Estimation of Power in High Altitude Freely Suspended Wind Turbine

Sampath S S, Prasanth Sreekumar, Chithirai Pon Selvan M

***Abstract:** Conventional wind turbines are restricted in its use due to certain limitations and challenges in its position. To use wind turbine efficiently and economically, it is required to overcome space requirements, noise, variation in air current and set up cost. This study attempts to design and fabricate suspended wind turbine to overcome the above stated hurdles. In this current work, the blades and the alternator are placed in the helium balloon housing which is suspended in the air and supported to the ground with tether. A tether made of conductive material is to transmit the generated power from the airborne housing to the ground base. Blades are made of aluminium and it ensures low rotational inertia. The proposed suspended wind mill in this study is able to generate power output which is comparatively cheaper than conventional wind turbines and also work will be able to cater the needs of electric power to remote areas and farms. Entire setup is modelled in 3D software Creo and the simulation is carried out using ANSYS software.*

***Keywords:** Alternator, finite element method, turbine blade, renewable energy, power*

I. INTRODUCTION

The problem of sustainable energy generation is one of the most urgent challenges that mankind is facing today. Fossil fuels cover more of the global energy consumption and are supplied by few producer countries. Due to the increase in demand the cost of energy obtained by fossil resources also continuously increases. There are lots of negative effects from fossil fuels like global warming, climate changes etc. One of the key points to solve these issues is the use of a suitable combination of alternative energy sources. One of the easily available sources of energy that is the wind energy is considered and a design of wind turbine is carried out [6]. Freely suspended wind turbine or airborne wind turbine is either flying or freely suspended in air or it is connected by tether to the ground like kites or tethered balloons. This kind of turbine produces significant power compared to vertical and horizontal wind mill [1]. Since airborne turbine reaches high altitude, it is possible to extract maximum amount of unused wind power source and also at higher altitudes the wind energy remains constant [7]. Also at high altitude the wind is much stronger and more consistent than close to the ground [1]. Airborne wind turbine systems harness the wind blowing up to 1000 m above the ground .Tether technology, aerodynamics and wing design, sensors, control specifically aims to improve airborne wind energy which is harnessed [2,3]. Technically wind power isn't economically competitive with fossil fuels but brings ecological benefits to justify [4]. Many technologies have been proposed that aimed at harnessing wind power at high altitudes. Two basic approaches have been proposed. Mechanical energy can be transmitted from altitude to the earth's surface, where generators would produce electricity at the ground. A simple example of this kind is the design of KiteGen shown in figure 1, consisting of tethered airfoils (kites) connected to a ground-based generator. Alternatively, electricity could be generated aloft and transmitted to the surface with a tether. Another design proposed by Sky Wind power consists of four rotors which are mounted on an airframe, tethered to the ground via insulated aluminum conductors wound with Kevlar-type cords. The rotors both provide lift and power electric generation. The aircraft can be lofted with supplied electricity to reach the desired altitude, but then can generate up to 40 MW of power with two lines, which are pulled and released by a control unit [5].

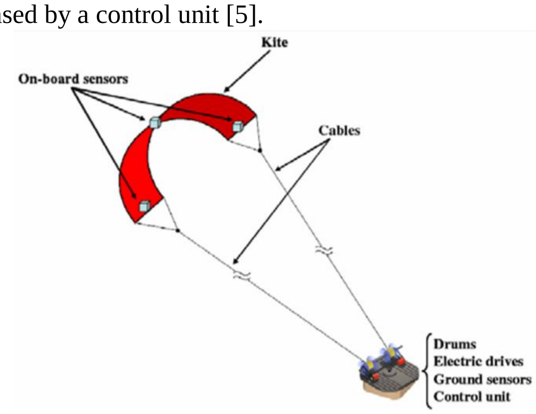

Figure 1: Kitegen type suspended wind turbine [6]

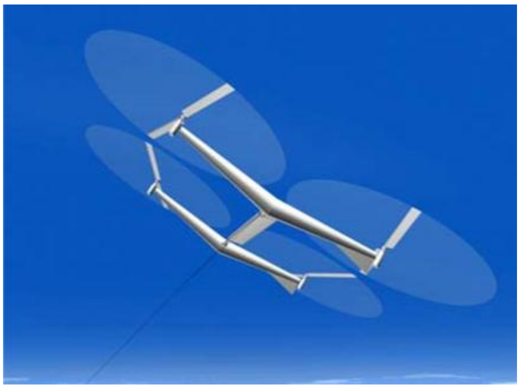

Figure 2: Sky wind power type suspended wind turbine [6]

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Balloon type Ariel wind turbine and Kytoon type are the other two types of airborne wind turbine design techniques. The Balloon wind turbines carried up into the air using balloons filled with lighter-than-air gas such as helium gas to provide buoyancy to the entire arrangement irrespective of air motion. The Kytoon type utilizes both kite and balloon arrangements for generating power from high altitude winds. Current paper focuses on the balloon type Ariel wind will where every element is selected and designed in order to generate required power output. The line diagram of the proposed Ariel wind turbine is shown is figure 3.

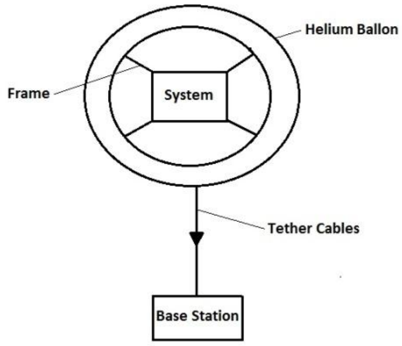

Figure 3: Schematic diagram of the proposed Ariel wind mill

From the figure the system which is an assembly of shaft, alternator, housing, fan, fin etc. is supported and lifted by a helium balloon. The power which is generated by the system is transmitted to the base station by the cables provided. The base station consisting of chargeable batteries in which it supply the energy to the destinations.

II. RELATED STUDY

Moritz Diehl [1] worked on the main ideas behind airborne wind energy, it made an attempt provide the basic concepts of airborne wind energy, its classification, criterion of design and its limitations. Fagiano and Marks [2] built a small scale prototype and provided guidelines while designing, selection of materials & cost calculation. The guidelines which are set are used in developing of test sensor fusion which provides automatic control solutions. Lorenzo Fagiano et.al [3] worked on new type of air borne wind energy technology named kite energy for the conversion of high-altitude wind energy into electricity. This paper includes the theoretical analysis, numerical simulation and experimental tests on this wind turbine which is used to calculate the power. NykolaiBilaniuk et al. [4] explored the practical needs that must be met by an airborne tethered wind generator technology to be both technologically feasible and economically viable. The paper inferred that autonomous survivability is a largely neglected but critical aspect of performance. Archer and Caldeira [5] analysed and interpolated the statistical data to study geographical distributions and persistency of winds at all altitudes. Furthermore, intermittency issues and global climate effects of large scale extraction of energy from high-altitude winds are investigated. This data plays a vital role in the design of a wind turbine. Lorenzo Fagiano et al. [6] presented the innovative technology of high-altitude wind power generation, which is indicated as KiteGen, which exploits the automatic flight of tethered airfoils to extract energy from wind blowing between 200 and 800 meters above the ground. This paper concludes that with the use of Ariel wind turbine the power generated is maximum compared to other wind turbines. Ockels [7] compared several concepts for wind energy exploitation from high altitudes winds. The comparison in this paper is limited to concepts that have the generator located on the ground. It showed that Ariel wind mill produces more power compared to the conventional ones. Alexander Bolonkin [8] suggested a new innovation which increases the power of the system. The main innovation consists of large free-flying air rotors positioned at high altitude power and air stream stability, and an energy cable transmission system between the air rotor and a ground based electric generator. Cristina L. Archer [9] worked on an airborne wind energy system (AWES) which convert the wind energy to electricity. This paper gives the insight of different wind conditions (Meteorology) which affects the performance of the device. Ezaki [10] developed a down type turbine with a variable coning angle and a front fin that can be inclined with the yaw shaft to cover a wide wind speed range. However, coning has glitches connected to increasing speed at cut-in and dropping the swept area; these difficulties must be overcome to ensure attitude stability and prevent damage from strong winds. This paper presents the field test results related to coning rotor. Helsen et al. [11] discusses how a drive train design is crucial for the reliable and optimal operation of the turbine. This paper explains various trends related to the drive train design for the upscaled machines. Morten Haastrup [12] evaluated the bushing models in modeling and mounting of a wind turbine gear boxes. The stiffness of the components of the gear box is calculated. Similarly torsional stiffness of the main shaft, gear box and mountings are calculated. It concludes that the stiffness calculations are crucial for wind turbine drive train. W.T.Chong [13] et al. analyzed the vertical axis wind mill and determined the total power generated in it. HarkiApriYanto [14] et.al discussed the design of a low tip-speed ratio, drag type vertical axis wind turbine which is built-in with permanent magnet synchronous generator with maximum power point tracking (MPPT) strategy of control system to obtain the optimal performance. Sampath et al. [15] built a vertical axis wind turbine and the power is determined. Various different types of turbine blades are considered and the optimum blade type is selected. Mechanical components of the entire setup are built to obtain maximum rotation per minute. The mechanical energy is transformed into the electrical energy by coupling coaxially between the shaft and the generator.

III. METHODOLOGY

Figure 4: Methodology in design and fabrication of freely suspended wind mill

Figure 4 shows the steps involved in developing an Ariel wind turbine. It begins with the problem definition which is to design a Ariel turbine. Collecting of supporting data is important before selecting the material [2]. Entire set up is designed and then it is modelled according to the required dimensions. Analytical analysis includes in the design of the shaft, chain drive, alternator, estimation of the power etc. Final stage is the testing phase where the entire set up is lifted at an altitude to obtain the results [5]. The validation of the data is essential to show that the design which is done is optimum and cost effective.

Equation (1) gives the total power generated by the suspended wind turbine. It is related with the density and velocity of the air. It considers both the bearing and generator efficiencies along with the coefficient of performance.

$$P = \frac{1}{2} pACpV^3 N_g N_b \qquad (1)$$

The shaft which is a key component of the wind turbine is designed with the consideration of various loads acting on it. Equation (2) gives the best value of the diameter of the shaft.

$$d = \left[\frac{16}{\pi\sigma_{max}}\left\{CmM + \sqrt{[(CmM)^2 + (CtT)^2]^{1/3}}\right\}\right] \qquad (2)$$

Total bending moment can be calculated by squaring the moments about horizontal and vertical directions. Equation (3) gives the value of total moment.

$$M = \sqrt{Horizonal\ Bending\ Moment^2 + Vertical\ Bending\ Moment^2} \quad (3)$$

Power which is obtained in the equation (1) is equated with the power obtained with the consideration of the torque. With the help of the equation (4) the value of the torsion acting on the shaft is found out in order to determine the diameter of the shaft.

$$P = 2\pi \mathrm{NT} \qquad (4)$$

Design, Construction and Working

During the course of the project a wide variety of fan (blade) design is considered. Due to the cost constraints as well as other design issues regular HDP (High-density polyethylene) fan is selected. The reasons for selection of this fan are its weight and its feature to work as flywheel. The start up speed required for the fan is around 3 m/s. it has been tested under various speed conditions. Figure 5 shows the design of the fan to run at high altitude.

Figure 5: Design of fan

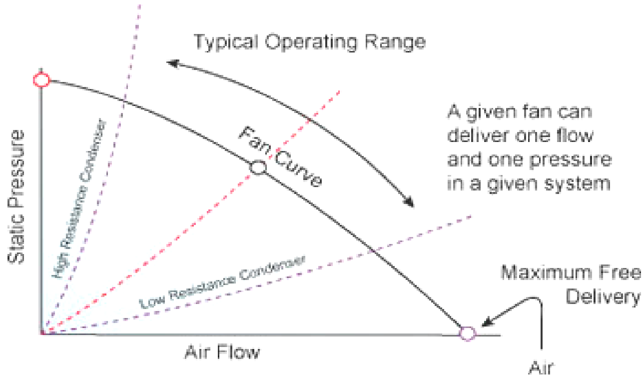

Figure 6: Fan law impacts on airflow in the model [16]

Fan laws govern all fans and propellers. Key inference of these laws is summarized graphically illustrated in figure 6 and the following points are considered. The system static pressure rises at the square of the air flow increases. As static pressure drops, the air flow rises along the fan curve for a given fan. Fan curves can have peak efficiency and cut out regions with implications for air moving performance and sound. With a given fan and system pressure, the air mass flow rate increases linearly with fan rpm [16]. Selection of drive train is key for transmitting the power [16]. Chain drive is used in this system is shown in figure 7. Power is conveyed by a roller chain known as transmission chain passes over sprocket gear. The teeth of the gear mesh with the holes in the links of the chain. The gear is turned, and this pulls the chain putting mechanical force into the system. Figure 8 shows the alternator which converts the mechanical energy to electric energy in the form of alternating current [11]. An alternator is an electrical generator that converts mechanical energy to electrical energy in the form of alternating current. Most alternators use a rotating magnetic field with a stationary armature. It is so-called 'DC generator', which converts AC current generated in the rotating armature to DC by the commutator and brushes. In an 'alternator', the AC current is generated in the stationary stator, and then is converted to DC by the rectifiers (diodes).

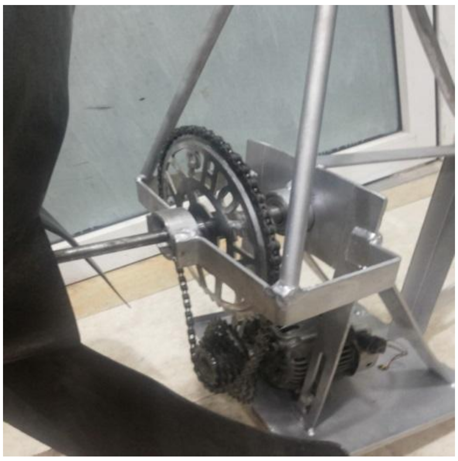

Figure 7: Chain drive

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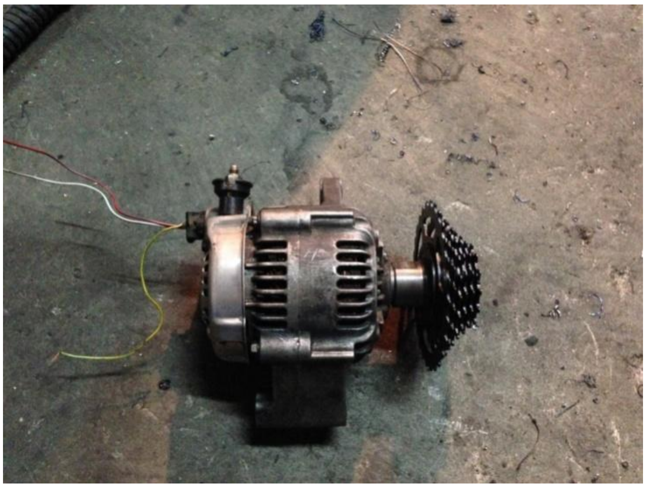

Figure 8: Alternator connected with driven sprocket

After assembling of the fan, chain drive and alternator it was observed that the model was not balanced. It was leaning towards the front where the fan was placed. The model being unbalanced was highly undesirable. Hence to balance the entire setup a fin or vertical stabilizer shown in figure 9 was fabricated. Aluminium sheet of 1.2 mm was used and a fin of 500 mm X 100 mm was designed. Though the fin was always part of the initial design of the wind turbine, it was doing double work and acting as counter balance also. The load towards the front of the model was around 2 kg, so the fin was fabricated and TIG welded it in such a way that the fin also weighed 2 kg. As there are ball bearing (as shown in figure), the whole model is rotating freely along the bearings. Once the fin comes in contact with the wind, it will rotate the whole model in the direction of the wind and then the fan starts rotating. Figure 10 shows the Shaft which is made of mild steel is a key element which transmits the power which is assembled with the fan at one end and the alternator at the other end [15]. Frame supports all the elements together to form an entire set up. Helium balloons are used to lift the entire wind mill at a desired altitude. The balloons may be tilted horizontal or vertical direction depending on the direction of the wind.

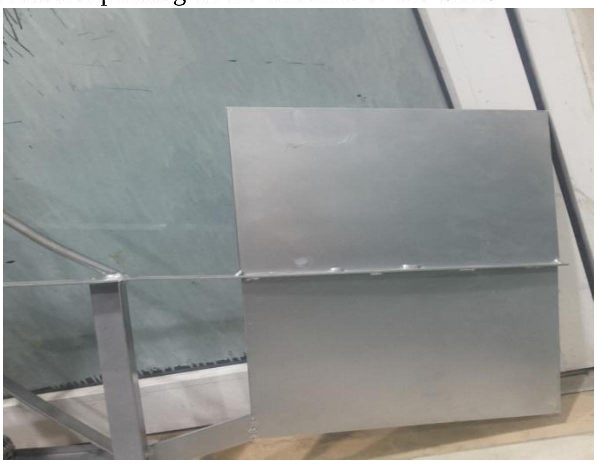

Figure 9: Fin or Vertical Stabilizer

Figure 10: Shaft

IV. FABRICATION OF THE MODEL

Figure 11 shows the fully fabricated Ariel wind mill. The Design of model was very crucial to optimize the output achieved by the model [1]. But it has to be understood that the project being carried out is one of its kind. There wasn't any one fixed design that could be directly worked upon. Repeated improvement of design is carried out over a course of time. Assembling and dismantling a number of completed designs in order to achieve the optimum design. A shaft (MS) is force fit in the selected. The other end of the shaft is connected to the main sprocket (driver) having 49 teeth. Meanwhile on the base, the alternator is mounted. On one end of the alternator, the secondary sprocket (driven) having 14 teeth is attached. The driver and driven are connected by a chain [11]. Various supports and columns are attached for strength of model and to decrease the vibration. On the other end of the fan, a fin is made to rotate the model in the direction of the wind. Two ball bearings are placed on the top and bottom to enhance the rotation of the model when it comes in contact with wind. Aluminium was selected as the material of choice for the frame as aluminum is very light material. Aluminum sheet of 0.7 mm is used to fabricate the frame of the model; the sheets were cut according to the design that was made.

Figure 11: Fabricated ariel wind mill

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V. EXPERIMENTATION & RESULTS

For a wind velocity of 7 m/s, speed at turbine end is 1000 rpm and with chain drive set up, speed of 3500 rpm at alternator end has been achieved. With this set up it was able to charge a battery of 12 V in time duration of 15 minutes. With the average wind velocity of 5 m/s, it was able to charge battery in 20 minutes. Further, if the entire set up is suspended with the help of helium balloon of 4 m diameter, it will be able to lift entire setup of 11 kg. The time duration for charging of battery can be minimized. This is justified by the initial trial run which was conducted with helium balloon of 2 m diameter. Table 1 shows the power calculations at various altitudes.

Table 1: Determination of power at various altitudes

Sl.No	Altitude (feet)	Density (kg/m^3)	Rotor swept area (m^2)	Coefficient of performance	Wind speed (m/s)	Generator efficiency (%)	Gearbox /bearing efficiency (%)	Power (W)
1	Sea level	1.225	1.13	0.35	5.4	80	80	24.41
2	1000	1.112	1.13	0.35	5.9	80	80	28.90
3	2000	1.007	1.13	0.35	6.4	80	80	33.40
4	3000	0.9093	1.13	0.35	7.9	80	80	56.72
5	4000	0.8194	1.13	0.35	8.3	80	80	59.26
6	5000	0.7364	1.13	0.35	10	80	80	93.14
7	6000	0.6601	1.13	0.35	10.8	80	80	105.23
8	7000	0.5900	1.13	0.35	11.5	80	80	113.56
9	8000	0.5258	1.13	0.35	12.1	80	80	117.88
10	10000	0.4135	1.13	0.35	13.5	80	80	128.75

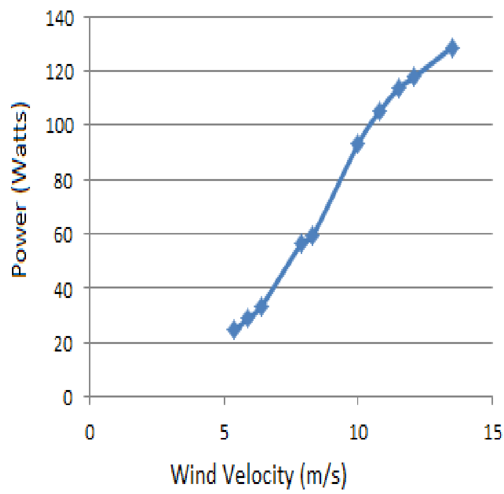

Figure 12: Variation of power with the wind velocity

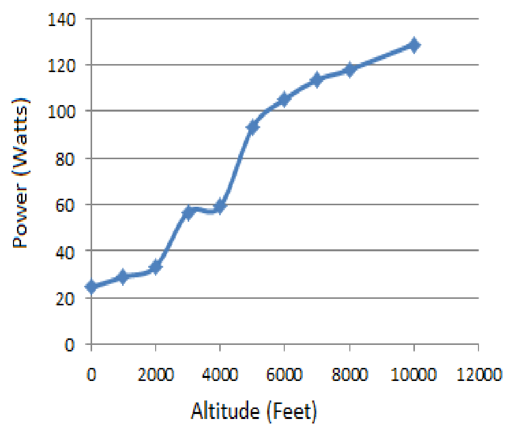

Figure 13: Power at different height from the reference

Figure 12 shows the variation of power with the change in the wind velocity and figure 13 shows the variation of power with the altitude at which the system is placed. In both cases the power rises. It means freely suspended wind mill generates much high power compared to the stationary ground wind turbine.

Design of shaft:

The loads acting on the shaft is considered. Since only vertical loads are acting only the vertical bending moment is obtained. The bending moment diagram for the entire setup with the consideration of loads is shown in the figure 14. The total maximum moment obtained from this diagram is 0.2213 N-m.

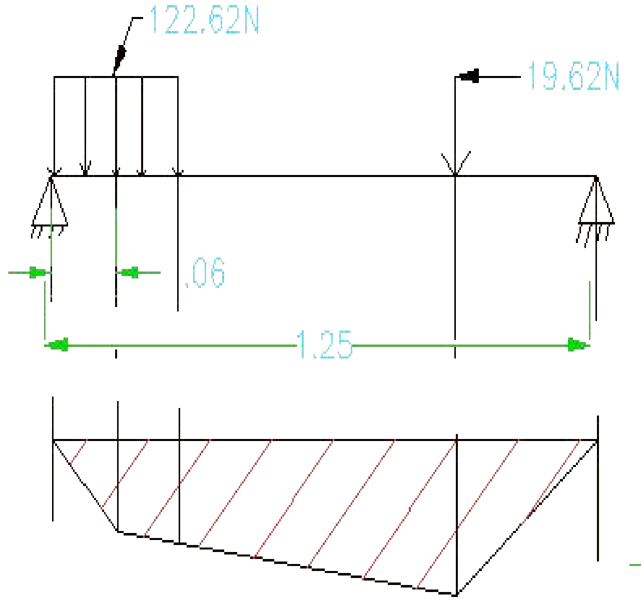

Figure 14: Bending moment diagram of shaft

The power obtained in equation 1 is compared with the equation 4 to obtain the torque in the system. For the above case at a speed of 1000 rpm the toque obtained is 0.08 N-m. The value of torque and the moment is substituted in

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equation 2 to obtain the diameter of the shaft. The value of the diameter obtained is in the range from 10 to 25 mm diameter.

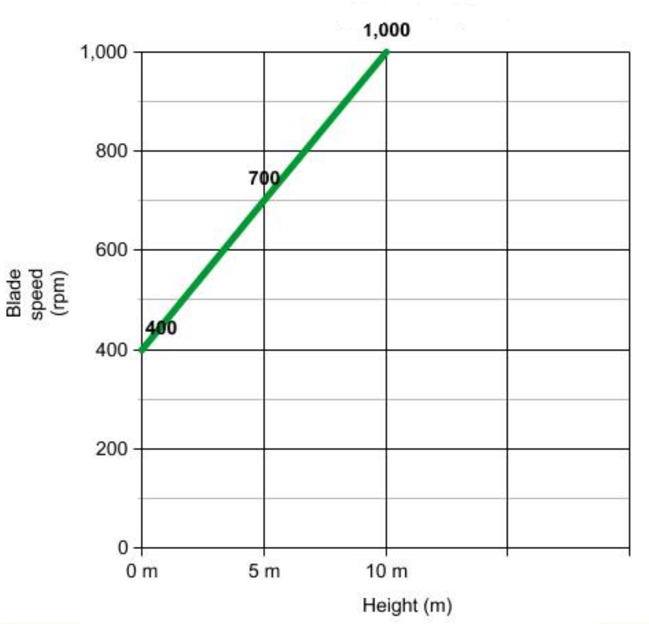

Figure 15: Height vs blade speed

Figure 15 shows the variation of the speed in rpm of rotor blade speed with respect to the change in height. During the testing process the model was tested for its power generation at different altitudes. It shows that with the increase in the height the speed of rotation of the blade rises.

Simulation and Validation

Figure 16 shows the modelling of the project on Creo software. The model was created in two different parts, the frame being the first and the fan blade being the second. These two were then assembled and the whole assembly was completed.

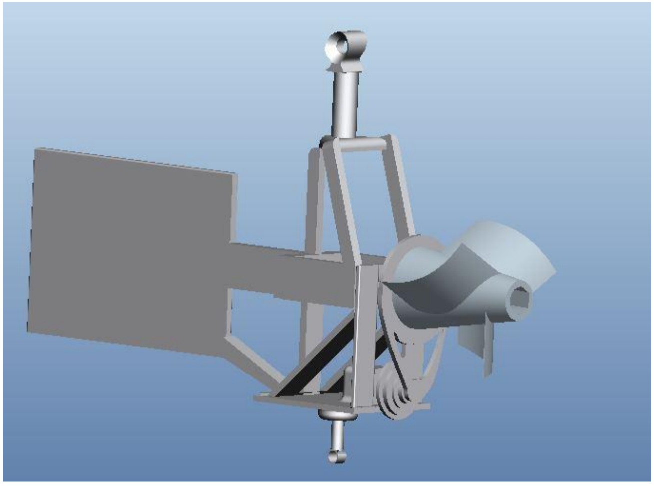

Figure 16: Proe/Creo model of the ariel wind mill setup

Figure 18 shows the maximum deformation of 0.005 m along negative y direction and Fig 17 shows the Von Mises stress distribution along a shaft which is considered as a beam element. Maximum stress lies at the extreme ends near the bearings.

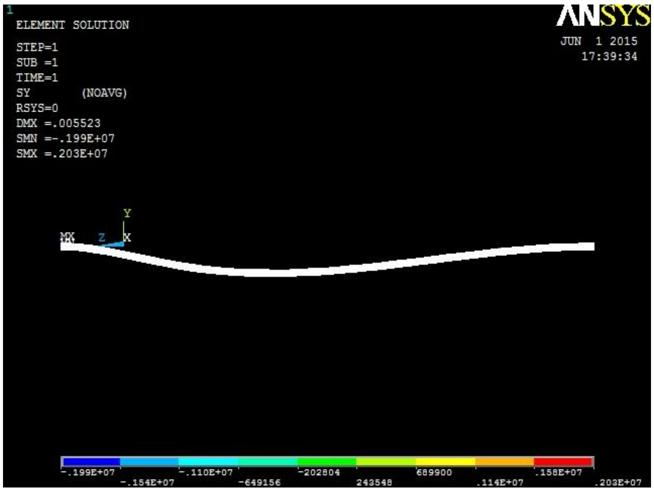

Figure 17: Stress Analysis of shaft

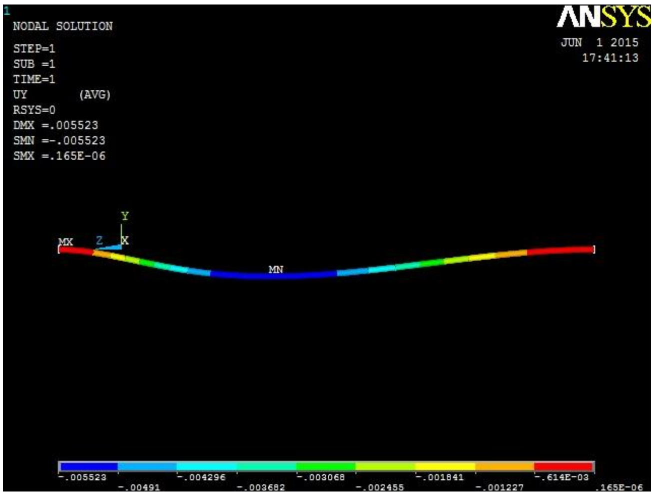

Figure 18: Maximum deformation in shaft

The deformation which is obtained in finite element method software Ansys is very low therefore the overall design of the shaft is safe to hold the loads specified. As the altitude increases there is a rise in the wind velocity which increases the power generated [4, 5]. There is a rise in the speed of rotation of the shaft with the increase in the altitude [8]. Hence the results which are obtained are validated and it is safe for operation purpose.

VI. CONCLUSIONS

Wind is one such energy has a higher operational life time & reliability. Ariel wind turbine is designed to generate power having relatively higher investment compared to the horizontal or vertical wind turbine. Electricity which is generated at high altitudes has its own challenges like crashing problems, rains, may require monitoring system etc. Therefore the design of every part is very important. Experimental results give the variation of power with the altitude and wind velocity. Since wind velocity goes on rising with the altitude there is a rise in the power due the increase in altitude and wind velocity. It shows there is a rise in the rotation of the shaft with the higher altitude which means there is a rise in the torque. Design of the balloon

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depends on the selection of the gas which lifts the entire system by providing counter force in upward direction. Therefore the balloon design depends on the weight of the system. Even though the initial investment is high the power generated at higher altitude is much higher than that of regular wind turbine.

This system doesn't take up much space, it can be easily set up over the roof top of every house. Even if one room in each house is electrified by this concept, it can make a phenomenal difference to the environment as well as economy of this country. It can be used in the farms deep inside the desert to electrify the camps instead of environmentally hazardous generators. This concept of wind turbine can also easily power a number of pumps. By providing the higher capacity battery, lot of energy wastage can be prevented and it can be utilized well. By having better aerodynamic design of the overall system and the proper wing design, there is a possibility to increase the power. By increasing the size of the prototype the overall power generation by the system could be increased. Power vs time period graph can be plotted by noting the wind velocity throughout the day with the help of control systems. Fluent software can be used to find various parameters related to fluid dynamics.

This research can be further improved by building a prototype which is controlled automatically and able to carry out consistently the desired energy generation cycle. Experimental values can be compared with the theoretical values, and it helps to give the correction factors to the theoretical expressions to carry out the numerical analysis effectively. The calculations of efficiency and effectiveness can be carried out which determines the nature of the system.

Nomenclature:

P = power, W

ρ = air density, kg/m3

A = rotor swept area, exposed to the wind, m2

Cp = coefficient of performance

V = wind speed, m/sec

Ng = generator efficiency (50% for car alternator, 80% or possibly more for a permanent magnet generator or grid-connected induction generator)

Nb = gearbox/bearings efficiency (depends, could be as high as 95%, if good)

d= shaft diameter, m

σmax= maximum stress, Pa

M= maximum bending moment, N-m

T= maximum Torsion, N-m

Cm= shock factor in bending moment

Ct= shock factor in torsion

N= speed of rotation, rpm

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