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PROPOSED AIRBORNE TECHNOLOGY TO EXTRACT HIGH ALTITUDE WIND ENERGY USING POWER KITES

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Abstract—With the increasing demand for alternate and sustainable energy sources worldwide, wind energy is eminently gaining global importance. Non-OECD (Organization for Economic Co-operation and Development) countries' economies are expected to grow their consumption rate almost 50% from 2005 to 2030. In addition to the environmental benefits, wind energy will ensure a sustainable solution over various issues regarding security of energy supply and volatile fossil fuel prices. High altitude wind energy is an emerging field of renewable energy that has embarked an increased attention for the last decade. Many innovative technological solutions were proposed for high altitude wind power generation to harness the clean energy from the regular and constant wind blowing between 200m to 1000m above the ground. This paper aims in presenting the advantages of airborne wind energy harnessing technology with a view to prove its potential to overcome the limitations of conventional wind turbines and issues regarding wind intermittency and low capacity factor of a wind farm, thus proving to be a quantum leap in this field to provide abundant quantities of green energy with competitive cost with respect to fossil fuels. Along with the technological effort of kite generator system and its challenges, the paper also focuses on the need for acceptance of newer technologies and its feasibility with the Indian climate and environmental conditions.

Index Terms—High altitude wind energy, Kite generator system, tether, lift force, renewable energy

I. INTRODUCTION

MODERNIZATION and industrialization, a boon to civic life has enormous energy dependency, especially on the fossil energy resources that is sure to run out sooner or later. It becomes necessary to account for the present global scenario and how it is expected to grow over the next two decades. The fossil fuels at present accounting for more than 80% of global energy share has been exploited so extensively for the last century [1] (as reported in 1, updated 2006) that the latest survey predicts the world's supply of gas and oil will not be able to secure the international energy demands some time before 2020. [2] Hence, the issue of sustainable energy generation is one of the most pressing challenges the mankind is struggling with today. On contrary the projections have proved that the world's energy consumption is expected to grow by 50% from 2005 to 2030 due to development of non-OECD (Organization of Economic Co-operation and Development) countries. The cost of energy generations from the nonrenewable fossil deposits is peaking due to the rapidly increasing demand. Moreover fossil fuels endanger the environmental conditions in their process of energy conversion by uncontrollable emissions of CO2 and greenhouse gasses leading to adverse effects like global warming. Hence, sustainable and alternative energy sources play a key role in reshaping the global energy generation scenario. Nuclear energy source was sometime considered as the most relevant and sustainable energy source till recent Fukushima Daiichi nuclear disaster on March 2011[3] which raised serious issues regarding its safety and future of nuclear energy. Wind can be considered as one of the ideal renewable energy. One would be interested to know that the recent studies claimed that [4] the worlds complete energy demand could be met by exploring 20% of global land sites which possess average wind speed greater than 6.9 m/s at 80 m above the ground.

This energy is extracted usually with a conventional, three blade rotating wind turbine which aims in converting kinetic energy or wind into electrical energy. Even though conventional wind turbines use no fuel and participate in clean energy conversion still the huge tower constructions and heavy fixations make the system in-competent as compared to fossil fuels. With lots of research and development wind turbine sizes have rapidly increased their sizes to reach up to heights as high as 200 m where the wind is still intermittent and unstable. The key aim at increasing the turbine sizes to reach higher altitudes where the wind is stronger and constant. Infact, the amount of the wind energy that is harvested has a cubical variation with the wind speed. But the conventional technology to harvest wind speed has reached its saturation limit, because further increase in the size of wind turbines would not be practically feasible due to huge tower construction costs and transportation limitations. There is a

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real need for looking into another axis of research that overcomes the limitations of classical wind turbines. Such a breakthrough in the wind energy generation can be established by capturing High Altitude Wind Energy (HAWE). The researchers have led to thinking of kite or airborne wind turbine to exploit wind energy at higher altitudes. This paper discusses about the theoretical background covering probability function, effect of variations of height on the wind speed, potential of wind energy and the amount of extractable power. 3rd section deals with the kite generation technology and detailed kite based system structure.

II. THEORY FOR WIND POTENTIAL ANALYSIS

A. Probability Density Function

Wind speed can be analyzed by characterization into several probability density functions. Weibull density function is most popular and widely employed for wind data analysis. The mathematical expression for the probability density function can be related as

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)\right] \quad 1$$

$$k > 0, v > 0, c > 1$$

where f(v) is the probability of having wind speed of v m/s, k is defined as a dimensionless shape factor, and c is the Weibull scale factor having same units as that of speed (m/s). The scale factor can be interpreted as the average wind speed through shape factor, describing wind speed distribution. Furthermore the Weibull shape factor (k) and scale factor (c) can be related to average value of wind speed (v_m) m/s by the static formulation

$$v_m = c\Gamma\left(1 + \frac{1}{k}\right) \quad 2$$

where Γ represents gamma function

By improvising linear regression analysis on the cumulative Weibull distribution function represented in equation 3, the shape factor and scale factor can be estimated.

$$f(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad 3$$

B. Variation Of Wind Speed With Height

Wind speed is assumed to increase as one goes higher above the ground.[6] The jet streams existing between 7 km to 16 km of high altitude [7] have magnitude of wind velocity in order of those near the ground. Despite of seasonal variations, the jet streams which buzzes total wind energy of about 100 times the world's total energy demand are continuous and persistent in the mid latitudes. [8] As one goes higher above the ground the surface effects and turbulence decreases, thus leading to greater wind speeds at higher distance above ground, which can be anticipated by an equation that predicts the velocity of wind at a particular height in comparison with others. Roughness of the terrain accounts to one of the key factors for variability of wind. A power law can be put together to obtain a common expression that characterizes the vertical variations of wind speed. [9]

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^{\gamma} \quad 4$$

$$v = v_0 \frac{\ln\left(\frac{h}{h_r}\right)}{\ln\left(\frac{h_0}{h_r}\right)]} \quad 5$$

where v represents wind speed to be determined at particular height h, v_0, $h_0$represents the velocity of wind at the corresponding height respectively. γ is the measure of surface roughness known as roughness coefficient and h_r is roughness factor. The surface roughness coefficient varies from 0.1 to 0.25 depending on the terrain. [10]

C. Potential Energy Of Wind

The amount of power that is available in the wind to be harnessed by the wind turbines is proportional to the cube of wind speed (v), while air density (ρ) going through the blades decreases exponentially [1] [11] taking into consideration the effects of above two quantities wind power available per unit of area swept by the blades (w/m^2) is given by

$$\delta = \frac{1}{2}\rho v^3 \quad 6$$

However only a fraction of total energy available can be extracted by a system working at its optimum efficiency which is determined by Betz limit (16/27). This coefficient of performance makes the extractable energy approximately 59.3% of the available energy over a period of time t expressed as [10]

$$E_m = 0.2965\rho A v^3 t \quad 7$$

III. KITE GENERATOR SYSTEM

A. Basic Concept

The innovative concept of implementing Kites to exploit high altitude wind energy was proposed in 1980 with a discussion that Lloyd made about the ability of a C5A plane based Kite model to generate upto 6.7 MW at wind speed of 10m/s, which is approximately thrice the power generated by an equivalent conventional wind turbine. [12]

Even though his paper was ignored completed then, now it is being considered as a revolutionary idea for the future of renewable energy generation. Lot of researchers are depicting their working on development of HWAE technology and early experiment have proven the potential. [13] Various proposed models differ in the construction and design kites and tethers along with control strategies that are being implemented. One of the structure that best describes the innovative structure of a kite based wind generation system can be referred to as kite generator system as shown in the figure 1 [14]

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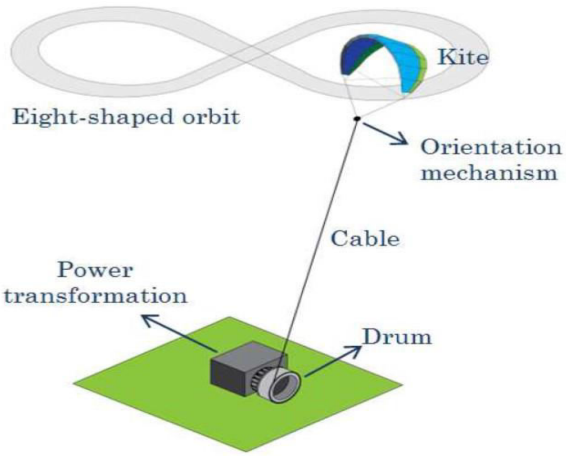


Figure 1Simple Kite Generator System.

The basic concept of KGS can be understood as a tethered kite which mechanically drives a ground based electrical generator. The kite is allowed to fly in the high crosswind speed thereby developing a huge pulling force which drives the generator shaft which in turn generates electricity, thus exploiting the potential wind energy at higher altitude. However while

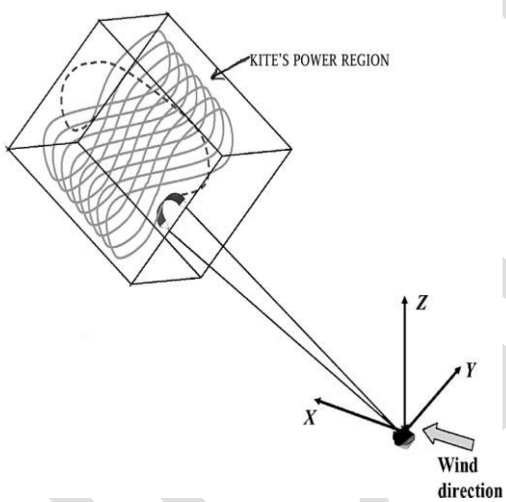


Figure 2 Open orbit mode of operation.

Understanding the technology closely, it is interpreted that the kite cannot pull constantly for the length of tether and kites power regions are limited. Hence the working of generation or consumption cycle is characterized as traction phase and recovery phase. The eight shaped orbit formed by the flight of kite ensures non-tangling and coiling of tethers along with high crosswind. Various scenarios have been presented to extract optimal power using KGS. [15] [16] [17] [18] [19] In open orbit pumping mode the kite flies in eight shaped orbital path with increasing height till the entire length of tether is unfolded(figure 2). This is called the traction phase which is followed by recovery phase that rewinds the tether, consuming a fraction of energy produced in traction phase. In closed orbit mode of operation the kite repeats a single eight shaped orbit, which is further distinguished into two operational regions. The traction phase is result of kites pumping cycle in which tether is pulled in high crosswind and in low crosswind the tether is wound that is recovery phase.

B. Structure Of Kite Generating System

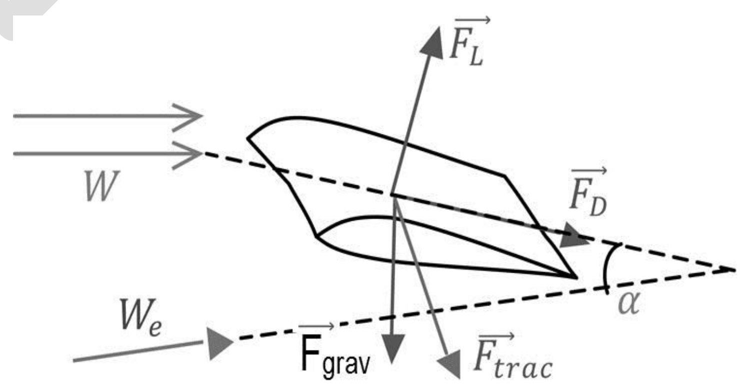
As discussed previously basic working principle is to drive the drum by a tether, which converts the traction force generated by kite into torque that drives the electric generator, converting mechanical traction into electrical energy. The important components can be understood in detail.

1. THE KITE

The operation of kite is similar to that of an airplane wing which is characterized by two dominant parameters namely its aspect ratio (AR) next, which is defined as the ratio of span (w_n) to the chord (c) of the kite; and aerodynamic efficiency (G_e) being the other. The kite operates only when enough lift force is acted upon. This zone of operation is commonly known as power zone. Aerodynamic efficiency introduces two more coefficients, the lift coefficient and drag coefficient (C_L, C_D). These coefficients are functions of kite's attack angle (α) at effective wind direction (We).

The forces acting on the kite are represented in the figure 3

a) Gravitational force(Fgrav)
b) Apparent force(Fapp)
c) Traction force or tether(Ftrac)
d) Aerodynamic force(Faero)



The aerodynamic force is split into two components, the lift force (FL) which is perpendicular to the surface ofkite (A) and drag force (FD) directed along the effective wind (We) as shown in the figure 3

$$F_L = \frac{1}{2}\rho_a A C_L \left|\overrightarrow{We}\right|^2 \quad 8$$

$$F_D = \frac{1}{2}\rho_a A C_D \left|\overrightarrow{We}\right|^2 \quad 9$$

where ρ_a is the air density.

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The aim is to obtain a large traction force that is, maximize the aerodynamic force and minimize the gravitational force. High aerodynamic efficiency, light weight, tensile strength, resistivity and maneuverability are the certain important criteria that must be assessed for thekite to exploit High Altitude Wind Energy (HAWE). The weight and strain depends on the material from which the kite is constructed, whereas design of kite plays a key role in determining rest of the criteria.

2. THE TETHER

The tether is required to transfer the aerodynamic lift force acting on the kite to the traction force which is used to drive the ground based generator. The design, diameter and composition of the cable (tether) are considered as the important aspects as they determine the tensile strength which can bear high traction and on contrary should have relatively light weight and small diameter so that the drag and gravitational force produced by the tether can be neglected.

C. Net Power Generated

To obtain the mathematical expression of the net power generated, modeling of kite and power transformation system is necessary. Let the following assumptions be considered for the ease of analysis

i. Consider single point model of the kite and the tether. This model is usually used to determine the generalized power, being robust it ignores the flexibility and deformations of kite.

ii. The tether is straight and inelastic. This assumption holds true for tethers length less than 1000 m and angle of inclination less than 80 degrees.

iii. Wind is uniform, because at higher altitudes wind speed is regular.

iv. Only the drag force Cdt is considered by neglecting the lift force.

v. The angle of attack is neglected, thus making drag andlift coefficients (CD, CL) constant.

vi. A factor called effective aerodynamic efficiency (Ge) canbe introduced as

$$G_e = \frac{C_L}{C_D + \frac{A_c}{4A} C_{dt}} \qquad 10$$

where A is the surface area of kite and Ac is the crosswind area of tether.

1. AVERAGE MECHANICAL POWER

The average mechanical energy over one period T is the product of the traction phase and the radial velocity V_L.

$$P_M = \frac{1}{T_a}\int_a^T F_{trac}(t) \,.\, V_L(t) dt 11$$

$$P_M = \frac{1}{2}\rho_a A C_L G_e^2 v^3 12$$

2. ELECTRICAL TRANSFORMATION SYSTEM

To transform the generated mechanical power into electrical, a power transformation system is needed, which mainly consists of Permanent Magnet Synchronous Machine (PMSM). The transmission of torque between kite and PMSM is achieved as follows. The translational motion of the tether is converted to rotational motion by means of a drum coupled to PMSM through gearbox. The traction force Ftrac is converted to as resistive torque CR which drives the synchronous machine. This can be expressed by a fundamental equation as

$$C_G - C_R - D\omega_s = J\frac{d\omega_s}{dt} \qquad 13$$

where $\omega_s = \frac{V_L}{K}$ is the rotational velocity, J is the total inertia of the kite, machine's rotor and drum, C_G is generator torque and D is effective damping.

IV. CONCLUSION

The need for search in alternative energy to fossil fuels has led to increased interest in High Altitude Wind Energy(HAWE) and their harnessing techniques. Kite Generator System (KGS) and its advancements ensure a promising solution for future energy demands. This paper deals in understanding the basic concept of kite energy to exploit HAWE. In addition it also focuses on the advantages when compared to conventional wind turbines such as regularity of wind, reduction of wind intermittency and availability of higher wind speeds, thus generating more amount of energy. The operation of KGS is mainly categorized into two modes, the traction phase and the recovery phase. Power is generated in traction phase only. The KGS will ensure very high adaptability, with an ease to modify its rated power by varying altitude and orbit of kite. The system will be cheaper due to elimination of bulky tower construction and easier to be maintained. Various control techniques can be used to optimize the power generated and control the flight of kite. This project work will be expanded to develop a closed loop control model followed by a prototype and the same can be extended to harness offshore strong wind currents.

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