

## **DEDICATION**

**...TO MY PARENTS**

**.AND TO, MY BROTHERS**

## **ACKNOWLEDGMENT**

I would like to extend my deep appreciation with recognition to Professor **Osman Mohammed Ali Sharfi** for his invaluable advice and supervision during this study. In addition, I am grateful to Professor **El Tayyib Idries Eisa**, the Co – supervisor, who provided basic guidance in conducting this work, and for his keen guidance and help

Thanks are also extended to Engineer **Alfadil Beraima Hamed** (M.Sc.Mech.Engineering) the Head of the Wind and Minihydro department at the Energy Research Institute for his efforts and help

.Thanks are offered to the workshop staff for their great help  
Finally grateful thanks are due to Engineer **Abdelazziz Ahmed Osman** who assisted me in conducting the experimental work, and to all those who made it possible to realize this work

## **ABSTRACTS**

The model of a horizontal – axis wind turbine was designed to generate 164 watts. Execution of design include the design of the rotor (3 m diameter) which is made of three wooden blades of a cambered airfoil section (NACA 4412 section), the blades were manufactured locally. The rotor is coupled to a small D.C. generator via a belt transmission system. The designs of the transmission subsystems (belts, shafts, and bearings) were achieved. The wind generator model is installed on a tower 3 meters above ground. A field test was carried out on a wind generator model at the Soba field owned by the Energy Research Institute. The output voltage and current were measured to determine the amount of electricity generated by the model.

After the test, it was found that the efficiency of the model is low. This was mainly due to the decrease of the wind speed at the 3 meters above ground (the height of the tower). In addition to that, the locally available technologies restrict the possibilities of manufacturing blades with the airfoil shapes that can extracts power with high efficiency.

## CONTENTS

|                                                               |          |
|---------------------------------------------------------------|----------|
| Dedication                                                    |          |
| Abstract                                                      |          |
| Acknowledgement                                               |          |
| List of symbols                                               |          |
|                                                               | Page     |
| CHAPTER 1: INTRODUCTION .....                                 | 1        |
| Wind potential in the Sudan .....                             | 3 1-1    |
| CHAPTER 2: HISTORICAL BACKGROUND .....                        | 5        |
| 2-1Wind Machines .....                                        | 5        |
| Horizontal – axis Wind Turbines .....                         | 16 2-1.1 |
| Vertical – axis Wind Turbines .....                           | 16 2-1.2 |
| Theoretical Background .....                                  | 19 2-2   |
| Available Wind Power .....                                    | 19 2-2.1 |
| Axial Momentum Theory .....                                   | 21 2-2.2 |
| Blade Element Theory .....                                    | 28 2-2.3 |
| Combination of Momentum Theory and Blade Element Theory ..... | 29       |
| Sudan previous experience .....                               | 33 2-3   |
| CHAPTER 3: WIND MACHINES FOR POWER GENERATION ..              | 35       |
| Types of Wind Machines .....                                  | 36 3-1   |
| Horizontal – axis Machines .....                              | 36 3-1.1 |
| Vertical – axis Machines .....                                | 47 3-1.2 |
| Matching Wind Machines to Loads .....                         | 54 3-2   |
| Prediction of Design Loads .....                              | 57 3-3   |
| Comparison between the HAWT and VAWT .....                    | 58 3-4   |

|                                                            |          |
|------------------------------------------------------------|----------|
| CHAPTER 4: SITE SELECTION.....                             | 60       |
| Wind Shear .....                                           | 60 4-1   |
| Turbulence .....                                           | 61 4-2   |
| Acceleration on Ridges .....                               | 61 4-3   |
| Wind Potential in Khartoum Area .....                      | 62 4-4   |
| CHAPTER 5: ROTOR DESIGN.....                               | 65       |
| Determination of the Rotor Parameters.....                 | 65 5-1   |
| Density of the Air .....                                   | 65 5-1.1 |
| Derivation of the Rotor Diameter and Design 5-1.2          |          |
| Power Relation.....                                        | 65       |
| Number of Blades .....                                     | 66 5-1.3 |
| Tip Speed Ratio .....                                      | 66 5-1.4 |
| Airfoil Data Selection .....                               | 67 5-1.5 |
| Calculation of the Chord.....                              | 69 5-1.6 |
| Design Procedure .....                                     | 69 5-1.7 |
| Method of the Airfoil Section Design.....                  | 71 5-2   |
| CHAPTER 6: DESIGN OF THE TOWER .....                       | 75       |
| Loadings acting on the Tower.....                          | 75 6-1   |
| Forces and Moments under Normal and Storm Conditions ..... | 75 6-2   |
| Normal Condition.....                                      | 75 6-2.1 |
| Storm Condition .....                                      | 80 6-2.2 |
| Design Criteria.....                                       | 81 6-3   |
| Normal Condition.....                                      | 81 6-3.1 |
| Storm Condition.....                                       | 81 6-3.2 |
| Summary of the Formulas .....                              | 81 6-4   |
| Normal Conditions .....                                    | 81 6-4.1 |
| Storm Condition .....                                      | 82 6-4.2 |
| Calculation of Forces and Moments .....                    | 82 6-5   |
| Normal Condition .....                                     | 82 6-5.1 |

|                                                      |     |       |
|------------------------------------------------------|-----|-------|
| Storm Condition.....                                 | 83  | 6-5.2 |
| Summary of the Loads .....                           | 84  | 6-6   |
| Types of the Towers .....                            | 85  | 6-7   |
| Calculation of the Loads acting on the Tower .....   | 86  | 6-8   |
| CHAPTER 7: DESIGN OF THE MODEL .....                 | 90  |       |
| Rotor Design .....                                   | 90  | 7-1   |
| Rotor Parameters .....                               | 90  | 7-1.1 |
| Blades Installation .....                            | 90  | 7-1.2 |
| Power Transmission .....                             | 90  | 7-2   |
| Selection of the Pulleys .....                       | 92  | 7-2.1 |
| Design of the Belts .....                            | 93  | 7-2.2 |
| Design of the V-belts using Manufacturing Data ..... | 93  | 7-2.3 |
| The Transmission System Installation .....           | 96  | 7-2.4 |
| Design of the transmission system.....               | 96  | 7-2.5 |
| Shafts and bearings design.....                      | 97  | 7-2.6 |
| The Electric Generator selection.....                | 105 | 7-3   |
| Tower selection.....                                 | 105 | 7-4   |
| The Tail Vane .....                                  | 105 | 7-5   |
| Field Test .....                                     | 105 | 7-6   |
| Analysis of the Test Results .....                   | 106 | 7-7   |
| CHAPTER 8: CONCLUSION & RECOMMENDATIONS .....        | 110 |       |
| References .....                                     | 111 |       |
| Appendix- A .....                                    | 113 |       |
| Abstract (in Arabic) .....                           | 118 |       |

## LIST OF SYMBOLS

|                       |                                            |               |
|-----------------------|--------------------------------------------|---------------|
| a                     | axial induction (interference) factor      | dimensionless |
| $\bar{a}$             | tangential induction (interference) factor | dimensionless |
| A                     | area                                       | $m^2$         |
| $A_{R \text{ proj.}}$ | the projected area of the rotor blades     | $m^2$         |
| $A_{T \text{ proj.}}$ | the projected area of the tower            | $m^2$         |
| B                     | number of blades                           | dimensionless |
| $B_x$                 | bending factor with respect to x – axis    | $cm^{-1}$     |
| $B_y$                 | bending factor with respect to y – axis    | $cm^{-1}$     |
| $c_t$                 | coefficient of wind pressure               | dimensionless |
| C                     | chord of blade                             | m             |
| $C_c$                 | the critical slenderness ratio             | dimensionless |
| $C_{\text{column}}$   | slenderness ratio of column                | "             |
| $C_d$                 | sectional drag coefficient                 | "             |
| $C_D$                 | blade drag coefficient                     | "             |
| $C_l$                 | sectional lift coefficient                 | "             |
| $C_{ld}$              | design lift coefficient                    | "             |
| $C_L$                 | blade lift coefficient                     | "             |
| $C_p$                 | power coefficient                          | "             |
| $C_Q$                 | torque coefficient                         | "             |
| $C_T$                 | thrust coefficient                         | "             |
| D                     | diameter                                   | m             |
| D                     | drag force                                 | N             |
| e                     | distance rotor plane – vertical axis       | m             |
| $e_r$                 | eccentricity of the rotor                  | m             |
| E                     | modulus of elasticity                      | $N/mm^2$      |
| f                     | frequency                                  | 1/s           |

|               |                                         |                        |
|---------------|-----------------------------------------|------------------------|
| $f_a$         | actual column stress                    | $\text{N}/\text{mm}^2$ |
| $f_y$         | yield stress                            | $\text{N}/\text{mm}^2$ |
| f.s.          | factor of safety                        | dimensionless          |
| $f_{bx}$      | actual bending stress about x – axis    | $\text{N}/\text{mm}^2$ |
| $f_{by}$      | actual bending stress about y – axis    | $\text{N}/\text{mm}^2$ |
| $F$           | force                                   | $\text{N}$             |
| $F_a$         | allowable column stress                 | $\text{N}/\text{mm}^2$ |
| $F_{bx}$      | allowable bending stress about x – axis | $\text{N}/\text{mm}^2$ |
| $F_{by}$      | allowable bending stress about y – axis | $\text{N}/\text{mm}^2$ |
| $F_w$         | wind pressure                           | $\text{N}/\text{m}^2$  |
| $g$           | acceleration of gravity                 | $\text{m}/\text{s}^2$  |
| $h$           | altitude                                | $\text{m}$             |
| $H$           | height of the tower                     | $\text{m}$             |
| $K$           | effective length factor                 | dimensionless          |
| $k_x$         | drag force                              | $\text{N}$             |
| $\tilde{k}_x$ | fluctuating force                       | $\text{N}$             |
| $k_y$         | yaw force                               | $\text{N}$             |
| $k_z$         | vertical force                          | $\text{N}$             |
| $l$           | length                                  | $\text{m}$             |
| $L$           | length of column                        | $\text{m}$             |
| $L$           | lift force                              | $\text{N}$             |
| $m$           | mass of the rotor                       | $\text{kg}$            |
| $m'$          | mass flow rate                          | $\text{kg}$            |
| $M$           | moment                                  | $\text{Nm}$            |
| $M_x$         | moment about x – axis                   | $\text{Nm}$            |
| $M_y$         | moment about y – axis                   | $\text{Nm}$            |
| $M_z$         | moment about z – axis                   | $\text{Nm}$            |
| $P$           | pressure                                | $\text{N}/\text{m}^2$  |
| $P^+$         | static pressure before the rotor        | $\text{N}/\text{m}^2$  |

|                    |                                          |                |
|--------------------|------------------------------------------|----------------|
| $\bar{P}$          | static pressure behind the rotor         | $\text{N/m}^2$ |
| $P$                | power                                    | W              |
| $P_{\text{equi.}}$ | Equivalent axial compression load        | N              |
| $Q$                | torque                                   | $\text{Nm}$    |
| $r$                | local radius                             | m              |
| $R$                | radius                                   | m              |
| $S$                | section modulus                          | $\text{cm}^3$  |
| $S_x$              | section modulus with respect to x – axis | $\text{cm}^3$  |
| $S_y$              | section modulus with respect to y – axis | $\text{cm}^3$  |
| $T$                | thrust force                             | N              |
| $V$                | wind velocity                            | $\text{m/s}$   |
| $V_{\text{ax}}$    | axial velocity through rotor             | $\text{m/s}$   |
| $V_1, V^\infty$    | undisturbed wind velocity                | $\text{m/s}$   |
| $\bar{V}$          | average wind velocity                    | $\text{m/s}$   |
| $V_2$              | wind velocity behind the rotor           | $\text{m/s}$   |
| $V_{\text{storm}}$ | peak velocity in storm                   | $\text{m/s}$   |
| $W$                | relative wind velocity                   | $\text{m/s}$   |
| $W_t$              | weight                                   | $\text{kg/m}$  |
| $z$                | coordinate height                        | m              |
| $z_0$              | roughness height                         | m              |
| $z_r$              | reference height                         | m              |

|             |                                                       |                   |
|-------------|-------------------------------------------------------|-------------------|
| $\alpha$    | angle of attack                                       | dimensionless     |
| $\alpha_d$  | design angle of attack                                | "                 |
| $\beta$     | blade setting angle                                   | "                 |
| $\delta$    | angle between the wind velocity and rotor axis        | "                 |
| $\eta$      | efficiency                                            | "                 |
| $\lambda$   | tip speed ratio                                       | "                 |
| $\lambda_d$ | design tip speed ratio                                | "                 |
| $\lambda_r$ | local tip speed ratio                                 | "                 |
| $\pi$       | 3.14159265359                                         | "                 |
| $\rho$      | density                                               | kg/m <sup>2</sup> |
| $\sigma$    | solidity ratio of the rotor                           | dimensionless     |
| $\Phi$      | angle between relative wind direction and rotor plane | "                 |
| $\omega$    | induced tangential angular wind velocity              | 1/s               |
| $\Omega$    | angular velocity of the rotor                         | 1/s               |
| $\varphi_1$ | a factor of the dynamic influence of the wind         | dimensionless     |

**STUDY AND DESIGN OF A HORIZONTAL AXIS – WIND  
TURBINE FOR ELECTRICITY GENERATION**

Thesis Submitted To The College Of Engineering Sudan University Of  
Science & Technology In Fulfillment Of The Requirements For  
Awarded Degree Of M.Sc. in Mechanical Engineering.

BY  
**MURTADA HASSAN ABDULRAHMAN**  
B.Tech. Mechanical Engineer

May, 2005