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Design and analysis of a small scale horizontal axis wind turbine using MartDes software

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ABSTRACT

This paper describes todesign and analysis of a small scale horizontal axis wind turbine by applying MarTDes Software for the part of solution of long term world's energy problem. A short overview about wind energy applications are explained with a basic analysis of energy. This report also includes some evaluations and discussions of wind energy systems in the following pages. Additionally, total cost of turbine and some benefits such as amount of generating electricity are calculated. The general purpose of the research is to find and analyze how efficiently small wind turbine works and generate energy at optimum conditions.

KEYWORDS

Wind turbine systems;
Energy planning;
Horizontal axis wind turbine;
MarTDes;
Wind turbine cost;
Small scale wind turbine;
Electricity production;
HAWT design.

INTRODUCTION

Compared to the other renewable energy resources wind power can considered to be more preferable renewable energy application. This is because of the low cost and the high wind potential of the World (Figure 1), which are the most important two parameters in the process of utilization of an alternative energy method, of implementation of wind power system[1]. This study also claims that the installed wind generation capacity has risen from 25000MW to more than 200000MW in a decade (from 2001 to 2010), especially in horizontal axis wind turbine because of the availability of this kind of turbine for the large scale electricity.

Modern technological development contributes to the wind turbine technology. The technological improvement on the wind turbine leads to use high capacity machine, higher tower high, wider swept area of the rotor blade, better aerodynamic and structural design faster computer based-machining techniques and as an inevitable result of this generation it is achieved high annual energy output, low noise and better weight of turbine as well as better feedback from government[4]. The study also mentions that the average wind speed, statistical wind speed distribution and the cost of wind turbine are used to determine about the economic potential of the system.

A Horizontal Axis Wind Turbine (HAWT) is a device which provides the extraction of the power in a moving mass air and generates electricity from

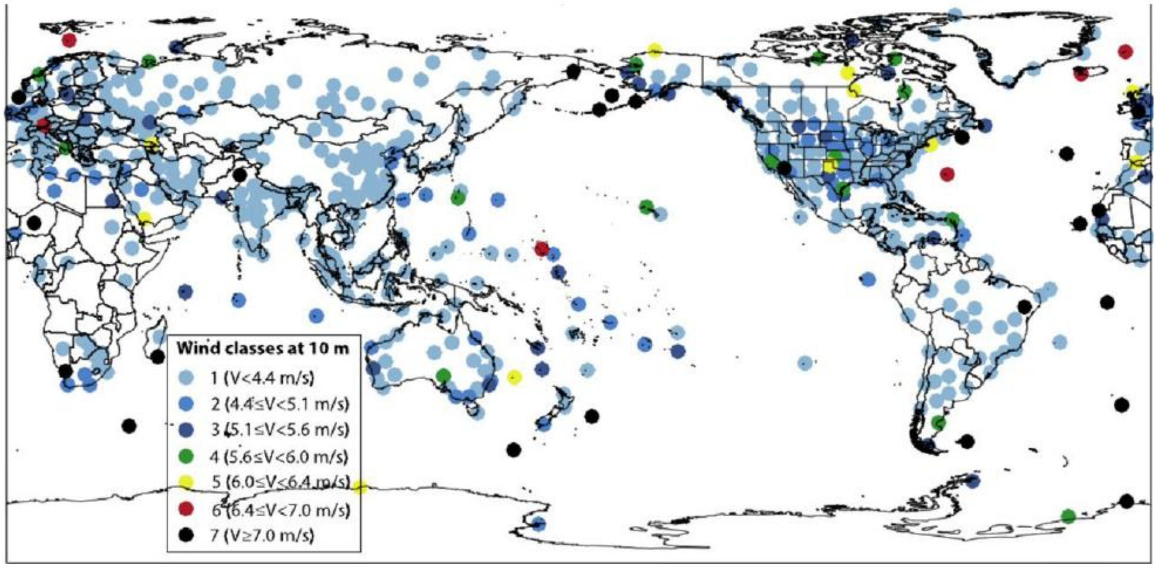

Figure1 : Average wind velocity in different regions of the world. (Adapted from: Bhutta et al.2012)

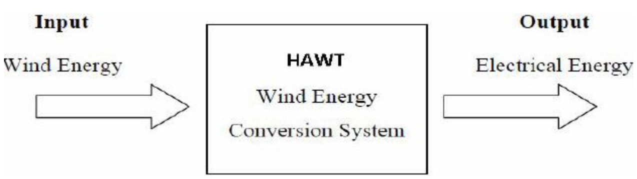

Figure 2 : HAWT system diagram

this power, (Figure 2).

There are some major components of HAWT (Figure 3); for example,

- Rotor- to convert the kinetic energy into rotational energy
- Generator- to convert the rotational energy into electrical energy.
- Tower and Foundation- These devices provide elevate turbine to generate electricity and stability in high speed winds.
- Energy Storage System- Batteries are usually used to store electricity. However, that electricity is converted for suitable grid connections with inverter.
- In addition to these components, blade pitch control systems, gearboxes and some braking systems are used for HAWK designs[2].

DESIGN PARAMETERS

Wind turbine sze

With the considerable increase in technology, wind turbine size increased significantly from about 100 kW in 1980 to 2500kW in 1990 and now it is available to have 3500 kW capacity of wind turbine[4]. Additionally, it is seem that Europe has the largest annual growthwith the rate of 22% and in the future it is expected that the penetration will continue and reach level of $1.9*10^9$ kW by the year 2030-3035.

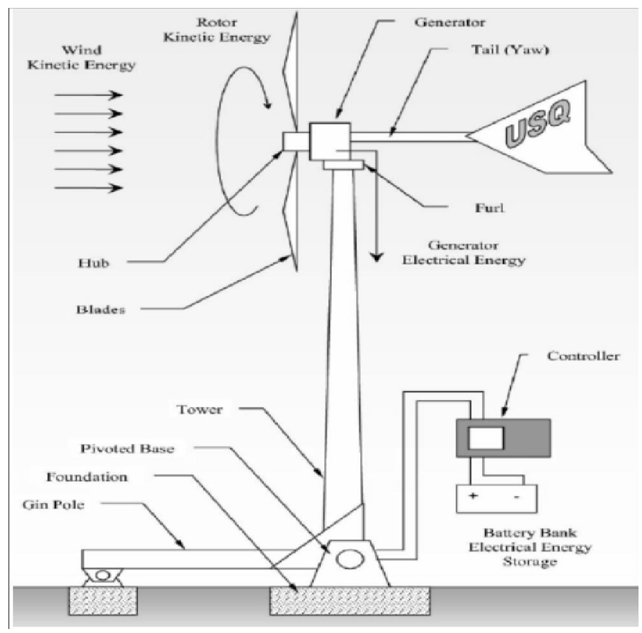

Figure 3 : HAWT Components (Simon James Strong, 2008)

Site selection

There are some important parameters which directly affect the availability of the efficiency of the wind turbine system; height above from ground, wind

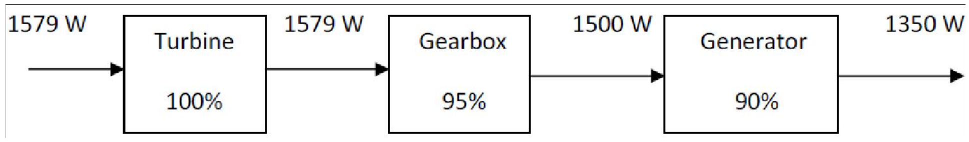

Figure 4 : Connections of Components, P= 1350/(0.90x0.95): 1578.9 W (power required)

TABLE 1 : Input and Output values of MartDes

V(m/s)	No of Blade	Turbine Diameter	The power (Watts):	Max power coefficient:	Tip Speed Ratio	The revs (RPM):	The torque (Nm):
6.8	2	4	1076.865	0.485	8.778	285	36.082
6.8	3	4.8	1571.434	0.491	9.979	270	55.578
6.8	**3**	**4.9**	**1637.829**	**0.491**	**10.187**	**270**	**57.926**
6.8	3	5	1704.994	0.491	10.395	270	60.302
6.8	3	5.2	1842.001	0.49	10.21	255	68.98

gusting wind availability. There are considerable numbers of scientist who focus on the find the most efficient method to determine sitting place for the wind power plant such as Mertens[7] explain the effects of flow feature and guidelines for the small scale wind turbine system by installing it on the roof.

Wind turbine technology

The other important development in the wind turbine technology is on the storage and conversation of energy. In this regard, it is mentioned that it is possible that several wind turbines can be connected to load and the battery storage and it can be injected a grid system easily by applying probabilistic model[5].

Design

A considerable number of methods are using to design calculation for the wind turbine performance and loading[4]. For example, a multi-objective optimisation method which is designed by Erdnesto et al, for the design of HAWTs, based on the coupling of aerodynamic model implementing the blade element theory and evolutionary algorithm.

Blade

Blade is being considered one of the important parts to increase the efficiency of the wind turbine by many scientists. Due to the importance of blade there are many researches about rising the efficiency of blade such as a multiplicative damage model is a new model developed by Patgetl for strength of fibrous composite materials. The aim of this model is to describe the failure of strength of these materials[4].

RESEARCH DESIGN

Wind speed

The wind speed goes up with height in the boundary layer. It is shown the following equation 1[3].

$$v_H = v_{wind}\left(\frac{H}{H_{hub}}\right)^{\alpha} \quad (1)$$

V_H : Wind velocity at height (m/s); H_{hub} : Height of turbine hub above ground level (m); H: Height from ground level (m); α = Hellmans's exponent

First of all, some values are given in the equation[3] as, α: 0.14, : 10 m, :6.8 m/s.

Then 'H' was chosen as, 10 m, so =:6.8 m/s

Power required

In theory, the maximum possible rotor power coefficient (Cp) is offered by the Betz Limit,

$$Cp = \frac{Rotor\ Power}{Wind\ Power} = \frac{16}{27} = 0.593$$ [6]

Nevertheless, in practical the maximum coefficient decreases because of some losses such as losses at the blade tips and electrical losses. Furthermore, the number of applications and kind of materials also cause a reducing in the maximum output power. Thus, the power output of the HAWT can be identified on Equation 2 as;

$$P = 0.125.Cp.\rho.\eta.\pi.D^2U^3 (W) \quad (2)$$ [2]

Where; Cp: power coefficient; η: efficiency of the turbine.

After that, Power, which is required of turbine,

TABLE 2 : Output values of V and P

RPM	V (m/s)	Power by wind(W)
240	108.7542	35456.49224
240	54.37229	10054.70501
240	36.24926	4999.391054
.	.	.
.	.	.
240	6.796537	1627.299153
240	6.396774	1361.151066
240	6.041366	1148.047158
240	5.723426	974.7719557
.	.	.
.	.	.
240	2.471478	9.362899846
240	2.416551	5.101838475
240	2.364022	1.372666056

was calculated with using of generator efficiency (90%), generator rated power (1350 W) and gearbox efficiency (95%). Figure 4 shows connections of such three components.

After the calculation of required minimum power, the program 'MarTDes' was used to compute suitable power which has to be just more than 1579 W. Some different values were entered to choose optimum Cp, Power and Torque. TABLE 1 shows different values that are used on MartDes Software to find said outputs.

According to the TABLE 1, one of the best results, which are marked black, was chosen because that provides optimum conditions; for instance, power is just over the 1579 W and max. Cp seems acceptable output when compare with theoretical coefficient.

OUTPUTS DESIGN

U vs. Power

In this section, a fixed RPM (240) was chosen to calculate different wind speed rates which depend on different Cp values, (Equation 3),[2].

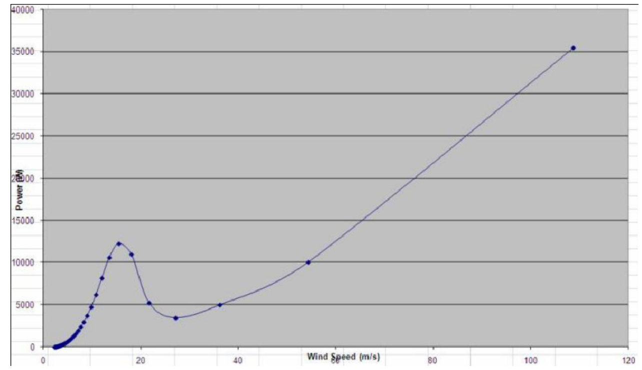

Figure 5 : U vs. Power

TABLE 3 : Some C_t and Thrust rates

V (m/s)	Ct	Thrust by wind(W)
9.885951	0.681718871	706.3607775
9.062049	0.691606831	602.1385548
8.365025	0.703938529	522.2201056
7.767471	0.717577361	458.9996044
7.249682	0.729555349	406.5186716
6.796537	0.739548157	362.1814039
6.396774	0.747561496	324.3047053
6.041366	0.753612706	291.6102974
5.723426	0.757812753	263.1833439
5.437229	0.760259755	238.2877211

$$U = \frac{\pi . D . N}{60 . Cp} \quad (3)$$

Where; N: 240 RPM, D: 4.9 m

After the all wind speed values were calculated, these values were represented on a tubular form and then these numbers were used to compute Power (by wind) by Equation 2;

$P = 0.125 . Cp . \rho . \eta . \pi . D^2 U^3$ (W) Where; D: 4.9 m, ρ:1.125 kg/, Cp and U :variable

Once Power could be calculated with fixed RPM value, ideal power will be computed as 1627,299 which is almost the same with MarTDes output power

As a result of evaluations, two equations (V and P), give 47 different wind speed and power values as from 108.7542 m/s to 2.3646 m/s and from 35456.49 W to 1.3726 W. Some of these rates were shown on TABLE 2.

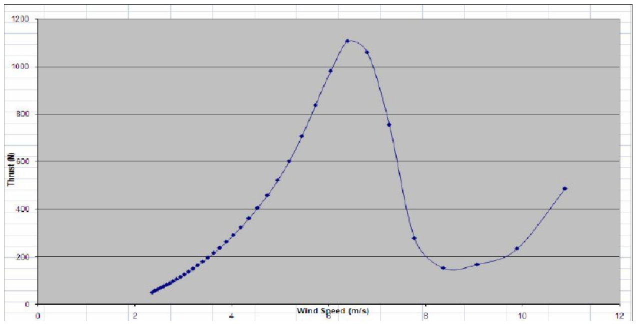

Figure 6 : U vs. Thrust

Furthermore, these data were used in a graph form namely V-Power,(Figure 5). This figure shows that how much energy might be generated with constant RPM and variable wind speed from this HAWT.

U vs. Thrust

In the same way, Wind speed- Thrust graph will be comprised. However values (by wind) have to be calculated with following equations 4 and 5[2].

Before calculation of Thrust (by wind), thrust coefficient rates were computed with utilizing thrust outputs of MarTDes.

$$C_T = \frac{8.T}{\rho.V_{wind}^2.\pi.D^2} \quad (4)$$

Where; ρ: 1.124 kg/, V: 6.8 m/s, D: 4.9 m ; Thrust: variable

After the calculation, results of values were formed and then these values are utilized to compute Thrust (by wind) rates with equation 5.

$$T = \frac{C_T.\rho.V^2.\pi.D^2}{8} \quad (5)$$

Where; V: wind speed (m/s) variable, ρ: 1.124 kg/, D: 4.9 m,: variable

Then at the end of this process, TABLE 3 represents some and Thrust rates. Moreover, Figure 6 illustrates on Thrust and Wind speed data.

TSR vs. Cp

The Figure 7 shows rates of Cp when TSR increases gradually. Both Cp and TSR data were taken from MarTDes.

According to the graph, From 0.5 to 3, proportion of Cp increases slowly and then continues to increases but sharply to 45% at early 5s (TSR).

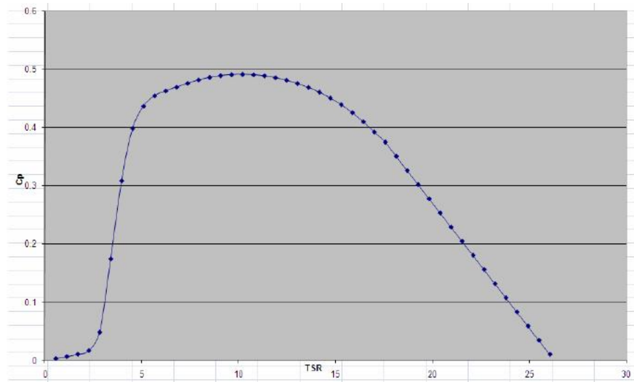

Figure 7 : TSR vs. Cp

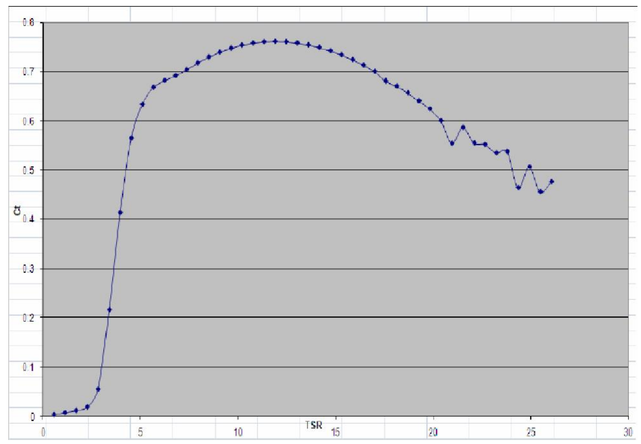

Figure 8 : TSR vs. Cp

Then, Cp reaches maximum efficiency (0.491) at 9.0552(TSR). After that point, between the TSR 9 to 12.4, Cp declines slightly and then continues to decrease but more steeply to approximately 0 (zero) at 26.0336(TSR).

TSR vs Cp.

The Figure 8 illustrates rates of values when TSR increases. values on this graph were calculated with equation 4 before and TSR rates were taken from MarTDes.

Basically, the graph explains that optimum rates can be taken between the TSR values 5 to 20.

Cut in and Cut out wind speed of Turbine

Commonly, wind turbine is designed to begin running at wind speeds somewhere around 3 to 5 meters per second. Cut in speed for this design was accepted as 5.437229 m/s where the generated power is about 832.5 W.

Cut out speed provide stop wind turbine at high wind speed to avoid damaging the turbine. Cut out

TABLE 4 : Pitch angle and C_p values

Tip Pitch Angle(deg.)	Max.Power Coefficient Cp
-10	0.068
-9	0.017
1	0.491
2	0.475
10	0.258
20	0.126
30	0.068
40	0.054

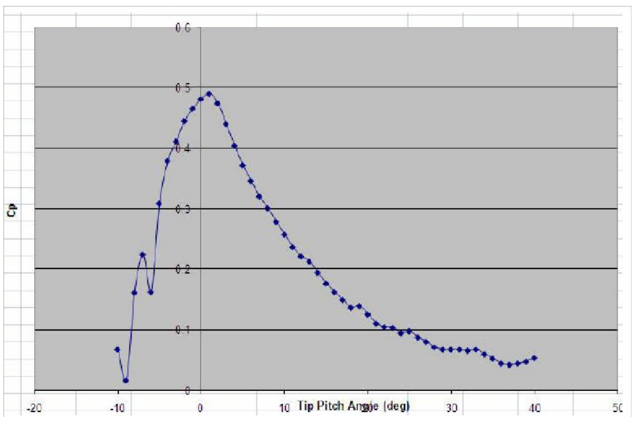

Figure 9 : Effect of Tip pitch Angle on Cp

speed for this designed can be almost as 7.76 m/s.

EFFECT OF PITCH ANGLE

In this stage, effect of pitch angle on Cp was investigated. For instance, wind speed, turbine diameter, tip chord length and number of blades are constant while only tip pitch angle were changed from -10 degree to 40 degreeincreasing by 1 degree. Then, maximum power coefficient rates were calculated for each degree. TABLE 4 shows some of these data which were calculated with MarKDes.

Furthermore, Figure 9 illustrates effect of pitch angle on power coefficient. All pitch angle degrees can be seen on the graph. The maximum Cp can be obtained at 1 and 2 degree.

In addition to above descriptions, 7 different tip pitch angle degrees as -5,-2,2,10,20,30 and 40 were taken to prove changing of Cp rates strongly. Firstly these angle values were entered on program and then all Cp max outputs are kept. Finally, 7 different series were comprised on Figure 10.

TABLE 5 : Wind speed and P (U*F (U) values

U(wind speed) m/s	P(U)*(F(U)
7.767470625	244.047037
7.249681949	212.12294
6.796536797	182.8645382
6.396773758	156.8263541
6.041366041	134.1945697
5.723426021	114.6641668
5.437229437	97.94336748

ESTIMATED ANNUAL ELECTRICITY GENERATED

In this part approximately annual energy generation will be calculated. As it is accepted before wind turbine might works between the cut-out speed and cut-in speed to protect damaging at high speeds. Thus, power values, P (U), were taken on this criteria.

Furthermore, probability function (F (U), equation 6), was used to calculate annual energy capture. Finally, these data were used on energy function (equation 7). TABLE 5 shows wind speed and P (U). F (U) rates.

$$f(U) = \frac{\pi \cdot U}{2 \cdot \overline{U}^2} \cdot e^{-\pi.(\frac{U}{2\overline{U}})^2} \quad \textbf{(6)}$$

$$E = T. \int_{Umin}^{Umax} P(U). f(U). dU \quad \textbf{(7)}$$

Estimation of Annual Energy Capture: 3331809.345 W = 3.331809 MW

COST OF COMPONENTS

The total cost of HAWT, which was designed above, was assumed as follows;

(a)The cost of Gearbox /Generator/Hub/Grid connections were given as; **£2250** (fixed)

(b)Blade Cost:

$\frac{Hub}{Diameter} = 0.10 \frac{Hub}{4.9} = 0.1$ Hub: =0.49 m (diameter)

A 1 m long blade £135

TABLE 6 : Comparison of different designs

V(m/s)	Height (m)	No of Blade	Turbine Diameter	The power (Watts):	Max power coefficient
6.8	10	3	4.9	1637.829	0.491
6.6	8	3	4.6	1318	0.49
Tip Speed Ratio	Gearbox Ratio	The torque (Nm):	Total Cost £	Annual elec.generated MW	
10.187	6.167	57.926	5313	3.331	
9.853	5.046	46.618	4391.83	2.719	

3 same blades were chosen and its diameter is 4.9 m

Blade Cost: (3x (2.45-0.245)x135=2050.65 **£893.025**

(c) Structure/Installation : $F = \frac{H.T}{d^3}$ (from assignment document)

Where; F: Failure Criterion

A 10m pole, of 0.1m diameter is suitable design speed load of 250 N and costs £1700 for installation and materials. However, Thrust was calculated different from this value.

So;

$$F = \frac{10.250}{0.1^3} = 2500000\ N$$

$$d = \sqrt[3]{\frac{10x362.2}{2500000}} = 0.113\ m$$ This F will be used for designing Thrust;

$$x = \frac{1700.10.0.113^2}{10.0.1^2} = 2170$$

Pole volume $H.d^2$

Structure/Installation cost : **£2170**

Total Cost: £2250 + £893.025 + £2170 = £5313

COMPARISON OF THIS DESIGN WITH DIESEL GENERATOR AND OTHER WIND TURBINES

TABLE 6 shows that once different size values are used, this event causes changingof outputs such as maximum power and annual electricity generation. In addition to this, a diesel generator, which requires same power with above wind turbine design, uses approximately 80000 liter diesel

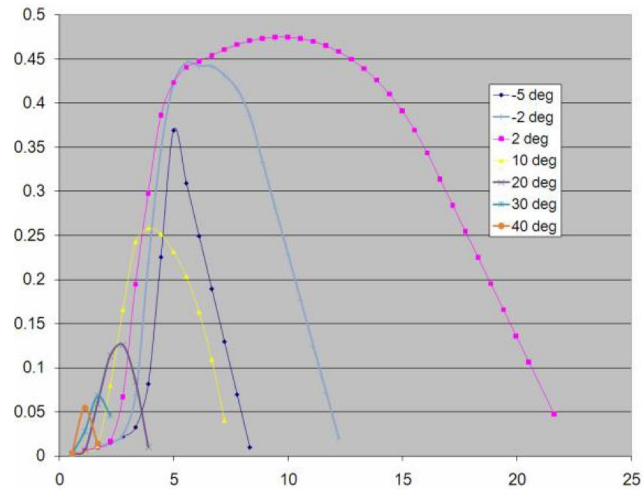

Figure 10 : Effect of Tip pitch Angle on TSR vs. Cp

(£87200).

CONCLUSION

There is a great demand for wind turbine technologies over the world, because these systems have a strong potential for remarkable primary energy savings. Furthermore, wind turbine systems have a wide market choices, so significant cost reduction of energy consumption can be possible in short-medium term.

The aim of this project was design of a small scale horizontal axis wind turbineby applying MarTDes Software. For this reason, some important values such as optimum wind speed, turbine diameter, power required, thrust and Cp were identified by utilizing MarTDes Software. Furthermore, basic definitions about wind turbine parameters and components were tried to explain in more detail. Additionally, annual energy generation and cost analysis of turbine were calculated. In fact, this study shows how wind turbine could be used to generate energy at optimum conditions. As a result, outputs of the system show that such horizontal axis wind turbine will be a new sector to provide environmentally-friendly energy for domestic use.

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