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A Novel Airborne Floating Circular Wind Energy Generation System for Distributed Electrical Energy Generation Applications

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ABSTRACT

To exploit the power of high altitude winds, a novel Airborne Floating Circular Wind Energy Generation System (AFCWEGS) is proposed. The proposed AFCWEGS consists of four parts: 1) main body, 2) flying kites, 3) conductive tether, and 4) a ground station. The conductive tether anchors the main body to the ground station. The flying kites are tethered to the floating circular main body and rotate it. By rotation of main body a generator will generate electrical energy. The generated electrical energy will be transmitted to a ground station. The lifting and the power generation systems of the AFCWEGS are independent and don not relay on together. All parts of the AFCWEGS are described in details. Moreover, an aerostatic analysis is performed to calculate the cross sectional area of the tether as well as the required volume for the main body. Also, the output power of AFCWEGS is estimated. To validate the proposed wind energy generation system a small prototype has been constructed and implemented. Obtained experimental data confirm the effectiveness of the proposed AFCWEGS.
KEYWORDS: AFCWEGS, Airborne Wind Energy, Kite.

INTRODUCTION

To harness high altitude winds, many flying wind energy generation systems have been proposed in the previous research works [1]. These systems can be classified in two groups based on the usage of lighter than air gas. In the systems of the first group, the flying wind energy generation system uses buoyant force produced by a lither than air gas to be floating at altitude. The extracted energy by the system is mechanically or electrically is transmitting to the ground. In the system of the second ground, any lighter than air gas is not used. Instead, the lifting force by wind will lift the system at altitude.

The high altitude wind energy generation technology is at early stages and not matured enough. For example, in [1], a KG-carousel wind turbine for high altitude wind energy generation is proposed. But, this system needs a high territory and land. That is because of the large diameter of this system which is 1 kilometer. Therefore, in this article we presented a new efficient wind energy system which is working at altitude. Thus, it will not occupy the land largely. The AFCWEGS includes four parts.

The first part, main body, is a floating circular body which is filled with a lighter than air gas. The first part is shaped as a circular body to be rotated with the flying kites. The main body is tethered to the ground via a conductive tether. The second parts include several flying kites which are tethered to the main body via conductive tethers. The third part is the conductive tether which transfers the generated electrical energy in the main body to the ground station. The Fourth part is the ground station which accepts the electrical energy from the tether and sends to load center or cities.

The scientific contributions of this paper is that a new wind energy system to exploit high altitude wind energy proposed, modeled, and the electrical output power is calculated. This system can be considered in the second ground of airborne wind energy generation system because lighter than air gas was used for creation of lifting force.

The rest of this paper was organized as follow: in section 2, a brief description of the four parts of the AFCWEGSis presented. In section 3, an aerostatic analysis to calculate the needed cross sectional for the third part, tether, is presented. Moreover, the needed volume for the first part, main body, is calculated. In section 4, the estimation of output electrical power is presented. Finally in section 5, the conclusion and an outlook on further required researches are given.

AFCWEGS DESIGN

The AFCWEGS consist four parts as show in Fig.1

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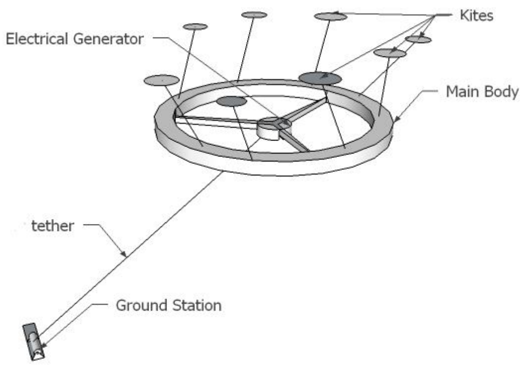

Fig.1. the AFCWEGS consist of four parts

A. First part, main body

The main body is a buoyant circular shape body which is filled with a lighter than air gas. The main body is shown in Fig.2. A generator is located at the center of the main body which is being rotating by the main body. The main body bouncy force can support both its weigh and the weight of the generator to be floating at altitude.

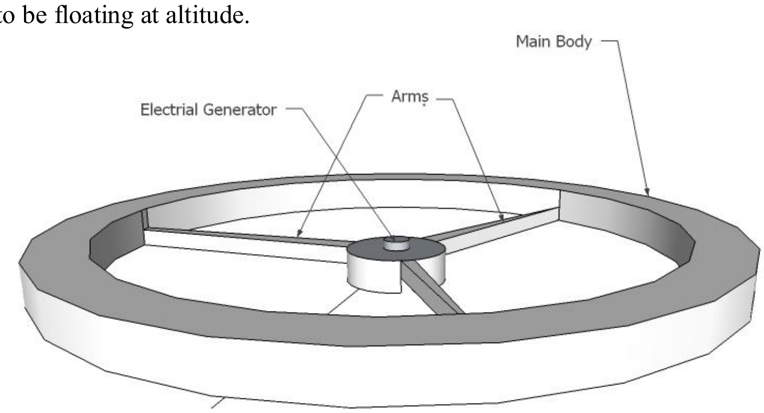

Fig. 2.Main body or the first part

Three light weight arms are supporting the electrical generator at the center of the main body.

B. Second part, Flying Kites

The second part of the AFCWEGS is several flying kite which are flying a high altitudes as shown in Fig. 3. The kites are tethered to the main body using their tethered. The pitch angle of the kites are controlling by control system so that the resulted puling force of them can rotate the main body in order to turning the electrical generator [2].

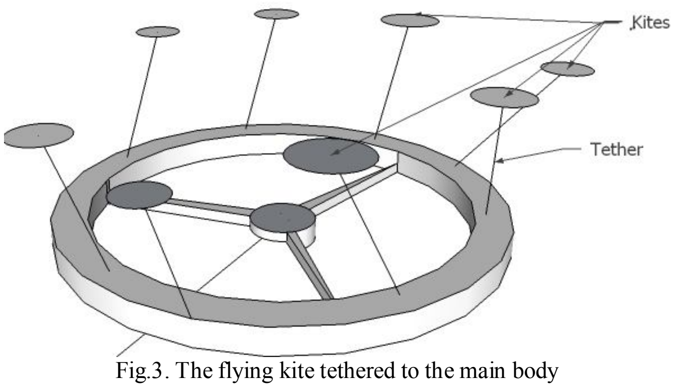

Fig.3. The flying kite tethered to the main body

C. Third Part, Conductive Tether

The generated electrical energy by the electrical generated should be transferred to the ground station. Thus, we used a conductive tether for both transferring the generated electrical energy to the ground and anchoring the main body to the ground as seen in Fig. 4. The conductive tether is a reinforce cable with fiber. In other word, the conductive tether consists of a cable and a fiber. In the next section, we will compute the required cross section area for the fiber to undergo the tension of the cable.

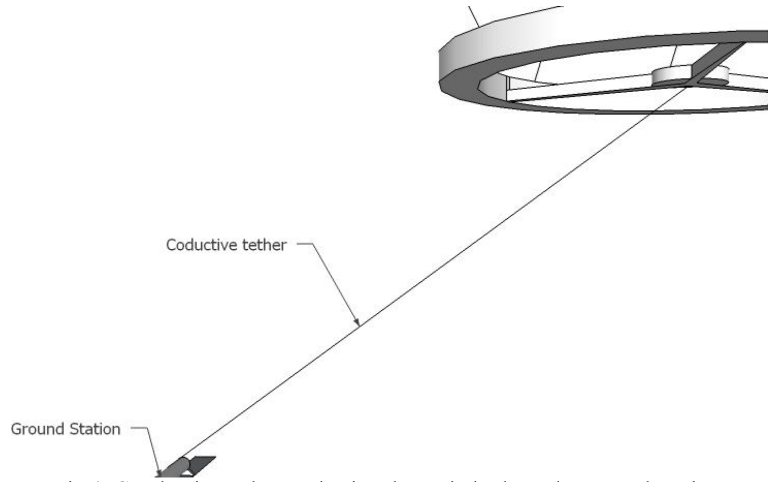

Fig.4. Conductive tether anchoring the main body to the ground-station

D. Forth Part, Ground Station

The main body transmits the generated electrical energy to the ground station via the conductive tether. The ground station is a drum which can be reel the tether as shown in Fig.5. Thus, in case of extreme whether condition, the tether can be reeled for landing of the AFCWEGS. Moreover, since the output voltage of the generator is too low to be transferred to other cities or load centers, in the ground station it will be increased.

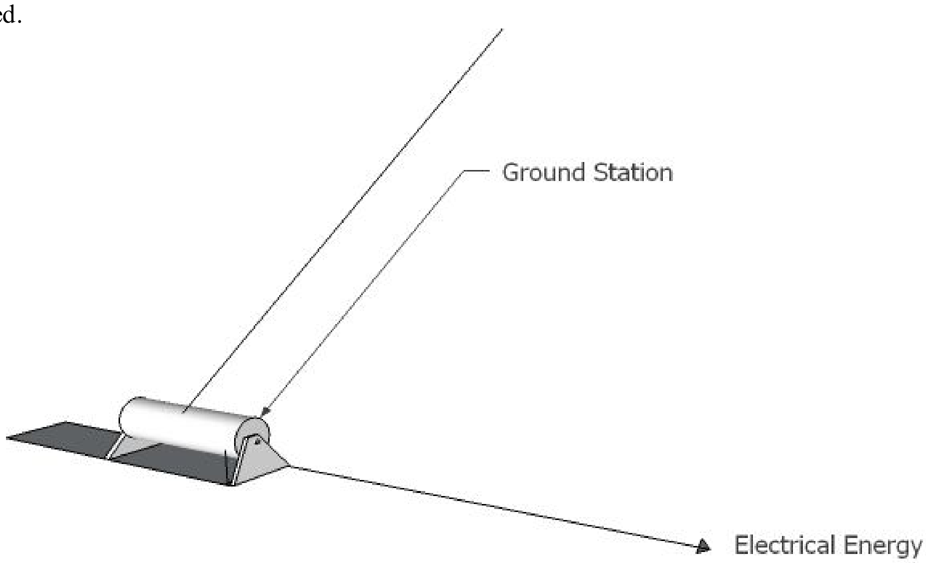

Fig. 5.The ground-station with the drum which is able to reel the tether

The conceptual representation of all parts of the AFCWEGS is shown in Fig. 6

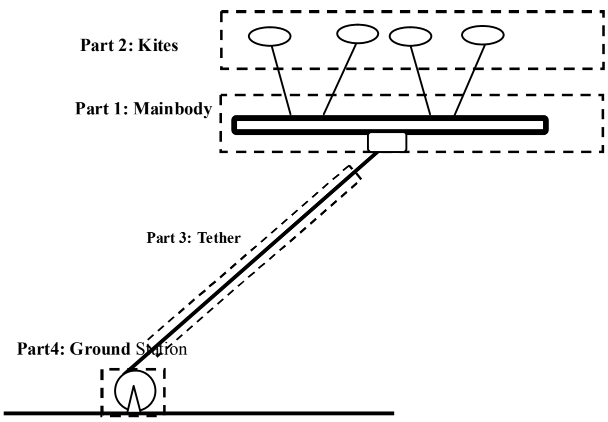

Fig. 6.Conceptual representation of AFCWEGS' parts

OPERATION PRINCIPLE

Fig.7 shows the assembly of the three parts. The center of gravity is axially coinciding with the center of buoyancy and the tether point.

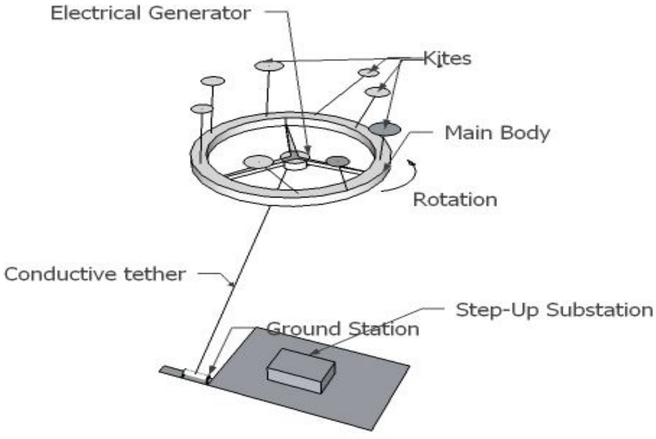

Fig. 7.The AFCWEGS during operation

ELECTRICAL SYSTEM

The Electrical system of the AFCWEGS consists of an electrical generator which is permanent magnet type, and the transmission system. The transmission system is the third part or the conductive tether. The conceptual diagram of the electrical system is shown in Fig.8.

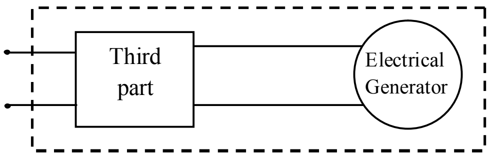

Fig.8. Conductive tether anchoring the main body to the ground-station

Since AFCWEGS should be to operate at altitude of 11-km the tether has a great share of its weight. Thus the actual trend will be to design electrical system so that reduce the weight of tether and its ohmic-loss. We used the approaches presented in in [3] for fully parameterized of a tether for a specific height.

ESTIMATION OF OUTPUT ELECTRICAL POWER

Estimation of output electrical energy of the AFCWEGS can be performed by estimation of generated energy by each of the kites.

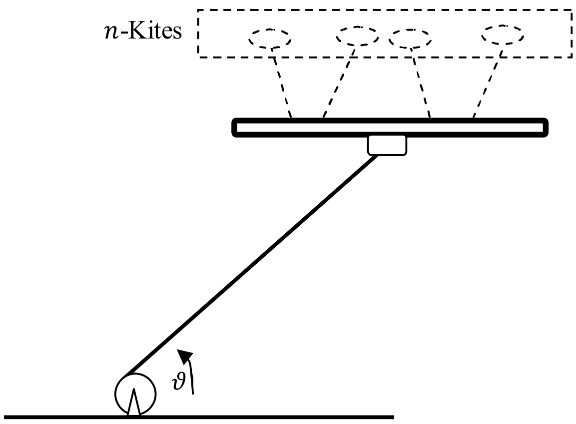

Fig. 9.The n numbers flying kite are rotating the floating circular main body

For estimation of generated power by each kite following simplifications is considered:
1. The operation height of the kits is constant
2. The output power of each kit is constant

3. The friction in all part of the system is negligible

To estimate the output power of the AFCWEGS we should consider the output power the AFCWEGS is sum of the generated power by each of the flying kites.

$$P_{FC} = nP_{kit}(1)$$
$$P_{kit} = \frac{1}{2}\rho_{air}AC_l V_{wind}^2 \frac{4}{27} G_e^2(2)$$
$$V_{wind} = V_0(\frac{h}{h_0})^{\alpha} \qquad (3)$$

Where V_w and A is the wind speed at altitude of h and swept area by the main rotor respectively. Theρ_{air} is air density A is apparent area of kit,$\vartheta$is mean angle of kiteline with respect to horizontal,η_{mech}, $\eta_{elec}$are the mechanical and electrical efficiencies of the electrical generator, respectively.

SIZING OF THE MAIN BODY

Since the main body provide bouncy to support itself and the generator, we should select enough volume to provide sufficient buoyancy to overcome the complete weight of the AFCWEGS to keeps it aloft. In other word:

$$B_{\text{AFCWEGS}} > W_{\text{AFCWEGS}}(4)$$

To find$Vol_{main\ body}$we should solve above equation in critical state:

$$B_{\text{AFCWEGS}} = W_{\text{AFCWEGS}}(5)$$

To solve above equation both the bouncy and weigh of the AFCWEGS must be found. AFCWEGS consist of four parts. Thus, weigh and bouncy of the whole system is sum of weight and bouncy of due to each part:

$$W_{\text{AFCWEGS}} = W_{Part-1} + W_{Part-2} + W_{Part-3} + W_{Part-4}(6)$$
$$B_{\text{AFCWEGS}} = B_{Part-1} + B_{Part-2} + B_{Part-3} + B_{Part-4}(7)$$

E. Bouncy of each Parts

Therefore we should find weigh and bouncy due to each of three parts:

1) First Part

The first part is filled with lighter than air gas. The volume of the first part is Vol. Thus, the buoyancy associate with it is:

$$B_{Part-1} = g(\rho_{air} - \rho_{gas})Vol_{main\ body}(8)$$

Where $Vol$is the volume of each of air rotor, ρ_{air} and ρ_{gas} are the densities of air and gas (helium) respectively and g is gravity acceleration ($9.8^{m}/_{s^2}$).

2) Second, third, and fourth parts

Since any lighter than air gas is not used in the tether, flying kites and ground station, the buoyancy associate with them is considered zero:

$$B_{Part-2} = B_{Part-3} = B_{Part-4} = 0\ (9)$$

F. Weights of each Part

1) First Part

The weight of the main body is considered as sum of the main circular structure and the generator

$$W_{Part-1} = W_{Cicular\ Str} + W_{Genrator}(10)$$

2) Second Part

Since the second part consists of several flying which are proving uplifting force the weight of this part will be;

$$W_{Part-1} = nW_{Kits} - nW_{\text{K}}(11)$$

3) Third Part

The weight of the tether is a significant share of the wind energy generation system. The tether weight is a significant share of AWES. For estimation of tether weight it requires to find conductor weight and fiber (for reinforcing the tether). The conductor weight can be found by calculation of its cross sectional:

$$A_{Conuctor} = r_{Al}\frac{L_t}{\propto}(12)$$

Where $\propto$ is the ratio between the power lost in the conductor and generated power P_{Gen} and V is the voltage.

Tether weight can be found by multiplying cross sectional at tether length and aluminum density:

$$W_{Al} = \rho_{Al}r_{Al}\frac{L^2{}_t}{\propto}\frac{P_{Gen}}{V^2}(13)$$

Where $P_{Gen}$is the output electrical of the AFCWEGS.

By finding the cross sectional of fiber we can calculate the weight of fiber. The cross sectional of tether depending on maximum acting tension the fiber.
The maximum tension of tether can be found :

$$T = nT_{kit} \quad (14)$$

Where, T_{kit} is the pulling force provided by each of the kites.

$$T_{kit} = \frac{1}{2}\rho_a A C_l V_{wind}^2 \frac{4}{27} G_e^2 \quad (15)$$

By division of maximum tension to fiber strength the, required fiber cross sectional can be found:

$$A_{fiber} = \frac{T}{\sigma_{fiber}} \quad (16)$$

Thus fiber weigh can be found:

$$W_{fib} = \delta_{fib} L_{tether} \frac{T}{\sigma_{fib}} \quad (17)$$

Thus the tether weight is:

$$W_{Part-3} = \delta_{fiber} L_t \frac{T}{\sigma_{fiber}} + \delta_{con} r_{con} \frac{L^2{}_t}{\propto} \frac{P_{out}}{V^2} \quad (18)$$

4) Forth Part

Since the ground station is positioned on the ground the weigh associate with it is considered as zero value:

$$W_{Part-4} = 0 \quad (19)$$

G. Net-Wight and Buoyancy of AFWEGS

Overall weight of hybrid wind generator

$$W_{\text{AFCWEGS}} = \delta_{fiber} L_t \frac{T}{\sigma_{fiber}} + \delta_{con} r_{con} \frac{L^2{}_t}{\propto} \frac{P_{out}}{V^2} + W_{Cicular\ Str} + W_{Genrator} + W_{Part-1} + nW_{Kits} - nW_{\text{K}} \quad (20)$$

$$B_{\text{AFCWEGS}} = (\rho_{air} - \rho_{gas}) g Vol_{main\ body} \quad (21)$$

By combination the equation of total weighs and bouncy, the output power of AFCWEGS can be expressed as:

$$Vol_{main\ body} = \frac{\delta_{fiber} L_t \frac{T}{\sigma_{fiber}} + \delta_{con} r_{con} \frac{L^2{}_t}{\propto} \frac{P_{out}}{V^2} + W_{Cicular\ Str} + W_{Genrator} + W_{Part-1} + nW_{Kits} - nW_{\text{K}}}{(\rho_{air} - \rho_{gas}) g} \quad (22)$$

EXPRIMNENTS

To validate the proposed model and feasibility analysis for the AFCWEGS should be tested. The characteristic of a small prototype of AFCWEGS which is construed din the lab are given in table 1

Table **1** Characteristics of AFCWEGS

$L_{ConductiveTether}$	12m	B_{Part-1}	130N
n	10	B_{Part-2}	0
V	12v	B_{Part-3}	0
W_{Part-1}	1.2kg	h	1m
W_{Part-2}	0.3kg	ρ_{gas}, ρ_{air}	1.29 kg/m^3
W_{Part-3}	0.21kg	δ_{fiber}	1.5 g/cm3
$W_{Genrator}$	0.5 kg	δ_{Al}	2.8 g/cm3
W_{kite}	10gr	T	3N
g	9.8 $^{m}/_{s}$	B_{Part-1}	130N
r_{Al}	2.7 × 10-8 Ω·m	B_{Part-2}	0

The out power for wind speed of 0 to 50 m/s of AFCWEGS can be predicted using the obtained equation and is charted in Fig.10

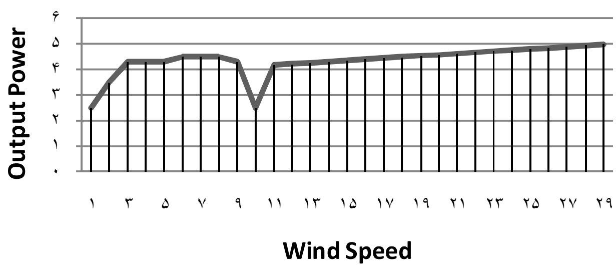

Fig. 10.The estimated power versus wind speed

After construction of AFCWEGS the system is anchored in wind tunnel with a condition similar to the condition of high altitude winds. The output power is measured. The wind was varied between speed of 0 to 30m/s. The obtain power is charted versus wind speed is shown in the Fig. 11

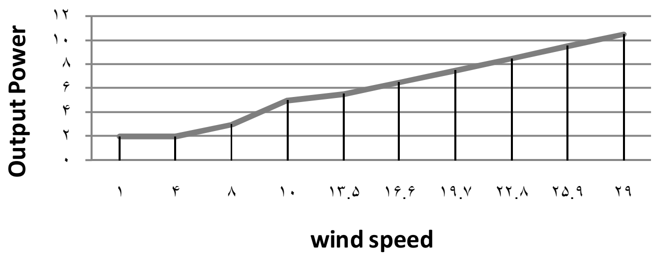

Fig. 11.The measured power versus wind speed

As seen in obtained power curve the output power speed of 15m/s the power output of AFCWEGS is 10w. The impressive difference between predict and measured value is mainly due to existing friction in generator. It can be predicted in higher scale there is better matching between the measured and analytical data.

CONCLUSION AND PERSPECTIVE

The paper sketch out design and construction of a novel AFCWEGS for high altitude wind energy generation. All the parts are described in detail. The output power of AWES is estimated using analytical approach. Moreover, a method for sizing of the main body was presented. To verify the viability of proposed wind energy system a prototype was assembled. The generated power by the wind turbine is charted and analyzed, which demonstrate the effectiveness of the proposed AFCWEGS.

APPENDIX

$L_{ConductiveTether}$	**Conductive Tether length**
n	Number of the flying kites
V	Nominal voltage of generator
W_{Part-m}	Weight of $m-th$ part
$W_{Genrator}$	Weight of Electrical Generator
W_{kite}	Weigh of a flying kite
g	Accelerate gravity (9.8 $^{m}/_{s}$)
r_{Al}	Conductor resistivity
n_a, n_c	Number of units in part A and C
B_{Part-m}	Bouncy of $m-th$ part
h	Operation Height of flying of kites
ρ_{gas}, ρ_{air}	Densities of air and gas
δ_{fiber},δ_{cond}	Density of fiber and conductor in the tether
σ_{fiber}	Fiber strength
T	Tension in tether
V_{wind}	Wind velocity
η_{mech},η_{elec}	Mechanical and electrical
Vol	Volume of main body
A	Apparent area of flying kites
C_L	Lift coefficient of flying kite
G_e	Aerodynamic efficiency of the kite

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