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AIRBORNE WIND ENERGY SYSTEM: DESIGN, FABRICATION AND TESTING OF A MANUAL PROTOTYPE

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ABSTRACT

Airborne Wind Energy System (AWES), an innovative and fascinating technology, is actively researched in many institutions all over the globe. Moreover, the fact that it can produce more energy than the traditional wind turbines, that too, at a lower cost draws more attention. This paper discusses the advantages of AWES over traditional wind turbine as well as presents the design, fabrication and testing processes of a small scale manually operated prototype of AWES. This research work was done to find out the feasibility of AWES in low winds. Furthermore, the research was done by conducting some experiments with the prototype. This prototype was tested in different altitudes at two different locations in Kerala. The major application of the AWES is in off-shore regions and other areas where installing a wind turbine is difficult and expensive. Additionally, the future scopes and design recommendations based on the behavior of kite are discussed in this paper.

INDEX TERMS: *Airborne Wind Energy System, AWES, High altitude wind, Kite energy.*

I. INTRODUCTION

In the present scenario, the rate of energy consumption is escalating rapidly around the globe. This energy demand is met by the mixture of conventional and non-conventional energy sources for decades. However, due to the inefficiency of the existing renewable energy technologies, the major proportion of the energy supplied is from conventional energy sources. These energy sources, nonetheless, produces high amount of environmental issues and the fossil fuel reserves are depleting at an alarming rate as well. Therefore, it is high time that we invest more resources in developing efficient renewable energy technologies that can replace conventional energy sources.

Moreover, there are numerous researches conducted in many universities and institutions all over the world. Airborne Wind Energy System (AWES) is one of the actively researched areas in most institutions. The AWES uses a kite or other airborne devices to harvest high altitude wind energy. According to Archer and Caldeira (2009) the wind power density is highest at high altitude compared to ground level [2]. Therefore, AWES can generate more amount of energy than wind turbines that operate at relatively lower altitudes.[1]

The idea of AWES was developed during the energy crisis of 1970s. A pioneering contribution was displayed in 1980, when American engineer Miles Loyd publishes his article “Crosswind Kite Power” which provided a quantitative analysis of airborne wind energy system [1].

A. Existing technologies

The AWES is an electro-mechanical machine that converts the kinetic energy of the high-altitude wind into electricity. It generally consists of two components namely, ground system and aircraft (or kite) which is mechanically connected by tethers.

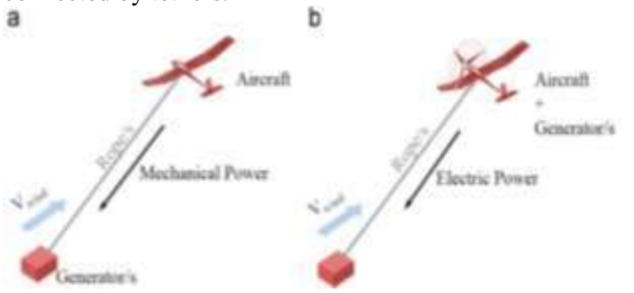

Figure 1: AWESs. Example of (a) Ground-Gen and (b) Fly-Gen AWESs [6]

The AWES concept can be broadly classified into Ground-Gen systems and Fly-Gen systems [6].

In a Ground-Gen AWES, electricity is generated on the ground station by converting the traction force on the kite, through tethers or ropes, which rotates an electrical generator. In a Fly-Gen AWES (FG-AWES), electricity is generated on the aircraft and it is transmitted to the ground station through insulated tethers which carries electrical cables. In this case, electrical energy conversion is generally achieved using wind turbines [6].

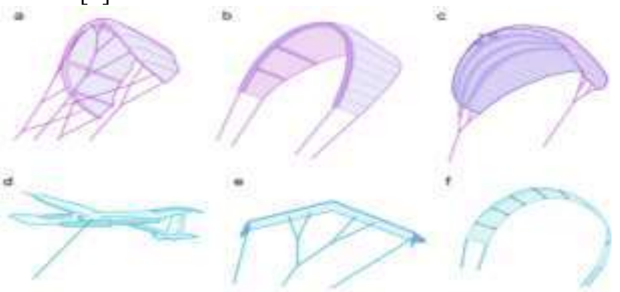

Figure 2: Different types of aircraft in Ground-Gen systems. (a) LEI SLE (Leading Edge Inflatable, Supported Leading Edge) Kite; (b) LEI C-kite; (c) Foil Kite, design from Skysails; (d) Glider, design from Ampyx Power; (e) Swept rigid wing, design from Enerkite; (f) Semi-rigid wing, design from Kitegen [6].

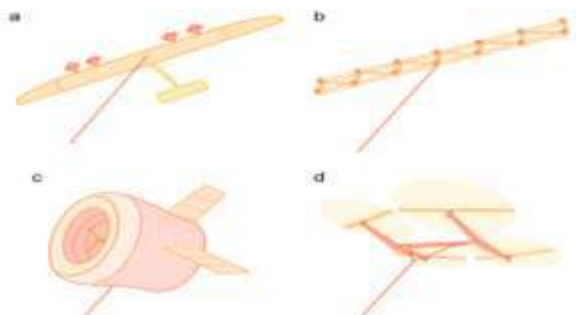

Figure 3: Different types of aircraft in Fly-Gen systems. (a) Plane with four turbines, design by Makani Power. (b) Aircraft composed bya frame of wings and turbines, design by Joby Energy. (c) Toroidal lifting aerostat with a wind turbine in the center, design by Altaeros Energies. (d) Static suspension quadrotor in autorotation, design by Sky WindPower. (Cherubini et al., 2015, cited by Maftouni, Amin and Shariat Bahadouri)

B. Comparison with conventional wind turbines

Power Generation

An Italian company KiteGen Research (KGR) conducted a comparative analysis, in Spain for the year 2015, between traditional wind turbine and KGR technology for high altitude wind exploitation (KiteGen Research, 2016).

The wind energy production data by all the traditional wind turbines in the year 2015 was collected. According to the report provided by KiteGen Research (2016):

The diagram in Fig. 1 shows the actual energy produced in each 1-hour time interval, in the course of the year 2015, by all wind turbines installed in Spain.

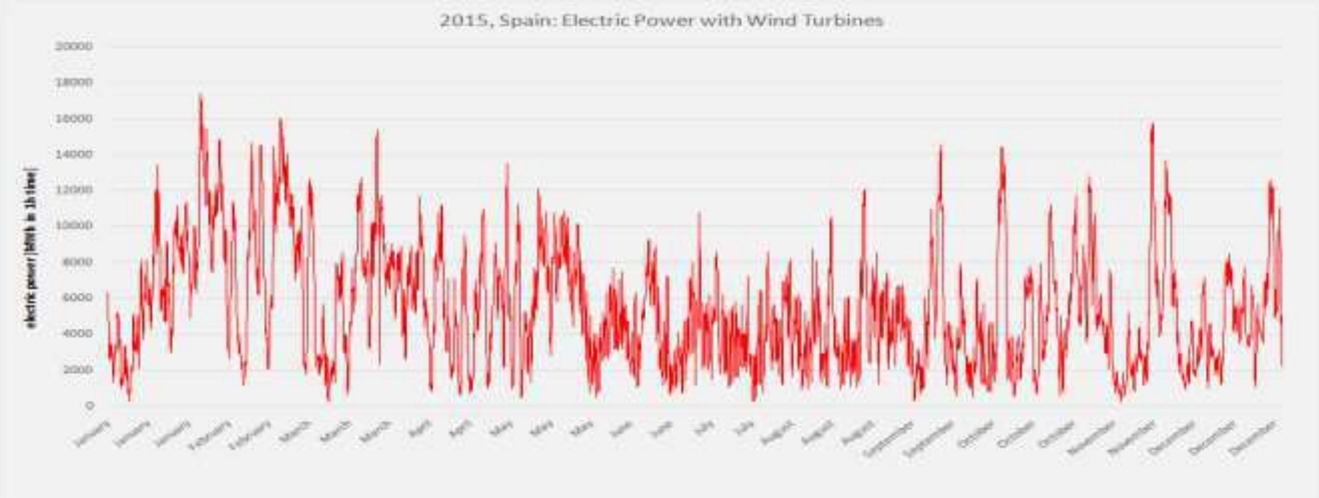

Figure 4: **2015, Spain: Electric Power with wind Turbines (KiteGen Research, 2016)**

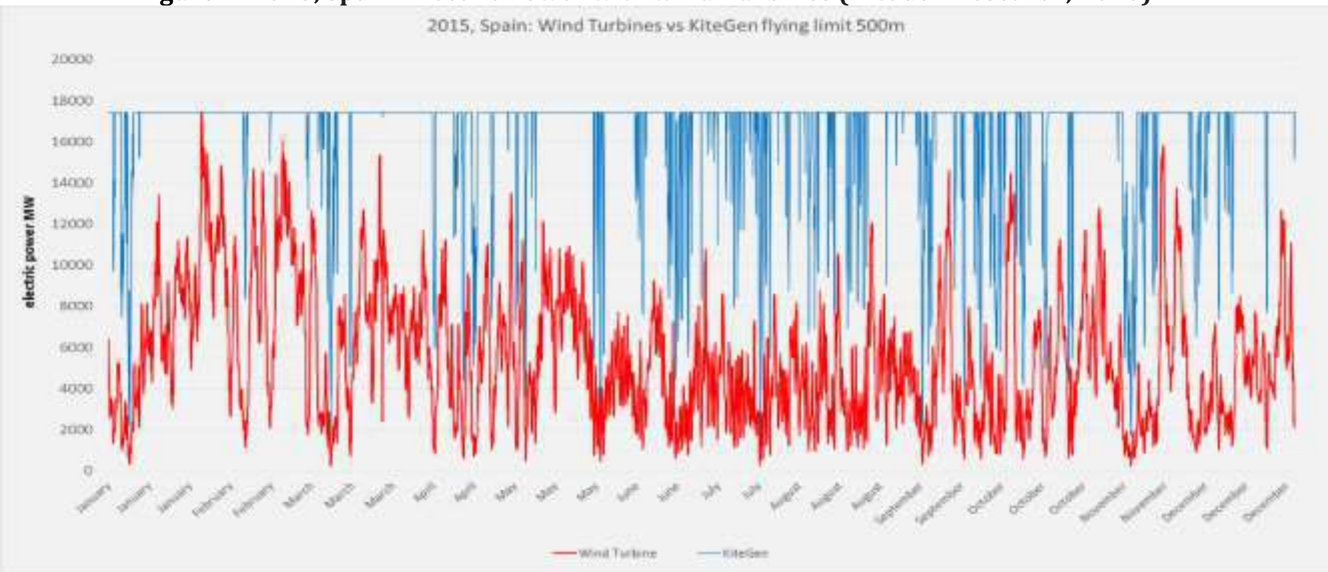

Figure 5: 2015, Spain: wind Turbines vs KiteGen at 500m (KiteGen Research, 2016)

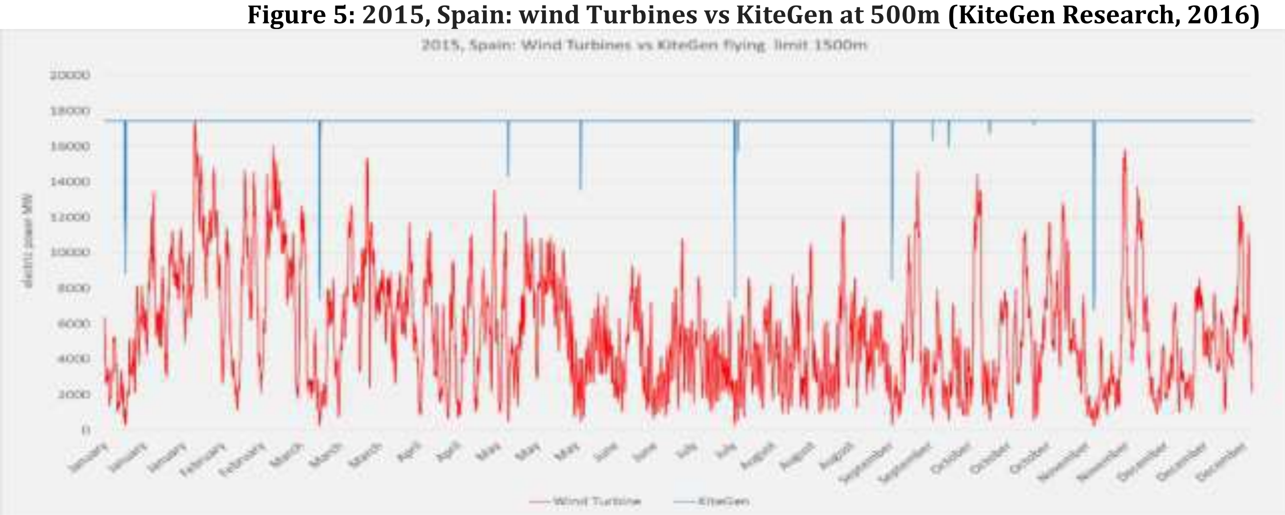

Figure 6: 2015, Spain: wind Turbines vs KiteGen at 1500m (KiteGen Research, 2016)

They assumed same working conditions for both technologies. Moreover, they limited the maximum power for KiteGen farms to the same highest power recorded by the wind turbines in 2015.

The picture in Fig. 5 shows comparison of the power produced from the same wind but by two of different technologies: traditional wind turbines (red curve) vs KiteGen (blue curve). The data for the wind turbines come from measurements of the year 2015. Meanwhile, the estimates for KiteGen are obtained from the same wind data and the assumptions reported in the text (KiteGen Research, 2016).

'*Fig. 6 is the same as Fig. 5, but with the kites flying at an average height of 1500m, where the wind blows faster and carries 8 times as much power than at 100m height'*(KiteGen Research, 2016).

Therefore, from these data, it's clear that the power produced by KiteGen technology is higher and more consistent than that of conventional wind turbine [7].

Initial Cost and cost of electricity

It is obvious that, the cost of AWES is much lower than that of traditional wind turbines. This is because of the fact that, the AWES eliminate about 90% of the raw materials used in wind turbines. The kite and tethers would cost less than the rotor blades and towers. Additionally, the cost of electricity generated by AWES is cheaper compared with that of wind turbine. KiteGen estimates that their machine can produce electricity at costs of $0.02-0.05 per kWh, when the wind turbines produce electricity at $0.15 per kWh [5].

According to Argatov and Shafranov (2016), '*[when comparing with a] small-scale wind turbines with the same rated power, the [AWES] operating at the maximum admissible height can produce more energy under the same wind conditions'*[3].

According Canale et al., a KiteGen generator with a $500m^2$ kite would produce 2 MW of power at a wind speed of 9m/s, while a wind turbine with 90m diameter (i.e 2 MW nominal power with 12m/s wind) would produce only 1 MW in the same wind condition. Moreover, it was observed that the 230 tons weighing rotor and tower of a wind turbine is replaced by the 3 tons weighing AWES, hence reducing construction costs. Moreover, a KiteGen generator could be installed also in locations where a wind turbine would not be profitable, due to weak wind between 0 and 150 m above the ground. Furthermore, it was stated that '*the average generated power per kilometers squared of a kite wind farm will be 3–9 times higher than that of an actual wind turbine farm in a "good" site. … This means that a KiteGen generator would produce more power than a wind turbine in the same site, with much lower construction and installation costs'* [5].

II. RESEARCH METHOD

A. Design and fabrication of a manual prototype

A small prototype of AWES was made and was tested in different wind velocities in two different locations. In addition, the amounts of energy produced in each case were calculated. Hence, this prototype helped us to understand the limitations in the design and the factors affecting the power generation in AWES.

a. Working of Airborne Wind Energy System

'Energy conversion is obtained through a two phase cycle consisting of a [traction phase], in which electrical energy is produced, and a recovery phase, in which a smaller amount of energy is consumed to [pull the kite to original position]. In these systems, the ropes, which are subjected to traction forces, are wound on winches that, in turn, are connected to motor-generators axes' [6].

- The device is first positioned depending upon the direction of the wind and the kite is launched. During the traction phase, the kite is pulled in a way to generate a lift force and consequently a traction force on the ropes that cause the rotation of the electrical generators. By the end of this phase the complete rope will be reeled out and the kite has reached the maximum altitude.
- In the recovery phase motors reel-in the ropes bringing the kite back to its original position. In order to have a positive balance, the net energy produced in the traction phase has to be greater than the energy consumed in the recovery phase. This is assured by a mechanism that adjusts the aerodynamic characteristics of the kite in a way to maximize the energy produced in the generation phase and to minimize the energy consumed in the recovery phase. This mechanism is called depower link. The depower link when pulled will fold the kite. Hence, reducing the air resistance on the kite.

Kite generators present a highly discontinuous power output, with long alternating time-periods of energy generation and consumption. Such an unattractive feature makes it necessary to use batteries or large capacitors [6]. So the components involved are a power kite, tethers, a generator coupled to the shaft, a battery connected to the generator and a motor which is powered by the battery to pull the kite during the recovery phase. Here for the recovery phase, we used a semi-automatic system in which depowering link is pulled manually to fold the kite so as to minimize the energy required in recovery phase.

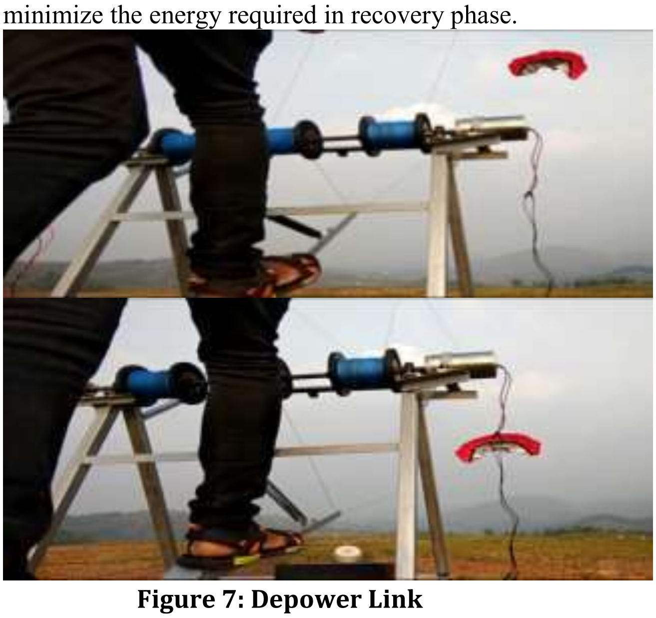

Figure 7: Depower Link

B. DESIGN

The kite used is a power kite and these kites are specially designed for producing traction force. The selection of the power kite was done on the basis of its capability to fly even at low wind speeds.

The ground station was designed in the dimension as shown in the Fig. 8 after referring several power kite guidelines. The length of the shaft in the ground station is same as the length of the handle bar used for power kitting (as shown in Fig. 9).

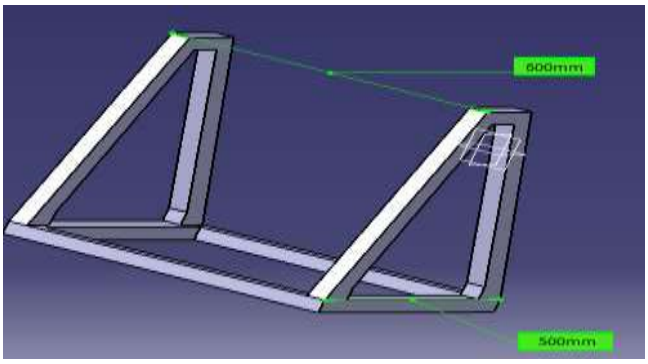

Figure 8: Frame CAD drawing

Figure 9: Power kite handle (Prism Kite Technology n.d.)

The depower lever has a plastic pulley at its end through which the depower link is passed. The depower lever is designed in such a way that when it's engaged, the kite folds and freely falls down. The permanent magnet generator, directly coupled to the shaft, produces $24V$ at a rated speed of 1000 rpm.

The kite gives a maximum torque of about $4Nm$ when inflated and an average torque of about $1Nm$ when depowered or folded. So the motor used to recover the kite is a $12V$ 500 rpm DC geared motor which provides a torque of $2.5Nm$.

The motor can be coupled and decoupled from the shaft to reduce the resistance on the shaft to rotate. This is function obtained by using bush with keyways on its both ends.

C. COMPONENTS AND DESCRIPTION

a. Kite

Kite is the main component of the power generation system. The material used must have minimum weight and high strength to withstand different types of forces acting on it. The kite used is a high quality 2.5m Dual Line Para foil Kite. It is made up of nylon and it weighs about $350g$. It is suitable for wind levels 2 to 6 or, in terms of wind velocity, $5km/h$ to $45km/h$. The dimension of the kite is as shown in Fig. 10. The kite is also fitted with an additional link called depower link at the center to fold it during recovery phase. Fig. 11 shows the power lines and depower link.

Figure 10: Kite (AliExpress n.d.)

Figure 11: Power lines and depower link

b. Ground Station

The ground station carries the tether and acts as a resting place for the kite, when not flying. It is made up of 1 inch square metal pipe and consumes less ground area. Additionally, the ground station consists of the generator, battery module, motor and depower lever.

The tethers are reeled on three identical bobbins, in which, two are for controlling the motion of the kite (blue tethers) and one for depowering the kite (yellow tether) as shown in the Fig. 12.

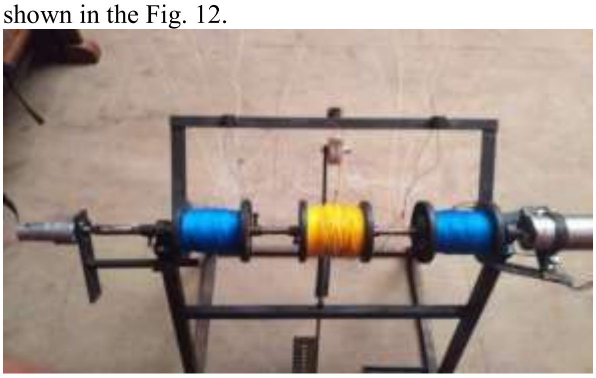

Figure 12: Ground Station

c. Depower Lever

The depower lever is a lever which is fitted to the center of the frame. It is welded to the bottom of the frame and attached with a spring above, so that it would return to its original position after depowering. When the lever is engaged the depower link will be pulled resulting in the folding of kite.

d. Tether

The tether acts as a link between the kite and the ground station. It is used to transmit traction force produced by the kite to the ground station. The material of the tether is made from 100% virgin Polypropylene with a diameter of $2mm$. It has extra tensile strength and best protection against UV degradation. The two tethers at each ends are power lines and the tether at the center is the depower link. These tethers are wound over bobbins of diameter $11.5cm$ and length $9cm$.

e. Permanent Magnet Generator (PMG)

A $24V$ 1000 rpm permanent magnet motor is used as the generator in this project. This motor when rotated at 1000 rpm generates about $24V$.

Figure 13: Permanent magnet DC motor

f. DC Motor

A $12V$ 500 rpm DC geared motor is used to recover the kite. The motor delivers a torque of $2.5N$on the shaft to pull the kite during recovery phase.

Figure 14: DC Geared motor

D. FABRICATION

Different parts of the machine were made separately and assembled together. These steps are briefed as given below-

Figure 15: Pipe cutting

Figure 16: Pipe welding.

- The frame of the machine is made from 1 inch GI sq. pipe according to the dimensions. The GI pipes were cut according to the dimension and are welded together by arc welding.
- Two bearings with inner diameter of $15mm$ were fixed on the frame and a $15mm$ shaft was passed through it.

Figure 17: Frame bearings are fixed

- The depower lever is welded on the frame bottom and a plastic pulley is fixed at its end. Then three metal bushes are welded to the frame which guides the tether to the bobbins directly thereby preventing tethers from tangling onto the shaft.
- Then three identical bobbins of diameter $11.5cm$ are placed by inserting the shaft into all three bobbins. All the tethers passes through the bushes and the depower link passes through depower lever and then the bushes.

Figure 18: Frame with bobbins

Then the PMG was coupled to the shaft on one side and the motor was coupled on the other side of the shaft. Furthermore, the motor can be coupled and decoupled from the shaft depending upon its requirement. This function is obtained by using a bush with keyways on its both ends as shown in Figure 19.

Figure 19: Motor coupling

E. SITE SELECTION

Since the prototype was developed in Kerala, a south Indian state, the site was selected after studying about the wind trends in Kerala. Consequently, the windiest area in Kerala was found out to be Ramakkalmedu, a hill station and a hamlet in Idukki district. Ramakkalmedu is said to be one of the most wind blowing area in Asia with a maximum wind speed of 35Kmph. Furthermore, another location called Vagamon, an Indian hill station town primarily located in Peerumade taluk of Idukki district was located as well. Moreover, the average wind speed of Vagamon was 12Kmph. Therefore, these two locations were finalized as the site for testing the AWES prototype.

F. MEASURING DEVICES

1. Multimeter was used for the measurement of generated voltage.
2. Tachometer was used for the measurement of shaft RPM.
3. Digital spring balance was used for the measurement of the traction pull given by the kite.

III. RESULTS

A. Case Study

Case Study I : VAGAMON

The device was tested in Vagamon on March 15, 2018 between 5:00PM to 6:30PM. On that day, the wind was low and unpredictable. The peak values of generator output voltage and speed of the shaft were recorded.

Known Values:

Wind velocity: 4 km/h
Traction force (pull) of kite, F:
$1kg * 9.81m/s^2$ = 9.81N
Diameter of the bobbins, d: 11.5cm = 0.115m
Max. Speed of rotation at the shaft, N: 260 rpm
Voltage output of PMG, V: 6.36V
Distance of the kite from ground station: 75m

Calculations:

Torque, $T = Force * Radius$……………..……….(1)
Force of the kite, F = 9.81
Radius of bobbin = 0.0575m
$Torque, T = 9.81 * 0.0575$…......(2)
$T = 0.564\ Nm$
Mechanical Power, $P_M = T\omega$……….(3)
Torque, T = 0.564
Speed of shaft, N = 260 rpm
$P_M = \frac{0.564*2\pi*260}{60}$
$P = 15.35W$
Since the efficiency of PMG = 75%
Output power(P_E) = Input power(P_M) * 0.75…..(4)
Electrical Power, P_E = P_M * 0.75
= 15.35 * 0.75
= 11.51W……………….….(5)
Hence, at a wind velocity of 4km/h the device can generate a power of 11.51W.

Figure 20: Case Study-I (Vagamon)

Case Study II : RAMAKKALMEDU

The device was tested in Ramakkalmedu, Idukki on March 22, 2018 between 3:00PM to 5:00PM. It was a sunny day with adequate amount of wind, but was not up to the level of a typical Ramakkalmedu climate. The peak values of generator output voltage and speed of shaft were observed and recorded.

Known Values:

Wind velocity: 21 km/h
Traction force (pull) of kite, F : $4.9kg * 9.81m/s^2$ =48.069 N
Diameter of the bobbins, d : 11.5cm = 0.115m
Max. Speed of rotation at the shaft, N : 1001 rpm
Voltage output of PMG, V: 22.9V
Distance of the kite from ground station : 150m

Calculations

Torque, $T = Force * Radius$………….(7)
Force of the kite, F = 48.069N
Radius of bobbin = 0.0575m
$T = 48.069 * 0.0575$……….(8)
$T = 2.763\ Nm$
Mechanical Power, $P = T\omega$………………. (9)
Torque, T = 2.763 Nm
Speed of shaft, N = 1001 rpm
$P = \frac{2.763*2\pi*1001}{60}$……… (10)
$P = 289.73W$
Since the efficiency of PMG = 75%
Output power (P_E) = Input power (P_M) * 0.75…… (11)
Electrical Power, P_E = P_M * 0.75 = 289.73* 0.75
= 217.29W

Hence, at a wind velocity of $20km/h$ the device can generate a power of $217.29W$.
Power consumption of the DC motor : 6W
Therefore the net power generated : $217.29\boldsymbol{W}$ – 6W
= 211.29W……(12)

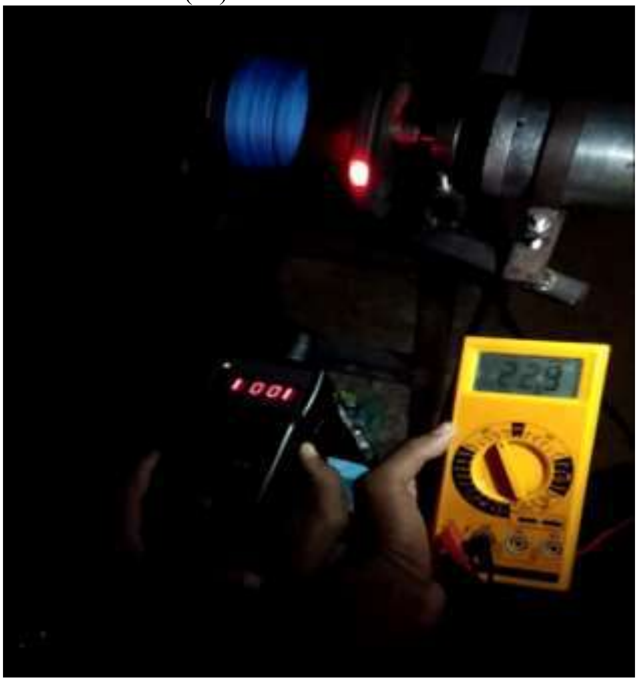

Figure 21: Case Study-II (Ramakkalmedu)

B. Observation

The table below shows the power output of the AWES prototype at different wind velocities.

Table 1: Wind speed and Output power

Sl.No	Wind Velocity @ 100m (in Kmph)	Traction force (pull) of kite (in N)	Output Power (in Watts)
1	4	9.81	11.51
2	10	21.582	91.56
3	13	29.43	127.02
4	21	48.069	211.29

The table below shows the traction force on the kite at different altitudes in the location Ramakkalmedu.

Table 2: Altitude and Traction force of kite

Sl. no	Altitude of kite (in meters)	Traction force of kite (in N)
1	75	16.12
2	100	23.41
3	150	48.069

IV. DISCUSSION AND CONCLUSION

In conclusion, this research mainly focused on the technology, design and fabrication of Airborne wind energy system. A small-scale manually operated prototype of AWES was fabricated and tested in two locations in Kerala namely, Vagamon and Ramakkalmedu. Moreover, from the readings obtained through the testing, it can be seen that the output power increases with increase in altitude and wind velocity.

The traction force of the kite at different altitudes at Ramakkalmedu is tabulated in table 2. It can be seen that, the traction force of the kite increases as the kite is allowed to fly at higher altitudes, starting from $75m$ to $150m$. Therefore, it is understood that the wind velocity is stronger and more stable as the altitude increases.

Design Limitations and Recommendations

There were several limitations in the manual design of the prototype. Firstly, a person was required to manually control the flying kite to prevent it from losing its balance. Therefore, the prototype should have an automatic control system, to guide the motion of the kite, in order to make it more user-friendly and efficient.

Secondly, it was difficult to control the kite during high wind speeds. Meanwhile, during low wind speeds, it took more time to reel-in the tether and failed to prevent the kite from hitting the ground. Hence, automated landing and launching maneuvers are required to land the kite during both, dangerously high wind speeds and unproductive low wind speeds.

As mentioned earlier, the energy production can be increased with the usage of larger kites. Moreover, more energy can be produced by using more efficient motor and generators as well.

Finally, lightning could damage the small sensors installed within the kite. Moreover, the wind farms will have to be positioned in a way that will not interfere with the flight paths of airplanes.

Off-Shore Applications

The existing off-shore wind turbines require humongous and costly foundations. Additionally, the transportation of their large towers and rotor blades consumes exorbitant amounts of energy. Meanwhile, AWES doesn't require a foundation because of its light-weight ground station and so it could be made to float above the water. Therefore, anchoring the floating ground station is the only requirement. Furthermore, the cost and complexity in harvesting off-shore wind energy can be reduced significantly.

Since India has great wind energy potential, it could be anticipated that Airborne Wind Energy System would be further studied and adopted in Indian wind farms within few years. Therefore, reducing the cost and increasing accessibility of electricity.

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