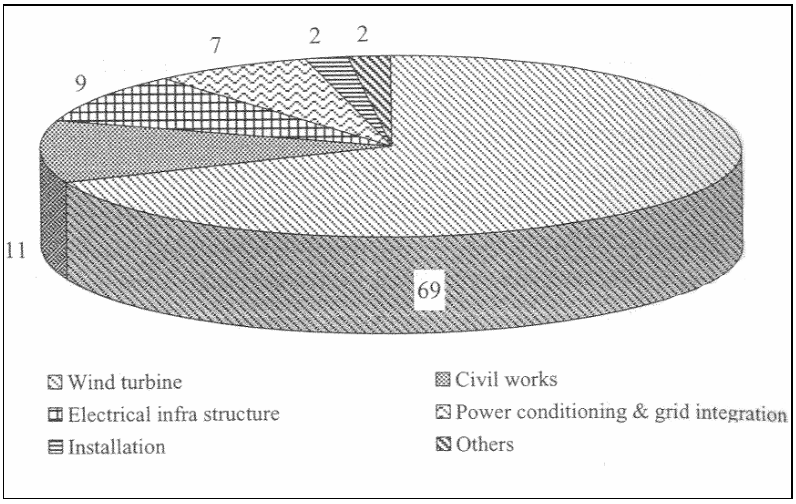


Figure 2.1: Fixed Costs Percentages [11]

Variable costs involve operation and maintenance costs of the system. They contribute to the 1.5-2 % of the overall system cost [11].

2.4.3 Present Worth Approach

In the present worth approach the annual costs are recalculated over wind energy project's lifetime. The formulation for present value approach is below;

$$PV(AP)_{1-n} = AP\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \qquad (2.9)$$

In the formulation AP is the annual payment, n is the lifetime and I is the real rate of interest. Real rate of interest (discount) is represented in terms of nominal interest rate (i) and inflation (r):

$$I = \frac{1+i}{1+r} - 1 \tag{2.10}$$

Also in terms of nominal interest rate (i), escalation (e), apparent escalation (e_a) and inflation (r) shown below:

$$I = \frac{1+i}{1+e_a} - 1 \tag{2.11}$$

$$e_a = (1+e)(1+r) - 1 \tag{2.12}$$

General present value approach becomes:

$$PV(AP)_{1-n} = AP\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right] \tag{2.13}$$

3 METHODOLOGY

Program WIND is a preliminary design program that involves analyses and optimization methods in order to guide designers to build an efficient and optimum wind energy conversion system. WIND's main advantage apart from different design codes is to achieve site specific WT design while predicting the wind project performance and costs.

Program enables user to do configuration selection and conceptual design. Additionally, user can evaluate observed wind data that the program uses as an input for the wind data analysis.

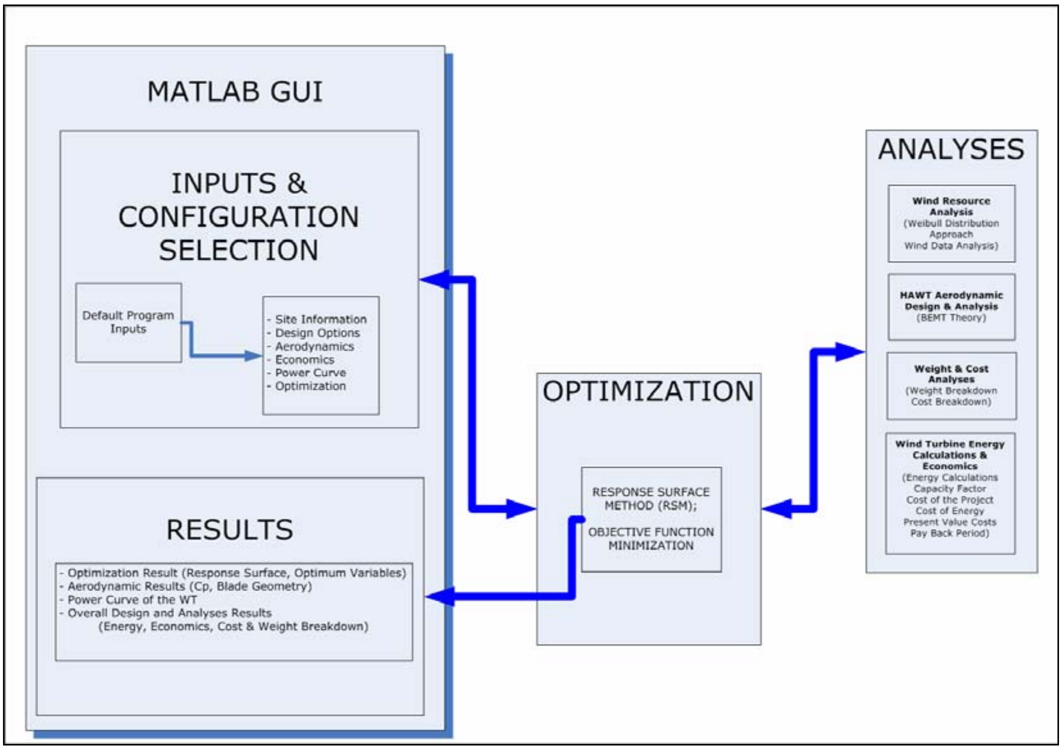


Figure 3.1: Flow Chart of WIND

In the GUI pages, user determines the inputs by selecting, entering values and selecting wind data text files. Program determines an initial design point and builds constraints for the chosen design variables.

In the optimization process, program runs the needed modules in order to generate design of experiments. Program uses RSM algorithm for finding optimum points for the objective function. For selected Design of Experiments (DOE), program runs the modules respectively, wind data analysis, aerodynamic analysis and design, weight and cost analyses and finally economics and energy analyses. It generates response surface and checks the surface is valid for the design variables. Objective function is consisting of different multidisciplinary elements. Their priority selection option gives user to select which component is more important for program to optimize.

3.1 Initial Design and Configuration Selection

Current study focuses on the conventional three bladed HAWT design. Rotor axis orientation of the wind turbine is selected as horizontal-axis. Compared to the vertical-axis wind turbines, horizontal-axis wind turbines are more efficient and they have low costs [5]. The comparison of power coefficients via tip speed ratios of different WT types are shown in below figure.

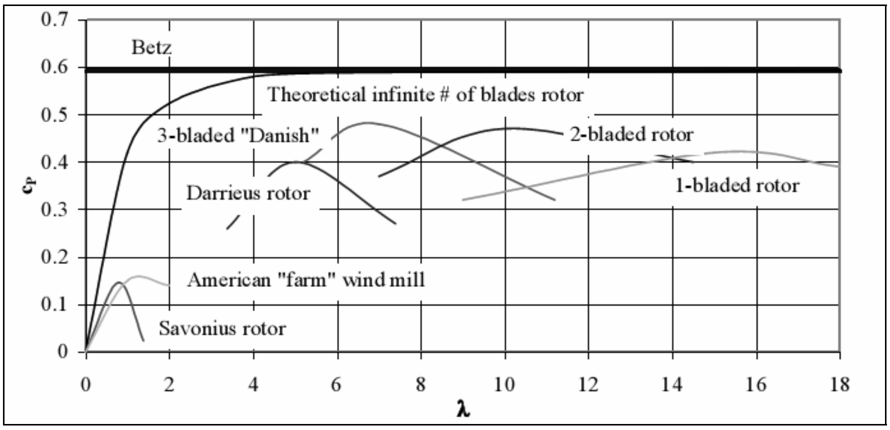


Figure 3.2: Comparison of Power Coefficients for Different Designs [6]

In the Figure 3.2 it is obvious that 3-bladed "Danish" type wind turbines have greater power coefficients. 3-bladed wind turbines have simple hub designs compared to the one or two-bladed wind turbines. Generally the blades are connected to the hub rigidly [9]. More number of blades are more efficient in theory, however when the system economy is considered, 3-bladed type design is the optimal selection.

Rotor positions relative to the wind are shown in Figure 3.3. In the current study, the position of the rotor will be upwind type. The advantage of this positioning is avoiding the tower wake effects.

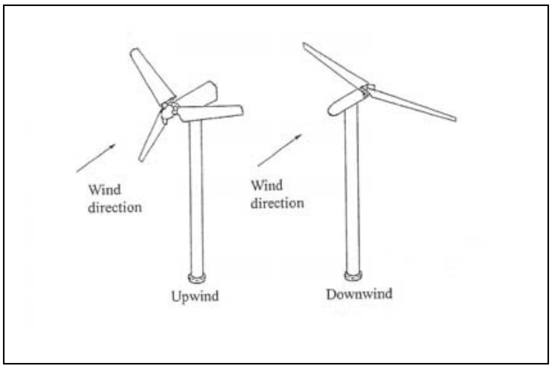


Figure 3.3: Upwind and Downwind Configurations [5]

The control of the power can be classified in three groups; pitch, stall and yaw control. The control mechanisms can be both active and passive. In the program user can select control mechanism as either pitch or stall.

Quality of power output is very important for the electricity generation of the wind turbine generators. The rotational speed type determines the performance of the output of WT. Currents wind turbines can have constant, variable or dual constant speed configurations. In the program constant speed configuration is selected for simplification in power curve calculation.

Generator and drive type selection is done according to the NREL studies summarized in [12]. The configurations are:

- Three-stage planetary/helical drive with high-speed generator
- Single-stage drive with medium-speed, permanent-magnet (PM) generator
- Multi-path drive with multiple PM generators
- Direct drive

Power losses (efficiency) due to power electronics and mechanical transmission are included in the program with a default value of 0.90.

For the tower the topology is selected as tubular type. This is a conventional design consisting of conical modules that are easy to construct. According to the natural frequency, this type tower is in the stiff tower class.

Material for WT blades, generally composites are used. Program has the options of different composite materials listed below:

- Glass-polyester
- Glass-epoxy

- Carbon-epoxy
- Wood-epoxy

In the program aerodynamic analysis uses only one airfoil configuration for the present. Current environmental information such as air density, viscosity and atmospheric boundary layer power law exponent are selected with default values defined in IEC standards.

In the economic analysis updated present rate of interest values are evaluated. Additionally parameters such as turbine lifetime are selected according to the IEC standards.

3.2 Wind Resource Analysis

3.2.1 Weibull Approach Wind Speed Distribution

In the current study the Weibull distribution approach is used for the energy calculations. Many wind resource analysis computer code use statistical methods. In conventional wind turbine and system design, Weibull Distribution method is widely used. Weibull method is accepted and defined by IEC Standards and by many certificate programs. Weibull wind distribution is a mathematical model for determining the wind characteristics. Typical Weibull Distribution is shown in Figure 3.4:

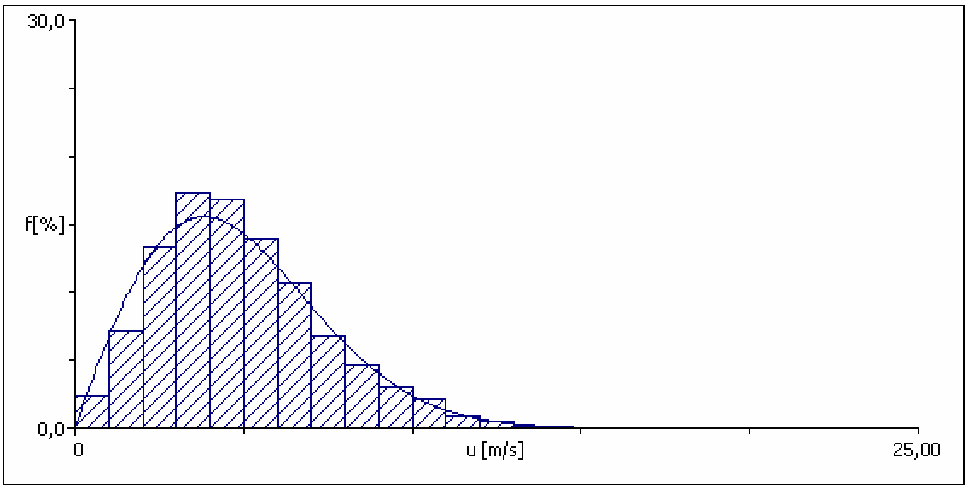


Figure 3.4: Typical Weibull Distribution [13]

The probability density function is used to characterize the wind speed variations;

$$f(V)=\frac{k}{c}\left(\frac{V}{c}\right)^{k-1}e^{-(V/c)^k} \tag{3.1}$$

According to this function, mean velocities expressed as;

$$V_m=\int_0^{\infty} V\, f(V)\, dV \tag{3.2}$$

Equivalently:

$$V_m=c\Gamma\left(1+\frac{1}{k}\right) \tag{3.3}$$

Γ is the gamma function given as;

$$\Gamma n=\int_0^{\infty} e^{-x}x^{n-1}dx \tag{3.4}$$

Here described as k (shape factor, m/s) and c (scale factor) are the Weibull parameters. Once the parameters and the mean velocities are known it is easy to calculate site's energy density and energy output.

For a given site wind velocities are extrapolated from the observed height to the designed wind turbine's hub height power law will be used.

$$\frac{V_{hub}}{V_{reference}}=\left(\frac{z_{hub}}{z_{reference}}\right)^{\alpha} \tag{3.5}$$

After applying power law, the wind velocities distributions are used for calculation of Weibull parameters and Weibull average speed. The parameters are calculated by the maximum likelihood method told by Mathew [11].

Shape factor is found by the iterative formula numerically, with the following formula:

$$k = \left[\frac{\sum_{i=1}^{n} V_i^k \ln(V_i)}{\sum_{i=1}^{n} V_i^k} - \frac{\sum_{i=1}^{n} \ln(V_i)}{n} \right]^{-1} \qquad (3.6)$$

When the shape factor is known, ‘c’ scale factor is calculated by the formula shown:

$$c = \left[\frac{1}{n} \sum_{i=1}^{n} V_i^k \right]^{1/k} \text{ [m/s]} \qquad (3.7)$$

In the program wind data is read from a text file and algorithm shown below is applied for analysis:

- Read wind speeds
- Extrapolate wind speeds to hub height values using power law
- Guess initial value for shape factor, $k_{initial}$=1.0
- Iteration for optimum shape factor
- Calculate scale factor
- Calculate Weibull mean wind speed

3.3 Aerodynamics

3.4 BEMT Theory

In the current study the BEMT theory is used for rotor performance calculations. In BEMT theory these conventional assumptions are made:

- Wake rotation effect included.
- Drag effect included
- Tip Effects (Prandtl Tip Loss Correction) included
- Root effects (Prandtl Hub Loss Correction) included
- Turbulent Wake State (Glauert) included

BEMT theory determines the equivalent forces (lift and drag) over the blade sections. Each blade sections have the airfoil geometry, and all aerodynamic calculations take place in these radial stations. In this theory there are two design parameters introduced as axial induction factor (a) and tangential induction factor (a'). These induction factors can be defined with velocities in a stream tube of a WT shown in figure 3.5. Induced velocities can be represented as:

$$V_{wind\ velocity\ at\ the\ rotor\ disc} = V_{upstream\ wind\ velocity} \times (1-a) \quad (3.8)$$

$$V_{downstream\ wind\ velocity} = V_{upstream\ wind\ velocity} \times (1-2a) \quad (3.9)$$

$$a' = \frac{\omega}{2\Omega} \quad (3.10)$$

Where ω is the induced tangential angular speed of the flow and Ω is the angular speed of the rotor.

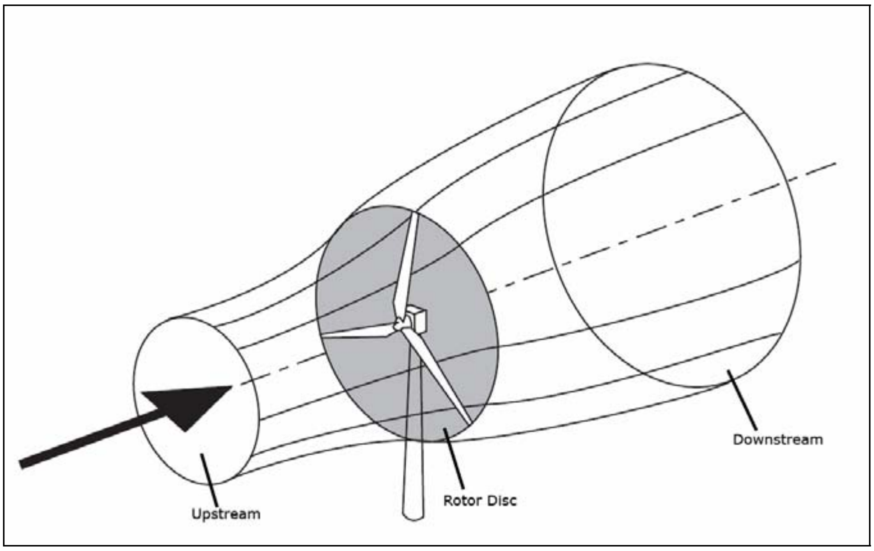


Figure 3.5: Stream tube of a WT [14]

Calculation of these parameters iteratively gives the optimum blade performance. As a result rotor performance outputs such as power, thrust, torque, blade loadings and optimum blade geometry can be calculated. In the figures 3.6 and 3.7 blade element geometry and blade loadings are shown in two orientations; downwind and upwind.

In the figure 3.8 one section of the blade is shown. It is obvious that the sum of the angle of attack and blade local twist angle is equal to the relative angle "ϕ".

$$\phi = \alpha + \theta \quad (3.11)$$

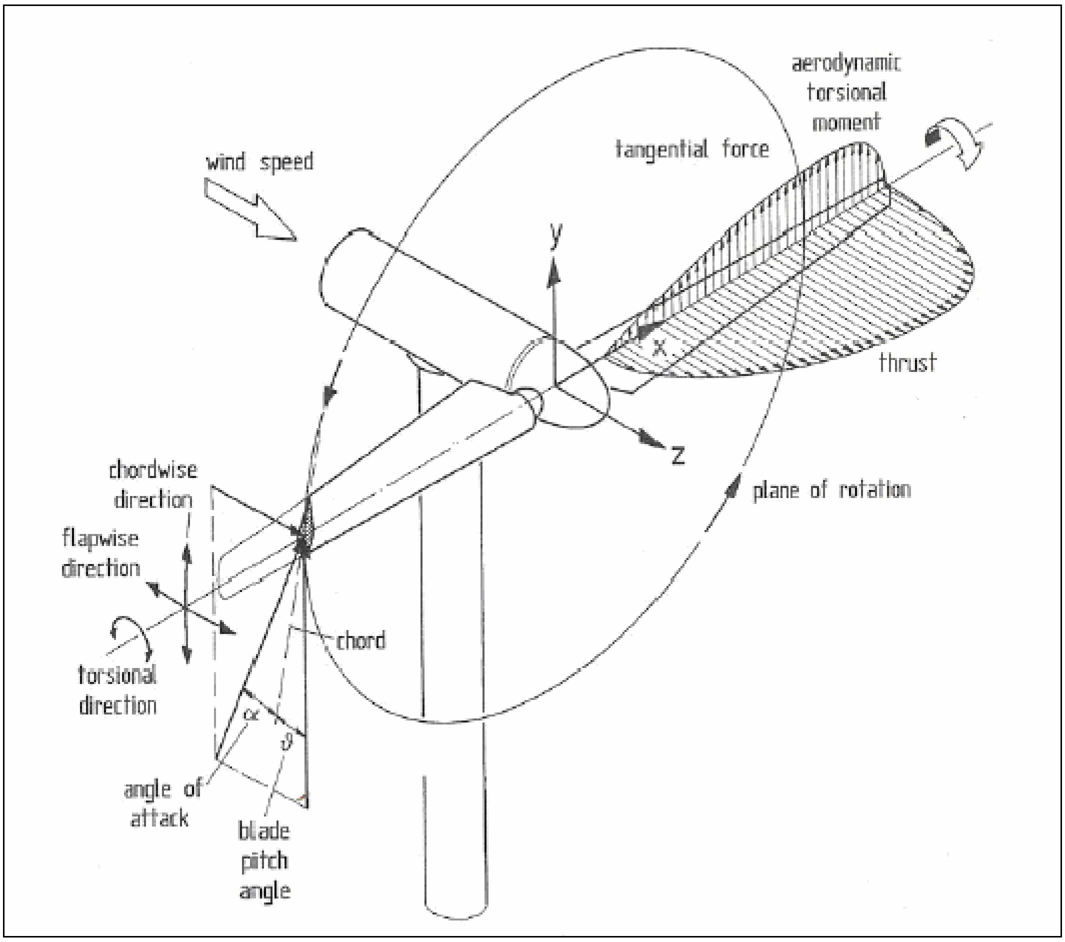


Figure 3.6: BEMT Theory; Blade Loadings Blade Sections, Downwind [15]

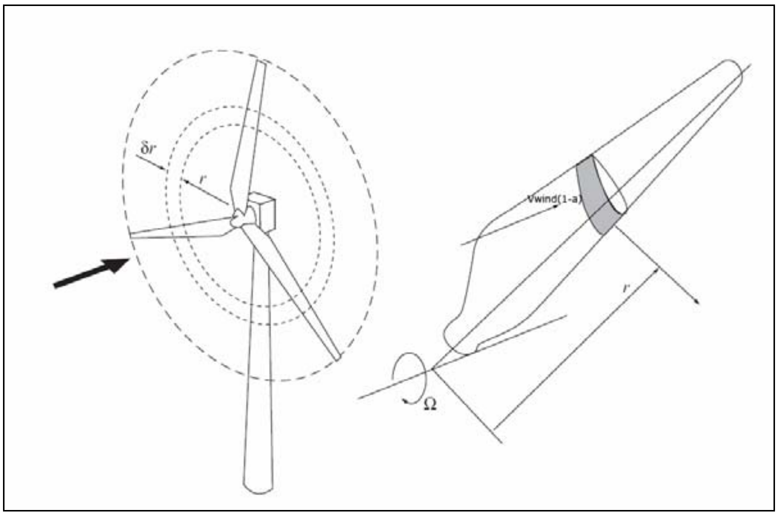


Figure 3.7: BEMT Theory; Blade Loadings Blade Sections, Upwind [14]

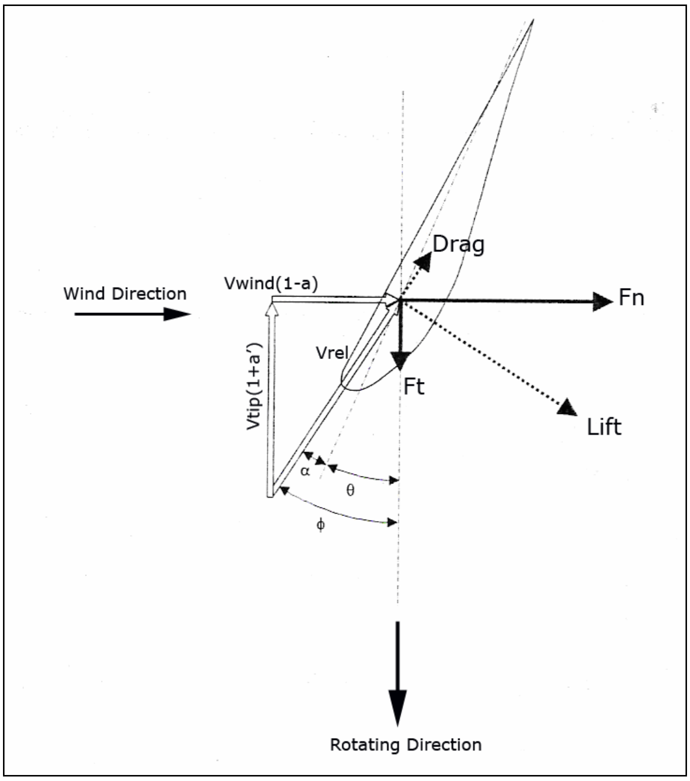


Figure 3.8: BEMT Theory; Blade Section [1]

From the geometry we get relative angle as:

$$\phi = \arctan \frac{V_{wind}(1-a)}{V_{tip}(1+a')} \tag{3.12}$$

Where the tip speed is:

$$V_{tip} = \Omega R \tag{3.13}$$

The speeds can be written in terms of local tip speed ratio as:

$$\tan \phi = \frac{1}{\lambda_r}\left(\frac{1-a}{1+a'}\right) \tag{3.14}$$

Where radial (local) tip speed ratio:

$$\lambda_r = \lambda \frac{r}{R} \tag{3.15}$$

Lift and drag forces on an airfoil is defined as:

$$Lift = L = \frac{1}{2}\rho V_{rel}^2 cC_l \tag{3.16}$$

$$Drag = D = \frac{1}{2}\rho V_{rel}^2 cC_d \tag{3.17}$$

Where relative wind speed is calculated as:

$$V_{rel} = \sqrt{V_{wind}^2 + V_{tip}^2} = \sqrt{V_{wind}^2 + (\Omega R)^2} \tag{3.18}$$

The tangential and the normal forces on the blade can be shown as:

$$F_N = L\,cos\,\phi + D\,sin\,\phi \tag{3.19}$$

$$F_T = L\,sin\,\phi - D\,cos\,\phi \tag{3.20}$$

For each blade element, the force and torque can be represented as:

$$dF_N = BF_N dr \tag{3.21}$$

$$dQ = rBF_T dr \tag{3.22}$$

From the momentum theory, for the force and torque calculation the two formulas are derived. Here "F" is the tip loss factor that will be detailed later in the next section.

$$dF_n = F\rho 4a(1-a)\pi r dr \tag{3.23}$$

$$dQ = 4Fa'(1-a)\rho V_{wind}\pi r^3 \Omega dr \tag{3.24}$$

For simplification the parameter, local solidity is introduced as:

$$\sigma_r = \frac{Bc}{2\pi r} \tag{3.25}$$

And the dimensionless force elements find:

$$C_n = C_l \cos\phi + C_d \sin\phi \tag{3.26}$$

$$C_t = C_l \sin\phi - C_d \cos\phi \quad (3.27)$$

The two equation pairs; torque and force for each blade element are made equal in order to calculate axial induction factor (a) and tangential induction factor (a').

$$a = \frac{1}{1 + \frac{4F\sin^2\phi}{\sigma_r C_n}} \quad (3.28)$$

$$a' = \frac{1}{\frac{4F\sin\phi\cos\phi}{\sigma_r C_t}} \quad (3.29)$$

When the axial induction factor becomes high (higher that 0.4), the momentum is no longer applicable. At that moment turbine operates in a state that called "turbulent wake state". Calculation of axial induction is done by Glauert's empirical relation. Axial induction is related with the thrust coefficient [5].

If $C_T > 0.96$ or equivalently $a > 0.4$, then;

$$a = \frac{1}{F}\left(0.143 + \sqrt{0.0203 - 0.6427*\left(0.889 - C_T\right)}\right) \quad (3.30)$$

Where:

$$C_T = \sigma_r \left(1-a\right)^2 \left(C_l\, cos\,\phi + C_d\, sin\,\phi\right) / \, sin^2\,\phi \quad (3.31)$$

3.4.1 Hub and Blade Tip Loss Effects

Prandtl has developed a method to predict losses at tip of blades because of vortices at the tip. The method is simple and can be applied to the momentum theory easily.

Prandtl tip loss factor is defined as:

$$F_{tip} = \frac{2}{\pi}\arccos e^{-f_{tip}} \quad (3.32)$$

Where:

$$f_{tip} = \frac{B}{2}\frac{R-r}{R\sin\phi} \tag{3.33}$$

Near to the hub similar loss factor is introduced as:

$$F_{hub} = \frac{2}{\pi}\arccos e^{-f_{hub}} \tag{3.34}$$

Where:

$$f_{hub} = \frac{B}{2}\frac{r-r_{hub}}{r_{hub}\sin\phi} \tag{3.35}$$

In the formula hub radius is selected as $r_{hub} = 0.20R$ which has a very low effect on the performance of the blade.

Effective total loss factor is calculated by multiplying these two factors.

$$F = F_{hub}F_{tip} \tag{3.36}$$

The loss factor is applied and showed in the previous blade element equations.

3.4.2 Blade Geometry

For the calculations rotor blade geometry has to be determined by the designer. Optimum blade geometry is defined with the chord and twist distributions. For the calculations these assumptions are made:

- Drag effect is neglected $C_d = 0$
- Tip losses are neglected $F = 1.0$
- Induced velocity is at its optimum value $a = 1/3$

Optimal chord distribution:

$$c = \frac{8\pi r(1-\cos\phi)}{BC_{L_{Design}}} \tag{3.37}$$

Optimal twist distribution:

$$\theta = \phi - \alpha_{Design} \tag{3.38}$$

3.4.3 Airfoil Selection

In the current study for the blade sections SG6040 airfoil at Reynolds Number of 500 000 is used. SG series are especially design for low-speed wind turbines by Selig [16]. Their Lift-to-Drag ratios are very applicable for efficient WT rotors. From the airfoil polar tables $C_l(\alpha)$ and $C_d(\alpha)$ relations are derived as in 3rd order polynomials. In blade geometry calculations design lift coefficient and design angle of attack is designated from the best Lift-to-drag ratio value at the polar tables. These values can be edited by the user in the interface of the program inputs [16].

3.4.4 Tip Speed Ratio

For calculations program determines optimum tip speed ratio with the empirical relation shown below [17]:

$$C_P = \frac{16}{27}\frac{\lambda}{\lambda + \dfrac{1.32 + \left(\dfrac{\lambda - 8}{20}\right)^2}{B^{2/3}}} - 0.57\frac{\lambda^2}{L/D\left(\lambda + \dfrac{1}{2B}\right)} \tag{3.39}$$

In the current study this relation is plotted as:

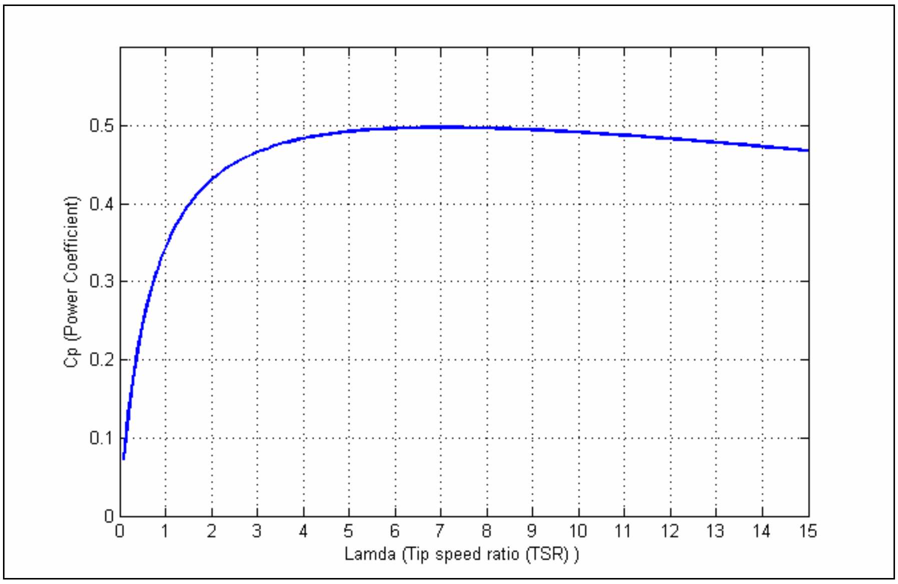


Figure 3.9: Cp – Tip Speed Ratio Relation

3.4.5 Calculation of Induction Factors

a and a' are can be calculated with the algorithm iteratively. The steps are:

- Determine design tip speed ratio from the C_P-λ relation;
- Determine the optimum blade geometry;

- Initial guesses for a and a' (a=0.0 and a'=0.0);
- Calculate ϕ angle;
- Calculate loss factors;
- Calculate angle of attack for known blade geometry (θ: twist distribution) for the best (Lift-to-Drag) L/D ratio of the airfoil characteristics;
- Calculate the C_l and C_d by using the $C_l(\alpha)$ and $C_d(\alpha)$ relations for the selected airfoil properties for calculated Reynolds number;
- Check for turbulent wake state;
- Finalize iteration with the optimum, new values of a and a'

The performance of the rotor can be calculated from the equation below [5]:

$$C_P = \frac{8}{\lambda^2}\int_{\lambda_0}^{\lambda} F\sin^2\phi\left(\cos\phi-\lambda_r\sin\phi\right)\left(\sin\phi+\lambda_r\cos\phi\right)\left[1-\left(\frac{C_d}{C_l}\right)\cot\phi\right]\lambda_r d\lambda_r \qquad (3.40)$$

Numerically this integral can be calculated with new values of a and a'.

$$C_P = \frac{8}{\lambda N}\sum_{1}^{N} F\sin^2\phi\left(\cos\phi-\lambda_r\sin\phi\right)\left(\sin\phi+\lambda_r\cos\phi\right)\left[1-\left(\frac{C_d}{C_l}\right)\cot\phi\right]\lambda_r^{\,2} \qquad (3.41)$$

3.5 Weight and Cost Analysis

In the current study weight analysis is done with according to the wind resource analysis, aerodynamic design and initial sizing of the parameters. In the weight analysis calculation of the weight breakdown of the components is done with the Sunderland weight and cost model and up-to-date statistical formulas that are derived by NREL.

3.5.1 Blade Weight Calculation

Blade weight calculations are done with the guidance of Sunderland weight and cost model. For the calculations design options and the design derives must be determined.

Rated power of a WT is calculated by the conventional formula shown below:

$$P_R = \frac{1}{2}\rho_{air} V_R{}^3 \pi R^2 \eta C_P \tag{3.42}$$

Fundamental operating parameters for the rotor have to be determined for the weight of the blade. Here design wind speed is introduced:

$$V_d = k_{velocity} V_{mean} \tag{3.43}$$

Here k_{speed} is selected as k=1.16 for stall controlled WTs and k=1.30 for pitch controlled WTs. Harrison et. al [9] states that selection of this constant is highly related with the WT's noise restrictions. These values of these constants causes rotor tip speeds be in the acceptable ranges (between 60-86 m/s) for the WT noise levels.

Rotor angular speed is found as in r/min:

$$RPM_{Rotor} = \frac{V_d \lambda}{R} \frac{60}{2\pi} \tag{3.44}$$

Rated torque of the wind turbine is calculated as follows:

$$Q_R = \frac{1}{2}\rho_{air} C_P \pi \frac{V_R{}^3}{V_{tip}} R^3 \tag{3.45}$$

Extreme thrust on the parked rotor blades is calculated as:

$$T_{ex} = \frac{1}{2}\rho_{air} \left(0.85 V_{ex}\right)^2 C_D \sigma \pi R^2 \tag{3.46}$$

Extreme wind speeds is selected according to the IEC standards class II wind speed. Its value is:

$$V_{ex} = 42.5 \text{ m/s} \tag{3.47}$$

Blade weight is divided into three components since its structural design.

- Blade Spar
- Airfoil cladding (blade airfoil surface)
- Blade root flange

Weight of the blade spar is:

$$W_{BS} = 0.085 F_{CL} F_{RC} \rho_{air} V_d^{\,2} \lambda^2 \left[\frac{1+t}{t}\right]\left[\frac{\rho_{SP}}{\sigma_{SP}}\right] BR^3 \tag{3.48}$$

Where "t" is the blade root thickness: [18]

$$t = 0.08\sqrt{\frac{R}{40}} \tag{3.49}$$

F_{CL} is the cyclic load factor and selected as:

Table 3.1: Cyclic Load Factor

Hub Type	Blade frequency type	F_{CL}
Rigid	Rigid	1.0
Teeter	Rigid	0.85
Rigid	Flexible	0.70
Teeter	Flexible	0.60

F_{RC} is the rotor control factor and selected as:

Table 3.2: Rotor Control Factor

Control Type	Rotor Speed	F_{RC}
Full-span variable pitch	Fixed	1.0
Stall	Fixed	0.85

Material properties that can be used for the blades are:

Table 3.3: Material Properties

Material	Admissible Strength σ_{adm} [Mpa]	Density ρ_m [kg/m^3]
Steel	110	7800
Glass-polyester	45	1800
Glass-epoxy	56	2000
Carbon-epoxy	200	1500
Wood-epoxy	12	550

Weight of the blade airfoil is:

$$W_{BA} = 30 F_A \left[1+t\right] \sigma \pi R^2 \tag{3.50}$$

F_A is airfoil weight factor and selected as:

Table 3.4: Airfoil Weight Factor

Airfoil Material	F_A
Glass reinforced polyester	1.0
Glass reinforced epoxy	0.6

Weight of the blade root flange is:

$$W_{BF} = 2.1F_{RF}\left[\frac{\rho_m}{\sigma_m}\right]T_{ex}D^{0.7}B \tag{3.51}$$

F_{RF} is the root flange factor and selected as:

Table 3.5: Root Flange Factor

Root flange factor	F_{RF}
Full-span pitch control (conventional)	1.0
Fixed hub, rigid blades, stall control	0.14

Total weight of the blades is calculated as:

$$W_{Blades} = B\left[W_{BS} + W_{BA} + W_{BF}\right] \tag{3.52}$$

The other component weights are calculated according to the blade weight and other design parameters. The models used in the calculations are done by Fingersh et al for NREL Wind Partnerships for Advanced Component Technology (WindPACT) and Low Wind Speed Technology (LWST) projects [12].

3.5.2 Component Weights

Rotor hub:

$$W_{Hub} = 0.954W_{Blades}/B + 5680.3 \tag{3.53}$$

Pitch mechanisms and bearings:

$$W_{PitchBearings} = 0.1295W_{Blades} + 491.31 \tag{3.54}$$

$$W_{Pitch} = 1.328W_{PitchBearings} + 555 \tag{3.55}$$

Nosecone (spinner):

$$W_{\text{Nosecone}} = 18.5D - 520.5 \tag{3.56}$$

Total rotor weight:

$$W_{Rotor} = W_{Blades} + W_{Hub} + W_{Nosecone} + W_{PitchBearings} + W_{Pitch} \tag{3.57}$$

Low-speed shaft:

$$W_{Shaft} = 0.0142 D^{2.888} \tag{3.58}$$

Main bearings:

$$W_{MainBearings} = \left[\frac{8D}{600} - 0.033\right] 0.0092 D^{2.5} \tag{3.59}$$

Gearbox:

Three-Stage Planetary/Helical:

$$W_{Gear} = 70.94 Q_R^{0.759}$$

Single-Stage Drive with Medium-Speed Generator:

$$W_{Gear} = 88.29 Q_R^{0.774}$$

Multi-Path Drive with Multiple Generators: (3.60)

$$W_{Gear} = 139.69 Q_R^{0.774}$$

Direct Drive:

$$W_{Gear} = 0.0$$

Generator:

Three-Stage with High-Speed Generator

$$W_{Generator} = 6.47 P_R^{0.759}$$

Single-Stage Drive with Medium-Speed, PM Generator (3.61)

$$W_{Generator} = 10.51 P_R^{0.9223}$$

Multi-Path Drive with PM Generators

$$W_{Generator} = 5.34 P_R^{\ 0.9223}$$

Direct Drive

$$W_{Generator} = 219.33 P_R$$

Mainframe (nacelle bedplate):

Three-Stage with High-Speed Generator

$$W_{Mainframe} = 2.233 D^{1.953}$$

Single-Stage Drive with Medium-Speed, PM Generator

$$W_{Mainframe} = 1.295 D^{1.953}$$

Multi-Path Drive with PM Generators (3.62)

$$W_{Mainframe} = 1.721 D^{1.953}$$

Direct Drive

$$W_{Mainframe} = 1.228 D^{1.953}$$

Platform and Railings:

$$W_{PlatformRailing} = 0.125 W_{Mainframe} \tag{3.63}$$

Nacelle cover (nacelle cladding):

$$W_{NacelCover} = 1.1537 P_R + 384.97 \tag{3.64}$$

Hydraulic and cooling systems:

$$W_{HydraulicCooling} = 0.08 P_R \tag{3.65}$$

Yaw system:

$$W_{Yaw} = 1.6\left(0.0009 R^{3.314}\right) \tag{3.66}$$

Mechanical brake, high speed coupling and associated components:

$$W_{Brake} = 0.19894 P_R - 0.01141 \quad (3.67)$$

Total towerhead weight:

$$\begin{aligned} W_{Towerhead} = & W_{Rotor} + W_{Shaft} + W_{Gear} + W_{Generator} + W_{MainBearings} \\ & + W_{Mainframe} + W_{NacelCover} + W_{Hydraulic} + W_{Platform Railing} + W_{Yaw} \end{aligned} \quad (3.68)$$

Tower:

$$W_{tower} = 0.3973 \pi R^2 H_{hub} \quad (3.69)$$

3.5.3 Cost Breakdown

Costs of the components are derived from the component weights. Specific costs; unit cost (US$) per kilograms are used which are given by [10]. Generally costs are calculated by the formula:

$$Cost_{Component} = K_{cost} W_{Component} \quad (3.70)$$

Additionally, cost of the generator is calculated by the formula with unit cost (US$) per kilowatts relation:

$$Cost_{Generator} = K_{cost} P_R \quad (3.71)$$

Specific costs are summarized in the table:

Table 3.6: Specific Component Costs

Component	Description	Specific Cost (Kcost)
Blades		12.0 $US/kg
Hub, machined		2.0 $US/kg
Pitch Mechanism		12.0 $US/kg
Nosecone		5.0 $US/kg
Rotor Shaft		3.5 $US/kg
Gearbox		8.0 $US/kg
Main Bearings		5.0 $US/kg
Mainframe		4.0 $US/kg
Nacelle Cover		5.0 $US/kg
Hydraulics		5.0 $US/kg
Platform & Railing		5.0 $US/kg
Yaw System		8.0 $US/kg
Tower		1.5 $US/kg
Generator	Three-Stage, High-Speed	65.0 $US/kW
	Single-Stage Drive, Medium-Speed PM	54.73 $US/kW
	Multi-Path Drive, PM	48.03 $US/kW
	Direct Drive	219.33 $US/kW

Cost of the control system (direct cost assumption) [12]

$$C_{ControlSystem} = 35000\ \$ \tag{3.72}$$

Addition to the component costs the balance of station costs has to be determined in order to calculate the total cost which is also equal to the capital investment of a WT [12].

Foundation and support structure:

$$C_{Foundation} = 303.24\left(H_{hub}\pi R^2\right)^{0.4037} \tag{3.73}$$

Transportation:

$$C_{Transportation} = K_{Transportation}P_R \tag{3.74}$$

Where K is the transportation cost factor:

$$K_{Transportation} = 1.581E-5P_R{}^2 - 0.0375P_R + 54.7 \tag{3.75}$$

Roads and civil work:

$$C_{RoadsCivilWork} = K_{RoadsCivilWork}P_R \tag{3.76}$$

Where K is the cost factor:

$$K_{RoadsCivilWork} = 2.17E-6P_R{}^2 - 0.0145P_R + 69.54 \tag{3.77}$$

Assembly and installation:

$$C_{AssemblyInstallation} = 1.965\left(H_{hub}D\right)^{1.1736} \tag{3.78}$$

Electrical interface and connections:

$$C_{ElectricalSystem} = K_{ElectricalSystem}P_{Rated} \tag{3.79}$$

Where K is the cost factor:

$$K_{ElectricalSystem} = 3.49E - 6P_R^{\ 2} - 0.0221P_R + 109.7 \quad (3.80)$$

Engineering, permits:

$$C_{EngineeringPermits} = K_{EngineeringPermits} P_{Rated} \quad (3.81)$$

Where K is the:

$$K_{EngineeringPermits} = 9.94E - 4P_R + 20.31 \quad (3.81)$$

Finally total cost can be found as initial investment:

$$\begin{aligned} C_I = &C_{Components} + C_{Transportation} + C_{RoadsCivilWork} \\ &+ C_{AssemblyInstallation} + C_{ElectricalSystem} + C_{EngineeringPermits} \end{aligned} \quad (3.82)$$

3.6 Wind Energy Calculations and Economics

3.6.1 Energy Calculations

Weibull approach is used for energy calculations. Energy generated by the turbine, the power curve of the designed WT has to be calculated. Generally for energy calculations of a system, a candidate wind turbine is selected for the site and power curves are maintained from the manufacturer. In specific sites, the current commercial wind turbines may not be suitable for the site. According to [11] for selected design wind speeds and other design options the power curve can be plotted and can be used for further calculations.

In the figure 3.10 typical power curve for a pitch controlled 1 MW wind turbine is shown. Formulation of the power curve is;

$$P_{curve} = P_R \left(\frac{V^n - V_{cut-in}^2}{V_R^n - V_{cut-in}^n} \right) \quad (3.83)$$

The formulation is valid for region one. Between rated wind speed and cut out wind speed, power output is constant at rated power. This is valid for only fixed speed WTs. The power exponential of the design speeds, ‘n’ value is specified by the designer of the machine. The design speeds (rated, cut-in, cut-out) are again calculated by the design of the machine.

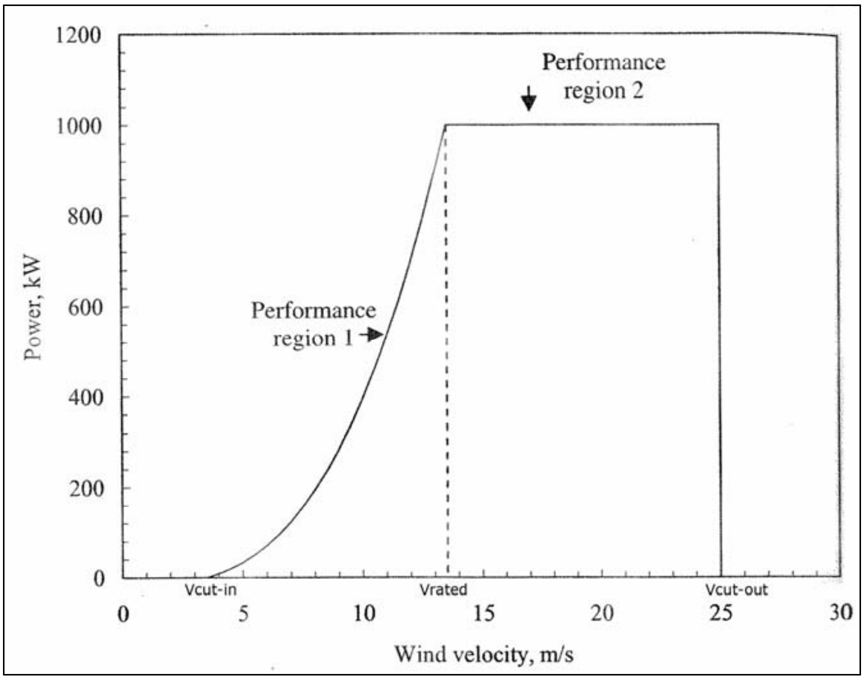


Figure 3.10: Power Curve representation [11]

Power curve identifies the power production of the machine. In operation wind turbine generates the energy resulting its power curve.

Total energy generated by the wind turbine with Weibull approach is given by:

$$E_T = T \int_{V_{cut-in}}^{V_{cut-out}} P_{curve} f(V)dV \tag{3.84}$$

Where:

$$T = availability \times time\ period\ (hours) = availability \times 8760\ hours (for\ annual) \tag{3.85}$$

Total energy can be divided into two for each region.

$$E_T = E_{IR} + E_{RO} \tag{3.86}$$

Between cut-in and rated wind speeds:

$$E_{IR} = T \int_{V_{cut-in}}^{V_R} P_{curve} f(V)dV \tag{3.87}$$

Between rated and cut-out speeds:

$$E_{RO} = TP_R \int_{V_R}^{V_{cut-out}} f(V)dV \tag{3.88}$$

For simplification the design speeds and Weibull parameters are rearranged,

$$X_I = \left[\frac{V_{cut-in}}{c}\right]^k, X_R = \left[\frac{V_R}{c}\right]^k, X_O = \left[\frac{V_{cut-out}}{c}\right]^k \tag{3.89}$$

Simply energy formulas have become:

$$E_{IR} = \frac{P_R T c^n}{\left(V_R - V_{cut-in}\right)} \int_{X_I}^{X_R} X^{n/k} e^{-X} dX - \frac{P_R T V_{cut-in}^n}{\left(V_R^n - V_{cut-in}^n\right)} \left[e^{-X_I} - e^{-X_R}\right] \tag{3.90}$$

$$E_{RO} = P_R T \left(e^{-X_R} - e^{-X_O}\right) \tag{3.91}$$

Capacity factor can be calculated when the WT's energy is known.

$$C_F = \frac{E_T}{TP_R} \tag{3.92}$$

3.6.2 Economics

For wind energy projects costs can be divided into two parts, fixed costs and variable costs. Fixed costs are consisting of initial investment costs that are detailed as component and supplementary costs in the cost analysis section. Initial investment also represents the wind turbine sales price. Variable costs are consisting of operation and maintenance costs that come with the wind energy generation for a wind energy project. Operation and maintenance costs can be calculated as percentage of the initial investment [11]:

$$C_{OM} = mC_I \tag{3.93}$$

Where $1.5 < m < 2.0$

Total cost of operation of a project can be defined as:

$$C_A = C_I + C_{OM} \tag{3.94}$$

Cost of operation with present value (net present value of all costs):

$$NPV(C_A)_{1-n} = C_I\left[1+m\left[\frac{(1-I)^n-1}{I(1+I)^n}\right]\right] \tag{3.95}$$

Yearly cost of operation with present value approach:

$$NPV(C_A) = \frac{NPV(C_A)_{1-n}}{n} \tag{3.96}$$

Annual energy production is given as:

$$AEP = E_T(\,when\ T{=}8760\,) = 8760 P_R C_F \tag{3.97}$$

When the cost of operation and the annual energy production is known, cost of wind energy can be calculated. Cost of wind generated electricity or cost of energy will show the how efficient is the overall project. It is calculated by [11]:

$$COE = \frac{C_A}{E_T} = \frac{NPV(C_A)}{AEP} = \frac{C_I}{8760n}\frac{1}{P_R C_F}\left[1+m\left[\frac{(1+I)^n-1}{I(1+I)^n}\right]\right] \tag{3.98}$$

Wind energy projects are evaluated by their benefits according to their electricity generation tariffs. The accumulated value of all benefits over the lifespan of the project is given by:

$$B_A = AEP \times ElectricityPrice \tag{3.99}$$

Net present value of all benefits:

$$NPV(B_A)_{1-n} = B_A\left[\frac{(1+I)^n I}{I(1+I)^n}\right] \tag{3.100}$$

An important economic criterion for the investors is the repayment period, also called the pay back period. It can be found by equating B_A to C_A [11].

$$NPV(B_A)_{1-n} = NPV(C_A)_{1-n} \tag{3.101}$$

Pay back period:

$$n_{PayBack} = -\frac{ln\left[1 - \frac{IC_I}{B_A - mC_I}\right]}{ln(1+I)} \tag{3.102}$$

3.7 Optimization

In the current study Response Surface Methodology (RSM) is used for the optimization processes. It is widely used in multidisciplinary aerospace design and optimization applications.

RSM uses statistical and mathematical techniques for the optimizing processes and it involves regression surface fitting for approximate responses in order to optimize objectives with the chosen design of experiments [19]. RSM defines objective functions and constraints simple functions [20]. Typically RSM develops polynomial approximation models by fitting sample data using least squares regression technique [21]. Response surface methodology is intimately connected to regression analysis [22].

Responses are used as a performance measure or quality characteristic for the optimizing processes. The input variables are called independent variables. For the approximating model response y and the independent (natural) variables $\xi_1, \xi_2 ..., \xi_k$ are used. In general form empirical response is [19]:

$$y = f\left(\xi_1, \xi_2 ..., \xi_k\right) + \varepsilon \tag{3.103}$$

Here k is the number of variables and ε is the model (random) error. For the RSM true response can written in terms of coded variables $x_1, x_2 ..., x_k$ which are dimensionless, zero mean, and have the same standard deviation [22]. In terms of coded variables response model becomes:

$$y = f\left(x_1, x_2 ..., x_k\right) + \varepsilon \tag{3.104}$$

For the f function RSM develops suitable approximations by using polynomials. In many cases first order or second order models are used. The first order form is [22]:

$$y = \beta_0 + \beta_1 x_1 + ... + \beta_k x_k \tag{3.105}$$

The second order form is:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i=1}^{k-1} \sum_{j=1}^{k} \beta_{ij} x_j \qquad (3.106)$$

In case of two variables the response surface is expressed as follows where $k = 2$:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 \qquad (3.107)$$

An example of a response surface in case of two variables is shown below where objective function named as state variable:

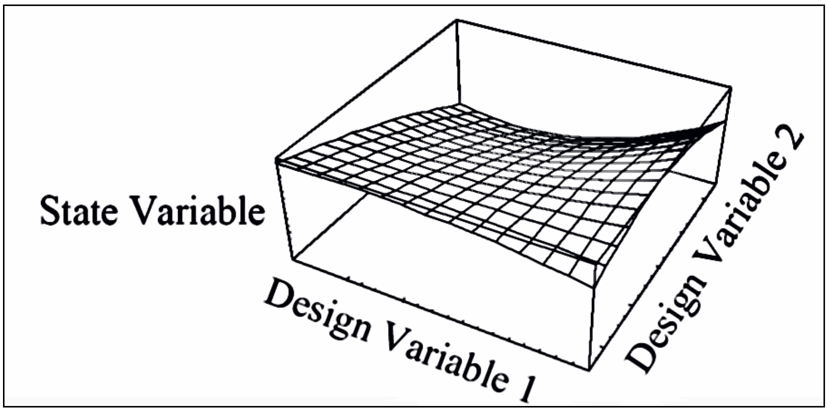


Figure 3.11: Response Surface with two variables [23]

The linear regression model of this response is represented as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 \qquad (3.108)$$

Equivalently in matrix form:

$$Y = XB + E \qquad (3.109)$$

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{bmatrix} \quad B = \begin{bmatrix} \beta_1 \\ \beta_2 \\ . \\ . \\ . \\ \beta_n \end{bmatrix} \quad E = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ . \\ . \\ . \\ \varepsilon_n \end{bmatrix} \quad X = \begin{bmatrix} 1 & x_{11} & x_{12} & \dots & x_{1k} \\ 1 & x_{21} & x_{22} & \dots & x_{2k} \\ . & . & . & \dots & . \\ . & . & . & \dots & . \\ . & . & . & \dots & . \\ 1 & x_{n1} & x_{n2} & \dots & x_{nk} \end{bmatrix} \qquad (3.110)$$

In equation 3.110, n is the number of design points.

The polynomial coefficients are calculated as:

$$B = \left(X^T X \right)^{-1} X^T Y \tag{3.111}$$

The second order model is used in this study, so the polynomial coefficients are estimated easily using least squares method. In the estimation of the parameters β with least squares method, inspection of the model adequacy is important. Here R^2 (coefficient of multiple determination) is introduced [19]:

$$R^2 = 1 - \frac{SS_E / \left(n - k - 1 \right)}{S_{yy} / \left(n - 1 \right)} \tag{3.112}$$

Where SS_E (error or residual sum squares) is:

$$SS_E = Y^T Y - B^T X^T Y \tag{3.113}$$

And S_{yy} (total sum squares) is

$$S_{yy} = Y^T Y - \frac{\sum_{i=1}^{n} y_i}{n} \tag{3.114}$$

Generally R^2 is in the range of $0 \le R^2 \le 1$, and values near to the upper limit shows that the surface is adequate. If the response is not adequate the number of variables and design points can be increased in order to get better results [24].

3.7.1 Design of Experiments

In RSM selection of design points are important for searching optimum responses. There are different types of design of experiments (DOE) matrices introduced in literature [25].

- Full Factorial Designs (FFDs), (3^k)
- Central Composite Designs (CCDs)
- Box Behnken Designs (BBDs)
- Expected integrated mean squared error optimal (EIMSE-optimal) designs

In the current study 3^k design method is used. According to this method for two variables nine design points are represented with DOE as:

$$
DOE = \begin{bmatrix} -1 & -1 \\ -1 & 0 \\ -1 & +1 \\ 0 & -1 \\ 0 & 0 \\ 0 & +1 \\ +1 & -1 \\ +1 & 0 \\ +1 & +1 \end{bmatrix} \qquad (3.115)
$$

Here '0' represents the midpoint value of the initial guesses for the design variables and '+1' and '-1' show the $x \pm \Delta x$ maximum and minimum limits for the design variables.

3.7.2 Objective Function and Constraints Formulation

In the current study two variables are optimized; rotor radius and hub height of the WT. Initial calculation for the rotor radius is done by the statistical relation given below:

$$
R_{initial} = \frac{1}{2}\left(\frac{P_R}{0.2857}\right)^{\frac{1}{2.0149}} \qquad (3.116)
$$

Initial guess for the hub height is defined as:

$$
H_{hub,initial} = 2R_{initial} \qquad (3.117)
$$

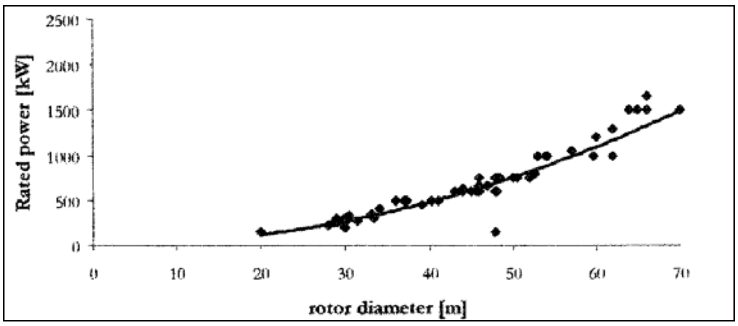


Figure 3.12: Rated Power vs. Rotor Diameter Variation [26]

Constraints for design variables are estimated as:

$$H_{hub,min} \leq H_{hub} \leq H_{hub,max} \tag{3.118}$$

$$R_{min} \leq R \leq R_{max} \tag{3.119}$$

Where:

$$H_{hub,min} = 1.5 R_{initial} \tag{3.120}$$

$$H_{hub,max} = 3.5 R_{initial} \tag{3.121}$$

$$R_{min} = 0.5 R_{initial} \tag{3.122}$$

$$R_{max} = H_{hub,min} - 15.0 \tag{3.123}$$

Objective function of the optimization algorithm is defined as:

$$F_{objective} = k_{COE} \frac{COE}{COE_{ref}} + k_{C_I} \frac{C_I}{C_{I,ref}} + k_{n_{PayBack}} \frac{n_{PayBack}}{n_{PayBack,ref}} + k_{E_T} \frac{E_{T,ref}}{E_T} \tag{3.124}$$

Here COE, C_I, $n_{PayBack}$ are minimized and E_T is maximized. Each component is made non-dimensioned due to the initial design point and multiplied with the priority constants. The priority constants (k) enable the user to determine which parameter is more important for the optimization process. The response surface is approximated and minimized for these components in the whole process. When the minimum design point is found the program does the needed calculations for the wind energy conversion system.

4 PROGRAM WIND & GUI

Program is built in MATLAB language consisting of GUI and source codes at the background. Source codes are consisting of MATLAB's own file types (.m, .mat, .fig). User defines inputs and configuration selection in six different pages. In these pages default values are selected written in the GUI strings. By the time inputs are defined, user can click the run button and program initiates the optimization process. In the results section needed results are showed with the graphs. Additional outputs can be viewed with in a .mat file where the whole variables and parameters are saved.

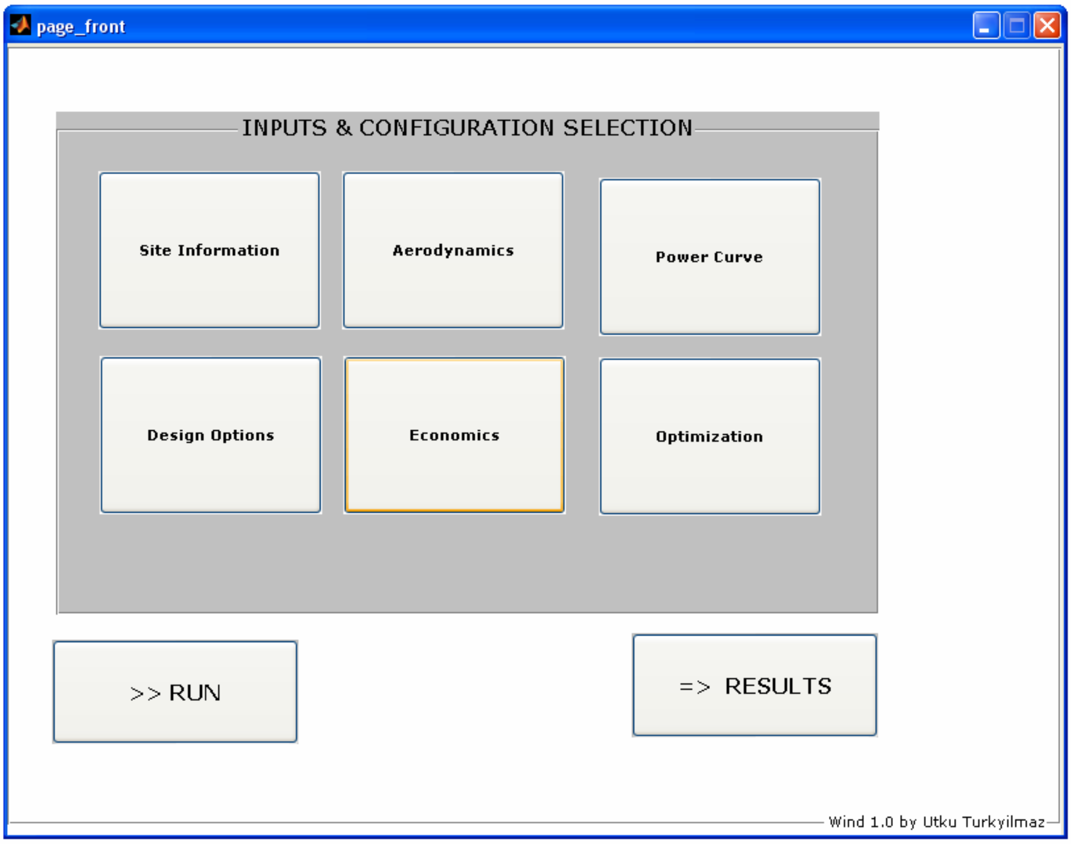


Figure 4.1: General Layout of the program

In the site information tab the default values are seen in the figure 4.2. The default values for the inputs for air density, viscosity and power law exponent are selected according to the IEC standards. The height of the observed wind is determined by the user due to the wind data recorded. The form needs wind data file from the user. The wind data is a text file and its format seen in the figure 4.2.

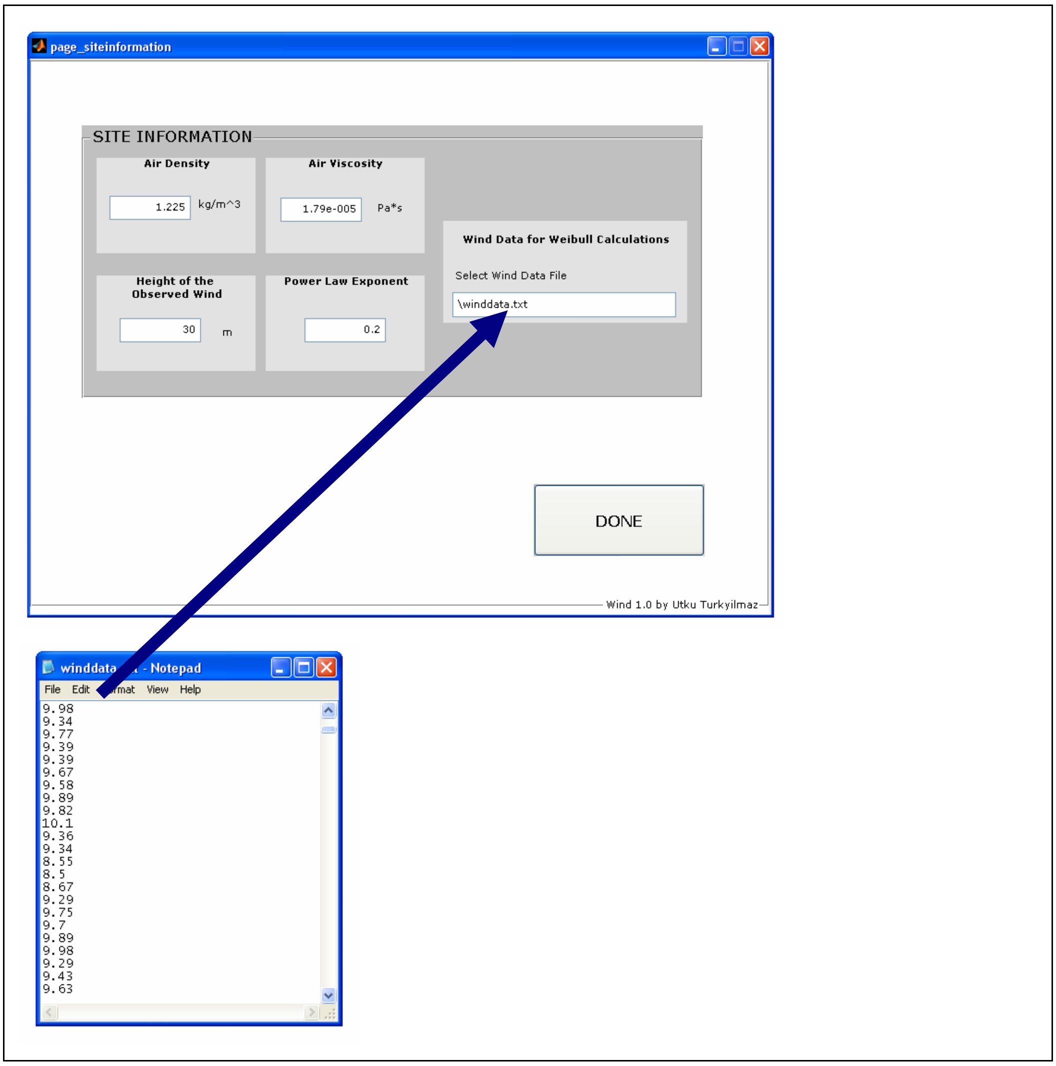


Figure 4.2: Site Information Tab

In the design options tab, configuration selection is done as a part of conceptual design. User defines a rated power value according to the project needs. It is shown in figure 4.3.

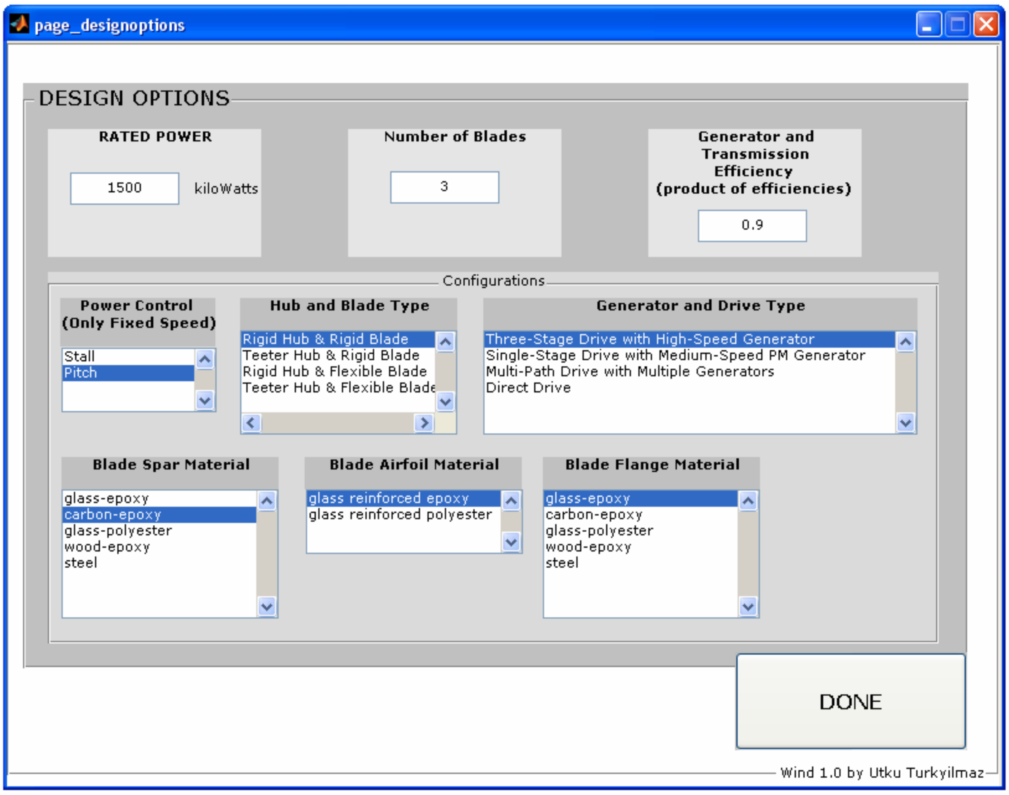


Figure 4.3: Design Options Tab

In the aerodynamics tab, as detailed in the previous sections program uses only one airfoil SG60 for the present. Current calculated values are used in the inputs, shown in figure 4.4.

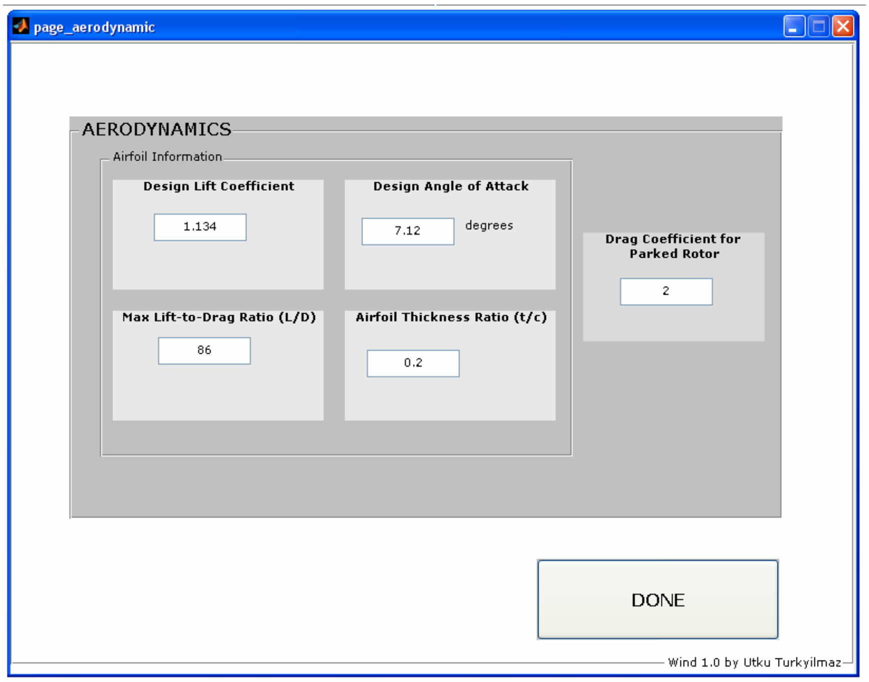


Figure 4.4: Aerodynamics Tab

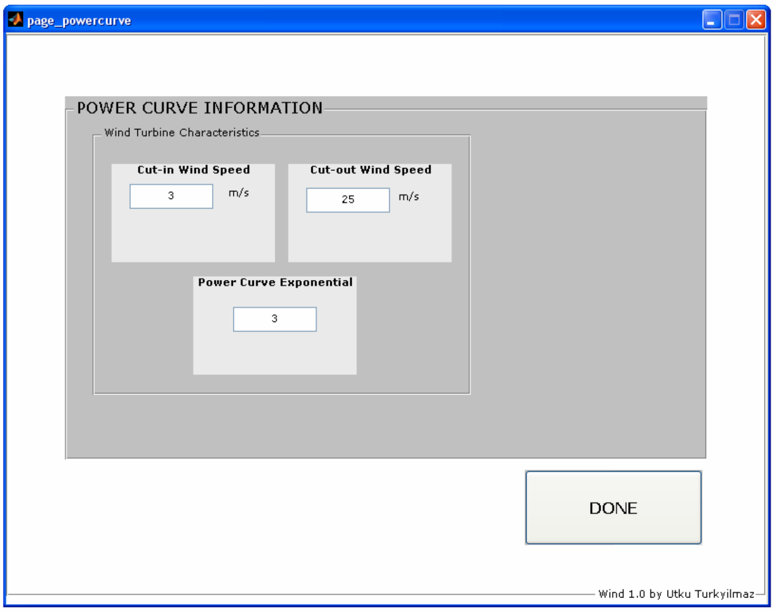


Figure 4.5: Power Curve Information Tab

In the power curve tab shown in figure 4.5 users can define cut-in and cut-out speeds for preliminary design. Here power curve exponential is introduced with a default value of 3.

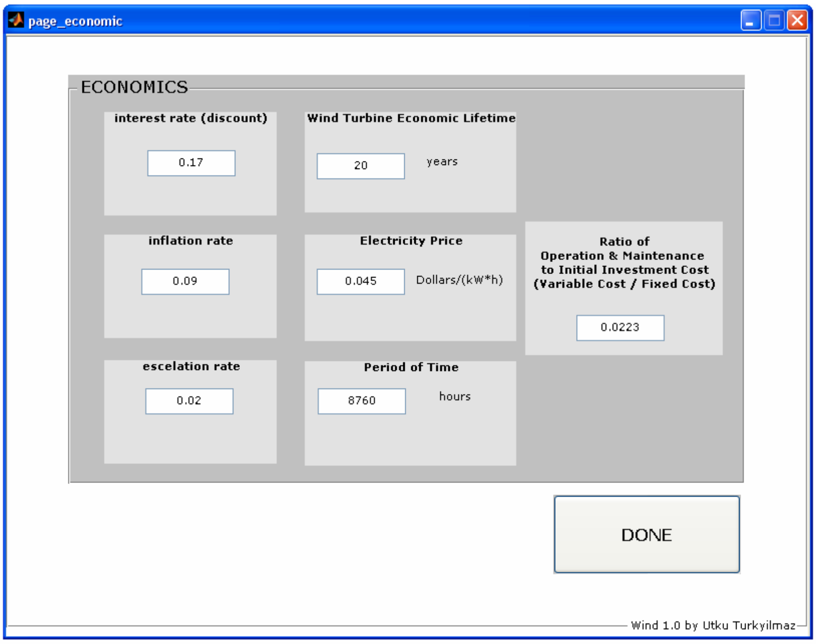


Figure 4.6: Economics Tab

Economics tab shows the present economic information which is defined according to the present economic values at where the project will be achieved.

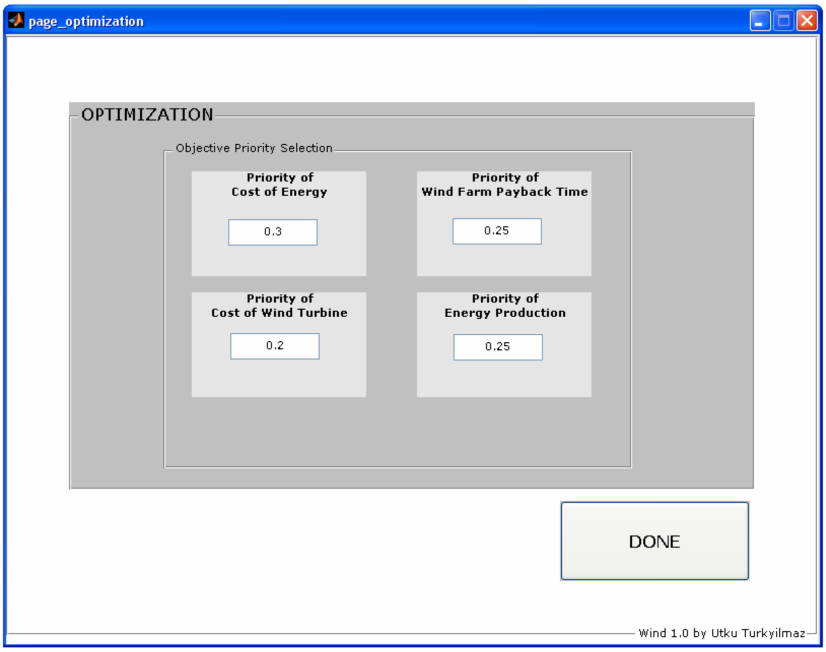


Figure 4.7: Optimization Tab

In the optimization tab user can select the optimization priority of the variables. The priorities are in the form of percentages with total value of 100 %.

In the results section overall results can be viewed with detailed optimization, aerodynamics and power curve sections.

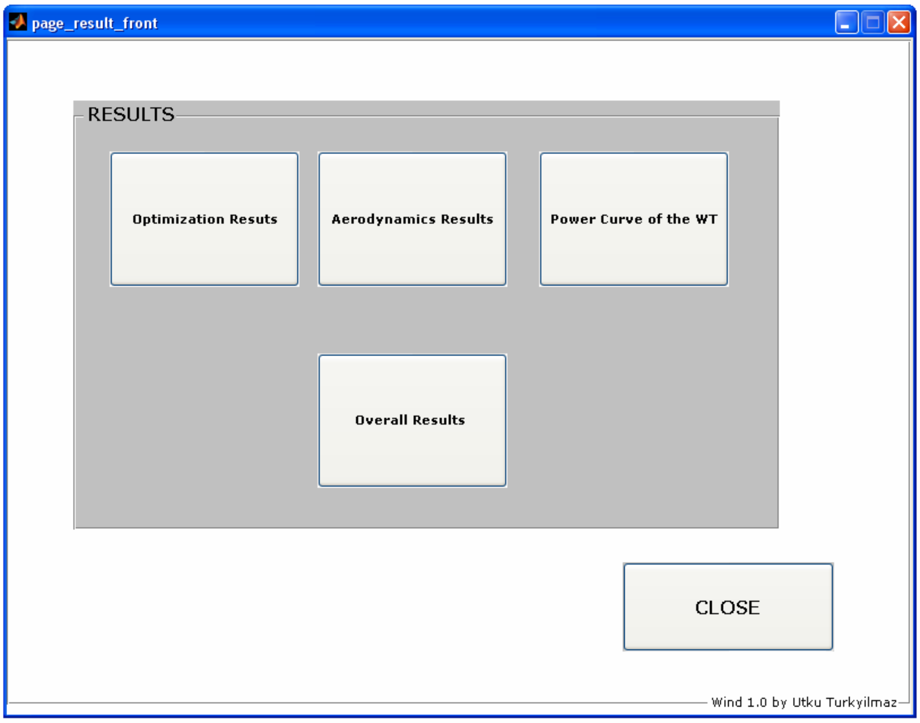


Figure 4.8: Program Results

5 RESULTS AND DISCUSSION

In the present study the design program is built in order meet designer's specifications under defined constraints.

5.1 Application of the Program

An application of the program is done with a chosen baseline model with user defined input values. Design starts with the generator selection. The rated power of the wind turbine must be determined for further calculations. The rated power is 1500 kW for the current study. This rating contributes to the technology of late 1990s. According to this rated power value a baseline turbine is selected. Baseline for the design will be NREL WindPACT Program's wind turbine having the same rated power [27].

Table 5.1: GUI Inputs

Design options	
Rated Power	1500 [kWatt]
Number of Baldes	3
Generator and Transmission Efficiency	0.90
Power Control	Pitch Control
Hub and Blade Type	Rigid Hub & Rigid Blade
Generator and Drive Type	Three-stage drive with medium-speed PM generator
Blade Spar Material	Carbon-Epoxy
Blade Airfoil Material	Glass Reinforced Epoxy
Blade Flange Material	Glass Reinforced Epoxy
Site Information	
Air Density	1.225 [kg/m^3]
Air Viscosity	1.79e-05 [Pa*s]
Power Law Exponent	0.20
Height of the Observed Wind	30 [meters]
Aerodynamics	
Airfoil Selection	SG 6040
Design Lift Coefficient	1.134
Design Angle of Attack	7.12 [degrees]
Max L/D	86
Airfoil Thickness	0.20
Drag Coefficient for Parked Rotor	2.0
Power curve	
Cut-in Speed	3 [m/s]
Cut-out Speed	25 [m/s]
Power curve exponential	3
Economics	
Interest Rate	0.17
Inflation Rate	0.09
Escelation	0.02
Wind Turbine Economic Lifetime	20 [years]
Electricity Sales Price	0.045 [Dollars/(kW*h)]
Period of Time	8760 [hours]
Optimization	
Priority of COE	0.30
Priority of Cost of Wind Turbine	0.20
Priority of Pay Back Time	0.25
Proirity of AEP	0.25

In the table current input values used in the application are shown, these values are also default GUI inputs.

In optimization process the initial values are calculated according to the rated power value. Initial rotor radius and hub height is shown below:

$$R_{initial} = 35.1\ m \tag{5.1}$$

$$H_{hub,initial} = 70.2\ m \tag{5.2}$$

Program generates constraints for the design variables. Possible ranges are shown below:

$$52.65\ m \leq H_{hub} \leq 122.85\ m \tag{5.3}$$

$$17.55\ m \leq R \leq 37.65\ m \tag{5.4}$$

Optimization process searches for optimum design point and generates response surface. Response surface is shown below figure 5.1:

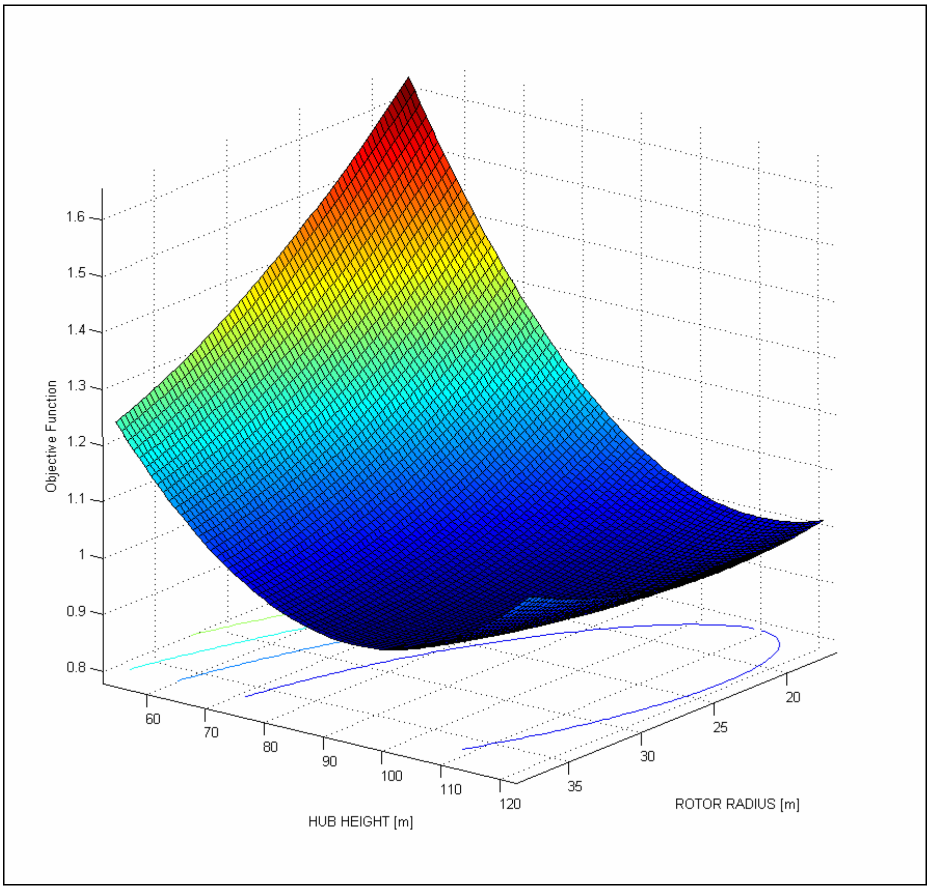


Figure 5.1: Response Surface

Optimum values for the design variables are:

$$R_{optimum} = 30.48\ m\ ,\quad H_{hub,optimum} = 104.91\ m \tag{5.5}$$

Response surface model is checked for adequacy and the factor R^2 is found:

$$R^2 = 0.988 \tag{5.6}$$

The R^2 value shows that the response surface is adequate for optimization.

Results for minimum objective function are shown in table below:

Table 5.2: Results of Objective Function

Initial Capital Cost	1,078,100 $
COE	0.017 $ / kWh
Pay Back Period	5.62 years
AEP	5564 MWh

Overall Results of optimization process is shown below table:

Table 5.3: Overall Results

Rated Power	1500 kW
Rotor Radius	30.48 m
Hub Height	104.91 m
Design Power Coefficient	0.43
Design Tip Speed Ratio	7
Rotor RPM	26.07 RPM
Rated Speed	12.60 m/s
Specific Towerhead Mass	20.06 kg/m^2
Rated Power per Rotor Swept Area	513.75 Watt/m^2
Weibull Shape Factor	1.828
Weibull Scale Factor, c	10.29 m/s
Weibull Average Speed	8.975 m/s
Capacity Factor	0.42
Rough Capacity Factor	0.37
Real Rate of Interest	0.052
Present Value of All Costs	1,371,900 $
Yearly Cost of Operation	68,594 $ / year
Initial Capital Cost	1,078,100 $
COE	0.017 $ / kWh
Pay Back Period	5.62 years
AEP	5564 MWh

In the application one year of hourly averaged wind data is used for calculations. The wind data is observed at 30 meters and the data is consisting of 8760 raw wind speed data. Program reads the data, extrapolates data to the hub height and evaluates Weibull calculations for the Weibull mean speed determination. Weibull calculations are also checked with the WAsP (the Wind Atlas Analysis and Application Program) and results agree with the current study results.

In the aerodynamic analysis optimum blade geometry is calculated. Chord and twist distributions with radial stations can be seen in following figures:

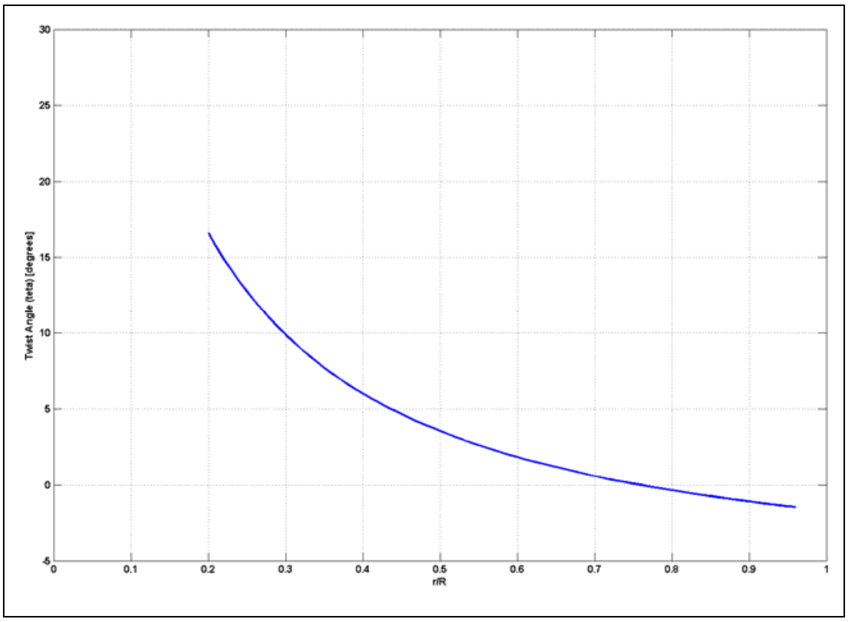


Figure 5.2: Optimal Twist Distribution

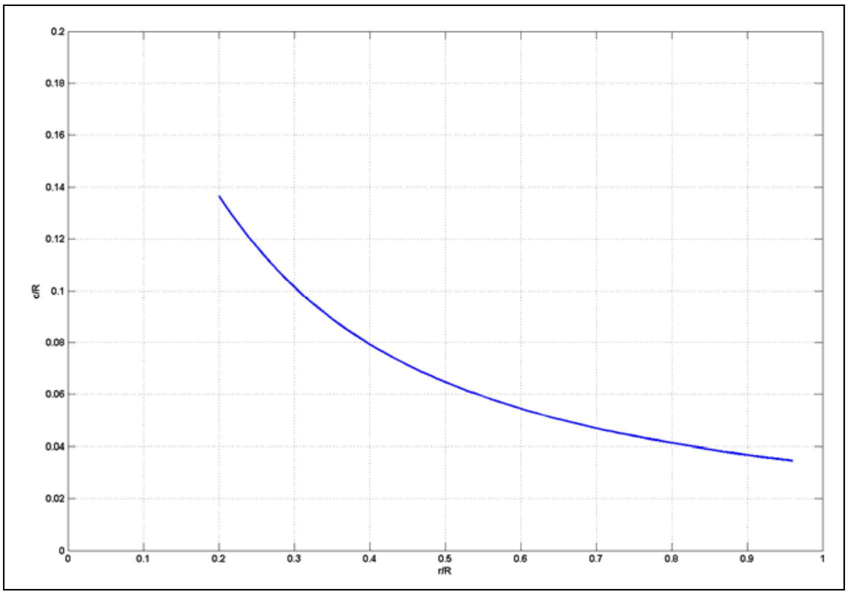


Figure 5.3: Optimal Chord Distribution

Blade element theory is applied from the station at %20 of the radius to the station at %96 of the radius.

For energy calculations following power curve is plotted:

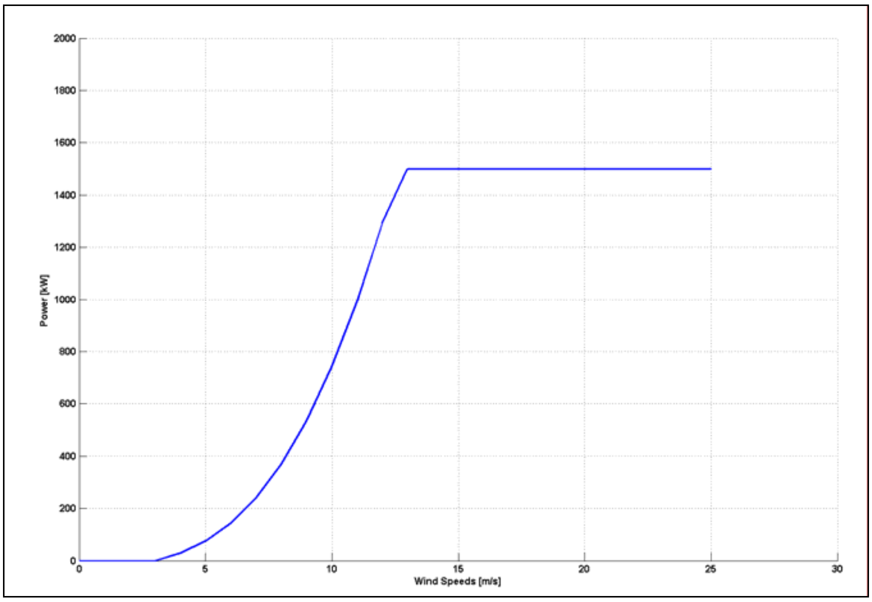


Figure 5.4: Power Curve Plot

The cost and weight breakdown is:

Table 5.4: Cost and Weight Breakdown

Components	Weights [kg]	Costs [$]
Blades	14971.00	178500
Hub	10441.00	20821
Pitch System	6212.30	45187
Nosecone (spinner)	607.46	3022
Rotor	32232.00	247530
Low-speed Shaft	2031.10	7054
Main Bearings	416.57	2063
Gearbox	8334.20	90859
Generator	5498.10	82095
Mainframe	6842.80	15791
Platform and Railings	855.35	2467
Nacelle Cover	2115.50	10578
Hyraulic and Cooling System	120.00	600
Yaw System	119.30	945
Brake System	298.40	1492
Towerhead	58565.00	461480
Tower	120280.00	179850
Total	178840.00	1170889

Additional costs including supplementary costs are shown in table:

Table 5.5: Additional Costs

Additional Costs	[$]
Control System	35000
Foundation / Support Structure	49659
Transportation	51034
Roads, Civil Work	79009
Assembly and Installation	57514
Electrical Interface / Connections	126600
Engineering, Permits	32701

5.2 Conclusion

The whole study gives sufficient information, how the WT machine will be designed and what will be the systems benefits through its lifetime. Consequently, the current study gives reasonable results. Improvements can be done in the future studies.

- Program can be improved with other disciplines modules. These modules may involve aeroelastic, structural, fatigue, dynamics, control and electrical designs.
- Wind resource analysis program can be improved by using different approaches such as Rayleigh distribution approach.
- The current aerodynamic module can be improved with additional models. Dynamic inflow, dynamic Stall, 3-D corrections, yaw misalignment, unsteady aerodynamics could be main future study areas. An airfoil database can be developed for comparing their performance with each other. Additionally new airfoils can be designed for specific projects. The current analysis module can be compared with the others methodologies, such as vortex theory and Computational Fluid Dynamics (CFD) codes.
- Component designs can be improved with detailed design for accurate calculations. Statistical data of current commercial wind turbines can be researched more extensively. Especially tower designs can be improved with detailed design using vibration analysis.
- Offshore wind turbine designs can be added.
- For the system design and overall economic aspects of the project, better comparison can be done with accomplished wind energy projects.
- In the optimization process the design variables and constraints may be modified for better results.

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RESUME

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