Design Of Small Wind Turbine To Operate Grain Mill

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Abstract

This work represent design of 37.037kw a horizontal- axis wind turbine with three blades to operate grain mill with power of 25KW in Sennar State. The problem of study that sennar suffer about unstable of power generation. The main components and parameters of design were obtained from Sennar state metrological authority and Sudan wind prospecting map from the year 2008 to 2017. These parameters included, average wind speed was5.6m/s at 50m high, wind direction is north, location of turbine in east bank of Blue Nile north Sennar Dam. Design calculation showed , swept area of blade (A)was 860mm^2, rotor radius(R)was523.34mm tip speed ratio(λ)was 4.189,angularspeed(ω)was0.0451rad/s, power coefficient (Cp)was0.4,power production(P)was37.037KW,annualenergyproduction (AEP)was54074.02KWh/year. Matlab software with Excel sheet used to obtain all characteristic curves between, pitch angle(β),power coefficient (cp), tip speed ratio(λ),rotor output power(P), relative power(Pr) vs wind speed. Inverter used to convert Ac current to Dc current, storage power by four batteries of 12volt-200amper for each .The study Recommended this work con be extended to include, design the gearbox, add storage unit, design the tower, consider of economic befits and the cost of design and material.

INTRODUCTION

Wind power is one of the fastest-growing renewable energy technologies. It has used on the rise worldwide, in part because costs are falling. Global installed wind-generation capacity onshore and offshore has increased by a factor of almost (75) in the past two decades, jumping from (7.5) giga watts (GW) in 1997 to some (564) GW by 2018, according to IRENA's latest data[1].Production of wind electricity doubled between 2009 and 2013, and in 2016 wind energy accounted for 16% of the electricity generated by renewables [2].

Sudan blessed with abundant wind energy potential ready to be exploited. Since 1980, wind energy used in rural areas in Sudan because of the increasing of production demand in rural areas. That was a reason for the Sudanese government to pay more attention to wind energy utilities especially in rural areas. Wind energy potential is very good in different locations in Sudan and it is attractive for wind pumps and in fact that the fuel is not sufficient, the wind pumps will spread widely through the rural areas. Currently, different types of wind pumps manufactured commercially in Sudan. Wind Energy in Sudan would be more profitable in local, small-scale applications for rural and remote areas in which the lack of electricity access is dominating [3]. Currently, Sudan has plans for establishing wind farm development in three different regions in the country, they are:

- Northern Sudan state, Dongola with capacity 100 MW
- Western Sudan state, Nyala with capacity of 20 MW
- The coastal region of eastern Sudan, the Red Sea coast with capacity of 180 MW
- **Wind energy:**

wind considered as one of the indirect solar energy forms,which are mainly caused by a combination of four concurrent events [4]:

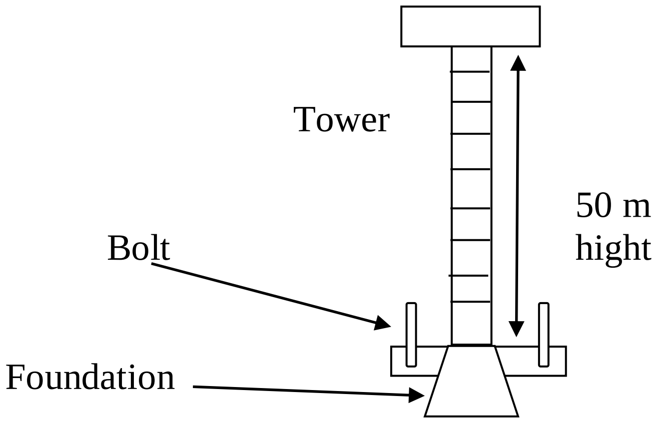
- The sun unevenly heating the atmosphere.
- Air pressure variation from one region to another.
- Irregularities of the earth’s surface, i.e., topology.
- The rotation of the earth.
- **2 Assessment of the wind resources:**
- Evaluation of wind resources for their usage in terms of energy generation with the aid of wind turbines (WTs) is very essential for efficient and feasible energy generation.Wind resource assessment revolves around the

geographical location, wind velocity, and wind characteristics. Many approaches suitable for this assessment captured in the literature, such as wind speed persistence, which is vital during the extraction of wind energy[5].

- wind energy is one of the promising environmentally friendly renewable energy resources. However, the unpredictable nature of wind in terms of speed and direction makes its forecasting very difficult [6].
- the selection of rated wind speed is the most important factor for the wind energy system and should be based on the optimization of energy production and cost according to the LCOE from one side and capacity factor from the other side [7].
- **Types of Wind Turbine:**
- Wind turbines (WTs) are mainly classified based on the orientations for the axis of rotation, type of generators, speed of rotation, and the control action used, as depicted in Figure (2.2). The optimum combination of these elements for a specific WT usually carried out according to the specific location characteristics [8]
- **Design of the Wind Turbine System:**
- Wind turbine systems made up of electromechanical systems that are very complex with several parts. There are key factors that determine the selection of the size and design of the WTs. Some of these factors include the site characteristics, demand, and wind profile. The overall aim of this is to reduce LCOE. A WT's system is made up of more than 8000 parts, but these parts are usually subdivided into six main parts, as shown in Figure (2.9): the blades, nacelle, hub and rotor, tower, yaw mechanism, and finally the foundation [9,10].
- **The objective of the study:**
- 37.037 kW Small-scale horizontal- axis Wind Turbine with three blades Design in Sennar State – Sudan

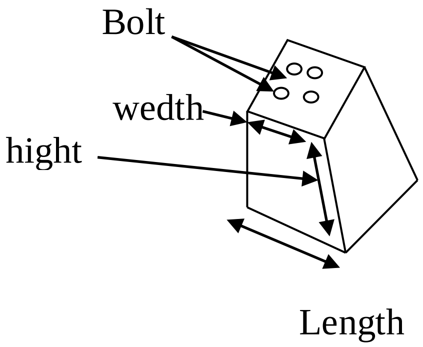
- **Design Of Small Wind Turbine**
- Site selection
- the location at east side of the river Nile, north of sennar Dam. This Site has good boundary condition, ,no high building, free of trees, no plane airport and far from building.
- lay out of wind turbine:
- 1 Tower:

Tower high 50m, has cylindrical tube made of sheet metal .knows as tubular tower.



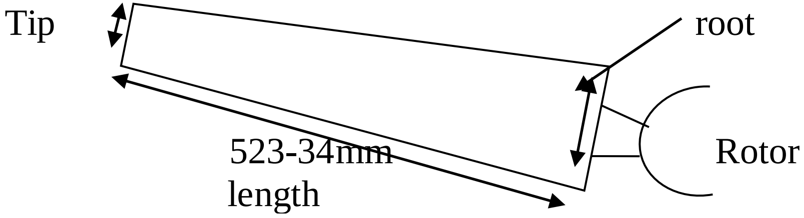
figur (.1) : tower of wind turbine

2 foundation : concrete foundation made of cement



figur (2) :cement foundation

3 Blade: mad of sheet metal it must be narrower at the Tip and wider at the root and it has shape of Airfoil



Figure(3) : shows blade dimension

Estimate power needs to operate grain mill

By experience design of grain mills

common grain mills works from20- 40(hp),power required of grain mill in this study=33.34(hp)

Where:

hP = horse power .

1hp = .75KW

(Pg) grain mill Power required =O.75×33.34= 25KW

Suitable high is 50m,because 10and20m has low average wind speed.table3.1shoes annual mean speed from January to December for ten year, from2008 to2017.

Table.(1) : shows mean wind speed at different high

Month	mean Wind speed at10m high	mean wind speedat20m high	Mean wind speed at50m high
January	4 m/s	5.11m/s	5.59m/s
February	4 m/s	5.21m/s	5.87m/s
March	4 m/s	4.93m/s	5.83m/s
April	4 m/s	4.24m/s	5.6m/s
May	4 m/s	4.09m/s	5.27m/s
June	4 m/s	4.81m/s	5.35m/s
July	5 m/s	5.04m/s	5.93m/s
August	4 m/s	4.45m/s	5.71m/s
September	4 m/s	3.39m/s	4.81m/s
October	3 m/s	3.41m/s	5.92m/s
November	4 m/s	4.56m/s	5.24m/s
December	3 m/s	5.04m/s	5.39m/s
Annual mean speed	4m/s	4.31m/s	5.6m/s

From the table above:-

average wind speed at 50m high was5.6m/s

Calculation of power required for turbine:

order power required from turbine, there are some losses have to be notice when convert power to grain mill , to calculate this losses we must consider the efficiency of grain mill, table blew shows different losses uses in wind energy studies .

table.(2) : shows losses of power

Factor	Typical efficiency
Rotor to shaft	92-97%
Shaft to gear box	93-96%
Gear box	99%
Pump or generator	60-75%

$$\text{Efficiency} = \frac{\text{out put power}}{\text{In put power}} \times 100\% \qquad (1)$$

$$\text{In put power} = \frac{\text{out put power}}{\text{Efficiency}} \times 100\% \qquad (2)$$

Before mill losses:

$$\text{Average efficiency of mill} = \frac{60+7.5}{2} = 67.5\%$$

$$\text{power} = \frac{25}{67.5} * 100\% = 37.037\text{KW}$$

(Pt) This is turbine power required

Calculation power coefficient (Cp)

According to betz theorem that Cp = 59.3%, but in actual Power of turbine we obtain 70% + 80% of this value (wind Energy handbook, Toney Borton, 2001) so the max value of cp.

$$\text{We take the average} = \frac{70 + 80}{2} = 75 \text{ X } 0.593 \qquad = 0.4$$

Radius of Rotor(R) can be obtained by this equation

$$(\text{Pt})\text{turbine power} = ½\, eAu^3 Cp[11] \qquad (3)$$

Where:

Pt = turbine power (kw) ρ = Air density (kg/ m^3)

A = swept Area by rotor (m^2) U = wind speed (m/s)

CP = power coefficient

We have Pt =37.037KW , u = 5.6m/s, cp = 0.4 ,ρ = 1.2 kg/m^3

A swept area = $\frac{37.037\times2}{1.2\times.4\times5.64^3}$ = 0.860m^2= 860mm^2

A (swept area) = π. R^2

Radius(R) = $\sqrt{\frac{860}{3.14}}$ = 523.34mm

.: Rotor diameter(D) =1046.68mm = 1.047m

radius = blade length (L) =523.34mm

the blade shape is Nasa 0012profile with The angle of attack=5°

Tip speed Ratio (TSR) (λ) can be obtain by using the following

equation

$$\lambda = \frac{4\pi}{N} \quad [70] \tag{4}$$

Where: λ= Tip speed Ratio N = number of Blades

Number of blades = 3 blades, common (HAWT) has three blade to achieve max power than tow or one blade [12]

.:$\lambda = \frac{4\pi}{3}$ = 4.189, this is optimum value of (TSR), λ optimum

Angular speed can be obtain by using the following equation(3.5)

equitation of Tip speed ratio:

$$(\lambda)\text{optimal}= \frac{R\omega_{design}}{U_{design}} \quad [13] \tag{5}$$

$$\text{Angular speed}(\ \omega) = \frac{\lambda \text{ optimal X u design}}{R} \tag{6}$$

(λ) Tip speed Ratio,(u) winds speed,(R) Radius of rotor

(ω) *Design* = $\frac{4.189 \text{ X } 5.6}{523.34}$ =0.0451 rad/s

3.10 Calculation of torque (T)

$$P = T \times \omega \tag{7}$$

Where

P = wind power (kw) T = Torque (K_N) ω = angular speed (Rad/s)

From equation (3.7) of tip speed ratio (TSR) (λ)

$$(\lambda) = \frac{R\omega}{U} \tag{8}$$

Where:

λ = Tip speed ratio (TSR) R = rotor radius (m) ω = angular speed (rad/s)

U = wind speed m/s

$$.: \omega = \frac{\lambda u}{R} \tag{9}$$

Substitute in equation (3.8)

$$T = \frac{P}{\omega} = 0.5 \times \frac{\rho \times A \times u^3 \times R^2 \times R}{\lambda \times u} = 0.5 \underset{-}{\times} \frac{\rho \times A \times u^2 \times \pi \times R^3}{\lambda} \tag{10}$$

$$= \frac{0.5X1.2X\ \pi X(5.6)^2(0.523)^3}{4.189} = 2.018\ Nm$$

Power output of the wind turbine:

The wind power on the rotor blades is given by:

$$P_{wind} = \frac{1}{2}\rho A u^3 \ldots[11] \tag{11}$$

Where

ρ= Air density, kg/m^3 A = Area swept by blades, m^2 u = Undisturbed wind speed, m/s

Mechanical power output of the wind turbine is given by:

$$P_{mechanical} = \frac{1}{2}\rho A u^3 C_p(\lambda, \beta) \ldots[14] \tag{12}$$

Where:

(λ, β) = the power coefficient of the turbine which depends on, Tip speed ratio (λ) and Pitch angle(β).

The tip speed ratio is defined as the ratio between the blade's tip speed and the wind speed.

$$\lambda = \frac{V_{tip}}{u}, \quad V_{tip} = R\omega \qquad (13)$$

Where: V tip=blade tip speed R= Radius of wind turbine(m).

ω = Angular velocity of the turbine(rad/s). u =Undisturbed wind speed(m/s).

The power coefficient of the rotor is given by:

$$C_p = C_1 (C_2 - C_3\beta^2 - C_4)^5 \qquad (14)$$

[72]

Where

C$_1$=0.5 , $C_2 = \frac{R}{\lambda}$, C$_3$=0.022 , C$_4$=5.6 , $C_5 = \frac{0.1\,R}{\lambda}$

β is kept constant at 1^{o} up to the rated wind speed.

3.12 Power coefficient ($Cp(\lambda)$) curve for pitch angle (β) = 1^{o}:

$$C_p = C_1(C_2 - C_3\beta^2 - C_4)e^{C5} \qquad (15)$$

$$C_p = 0.5(\frac{R}{\lambda} - 0.022 \times 1^2 - 5.6)e^{\frac{-0.17R}{\lambda}}$$

$$C_p = 0.5(\frac{2.4}{\lambda} - 5.622)e^{\frac{-6.8}{\lambda}}$$

Cp vs λ Characteristic curve is obtained using Matlab as shown in Fig .1

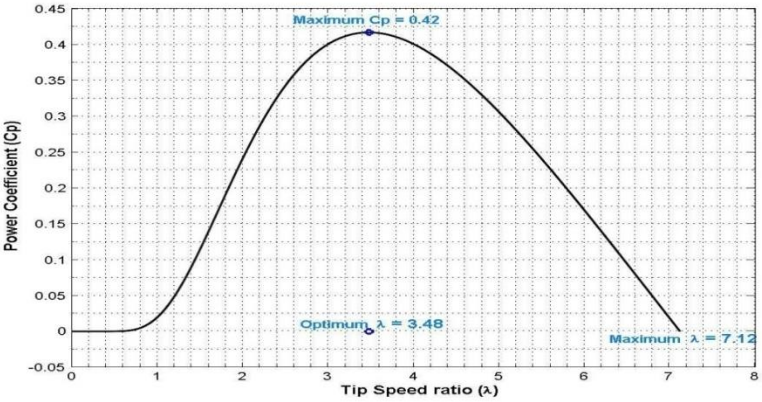


Fig..1 Power coefficient (C_p) vs. tip speed ratio (λ) characteristic curve

As per the Fig..1, following values can be obtained.

$C_{p\ max} = 0.4$, $\lambda_{optimal} = 4.189$ and

$\lambda_{maximum} = 7.12$

3.14 Calculations in the maximum power coefficient ($C_{p,\ max}$) region

In torque controller region, λ *is maintained at its optimal value(*$\lambda_{optimal}$*) of 4.189 for the design wind speed (*u_{design}*) of 5.6m/s in order to extract the maximum power.*

$$\lambda = \frac{R\omega}{u} \tag{16}$$

For the optimal

$$= \quad \omega\ design = \frac{5.6 \times 4.189}{523.34}$$

$$\omega_{design} = 0.0451 rad/s = 0.4307 rp$$

Since the turbine could be operated in a range of ω_{design} ±5% by keeping power coefficient at $C_{p\ max}$, over the specified range of wind speed.

According to the above design criteria, the maximum rotational speed of the turbine,

$$\omega_{max} = \frac{0.4307\times 105}{100}$$

$$\omega_{max} = 0.4522\text{rpm} = 0.0476\text{rad/s}$$

the minimum rotational speed of the turbine

$$\omega_{min} = \frac{0.4307\times 95}{100}$$

$$\omega_{min} = 0.4092\text{rpm} = 0.0428\text{rad/s}$$

Hence, according to the above obtained results the tip speed ratio is kept at $\lambda_{optimal}$ within the range of turbine speed; 0.0428 rpm and 0.0476 rpm. Also, it can be found the range of wind speed corresponding to the above range of rotational speeds of the turbine by keeping the λ at its optimum value

$$\lambda = \frac{R\omega}{u}$$

Annual energy production (AEP):-

Equation of annual energy production:

annualpower(kwh/year)=365(days)×24(hr)×powerrated×capacityfactor(CF).[73] (17)

capacity factor(CF) of turbine is a ratio of its actual output power to its maximum power out put

CF= actual output power /maximum power output. (18)

maximum power (p max) happen at wind speed t 7.5m/s

From sudan-wind prospecting map ,rated wind speed was7.5m/s and cut-off wind speed was12.5m/s.

(p) ma x = .5×ρ× A× U^3× Cp

$=.5\times1.2\times\pi\times(0.523)^2\times(7.5)^3\times0.4 = 86.9617$kw.

CF = 37.037 /86.9617 =o.4

To calculate annual power assume grain mill works 10 hours by day.

Annual power production (AEP) =365×10×37.037×.4 =54074.02kwh /year

Results and discussion

Results

As mentioned above design requirement and element shows in table(3.3)

Table 2 shows the elements of wind turbine and grain mill

No	Data	Value	sample
1	Power required for grain mill	25KW	P_g
2	Power required for turbine	37.037KW	P_t
3	Tip speed ratio	4.189	Λ
4	Blade swept area	860mm^2	A
5	Blade length	523,34mm	L
6	Rotor diameter	1.047m	D
7	Number of blade	3 blades	N
8	Angular speed	0.0451rad/s	Ω

9	Rotational speed	0.4307rpm	RPM
10	Torque	2.018KN	T
11	Average wind speed	5.64m/s	U
12	Cut-in wind speed	1.7983m/s	u_{cut-in}
13	Rated wind speed	7.5m/s	u_{rated}
14	Cut-off wind speed	12.5m/s	$u_{cut-off}$
15	Capacity factor	0.4	CF
16	Annual energy production	54074.02Kwh/year	AEP
17	Power coefficient	0.4	Cp

Design characteristic curves obtained in graph of figures showing blew

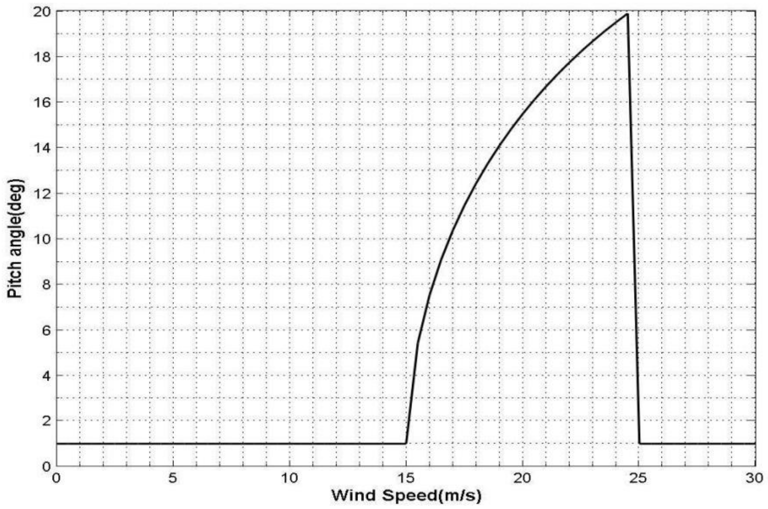


Figure. 2. Pitch angle (β)

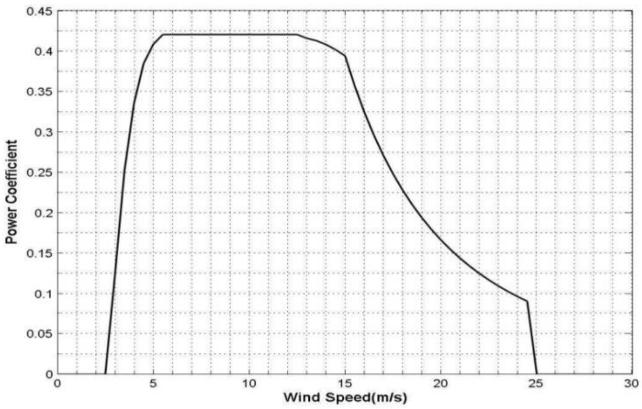


Figure. 3. Power coefficient (C_p)

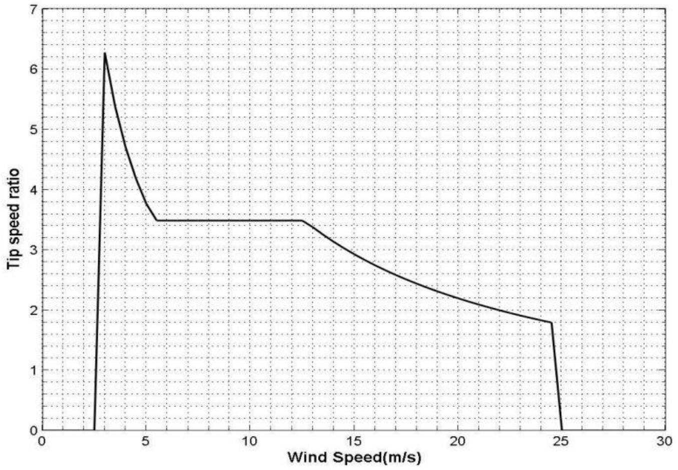


Figure. 4. Tip speed ratio (λ)

Discussion

From table (2) and figures we can notice the following :-

In figure.2 above pitch angle of blade turbine starts from 1degree and kept this value till 7.5m/s wind speed (rated wind speed), after that increase when wind speed increase and becomes at max value β max . At cut- off wind speed kept at 1 degree, so we can say that pitch angle regulate the pitch of blade turbine at max power. In figure.3 above the power Coefficient (cp) starts form zero value when cp< u cut-in speed area then increase when speed increase till becomes at maximum value, After that decrease till becomes zero at cut-off wind speed, This agree with turbine operation which is kept rest at cut-in and cut-off wind speed.

In figure 4. above the tip speed ratio starts form zero value at cut-in wind speed area then increase till becomes maximum, then decrease by increase of wind speed, then becomes stable , then decrease till becomes zero at cut-off wind speed, so this behavior explained that tip speed ratio has different value with specific range of wind speed

In figures 3. and4. the power value starts from cut –in wind speed area , then increase when wind speed increase till becomes at maximum value at 7.5m/s (rated wind speed), do not change till becomes zero at cut-off wind speed, so that the maximum power of turbine extract at rated wind speed

تصميم توربين رياح صغير لتشغيل طاحونة حبوب

ملخص البحث

هذا العمل يمثل تصميم توربين رياح أفقي المحور بثلاث شفرات بقدرة 37 كيلو واط لتشغيل طاحونة حبوب بقدرة 25كيلو واط في ولاية سنار. مشكلة البحث ان سنار عانت من عدم استقرار الطاقة المنتجة. البيانات الأساسية للتصميم استخلصت من هيئة الأرصاد الجوية ولاية سنار مع برنامج خريطة الرياح للسودان من العام 2008 حتى العام 2017.هذه البيانات شملت ,متوسط سرعة الرياح و كانت 5.6متر\ثانية, اتجاه الرياح شمال , مكان تثبيت التوربين في الضفة الشرقية للنيل الأزرق شمال خزان سنار. نتائج البحث أوضحت, المساحة المزاحة بالشفرات كانت1860 ملم^2 ,نصف قطر الدوار 523.34ملمتر, نسبة سرعة طرف الريشة4.189, السرعة الزاوية 0.0451راديان\ثانية, معامل القدرة 0.4,القدرة المنتجة 37كيلو واط , الطاقة المنتجة خلال العام54074.02كيلو واط ساعة\السنة . تم استخدام برنامج ماتلاب مع برنامج اكسل لاستخلاص منحنيات الأداء لكل من زاوية الخطوة (β) , معامل القدرة (Cp) , نسبة سرعة الريشة (λ) , القدرة المنتجة (p) , القدرة المصاحبة (Pr) مع سرعة الرياح , يستخدم المحول لتحويل التيار من تيار متردد إلى تيار مباشر , استخدمت 4 بطاريات (12 فولت - 200 أمبير) لتخزين الطاقة , وصت الدراسة بزيادة عناصر التصميم ليشمل تصميم صندوق التروس ليربط مع التوربين, تصميما البرج الذي يثبت عليه التوربين,الفوائد الاقتصادية للتصميم وكذلك حساب التكلفة .

Conclusion and Recommendation

Conclusion

1- this study started by determine the power required for grain mill, by experience design found the power required was 25KW, to calculate turbine we must consider grain mill efficiency , so turbine required power was 37KW.

2- Average wind speed obtained from sennar metrological authority and sudan wind prospecting map from the year 2008 to 2017, found average speed was 5.6m/s at 50m high.

3- Design elements and parameters calculation from turbine power, these elements included power coefficient (Cp) was 0.4, tip speed ratio was 4.189, blade swept area was 860mm^2 , radius was 523.34mm and angular speed was 0.0451rad/s .

4- All design elements and components showed in table 3.3. Matlab program used for caractristic curves of bitch angle, power coefficient , tip speed ratio, power out put vs wind speed.

5- Inverter used to convert Ac current to Dc current. Storage system consist of four batteries (12volt-220 amper).

6- Study presented good idea of wind energy potential in sennar.

Recommendation:

this work con be further extended to include the following :

design of Gearbox to engage the mill and wind turbine.

add storage unit.

design the tower.

consider the economic benefits.

design and material cost.

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