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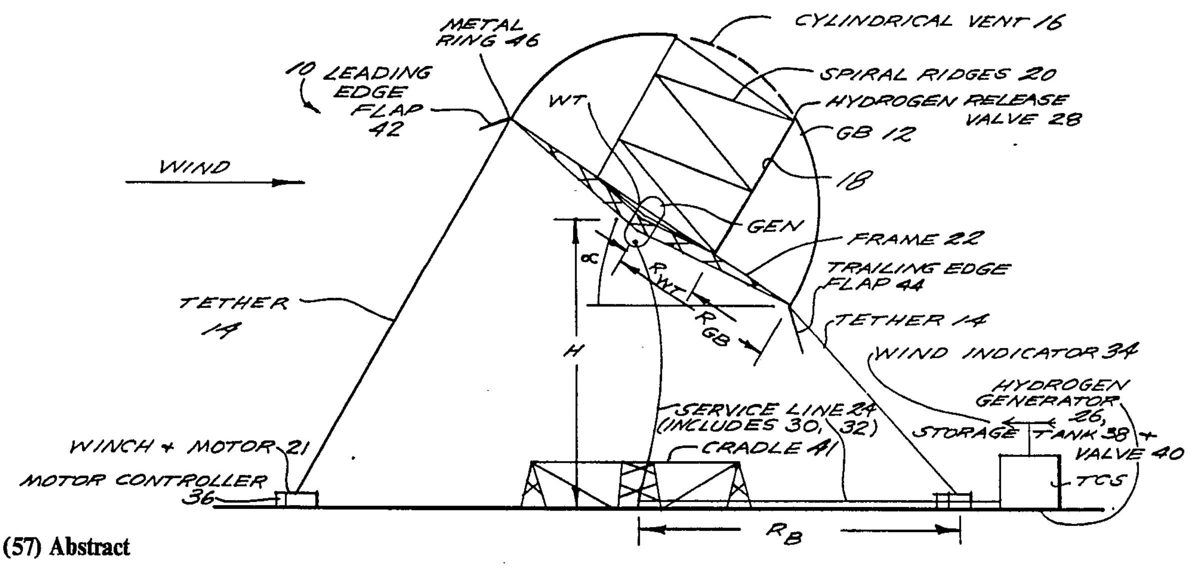

(57) Abstract

A generally toric lighter-than-air gas bag-type airfoil (12) is tethered by tethers (14) to the ground at a plurality of angularly widely distributed points at whinches (21) about the periphery of the gas bag. A wind turbine (WT) is mounted at the entrance to the axially central vent (16). The tether lines are entrained about individually operable power winches (21), preferably controlled by a micro-processor (TCS) which takes in wind direction and tether line tension data and operates the winches (21) and inflation gas inlet and outlet valves (40, 28) to orient the wind turbine into the wind for maximum power output. In other embodiments, a plurality of wind turbines (WT) are supported aloft on the same tethered airfoil (112) which is provided with apparatus (124, 130, 132, 134, 126, 140, TCS) for orienting the wind turbines (WT) into the wind. Various ways and devices, see Fig. 2, are described for converting the wind energy into electrical power and for connecting and providing the plural outputs to the same electrical power grid. The principles are applicable whether there are a small number of relatively large wind turbines, a large number of relatively small wind turbines or some of each.

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MULTIPLE WIND TURBINE TETHERED AIRFOIL WIND ENERGY CONVERSION SYSTEM

BACKGROUND OF THE INVENTION

There is shown schematically in FIGURE 1 an elevational view of a first-generation tethered airfoil wind energy conversion system, which was designed by the present inventor and which is included here for illustrative purposes. Referring to that FIGURE, the following derivation is made.

Consider the tethered airfoil wind energy conversion system (hereinafter "TAWECS") of FIGURE 1 to be a large circular airfoil of planform surface area S, and wind passing over it produces lift L. The portion of L that is effective in reducing the air pressure over the TAWECS vent (in which is mounted a conventional wind turbine and electric generator) should be $(A_V/S)L$, where A_V is the area of the vent. Then the RMS decrease in air pressure over the TAWECS vent caused by the wind,

$$\overline{\Delta P} = (A_V/S)L \div A_V = L/S \qquad (\text{lb/ft}^2)$$

The RMS head due to wind input to the TAWECS,

$$\bar{h} = \overline{\Delta p}/\rho = L/S\rho \qquad (\text{ft})$$

where ρ is the air density (0.0023 slug/ft^3). From O. W. Eshbach, "Handbook of Engineering Fundamentals", 2nd Ed., Wiley, 1952, p. 7-75 to 7-77,

$$C_L = L/(1/2\ \rho\ \overline{V}_w^{\,2}\ S) = (3/20)a$$

where C_L = coefficient of lift

$\overline{V}_W$ = RMS velocity of wind over the airfoil surface (ft/sec)

a = maximum camber of airfoil in % of chord

= (camber/chord) 100

= 2/3 of design C_L in tenths = 2/3 C_L X 10

Then $L = 3/40\ a\ \rho\ \overline{V_w}^2\ S$ (lb)

$\overline{h} = 3/40\ a\ \overline{V_w}^2 = \overline{\Delta p}/\rho$ (ft)

The above derivation, which will be useful in the detailed description to follow, does not provide for the local variations in pressure over the airfoil surface. Instead, these calculations were for gross, first order feasibility estimates, using overall or average airfoil properties, and RMS values for the time-varying parameters. (A more detailed analysis using partial differential equations would be required to predict local pressure variations.)

In literature searching prior to the preparation of this document, the present inventor has become aware of the following prior art:

Prior US Patents

Patentee	Patent No.	Issue Date
Bolie	4,017,205	April 12, 1977
Carson, et al	4,018,543	April 19, 1977
Bolie	4,116,581	Sept. 26, 1978

Bolie, in U.S. Patent 4,116,581, has described a wind turbine (hereinafter "WT") employing airfoil principles to enhance the pressure drop across the WT, i.e., reduced pressure on the suction side. The Bolie structure employs a fixed hemispherical shell containing the WT in the lower half of the structure, and a rotating hemispherical shell in the upper half, with a vent oriented into the wind, and curved deflectors to direct the wind into the WT. The Bolie structure is rigid, implying size limitation, dictated by strength of materials considerations, on WT radii of probably 50 feet or less. Since the Bolie structure is approximately a sphere, with two opposing suction sides and camber of approximately 0, the reduced pressures on the top and bottom hemispheres should approximately cancel each other, leaving only the wind flowing through the aperture being effective in driving the WT, thus providing no aerodynamic advantage over a conventional horizontal axis WT, and a considerable economic disadvantage.

In both of the Bolie patents, the angle of attack of the airfoil $\alpha = 0$; an angle of attack $\alpha>0$ is impractical with the Bolie embodiments. Further, the Bolie structure in U.S. Patent 4,116,581 must rotate into the wind, implying mechanical wear problems.

SUMMARY OF THE INVENTION

The present invention provides a tethered airfoil wind energy conversion system which holds promise for being more efficient than those of the prior art. In particular, the device of the invention preferably has an optimum angle of attack α of up to at least 30° in the preferred embodiment, which increases the coefficient of lift by a factor of at least 6-8 with respect to an airfoil with $\alpha = 0$. See Eshbach, supra, p. 7-78. Further the device of the invention preferably is deployed into the wind without a requirement for being rotated and does not have the size limitation implied in prior art structures.

In its foregoing aspects the invention provides several variations of a device for converting wind power to electricity, using a wind turbine supported aloft on a specially-designed tethered airfoil. The device includes means for orienting the wind turbine optimally into the wind without requiring rotation of the tethered airfoil. Among the variations set forth are a first embodiment in which the wind turbine is supported on the tethered airfoil via a 3-armed frame and a second embodiment in which the wind turbine is supported on the tethered airfoil via a radially inner and a radially outer support ring, with a plurality of radiating spokes held in tension between them. Of these the second appears to be most economical. In addition, the outer ring provides a rigid leading edge for the airfoil, which may be essential for use in winds above a light breeze. The outer ring also provides a support for the leading and trailing edge flaps of the airfoil.

In further embodiments, a plurality of wind turbines are supported aloft on the same tethered airfoil which is provided with means for orienting the wind turbines into the wind. Various ways and means are described for converting the wind energy into electrical power and for connecting and providing the plural outputs to the same electrical power grid. The principles are applicable whether there are a small number of relatively large wind turbines, a large number of relatively small wind turbines or some of each.

Other distinctions and advantages will become apparent in the following description.

The principles of the invention will be further discussed with reference to the drawings wherein preferred embodiments are shown. The specifics illustrated in the drawings are intended to exemplify, rather than limit, aspects of the invention as defined in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a diagrammatic elevational view of a first generation TAWECS device, discussed in the "Background" section hereinabove;

FIGURE 2 is a diagrammatic elevational view of a first embodiment of the TAWECS device of the present invention;

FIGURE 3 is a perspective projection showing the geometry of a tether control system therefor;

FIGURES 4a and 4b are plots of predicted performance data for the TAWECS of FIGURE 2 at two different average wind velocities;

FIGURE 5 is a top plan view of a modified gas bag base for the TAWECS, in effect a second embodiment thereof;

FIGURE 6 is a simplified longitudinal vertical sectional view of a multiple wind turbine tethered airfoil wind energy conversion system, taken on line 6-6 of FIGURE 8. In this version, the individual electrical cables all descend to the ground;

FIGURE 7 is a schematic diagram of the apparatus of FIGURE 6;

FIGURE 8 is a simplified top plan view of the embodiment of FIGURE 6;

FIGURE 9 is a simplified, fragmentary top plan view of a first variation, wherein the electrical outputs are combined before a common cable descends to the ground;

FIGURE 10 is a schematic diagram of the apparatus of FIGURE 9;

FIGURE 11 is a simplified, fragmentary top plan view of a second variation, wherein the electrical outputs are beamed to the ground via a microwave transmitter/receiver set; and

FIGURE 12 is a schematic diagram of the apparatus of FIGURE 11.

DETAILED DESCRIPTION

A first embodiment of a tethered airfoil wind energy conversion system, TAWECS, is shown in FIGURE 2 at 10. In this embodiment, a gas bag airfoil 12 of approximately hemispherical shape is filled with enough lighter-than-air gas, e.g., hydrogen to lift the TAWECS components and provide a moderate tension on the three tethers 14. The WT is mounted in the bottom center of the gas bag 12, with a cylindrical vent 16 above the WT.

In a typical such TAWECS configuration, by requiring that the radius of the gas bag (R_{GB}) be at least three times the radius of the wind turbine (R_{WT}), the cylindrical vent may be tall enough to produce and sustain a confined vortex by lining the interior sidewall 18 of the cylindrical vent with spiral ridges 20 to impart an angular acceleration to the air flowing vertically in the cylindrical vent, as in the vortex generator (VG) described by Yen in U.S. Patent 4,070,131. The vortex thus produced further reduces the pressure above the WT in addition to the pressure reduction caused by the suction side of the hemispherical airfoil shape of the gas bag.

The gas bag, being flexible, should prevent ice and snow buildup, by being free to deflect in six modes: roll, pitch, yaw, heave, sway, and surge. Since gas bags may be of almost arbitrary size, it is likely that the size limitation is determined by the WT vanes, and 150-foot vanes are now under development by others. A hemispherical airfoil produces maximum camber/chord ratio, maximizing pressure drop across the WT, and thus maximizes power produced.

The hemispherical hydrogen-supported gas bag is tethered by three or more lines 14 (shown in the elevation view of FIGURE 2 as if there were four), which are adjusted by winches driven by motors 21 controlled by a tether control system (TCS) to control the tilt of the gas bag 12 into the wind, such that the angle of attack α is optimum to maximize the pressure drop across the WT. Each tether 14 ends at the outer end of the frame 22 that supports the WT and the generator (GEN) driven by the WT. The gas bag is attached to this frame to lift the TAWECS components. In addition to those components already mentioned, a service line 24 is provided from the bottom of the GEN to the ground, and along the ground a distance greater than R_{GB}, to provide hydrogen replenishment from a hydrogen generator 26 on the ground, power for aircraft warning lights, if required, control signals for a hydrogen release valve 28 in the top of the gas bag, control signals for pitch control of the WT vanes, lightning ground cable 30 and a power output cable 32. Service line 24 may be led along one of the tether lines 14, instead of vertically to the ground as shown in FIGURE 2. This will enable placing two or more TAWECS one above the other at particularly desirable (windy) sites. The power output cable of service line 24 may be replaced with a microwave transmitter in the TAWECS and a microwave receiver on the ground. A wind direction indicator 34 is required on the ground to supply a wind direction-representing signal to the TCS, which calculates the required lengths of the three tethers 14 to tilt the TAWECS into the wind at its optimum angle of attack α to maximize power output. Control signals are then sent to the three tether winch motor controllers 36 to set the three tether lengths in accordance with these calculations.

To obtain the equations that must be solved in real time by the TCS to control the three tether winches 21, consider FIGURE 3, in which the circle at elevation H above the ground at its center represents the bottom of the gas bag 12. Let

$$\angle AOC = \angle COB = \angle AOB = 2\pi/3$$

$OA = OB = OC = R_{GB}$, the three frame arms

$O'D = O'E = O'F = R_B$ in the ground plane

Then
$$a_1 = (a_2^2 + a_3^2)^{1/2} = (a_2^2 + (H - a_5)^2)^{1/2}$$
$$b_1 = (b_2^2 + b_3^2)^{1/2} = (b_2^2 + (H - b_5)^2)^{1/2}$$
$$c_1 = (c_2^2 + c_3^2)^{1/2} = (c_2^2 + (H - c_5)^2)^{1/2}$$

where $a_2 = R_B - a_4 = R_B - a_6 = R_B - (R_{GB}^2 - a_5^2)^{1/2}$

$b_2 = R_B - b_4 = R_B - b_6 = R_B - (R_{GB}^2 - b_5^2)^{1/2}$

$c_2 = R_B - c_4 = R_B - c_6 = R_B - (R_{GB}^2 - c_5^2)^{1/2}$

and for $\theta = 0$ to $2\pi/3$,

$a_5 = R_{GB}\sin\alpha\cos 3\theta/2$

$b_5 = -R_{GB}\sin\alpha\cos 3\theta/2$

$c_5 = -R_{GB}\sin\alpha$

for $\theta = 2\pi/3$ to $4\pi/3$,

$a_5 = -R_{GB}\sin\alpha$

$b_5 = -R_{GB}\sin\alpha\cos 3\theta/2$

$c_5 = R_{GB}\sin\alpha\cos 3\theta/2$

for $\theta = 4\pi/3$ to 2π,

$a_5 = -R_{GB}\sin\alpha\cos 3\theta/2$

$b_5 = -R_{GB}\sin\alpha$

$c_5 = R_{GB}\sin\alpha\cos 3\theta/2$

These equations are readily solvable by many commercially available, inexpensive micro-processors, for given values of R_B, R_{GB}, H, and α, with θ obtained from the wind direction indicator 34.

The hydrogen generator 26 may be one of several known types, which produce hydrogen by electrolysis of water (possibly obtained from condensed water vapor in the air), or by the process described by Pangborn, et al in U.S. Patent 4,075,313, or by other means. (The Pangborn process for generating hydrogen requires use of at least one of several high temperature subprocesses, one of which is preferably carried out at 750°C-950°C. For those subprocesses requiring temperatures exceeding that obtainable from a rotary mechanical heat generator, either a double convex lens may be used when the sun is available (or some other means of concentrating the sun's rays), or some of the hydrogen generated may be burned to produce the required temperature. Electric heating could be used in the Pangborn process for hydrogen production, and probably would be preferable, connected to the WT-driven electric generator [either resistance, arc, or induction heating]. In fact, electric heating may be preferable for all the subprocesses requiring heat, to avoid burning any of the hydrogen produced by the hydrogen generator.)

The hydrogen generator 26 must have a storage tank 38 and reserve capacity enough for a heavy snow or ice load accumulating during a period of no wind, to provide the extra lift required to keep the gas bag aloft with moderate tension on the tethers. The hydrogen generator may supply hydrogen not only to the airfoil, but elsewhere as an end product of the TAWECS. The hydrogen generator may be borne aloft by the airfoil. The TCS must sense tension on the tethers, and open the hydrogen supply valve 40 when tension becomes too low. The TCS must also sense excessive tension on the tethers, and open a release valve 28 in the top of the gas bag to release excess hydrogen to lower the tension on the tethers. The TCS must also provide for manual control of the tether winch motors for use in lowering the TAWECS for maintenance, which would require sufficient control to settle the GEN and frame gently into a special cradle 41.

Leading and trailing edge flaps 42, 44, which increase the camber, coefficient of lift, and optimum angle of attack of an airfoil, can be added to the hemispheric gas bag airfoil by adding a metal ring 46 around the base of the gas bag of sufficient strength to support the flaps, and attached to the frame 22 that supports the WT and GEN and connects to the tethers 14. Such a metal ring may be desirable for another reason - to provide tie points for hold-down lines (not shown) or a net (not shown) over the gas bag.

In lieu of an electric generator GEN, the WT may drive a flexible shaft (not shown) connected to a mechanical load (not shown) on the ground.

The equation set forth hereabove in regard to the simplified system shown in FIGURE 1, relating pressure across the WT, airfoil geometry, and wind velocity, may be rewritten;

$\overline{\Delta p}/\overline{V}_w^2 = 0.075\ a\ \rho$ and compared with test data for an airfoil approximating a hemisphere, to confirm the derivation. In "Aerofoil Sections", F. W. Riegels, Butterworth, London, 1961, the airfoil with a section closest to that of a hemisphere is the Gö 625, tested at Göttingen in 1941, for which a = 10, pressure coefficient $C_p = -1.6$ on the suction side and 0 on the pressure side at 20% of chord (length from leading edge) for a design coefficient of lift $C_L{}^*$ of 0.075, and α = 14° for C_L max of 1.5. From Riegels, p. 275,

$$C_p = \Delta p/q = \Delta p/(1/2\ \rho\ V_w^2)$$
$$\Delta p/V_w^2 = 1/2\ \rho\ C_p$$

Comparing the derivation with regard to FIGURE 1 for $\overline{\Delta p}/\overline{V}_w^2$ with test data for this airfoil,

$$0.075\ a\ \rho = 1/2\ \rho\ C_p$$
$$0.15\ a = C_p.$$

1.5 ≈ 1.6 and the derivation is approximately confirmed. In "Handbook of Airfoil Sections for Light Aircraft", by M. S. Rice, Aviation Publications, Milwaukee, 1971, p. 73 shows the test data for a USA-35A airfoil, with a section closest to that of a hemisphere. No test date is given, but most of the 125 airfoils in the handbook were tested between 1918 and 1937. The USA-35A airfoil has a value of a of 9.35 at 30% of chord, with $\alpha = 20°$ for maximum value of C_L. No data on C_p are given in Rice. From the data for these two airfoils, a hemispherical airfoil with a cylindrical central vent, and $R_{GB} = 3R_{WT}$, should have a value of a of about 20 at 50% of chord, and an α of about 30°. (a_{max} for a hemisphere = (1/2 r/2r)100 = 25).

Having confirmed from test data that $\overline{\Delta p}/\rho = 0.075\ a\ \overline{V}_w^2$, the derivation with regard to FIGURE 2 for RMS power obtainable from the WT then follows:

$$\begin{aligned}\overline{P} &= \overline{h}\ \dot{w}\ c_p \\ &= \overline{h}\ A_v\ V_v\ \rho\ c_p \\ &= \overline{h}\ A_v\ (2g\overline{h})^{1/2}\ \rho\ c_p\end{aligned}$$

where $\dot{w}$ = mass rate of air flow through the WT in lb/sec

c_p = power coefficient of the WT, assumed to be 0.4 from "Wind Machines", by F. R. Eldridge, Mitre Corp., Publication No. MTR-6971, October 1975, p. 55

A_v = elliptical area facing the wind of the vent in which the WT is located (i.e., the vertical projection of the circular vent) (ft^2)

V_v = vertical air velocity in the vent (ft/sec)

g = gravitational acceleration = 32.2 ft/sec^2

Then $\bar{P}$ = 0.0023 (8.02) $A_v\bar{h}^{1.5}(0.4)$ (ft lb/sec)

$= 0.0184\ A_v\bar{h}^{1.5}(0.4)(0.746/550)$ (KW)

$= 0.0000100\ A_v\bar{h}^{1.5}$

$= 0.0000100\ \pi\ R_{WT}{}^2 \sin\alpha\ (\overline{\Delta p}/\rho)^{1.5}$

$= 0.000031\ R_{WT}{}^2 \sin\alpha\ (0.075\ a\ \bar{V}_w{}^2)^{1.5}$

$= 0.000000637\ R_{WT}{}^2 \sin\alpha\ (a\ \bar{V}_w{}^2)^{1.5}$ (KW)

To obtain estimates for plant cost per unit of power produced, the volume of hydrogen required to lift the TAWECS components must first be found from the equation

$\text{Lift} - W_T = \varepsilon$

where $\text{Lift} = (\text{density}_{air} - \text{density}_{H_2})\ \text{Volume}_{H_2}$

$= (0.08071 - 0.00561)\ \text{Vol}_{H_2} = 0.0751\ \text{Vol}_{GB}$

for the case in which Vol_{H_2}

$= \text{Vol}_{GB}$

Then

$\text{Lift} = 0.0751\ (2/3\pi R_{GB}{}^3 - \pi\ (1.1R_{WT})^2\ R_{GB})$

$= 0.0751\ \pi R_{GB}\ (2/3\ R_{GB}{}^2 - 1.21\ R_{WT}{}^2)$

W_T = total weight of the components lifted by the gas bag

ε = an arbitrary moderate lift, found by successive approximation by varying R_{GB}, to ensure moderate tension on the tethers. An $\varepsilon \simeq 10\ R_{WT}$ was used in the following calculations.

For each successive approximation of R_{GB}, an approximate value of a is first assumed, ε is calculated and a revised value of a is found from

$$a \doteq (1/2\ (R_{GB} - R_{WT})/2R_{GB})100 = 25(1 - R_{WT}/R_{GB})$$

Then ε is recalculated using this revised value of a and this process is iterated until ε meets the above criterion. Then the component costs are estimated and summed, and the sum $\$_T$ is divided by $\overline{P}$. Let

$$W_T = W_{GB} + W_{WT} + W_{GEN} + W_{FRAME} + W_{TETHERS} + W_{LINE} + W_{FLAPS}$$

and let $\overline{d}$ be the unit weight for each component to be lifted by the gas bag. Then

$$W_{GB} = \overline{d}_{GB} A_{GB} = \overline{d}_{GB} \; (2\pi R_{GB}{}^2 + \pi R_{GB}{}^2 - 2\pi(1.1R_{WT})^2 + 2\pi(1.1R_{WT}) R_{GB}) 3$$

where the factor 3 is included to account for the compartmentation of the gas bag necessary to prevent one puncture causing catastrophic damage. Then

$$W_{GB} = \overline{d}_{GB} \; (3\pi(R_{GB}(3\; R_{GB} + 2.2\; R_{WT}) - 2.42\; R_{WT}{}^2))$$

	Let $\overline{d}_{GB} = 0.1$ lb/ft^2
$W_{WT} = \overline{d}_{WT}\; 2R_{WT}$	Let $\overline{d}_{WT} = R_{WT}/4$ lb/ft
$W_{GEN} = \overline{d}_{GEN}\; P$	Let $\overline{d}_{GEN} = 5$ lb/KW
$W_{FRAME} = 3\; \overline{d}_{FRAME}\; R_{GB}$	Let $\overline{d}_{FRAME} = R_{WT}/2$ lb/ft
$W_{TETHERS} = 3\; \overline{a}_1\; \overline{d}_{TETHERS}$	Let $\overline{a}_1 = 3\; R_{WT}$
	Let $\overline{d}_{TETHERS} = R_{WT}/100$ lb/ft
$W_{LINE} = \overline{d}_{LINE}\; 2R_{WT}$	Let $\overline{d}_{LINE} = R_{WT}/50$ lb/ft
$W_{FLAPS} = \overline{d}_{FLAPS}\; 2\; R_{GB}$	Let $\overline{d}_{FLAPS} = R_{WT}/10$ lb/ft

$$W_T = 0.1\; A_{GB} + R_{WT}{}^2(0.5 + 0.09 + 0.04) + R_{WT}\; R_{GB}(1.5 + 0.2\pi) + 5\; \overline{P}$$
$$= 0.1\; R_{GB} + 0.63\; R_{WT}{}^2 + 2.128\; R_{WT}\;\; GB + 5\; \overline{P}$$

Let $\$_T = \$_{GB} + \$_{WT} + \$_{GEN} + \$_{FRAME} + \$_{TETHERS} + \$_{LINE} + \$_{FLAPS} + \$_{TCS} + \$_{H_2} + \$_{H_2GEN} + \$_{CRADLE}$

and let $\bar{C}$ be the production model unit costs for each component of the TAWECS system, both those to be lifted by the gas bag, and the ground supported components. Then

$$\$_{GB} = \bar{C}_{GB} A_{GB}$$
$$\$_{WT} = 2 \bar{C}_{WT} R_{WT}$$
$$\$_{GEN} = \bar{C}_{GEN} \bar{P}$$
$$\$_{FRAME} = 3 \bar{C}_{FRAME} R_{GB}$$
$$\$_{TETHERS} = 3 \bar{C}_{TETHERS} a_1$$
$$\$_{LINE} = \bar{C}_{LINE}(2R_{WT} + 4R_{WT})$$
$$\$_{FLAPS} = \bar{C}_{FLAPS} 2\pi R_{GB}$$

Let $\bar{C}_{GB} = 0.2$ and 0.5 \$/ft^2
Let $\bar{C}_{WT} = R_{WT}$ \$/ft
Let $\bar{C}_{GEN} = 50$ \$/KW
Let $\bar{C}_{FRAME} = R_{WT}/2$ \$/ft
Let $\bar{C}_{TETHERS} = R_{WT}/100$ \$/ft
Let $\bar{C}_{LINE} = R_{WT}/25$ \$/ft
Let $\bar{C}_{FLAPS} = R_{WT}/5$ \$/ft

$$\$_{TCS} = \$_{Control\ System} + 3 \bar{C}_{Winch\ and\ Motor}$$

Let $\$_{Control\ Sys} = \$300$; Let $\bar{C}_{Winch\ and\ Motor} = 4 R_{WT}$ \$/Winch and Motor

$$\$_{H_2} = \bar{C}_{H_2} Vol_{GB}$$
$$\$_{H_2GEN} = \bar{C}_{H_2GEN} R_{WT}^3$$
$$\$_{CRADLE} = 3R_{WT}^2$$

Let $\bar{C}_{H_2} = 0.02$ \$/ft^3
Let $\bar{C}_{H_2GEN} = 0.05$ \$/ft^3

$$\$_T = \bar{C}_{GB} A_{GB} + 0.02\, Vol_{GB} + 0.05\, R_{WT}^3 + R_{WT}^2(2 + 0.09 + 0.24 + 3) + R_{WT} R_{GB}(1.5 + 0.4\pi) + 300 + 12\, R_{WT} + 50\, \bar{P}$$

$$= \bar{C}_{GB} A_{GB} + 0.02\, Vol_{GB} + 0.05\, R_{WT}^3 + 5.33\, R_{WT}^2 + 2.756\, R_{WT} R_{GB} + 300 + 12\, R_{WT} + 50\, \bar{P}$$

Using these equations provides the data in FIGURES 4a and 4b, which indicate that this TAWECS configuration should produce power economically, but there may be little or no economic advantage to large values of R_{WT}. However, all the assumed values for component unit weights and costs are subject to revision, and the increase in $\$_T/\bar{P}$ is probably due to too large an assumed unit cost (and/or unit weight) for at least one component. Even if the unit costs are too low by a factor of 1/2 - 1/5, $\$_T/\overline{P}$ should be economic for either power grid or remote site applications.

FIGURE 5 relates to a second embodiment of the invention in which there is provided an alternative to the metal ring 46 of the embodiment of FIGURES 2-4. FIGURE 5 shows the second embodiment in schematic top plan view of the level of the gas bag base. Two metal rings 60, 62 may be used, made of shaped steel or aluminum (e.g., tubular), with spokes 64 in tension between the rings to support the inner ring 60. The outer ring 62 supports the flaps 42, 44. The inner ring supports a three-arm frame 22' which supports the WT and GEN. The gas bag is connected to both rings to support the TAWECS components borne aloft. The gas bag should be constructed in sections of about 30° per section, or less, each section self-contained, to minimize damage and gas loss from one puncture. The section vertical sides and bottoms may be black plastic or fabric, with transparent hemispherical section tops, to warm the hydrogen inside by solar radiation and greenhouse effect, and increase lift by decreasing the density of the hydrogen. The gas bag sections connect at the top center to a circular member such as a tube (not shown) which supports the hydrogen release valve, the aircraft warning lights, if required, and the lightning rods. With these structural changes in the TAWECS, the previous calculations are modified as follows:

$W_{Outer\ Ring} = \bar{d}_{OR}\, 2\pi R_{GB}$	Let $\bar{d}_{OR} = R_{WT}/3$ lb/ft
$W_{Inner\ Ring} = \bar{d}_{IR}\, 2\pi(1.1R_{WT})$	Let $\bar{d}_{IR} = R_{WT}/6$ lb/ft
$W_{FRAME} = 3\, \bar{d}_{FRAME}(1.2R_{WT})$	Let $\bar{d}_{FRAME} = R_{WT}/2$ lb/ft

$W_{Spokes} = 2(6)\ \bar{d}_{Spokes}(1.1R_{GB})$ Let $\bar{d}_{Spokes} = R_{WT}/50$ lb/ft

$W_{GB} = \bar{d}_{GB}\ A_{GB}$ Let $\bar{d}_{GB} = 0.1$ lb/ft^2

where

$$A_{GB} = \pi(R_{GB}(3\ R_{GB} + 2.2\ R_{WT}) - 2.42\ R_{WT}^2) + 2\cdot(12)\ (\pi R_{GB}^2/4 - R_{GB}\ (1.1\ R_{WT}))$$
$$= \pi(R_{GB}(9\ R_{GB} + 2.2\ R_{WT}) - 2.42\ R_{WT}^2) - 26.4\ R_{GB}\ R_{WT}$$
$$= \pi(R_{GB}(9\ R_{GB} - 6.19\ R_{WT}) - 2.42\ R_{WT}^2)$$

Then

$$W_T = W_{GB} + W_{OR} + W_{FLAPS} + W_{IR} + W_{Spokes} + W_{FRAME} + W_{WT} + W_{GEN} + W_{TETHERS} + W_{LINE}$$
$$W_T = 0.1\ A_{GB} + R_{WT}^2(1.1/3\pi + 1.8 + 0.5 + 0.09 + 0.04) + R_{WT}\ R_{GB}(2/3\pi + 0.2\pi + 13.2/50) + 5\ \bar{P}$$
$$= 0.1\ A_{GB} + 3.58\ R_{WT}^2 + 2.99\ R_{WT}\ R_{GB} + 5\ \bar{P}$$

$\$_{OR} = \bar{C}_{OR}\ 2\pi R_{GB}$ Let $\bar{C}_{OR} = R_{WT}/3$ \$/ft

$\$_{IR} = \bar{C}_{IR}\ 2\pi(1.1\ R_{WT})$ Let $\bar{C}_{IR} = R_{WT}/6$ \$/ft

$\$_{Frame} = 3\ \bar{C}_{Frame}\ (1.2\ R_{WT})$ Let $\bar{C}_{Frame} = R_{WT}/2$ \$/ft

$\$_{Spokes} = 12\ \bar{C}_{Spokes}(1.1R_{GB})$ Let $\bar{C}_{Spokes} = R_{WT}/50$ \$/ft

$\$_{GB} = \bar{C}_{GB}\ A_{GB}$ Let $\bar{C}_{GB} = 0.2$ and 0.5 \$/ft^2

$\$_{Cradle} = 6\ \bar{C}_{Cradle}$ Let $\bar{C}_{Cradle} = R_{WT}/2$ \$/Cradle

Then

$$\$_T = \$_{GB} + \$_{OR} + \$_{Flaps} + \$_{IR} + \$_{Spokes} + \$_{Frame} + \$_{WT} + \$_{GEN} + \$_{Tethers} + \$_{Line} + \$_{TCS} + H_2 + \$_{H_2Gen} + \$_{Cradle}$$
$$= \bar{C}_{GB}\ A_{GB} + 0.02\ Vol_{GB} + 0.05\ R_{WT}^3 + R_{WT}^2\ (1.1/3\pi + 1.8 + 2 + 0.09 + 0.24) + R_{WT}\ R_{GB}\ (2/3\pi + 0.2\pi + 13.2/50) + 50\ \bar{P} + 300 + R_{WT}\ (12 + 3)$$
$$= \bar{C}_{GB}\ A_{GB} + 0.02\ Vol_{GB} + 0.05\ R_{WT}^3 + R_{WT}(5.28R_{WT} + 2.99R_{GB} + 15) + 300 + 50\ \bar{P}$$

Using these modified equations, significant decreases in $\$_T/\bar{P}$ are obtained when compared with

FIGURE 4 (approximately 23% for $\overline{V}_w$ = 10 mph and 12% for $\overline{V}_w$ = 15 mph).

For the TAWECS of FIGURES 2 and 5, with $R_{GB} = 3\ R_{WT}$ and a confined vortex generated and sustained, the volume of hydrogen necessary for $\varepsilon = 10\ R_{WT}$ may be found by solving for it in

$$\text{Lift} - W_T = \varepsilon$$

Let a = 20, $\alpha = 30°$, and $\overline{P}$ = twice the power produced by a TAWECS without a confined vortex. Let air at a pressure slightly greater than ambient fill the volume of the gas bag not required by the hydrogen. Making these changes,

$$\overline{P} = 0.001837\ R_{WT}^2 \overline{V}_w^3$$

$$A_{GB} = \pi(3\ R_{WT}(27\ R_{WT} - 6.19\ R_{WT}) - 2.42\ R_{WT}^2) = 60\ \pi\ R_{WT}^2$$

$$W_T = 0.1\ A_{GB} + 12.55\ R_{WT}^2 + 5\ \overline{P} = (10.37 + 12.55)\ R_{WT}^2 + 5\ P = 22.92\ R_{WT}^2 + 5\ \overline{P}$$

$$\text{Lift} = 0.0751\ \text{Vol}_{H_2} = W_T + 10\ R_{WT}$$

$$\text{Vol}\ H_2 = 13.32(22.92\ R_{WT}^2 + 5\ \overline{P} + 10\ R_{WT})$$

$$\$_T = \overline{C}_{GB}\ A_{GB} + 0.02\ \text{Vol}\ H_2 + 0.05\ R_{WT}^3 + R_{WT}(14.25\ R_{WT} + 15) + 300 + 50\ \overline{P}$$

Using these equations, the data obtained show a decrease in $\$_T/\overline{P}$ when compared with the TAWECS of FIGURES 2 and 5 of approximately 22% for $\overline{V}_w$ = 10 mph and 7% for $\overline{V}_w$ = 15 mph. Whether or not this case is in fact more economic than that of the first embodiment will be determined by the strength of the vortex (if any) that is generated and sustained, which can only be determined by further experiment.

In FIGURE 2, the TAWECS is shown disposed over a flat terrain surface. It would be apparent that a hilltop site is included in the purview of the invention, even preferred, since wind velocity is generally greater at such sites.

The TAWECS could be assembled on a relatively flat terrain surface, inflated, and then moved to a relatively inaccessible site for installation, such as a hilltop, marsh, or over water by using one helicopter per tether.

To decrease the weight and cost of the generator connected to the wind turbine, a synchro generator could be used, connected electrically to a synchro motor on the ground at some convenient distance away, which is then connected to the load (electrical or mechanical).

It should now be apparent that the present invention provides a tethered airfoil wind energy conversion system preferably incorporating the following features and advantages:

A flexible gas bag support which

a. Provides a maximum ratio of camber/chord, which produces a maximum pressure drop across the vent containing the wind turbine, thus maximizing the power produced by the wind turbine;

b. Provides a means of eliminating ice and snow buildup;

c. Allows wind turbines probably limited in size only by the wind turbine vanes;

d. May provide in one configuration a confined vortex above the wind turbine to further increase the pressure drop across the wind turbine; and

A tether control system to keep the hemispheric gas bag airfoil oriented into the wind from any direction at an optimum angle of attack to maximize power output.

There are many forms of airfoils for aircraft applications employing reduced pressure on the suction side and increased pressure on the pressure side (as described in any aerodynamics text). A variety of gas bag shapes employing these basic principles may be used for wind turbine applications in place of the hemispherical form shown.

In FIGURES 6-8 there is shown simply and schematically depicted a multiple wind turbine tethered airfoil wind energy conversion system (a MWT-TAWECS) 110.

In this embodiment, a gas bag three-dimensional body of revolution airfoil 112 shown as an approximately hemispherical shape for simplicity is filled with enough lighter-than-air gas, e.g., hydrogen to lift the TAWECS components and provide a moderate tension on the three tethers 114. Thus, the gas bag airfoil 112 is borne aloft with its rounded surface pointed generally upwards and its generally flat underside pointed generally downwards. Towards its geometric center and generally parallel to its longitudinal axis, the gas bag airfoil is provided with a tubular vent 116, having an upper end opening up through the rounded surface of the gas bag and a lower end opening down through the generally flat surface of the gas bag. At its lower end, the vent 116 has a plurality of wind turbines WT mounted so as to be rotated by the wind.

A preferred diffuser augmenter is shown at DA, being a specific configuration of the vent sidewall for augmenting the pressure drop across the wind turbines, in order to increase the power output and decrease the equipment cost per unit of power produced. In order to provide the diffuser augmenter, the radius of the vent is increased exponentially from bottom to top.

For the purpose of mounting the wind turbines at the bottom of the vent a framework is mounted to the airfoil by any convenient means. This framework preferably includes two metal rings 160, 162, made of shaped steel or aluminum (e.g. tubular), with spokes 164 in tension between them so that the outer ring 162 supports the inner ring 160 from the airfoil via the tensioned spokes 164. The outer ring 162 also supports flaps 142, 144 and the inner ring supports the frame structure 122 which supports the wind turbines WT and the electric generators GEN which are driven by the wind turbines. The gas bag may be connected to both rings 160, 162, e.g. by means of hold-down lines (not shown) or a net (not shown) extending over the gas bag.

The leading and trailing edge flaps 142, 144 act to increase the camber, coefficient of lift, and optimum angle of attack of the airfoil.

The gas bag, by being flexible, should prevent ice and snow buildup, by being free to deflect in six modes: roll, pitch, yaw, heave, sway and surge. Since gas bags may be of almost arbitrary size, it is likely that the size limitation is determined by the WT vanes, and 150-foot vanes are now under development by others. A hemispherical airfoil produces maximum camber/chord ratio, maximizing pressure drop across the WT's, and thus maximizes power produced.

The hemispherical hydrogen-supported gas bag is tethered by three or more lines 114, which are adjusted by winches driven by motors 121 controlled by a tether control system TCS to control the tilt of the gas bag 112 into the wind, such that the angle of attack α is optimum up to at least 30° to maximize the pressure drop across the wind turbines WT. Each tether 114 ends at the outer ring 162, at a terminating point for spokes 164. In addition to those components already mentioned, at least one service line 124 is provided from the bottom of the electric generators GEN to the ground, and along the ground a distance greater than the radius of the gas bag, to provide hydrogen replenishment from a hydrogen generator 126 on the ground, power for aircraft warning lights, if required, control signals for hydrogen release valve 128 in the top of the gas bag, control signals for pitch control of the WT vanes, lightning ground cable 130 and a power output cable 132. In the version shown in FIGURES 6-8 there may be provided three service lines 124. In the version shown in FIGURES 9 and 10, the individual service lines combine aloft into one common line that extends down to the ground. In either version, each service line 124 may be led along one of the tether lines 114, instead of vertically to the ground. This will enable placing two or more MWT-TAWECS one above the other at particularly desirable (windy) sites. The power output cable of service line 124 may be replaced with a microwave transmitter in the TAWECS and a microwave receiver on the ground (as shown in FIGURES 11 and 12).

A wind direction indicator 134 is required on the ground to supply a wind direction-representing signal to the TCS, which calculates the required lengths of the respective tethers 114 to tilt the MWT-TAWECS into the wind at its optimum angle of attack to maximize power output. Control signals are then sent to the three tether winch motor controllers 136 to set the individual tether lengths in accordance with these calculations. To this purpose the tether control system TCS may incorporate commerically available, inexpensive microprocessors, as explained in more detail in my aforesaid copending application.

For sites with a constant wind direction, the tether lines may be of predetermined fixed lengths to orient the airfoil into the wind at an optimum angle of attack. At such sites no winches would be required to lengthen and shorten the tether lines, no wind direction sensing means is required, and no tether control system is required. In such a case, the winches may be replaced with fixed tie-down means being disposed around the airfoil on the ground in any distributed configuration.

The hydrogen generator 126 may be of several known types, which produce hydrogen by electrolysis of water (possibly obtained from condensed water vapor in the air), or by the process described by Pangborn, et al in U.S. Patent 4,075,313, or by other means.

The hydrogen generators 126 must have a storage tank 138 and reserve capacity enough for a heavy snow or ice load accumulating during a period of no wind, to provide the extra lift required to keep the gas bag aloft with moderate tension on the tethers. The hydrogen generators may supply hydrogen not only to the airfoil, but elsewhere as an end product of the MWT-TAWECS. The hydrogen generators may be borne aloft by the airfoil. The tether control system TCS must sense tension on the tethers, and open the hydrogen supply valve 140 when tension becomes too low. The tether control system TCS must also sense excessive tension on the tethers, and open a release valve 128 in the top of the gas bag to release excess hydrogen to lower the tension on the tethers. The tether control system TCS must also provide for manual control of the tether winch motors for use in lowering the MWT-TAWECS for maintenance, which would require sufficient control to settle the framework including rings 160, 162 gently into a special cradle 141.

In lieu of electric generators GEN, the wind turbines WT may drive one or more flexible shafts (not shown) connected to a mechanical load (not shown) or respective mechanical loads (not shown) on the ground.

The gas bag should be constructed in sections of about 30° per section, or less, with each section being self-contained, to minimize damage and gas loss from one puncture. The section vertical sides and bottoms may be black plastic or fabric, with transparent hemispherical section tops, to warm the hydrogen inside by solar radiation and greenhouse effect, and increase lift by decreasing the density of the hydrogen. The gas bag sections connect at the top center to a circular member such as a tube (not shown) which supports the hydrogen release valve, the aircraft warning lights, if required, and the lightning rods. The MWT-TAWECS is shown disposed over a flat terrain surface. It should be apparent that a hilltop site is included in the purview of the invention, even preferred, since wind velocity is generally greater at such sites.

The MWT-TAWECES could be assembled on a relatively flat terrain surface, inflated, and then moved to a relatively inaccessible site for installation, such as a hilltop, marsh, or over water by using one helicopter per tether.

To decrease the weight and cost of the generators connected to the wind turbines, synchro generators could be used, connected electrically to one or more synchro motors on the ground at some convenient distance away, each of which is then connected to a load (electrical or mechanical).

If the electrical outputs of the generators GEN of the individual wind turbines WT are to be integrated and supplied to a load (e.g. a common power grid) an electrical power integrating means is needed. Fortunately several such means are commencially available. In particular,

(a) The generators GENs may be individual constant voltage DC generators parallel connected to the same power output cable (or to a DC load on the ground, such as a water hydrolysis hydrogen generator (not shown in detail)).

(b) Unsynchronized AC generators, which currently are cheaper than DC generators, may be connected in parallel through individual power output cables to recitifiers and filters located on the ground, and thence to either a DC load or, through an inverter, to an AC load.

(c) AC generators sychronized to the power grid frequency and connected through a common power output cable to the power grid. This requires the use of a gear box or the like between each wind turbine WT and the respective generator GEN that is associated therewith. Each gear box transforms the actual angular rotation output of the associated wind turbine WT to that required for the respective schronized AC generator. The power output from each generator can then be fed through a common power output bus to the ground for voltage and current transformation, if necessary, and connection to the grid.

(d) A plurality of variable voltage DC generators connected through separate power output cables to separate DC loads on the ground, or to separate synchronous inverters on the ground, and thence to the power grid or the AC load.

All these electricl integration techologies are well known. A useful summary thereof is provided in the paper "Electrical Technology Overview and Research at Oklahoma State University as Applied to Wind Energy Systems", R. Ramakumar et al, published in Proceedings of the Second Workshop on Wind Energy Conversion Systems, F. R. Eldrige, editor, 1975, Mitre Corp. report RAN - 75-0500.

Although the MWT-TAWECS 110 of FIGURES 6-8 is shown having three wind turbines WT, a greater or lesser number of similarly clustered wind turbines could be employed; for example, the number of wind turbines provided in the vent may be two, three, seven (e.g. six encircling one), or nineteen. My current preference is for three wind turbines WT as illustrated in FIGURES 6-8, and the use of generator option (c) explained hereinabove.

It should now be apparent that the present invention provides a multiple wind turbine tethered airfoil wind energy conversion system preferably incorporating the following features and advantages:

A flexible gas bag support which:

a. provides a maximum ratio of camber/chord, which produces a maximum pressure drop across the vent containing the wind turbines, thus maximizing the power produced by the wind turbines,

b. provides a means of eliminating ice and snow buildup,

c. allows wind turbines probably limited in size only by the wind turbine vanes,

d. provides a diffuser augmenter above the wind turbines to further increase the pressure drop across the wind turbines, and

e. provides a tether control system to keep the hemispheric gas bag airfoil oriented into the wind from any direction at an optimum angle of attack to maximize power output.

There are many forms of airfoils for aircraft applications employing reduced pressure on the suction side and increased pressure on the pressure side (as described in any aerodynamics text). A variety of gas bag shapes employing these basic principles may be used in place of the hemispherical form shown.

It should now be apparent that the wind turbine tethered airfoil wind energy conversion system as described hereinabove, possesses each of the attributes set forth in the specification under the heading "Summary of the Invention" hereinbefore. Because it can be modified to some extent without departing from the principles thereof as they have been outlined and explained in this specification, the present invention should be understood as encompassing all such modifications as are within the spirit and scope of the following claims.

WHAT IS CLAIMED IS:

1. A tethered airfoil wind energy conversion system, comprising:

a positive-lift, lighter-than-air, flexible gas bag-type airfoil provided with a lined vent which extends completely generally axially therethrough;

a wind turbine having a power output-providing device;

frame means supported by said airfoil and mounting said wind turbine for rotation relative to said airfoil in axial alignment with said vent;

a pluraity of motorized, individually operable winches, being at least three in number, and being for disposition at spaced sites generally in an imaginary ring on the ground;

each such winch having a tether line wound thereon and having a respective outer end;

means connecting each tether line outer end to said airfoil radially distally of said vent, so that said airfoil is tethered to said winches from a plurality of widely distributed sites;

a means for supplying inflating lighter-than-air gas from within the airfoil, this means including a gas release control valve;

means for controlling the pitch of the wind turbine vanes;

means for sensing wind direction incident upon said airfoil and for providing an output signal in relation thereto;

a tether control system incorporating means for determining for each of a plurality of various different wind direction-related output signals received from said sensing means, respective control signals equating to the amounts by which each of the respective tether lines must be reeled in or played out in order to tilt the airfoil into the wind at an optimum angle of attack to maximize power output of said power output-providing device of said wind turbine;

means operatively connecting said sensing means to said tether control system for furnishing said output signal to said tether control system, and

means operatively connecting said tether control system to each of said motorized, independently operable winches for furnishing said respective control signals to the respective said winches.

2. The tethered airfoil wind energy conversion system of claim 1, wherein:

the airfoil is of generally hemispherical shape, base generally downwards, with said wind turbine being mounted generally at the lower end of said vent.

3. The tethered airfoil wind energy conversion system of claim 2, further including flap means skirting said airfoil at the base thereof.

4. The tethered airfoil wind energy conversion system of claim 1, wherein:

said tether control system operates in use to tilt said airfoil at an angle of up to about 30° from horizontal, headed into the wind.

5. The tethered airfoil wind energy conversion system of claim 1, wherein:

said lined vent is superficially provided with ridge means spiraling thereabout along the length thereof for creating a vortex of the wind passing therethrough.

6. The tethered airfoil wind energy conversion system of claim 1, wherein:

said means for supplying inflating lighter-than-air gas to the airfoil includes a gas generator.

7. The tethered airfoil wind energy conversion system of claim 6, wherein said gas generator is a hydrogen generator.

8. The tethered airfoil wind energy conversion system of claim 7, wherein:

said hydrogen generator is borne aloft by said airfoil.

9. The tethered airfoil wind energy system of claim 7, wherein:

said hydrogen generator constitutes at least part of said power output-providing devices by having a capacity, when in use, to provide substantially more hydrogen, as an output product, than is required for providing inflating gas for said airfoil; and means for taking off excess hydrogen from said hydrogen generator as an output product.

10. The tethered airfoil wind energy conversion system of claim 1, further including:

means communicated to said tether lines, said tether control system, and said control valves, for sensing the tension on said tether lines and for admitting inflating gas to said airfoil and for releasing inflating gas from said airfoil for maintaining said tension within a preselected range.

11. The tethered airfoil wind energy conversion system of claim 1, wherein:

said power output-providing device comprises a rotary-driven electrical generator operatively coupled to said wind turbine.

12. The tethered airfoil wind energy conversion system of claim 11, wherein:

said electrical generator is supported aloft by said airfoil.

13. The tethered airfoil wind energy conversion system of claim 12, further comprising:

a service line connected with said electrical generator and extending therefrom for taking-off electrical power generated by operation of said electrical generator.

14. The tethered airfoil wind energy conversion system of claim 13, wherein:

said service line extends to the ground along one of said tether lines.

15. The tethered airfoil wind energy conversion system of claim 12, further comprising:

means for transmitting electrical power generated by operation of said electrical generator to remotely of said electrical generator.

16. The tethered airfoil wind energy conversion system of claim 15, wherein:

said transmitting means is constituted by a microwave transmitter supported by said airfoil and a microwave receiver located on the ground.

17. The tethered airfoil wind energy conversion of claim 1, wherein:

said power output-providing device comprises a rotary shaft.

18. The tethered airfoil wind energy conversion system of claim 17, wherein:

said rotary shaft is flexible.

19. The tethered airfoil wind energy conversion system of claim 2, wherein:

said airfoil being internally divided into a plurality of individual compartments by internal wall means, in order to prevent one puncture from causing catastrophic loss of inflating gas from said airfoil.

20. The tethered airfoil wind energy conversion system of claim 19, wherein:

said internal wall means comprises a plurality of internal walls of flexible sheet extending perpendicularly to said base and radially of said vent at about 30° intervals.

21. The tethered airfoil wind energy conversion system of claim 20, wherein:

said base and said internal walls are relatively dark-colored and, wherein the remainder of said airfoil is relatively transparent for enhancing warming by solar radiation of inflating gas contained in said airfoil.

22. The tethered airfoil wind energy conversion system of claim 1, wherein:

said frame means comprises three arms and ring, of which the three arms extend from the wind turbine generally radially outwards to said ring and said ring extends about the outer periphery of the airfoil.

23. The tethered airfoil wind energy conversion system of claim 1, wherein:

said frame means comprises three arms extending from said wind turbine to the base of said lined vent, a ring having said three arms joined thereto at the base of said lined vent; an outer ring extending around the outer periphery of the airfoil; and a plurality of tensioned mechanical tie means interconnecting the inner and outer rings at a a plurality of angularly spaced points.

24. The tethered airfoil wind energy conversion system of claim 1, further comprising:

a cradle disposed on the ground beneath said airfoil; and means for guidingly lowering said airfoil down onto said cradle to a non-use position thereon.

25. A tethered airfoil wind energy conversion system, comprising:

a wind turbine having a power output-providing device for providing a power output as the wind turbine is rotated by the wind;

a generally toric, lighter-than-air gas-filled airfoil having a generally hemispherical outer, upper side and a generally flat inner, lower side, with a generally central, lined vent passageway communicating generally axially between said sides so as to have an entrance through said lower side and an exit through said upper side;

means coaxially mounting said wind turbine relative to said vent entrance;

a plurality of angularly widely distributed tether lines each attached to said airfoil distally of the longitudinal axis thereof;

a plurality of ground-based tether line payout/takeup devices, each having a respective said tether line connected therewith, so that individual said devices may be operated to increase and decrease the lengths of the individual tether lines effectively in use, for tilting the wind turbine into the wind without need for rotating the airfoil.

26. A tethered airfoil wind energy conversion system comprising:

a wind turbine having a power output shaft means;

frame means mounting the wind turbine for rotation about a generally vertical, but tiltable axis;

a buoyant-in-air gas bag means having said frame means mounted thereto for deploying the resulting wind turbine, frame means, gas bag means assembly above a datum surface;

a plurality of tether lines each having an upper end secured to said assembly and a lower end extended down to adjacency with said datum surface;

a separate means anchoring each said tether line lower end relative to said datum surface and including means for acting upon the respective tether line for effectively lengthening and shortening the distance between each respective tether line upper end and said datum surface;

control means connected to all of said effectively lengthening and shortening means and being operable to coordinately modify said distances by shortening at least one and/or lengthening at least another for selectively tilting said axis and thus heading the wind turbine into the wind.

27. A method for deploying a wind turbine into the wind, comprising:

suspending the wind turbine in mid-air above a datum surface by buoying the wind turbine with a lighter-than-air gas bag so that the wind turbine longitudinal axis is generally vertically oriented;

tethering the wind turbine down to the datum surface using a plurality of perimetrically widely distributed tether lines; and

coordinately relatively lengthening and shortening said tether lines in order to incline the wind turbine longitudinal axis in the azimuthal direction and to the degree which maximizes wind energy conversion by said wind turbine to rotary output power.

28. A wind energy conversion device tethered airfoil wind energy conversion system, comprising:

a positive-lift, lighter-than-air, flexible gas bag-type airfoil provided with a lined vent which extends completely therethrough;

a wind energy conversion device comprising a means for accepting a wind energy mechanical input and providing a converted power output;

means mounting said wind energy conversion device on said airfoil for movement with respect thereto incident to accepting said input and providing said converted output, said wind energy conversion device being disposed athwart said vent, so that at least some wind in order to transmit said vent must impact said wind energy conversion device;

a plurality of tether lines, being at least three in number, each having a first end effectively secured to the airfoil and a depending second end;

anchor means for each tether line;

the tether lines between the respective first ends thereof and the respective said anchor means associated therewith, being equipped to be maintainable to at least two different effective lengths so that in use the tether lines will not all extend down from the airfoil to where the respective tether lines are respectively anchored by said anchor means, unless the airfoil tilts, whereby the vent is aimed relative to the wind, for regulating the acceptance of wind energy by said wind energy conversion device.

29. The wind energy conversion device tethered airfoil wind energy conversion system of claim 28 wherein:

said wind energy conversion device comprises a wind turbine and frame means mounting that wind turbine on the airfoil.

30. The wind energy conversion device tethered airfoil wind energy conversion system of claim 28 wherein:

said wind energy conversion device comprises an electrical generator for converting mechanical motion to electrical power.

31. The wind energy conversion device tethered airfoil wind energy conversion system of claim 28 wherein:

said system further includes means for communicating said converted power output to a ground site off-board said airfoil.

32. The wind energy conversion device tethered airfoil wind energy conversion system of claim 28 wherein:

said anchor means as to each tether line includes means for effectively adjusting the length in use of each tether line for correspondingly adjusting the vector of tilting of said airfoil and thus adjusting the aiming of said vent, for regulating the acceptance of wind energy by said wind energy conversion device.

33. A multiple wind turbine tethered airfoil wind energy conversion system, comprising:

a positive-lift, lighter-than-air, flexile gas bag-type airfoil provided with a lined vent which extends completely generally axially therethrough;

a plurality of energy conversion devices each having a power output-providing device;

frame means supported by said airfoil and mounting said wind energy conversion devices for rotation relative to said airfoil, each being axial aligned so as to be substantially parallel with said vent;

a plurality of motorized, individually operable winches, being at least three in number, and being for disposition at spaced sites generally in an imaginary ring on the ground;

each such winch having a tether line having a first end connected therewith and having a respective outer end;

means connecting each tether line outer end to said airfoil radially distally of said vent, so that said airfoil is tethered to said winches from a plurality of widely distributed sites;

a means for supplying inflating lighter-than-air gas to the airfoil, this means including a gas inlet control valve;

a means for releasing inflating lighter-than-air gas from within the airfoil, this means including a gas release control valve;

means for sensing wind direction incident upon said airfoil and for providing an output signal in relation thereto;

a tether control system incorporating means for determining for each of a plurality of various different wind direction-related output signals received from said sensing means, respective control signals equating to the amounts by which each of the respective tether lines must be reeled in or played out in order to tilt the airfoil into the wind at an optimum angle of attack to maximize power output of said power output-providing devices of said wind energy conversion devices;

means operatively connecting said sensing means to said tether control system for furnishing said output signal to said tether control system; and

means operatively connecting said tether control system to each of said motorized, independently operable winches for furnishing said respective control signals to the respective said winches.

34. The multiple wind turbine tethered airfoil wind energy conversion system of claim 33, wherein:

the airfoil is of generally hemispherical shape, base generally downwards, with each wind energy conversion device being constituted by a respective wind turbine mounted generally at the lower end of said vent.

35. The multiple wind turbine tethered airfoil wind energy conversion system of claim 33, further including flap means skirting said airfoil at the base thereof.

36. The multiple wind turbine tethered airfoil wind energy conversion system of claim 33, wherein:

said tether control system operates in use to tilt said airfoil at an angle of up to about 30° from horizontal, headed into the wind.

37. The multiple wind turbine tethered airfoil wind energy conversion system of claim 33, wherein:

said lined vent increases exponentially in radius from bottom to top in order to provide a diffuser augmenter.

38. The multiple wind turbine tethered airfoil wind energy conversion system of claim 33, wherein:

said means for supplying inflating lighter-than-air gas to the airfoil includes a gas generator.

39. The multiple wind turbine tethered airfoil wind energy conversion system of claim 38, wherein said gas generator is a hydrogen generator.

40. The multiple wind turbine tethered airfoil wind energy conversion system of claim 39, wherein;

said hydrogen generator is borne aloft by said airfoil.

41. The multiple wind turbine tethered airfoil wind energy conversion system of claim 39, wherein:

said hydrogen generator constitutes at least part of said power output-providing device by having a capacity, when in use, to provide substantially more hydrogen, as an output product, than is required for providing inflating gas for said airfoil; and means for taking off excess hydrogen from said hydrogen generator as an output product.

42. The multiple wind turbine tethered airfoil wind energy conversion system of claim 33, further including:

means communicating to said tether lines, said tether control system, and said control valves, for sensing the tension on said tether lines and for admitting inflating gas to said airfoil and for releasing inflating gas from said airfoil for maintaining said tension within a preselected range.

43. The multiple wind turbine tethered airfoil wind energy conversion system of claim 34, wherein:

each power output-providing device comprises a rotary-driven electrical generator operatively coupled to a respective said wind turbine.

44. The multiple wind turbine tethered airfoil wind energy conversion system of claim 43, wherein:

said electrical generator is supported aloft by said airfoil.

45. The multiple wind turbine tethered airfoil wind energy conversion system of claim 44, further comprising:

a respective service line connected with each said electrical generator and extending therefrom for taking off electrical power generated by operation of said electrical generator.

46. The multiple wind turbine tethered airfoil wind energy conversion system of claim 45, wherein:

each service line extends to the ground along one of said tether lines.

47. The multiple wind turbine tethered airfoil wind energy conversion system of claim 44, further comprising:

means for transmitting electrical power generated by operation of said electrical generators to remotely of said electrical generators.

48. The multiple wind turbine tethered airfoil wind energy conversion system of claim 47, wherein:

said transmitting means is constituted by at least one microwave transmitter supported by said airfoil and at least one microwave receiver located on the ground.

49. The multiple wind turbine tethered airfoil wind energy conversion system of claim 33, wherein:

each power output-providing device comprises a respective rotary shaft.

50. The multiple wind turbine tethered airfoil wind energy conversion system of claim 49, wherein:

each said rotary shaft is flexible.

51. The multiple wind turbine tethered airfoil wind energy conversion system of claim 33, wherein:

said airfoil is internally divided into a plurality of individual compartments by internal wall means, in order to prevent one puncture from causing catastropic loss of inflating gas from said airfoil.

52. The multiple wind turbine tethered airfoil wind energy conversion system of claim 51, wherein:

said internal wall means comprise a plurality of internal walls of flexible sheet extending perpendicularly to said base and radially of said vent at about 30° intervals.

53. The multiple wind turbine tethered airfoil wind energy conversion system of claim 52, wherein:

said base and said internal walls are relatively dark-colored and wherein the remainder of said airfoil is relatively transparent for enhancing warming by solar radiation of inflating gas contained in said airfoil.

54. The multiple wind turbine tethered airfoil wind energy conversion system of claim 34, wherein:

said frame means comprises a structure extending from said wind turbines to the base of said lined vent, a ring having said structure joined thereto at the base of said lined vent; an outer ring extending around the outer periphery of the airfoil; and a plurality of tensioned mechanical tie means interconnecting the inner and outer rings at a plurality of angularly spaced points.

55. The mutliple wind turbine tethered airfoil wind energy conversion system of claim 33, further comprising:

a cradle disposed on the ground beneath said airfoil; and

means for guidingly lowering said airfoil down onto said cradel to a non-use position thereon.

56. The multiple wind turbine tethered airfoil wind energy conversion system of claim 43, further comprising:

means for integrating the outputs of all of said generators and for providing the resulting output to an electrical distribution grid.

57. A multiple wind turbine tethered airfoil wing energy conversion system, comprising:

a plurality of wind turbines each having a power output-providing device for providing a power output as that wind turbine is rotated by the wind;

a generally toric, lighter-than-air gas-filled airfoil having a generally hemispherical outer, upper side and a generally flat inner, lower side, with a generally central, line vent passageway communicating generally axially between said sides so as to each have an entrance through said lower side and an exit through said upper side;

means for mounting each wind turbine with axes parallel to said vent adjacent said vent entrance;

a plurality of angularly widely distributed tether lines each attached to said airfoil distally of the longitudinal axis thereof;

a plurality of ground-based tether line payout/takeup devices, each having a respective said tether line connected therewith, so that individual said devices may be operated to increase and decrease the lengths of the individual tether lines effectively in use, for tilting the wind turbine into the wind without need for rotating the airfoil.

58. A multiple wind turbine tethered airfoil wind energy conversion system comprising:

a plurality of wind turbines each having a respective power output shaft means;

frame means mounting the wind turbines for rotation about respective generally vertical, but tiltable axes;

a buoyant-in-air gas bag airfoil means having said frame means mounted thereto for deploying the resulting wind turbines, frame means, gas bag means assembly above a datum surface;

a plurality of tether lines each having an upper end secured to said assembly and a lower end extended down to adjacency with said datum surface;

a separate means anchoring each said tether line lower end relative to said datum surface and including means for acting upon the respective tether line for effectively lengthening and shortening the distance between each respective tether line upper end and said datum surface; and

control means connected to all of said effectively lengthening and shortening means for being operable to coordinately modify said distance by shortening at least one and/or lengthening at least another for selectively tilting said axis and thus heading the airfoil into the wind.

59. A method for deploying a plurality of wind turbines into the wind, comprising:

suspending all the wind turbines in mid-air above a datum surface by buoying all the wind turbines with a common lighter-than-air gas bag airfoil so that the respective wind turbine longitudinal axes are generally vertically oriented;

tethering the wind turbines down to the datum using a plurality of perimetrically widely distributed tether lines; and

coordinately relatively lengthening and shortening said tether lines in order to incline the respective wind turbine longitudinal axes in the aximuthal direction and to the degree which maximizes wind energy conversion by said wind turbines to rotary output power.

60. A multiple wind energy conversion device tethered airfoil wind energy conversion system, comprising:

a positive-lift, lighter-than-air, flexible gas bag-type airfoil provided with a lined vent which extends completely therethrough;

a plurality of wind energy conversion devices, each comprising a means for accepting a wind energy mechanical input and providing a converted power output;

means mounting all said wind energy conversion devices on said airfoil for movement with respect thereto incident to accepting said input and providing said converted output, said wind energy conversion devices being disposed athward said vent, so that at least some wind in order to transit said vent must impact said wind energy conversion devices;

a plurality of tether lines, being at least three in number, each having a first end effectively secured to the airfoil and a depending second end;

anchor means for each tether line;

the tether lines between the respective first ends thereof and the respective said anchor means associated therewith, being equipped to be maintainable to at least two different effective lengths so that in use the tether lines will not all extend down from the airfoil to where the respective tether lines are respectively anchored by said anchor means, unless the airfoil tilts, whereby the vent is aimed relative to the wind, for regulating the acceptance of wind energy by said wind energy conversion devices.

61. The multiple wind energy conversion device tethered airfoil wind energy conversion system of claim 60, wherein:

each of said wind energy conversion devices comprises a wind turbine and frame means mounting that wind turbine on the airfoil.

62. The multiple wind energy conversion device tethered airfoil wind energy conversion system of claim 61, wherein:

said frame means is constituted by a unitary frame for all of said wind energy conversion devices.

63. The multiple wind energy conversion device tethered airfoil wind energy conversion system of claim 60, wherein:

each of said wind energy conversion devices comprises an electrical generator for converting mechanical motion to electrical power.

64. The multiple wind energy conversion device tethered airfoil wind energy conversion system of claim 60, wherein:

said system further includes means for communicating said converted power output to a ground site off-board said airfoil.

65. The multiple wind energy conversion device tethered airfoil wind energy conversion system of claim 60, wherein:

said anchor means as to each tether line includes means for effectively adjusting the length in use of each tether line for correspondingly adjusting the vector of tilting of said airfoil and thus adjusting the aiming of said vent, for regulating the acceptance of wind energy by said wind energy conversion device.

1/6

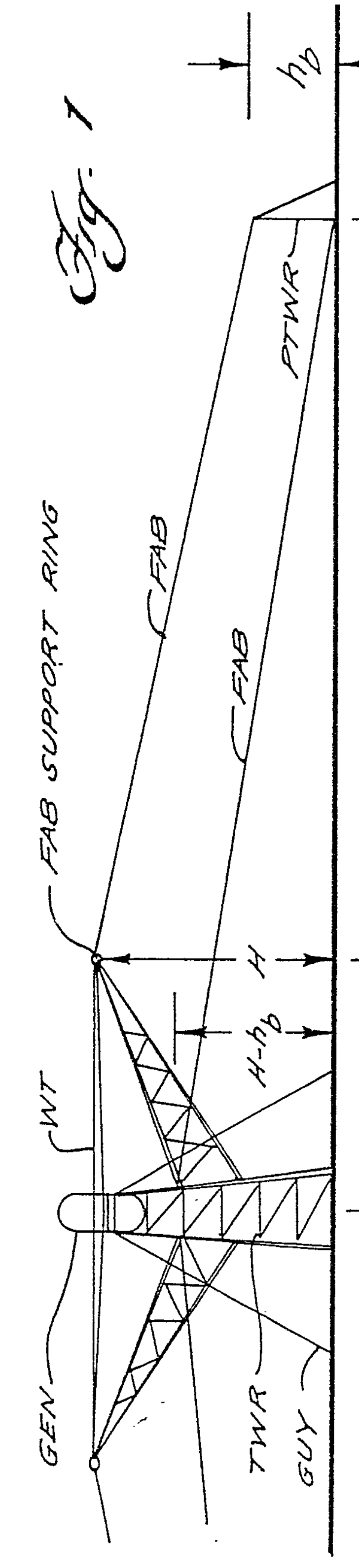
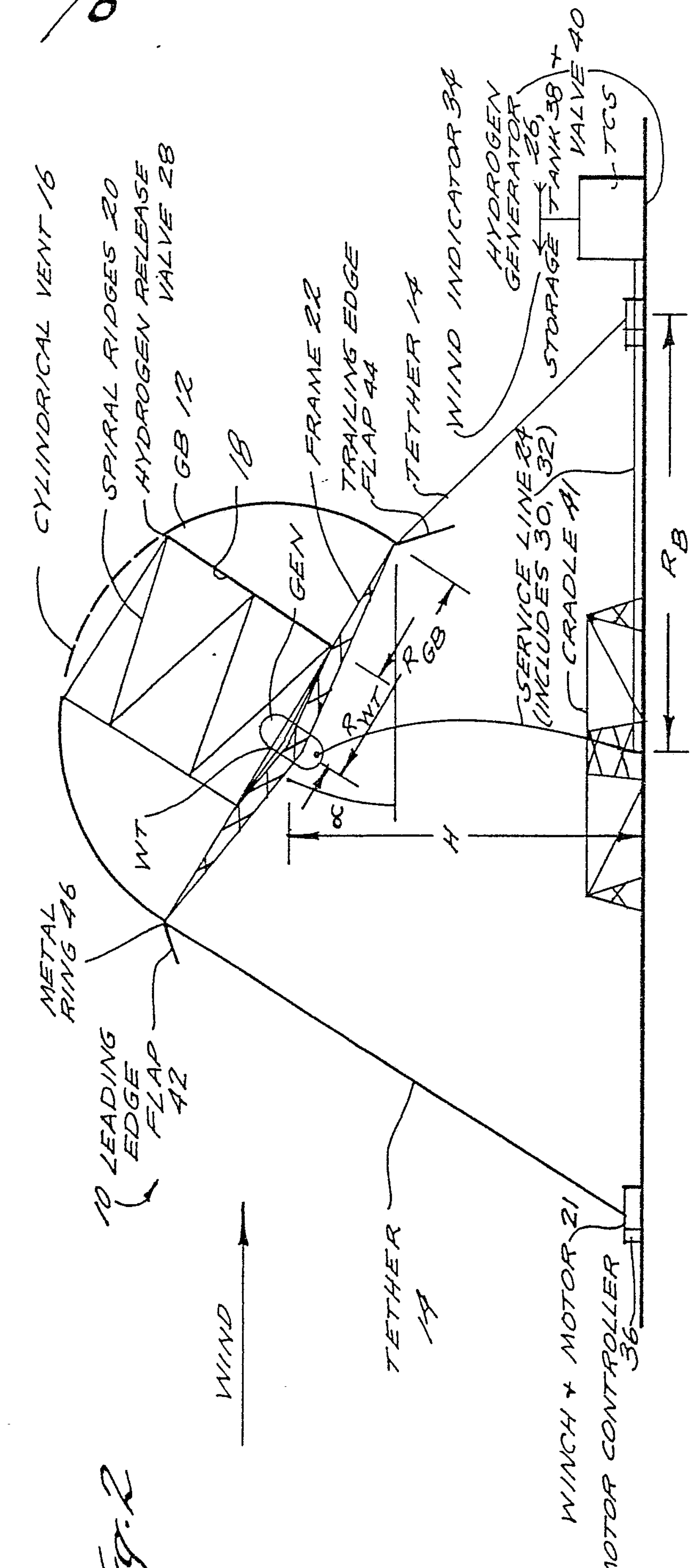

FAB SUPPORT RING
FAB
FAB
PTWR
WT
GEN
TWR
GUY
H
H-hb
hb
B
R WT

Fig. 1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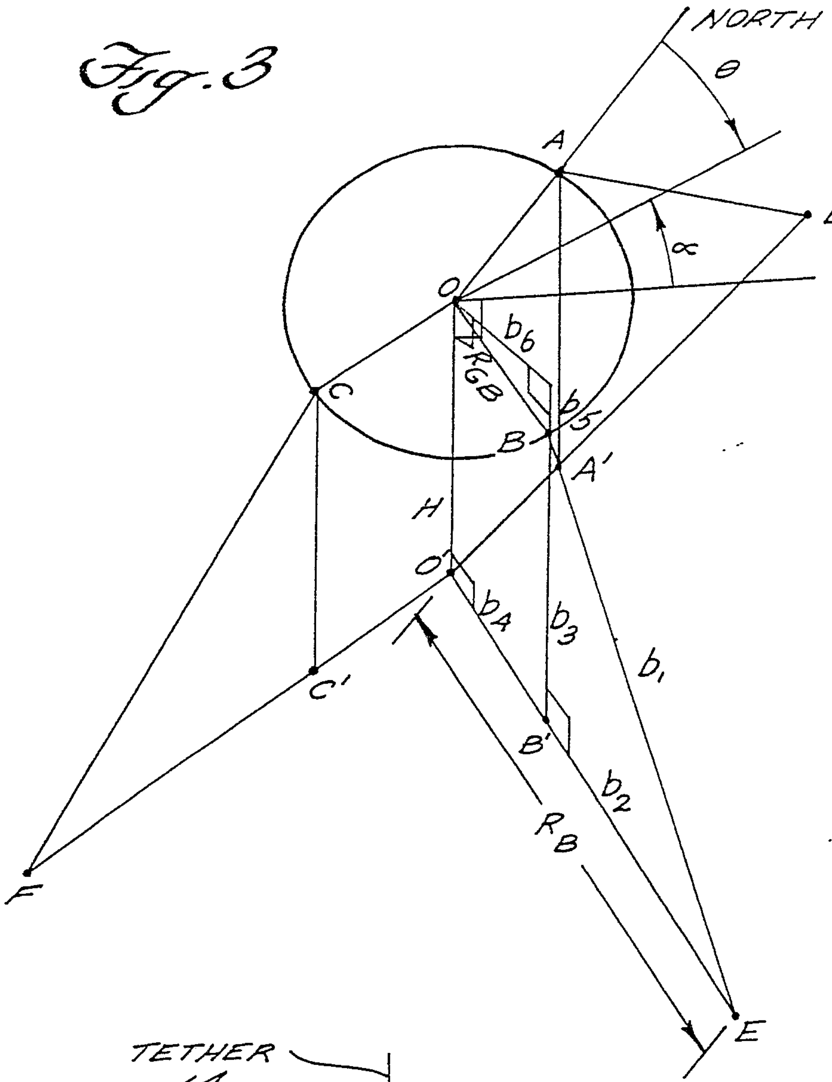
SPIRAL RIDGES 20
HYDROGEN RELEASE VALVE 28
GB 12
18
FRAME 22
TRAILING EDGE FLAP 44
TETHER 14
WIND INDICATOR 34
HYDROGEN GENERATOR 26,
TANK 38 + VALVE 40
STORAGE
TCS
GEN
SERVICE LINE 24 (INCLUDES 30, 32)
CRADLE
R GB
R WT
α
H
R B
WT
METAL RING 46
10
LEADING EDGE FLAP 42
WIND
TETHER 14
WINCH + MOTOR 21
MOTOR CONTROLLER 36

Fig. 2

Fig. 3


NORTH
θ
A
D
∝
O
b6
RGB
C
b5
B
A'
H
O'
b4
b3
b1
C'
B'
b2
RB
F
E

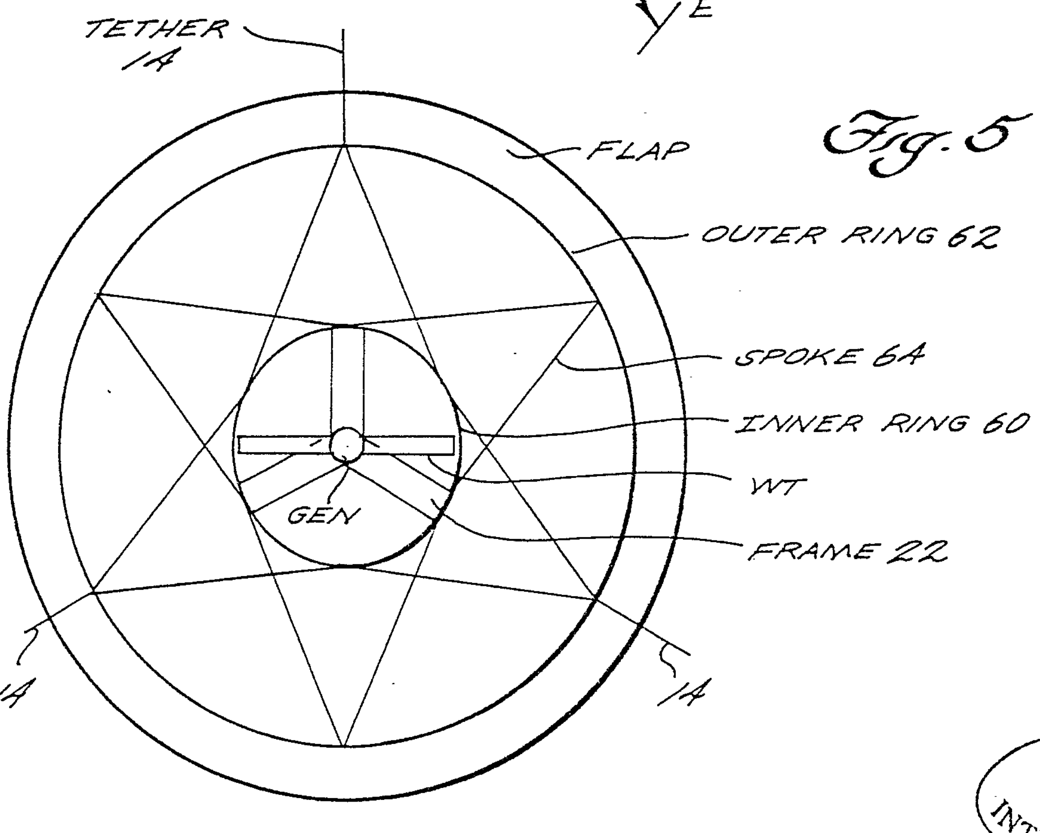

TETHER
1A
FLAP
OUTER RING 62
SPOKE 64
INNER RING 60
WT
GEN
FRAME 22
1A
1A

Fig. 5

3/6

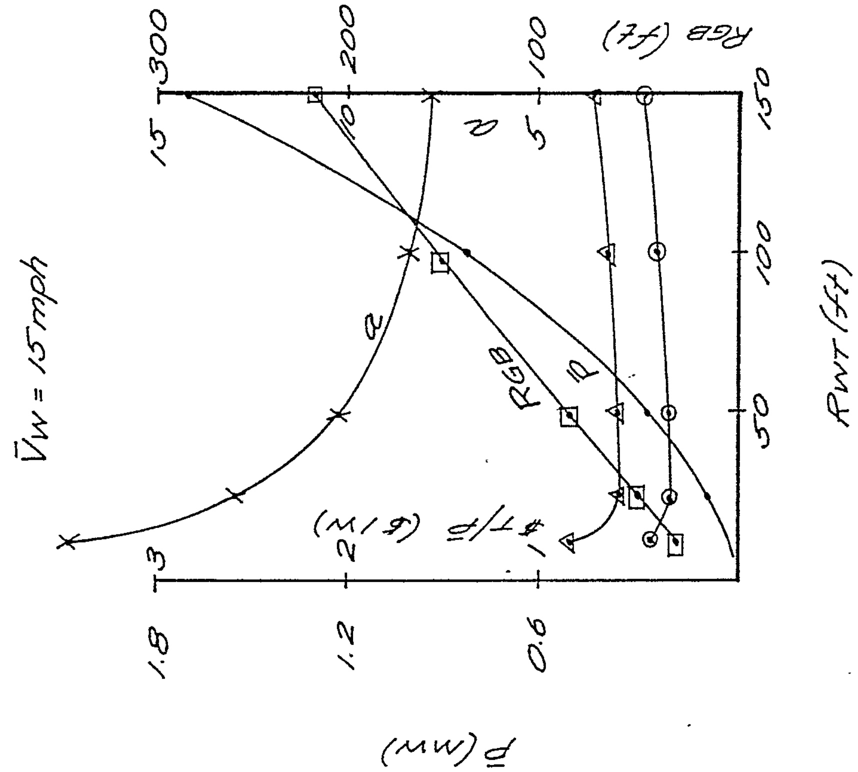
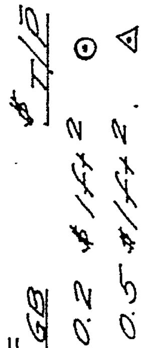


Fig. 4b



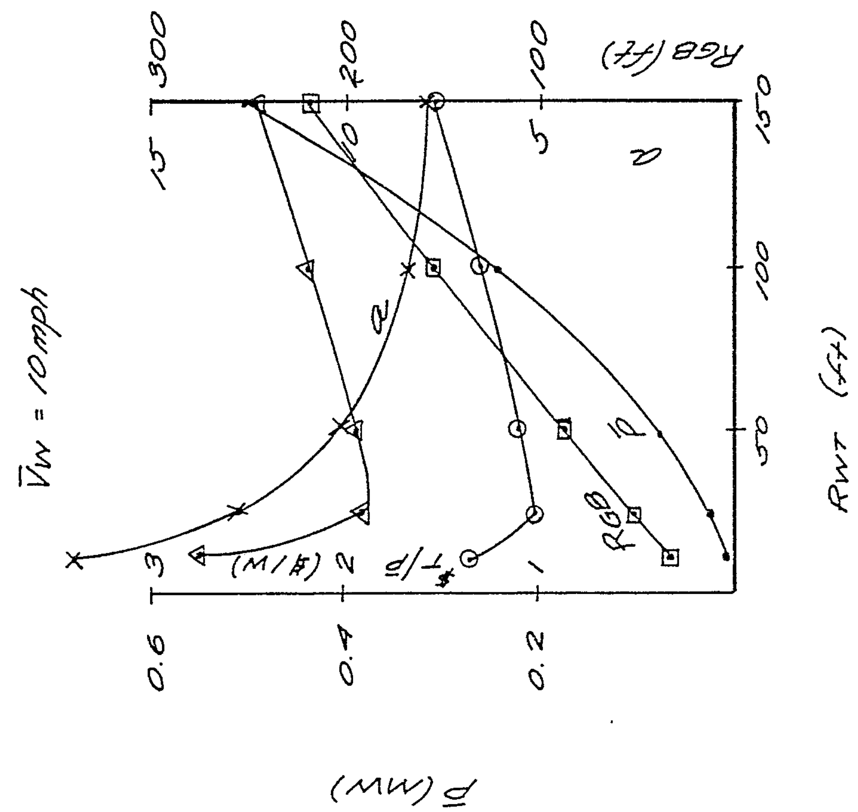
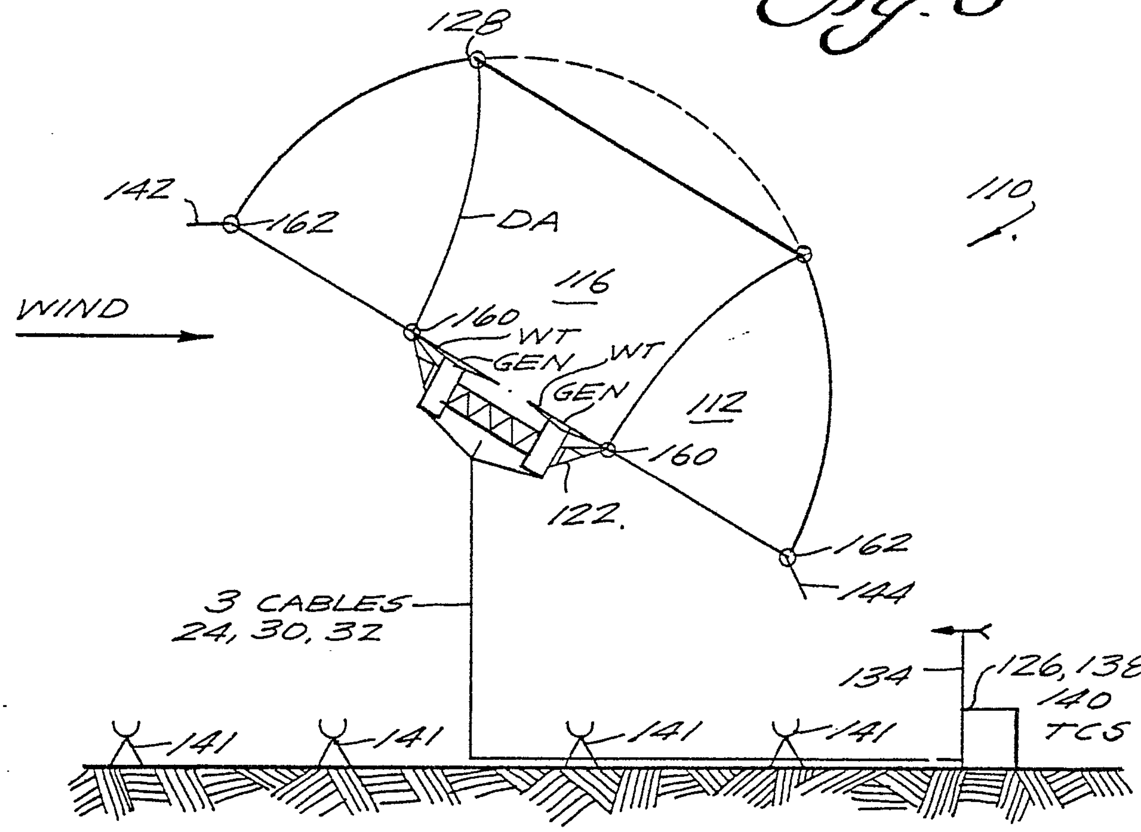


Fig. 4a

4/6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142
162
DA
110
116
WIND
160
WT
GEN
WT
GEN
112
160
122
162
144
3 CABLES
24, 30, 32
134
126, 138,
140
TCS
141
141
141
141

Fig. 6

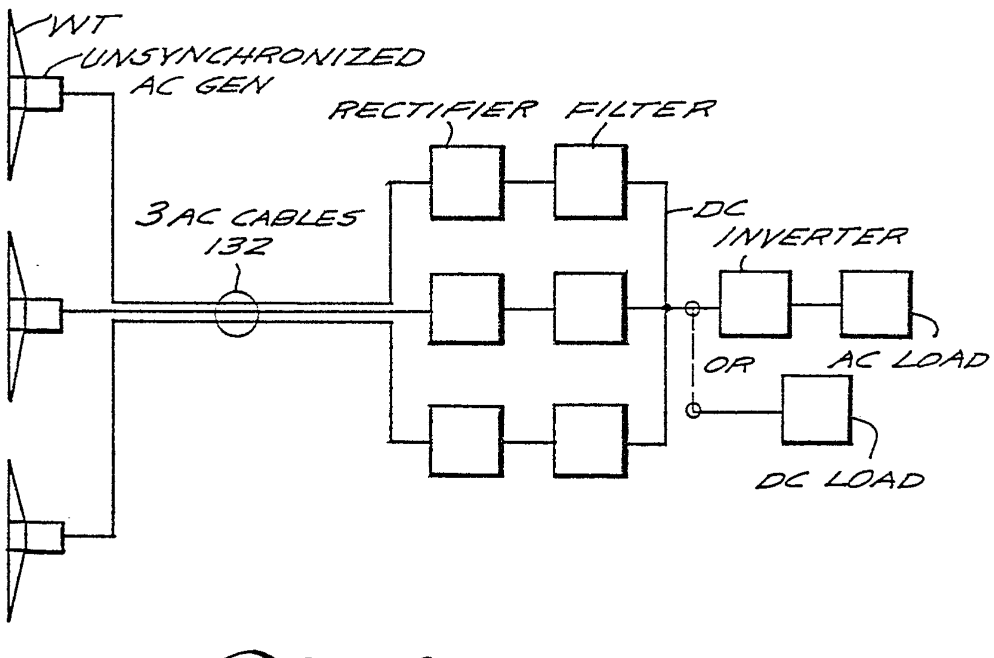
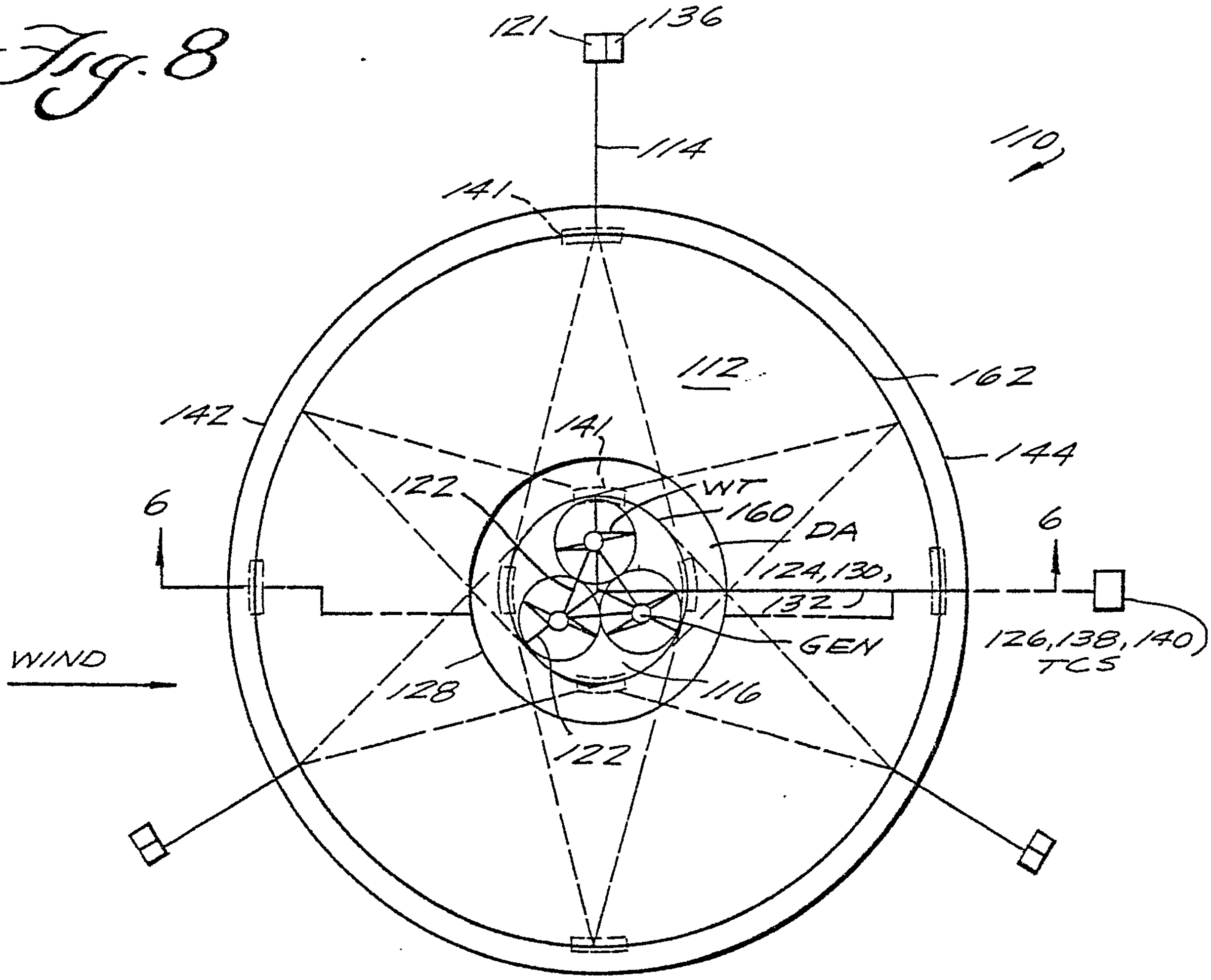

WT
UNSYNCHRONIZED
AC GEN
RECTIFIER
FILTER
3 AC CABLES
132
DC
INVERTER
OR
AC LOAD
DC LOAD

Fig. 7

Fig. 8


121
136
114
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141
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162
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141
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122
WT
160
DA
6
6
124,130,
132
GEN
126,138,140
TCS
WIND
128
116
122

Fig. 9

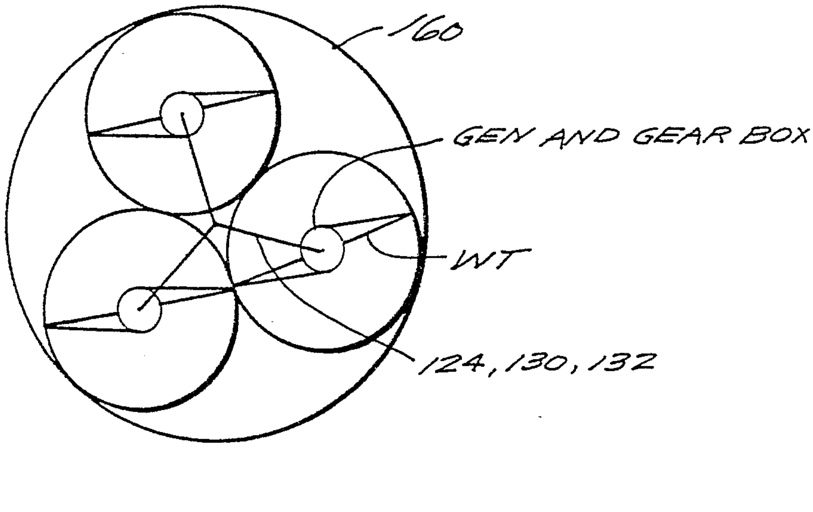

160
GEN AND GEAR BOX
WT
124,130,132

Fig. 10

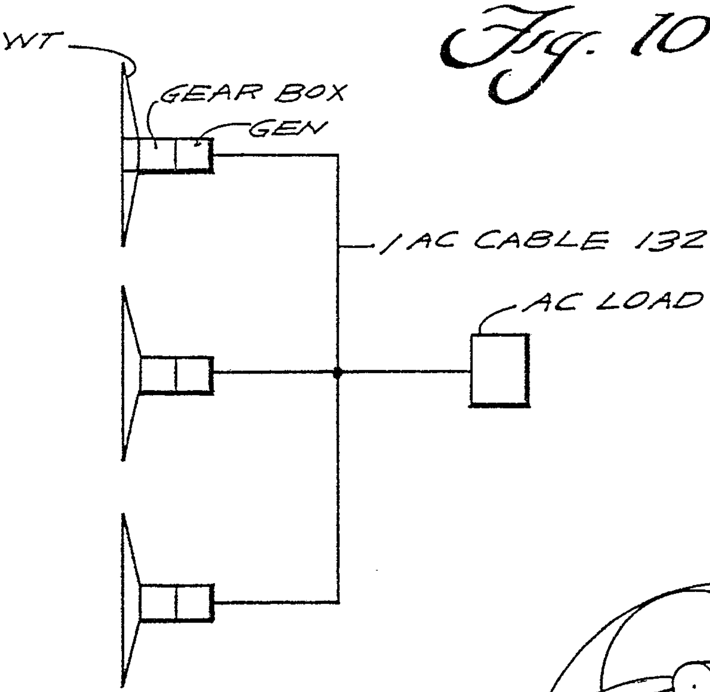
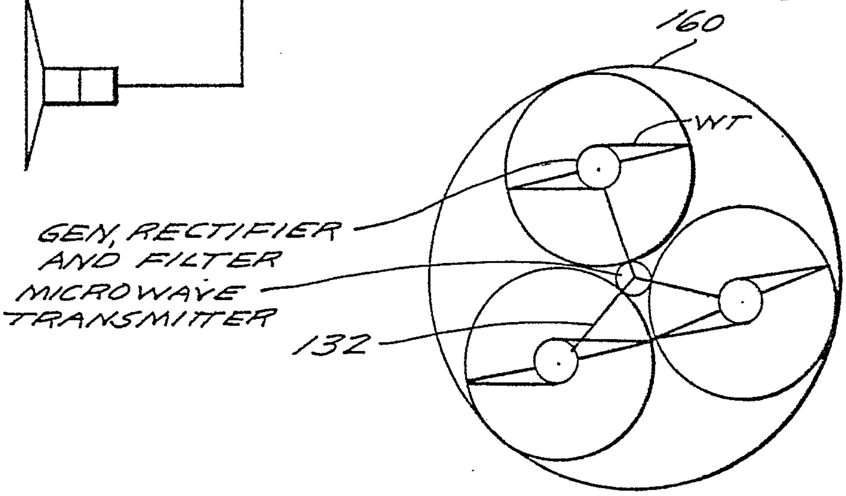


Fig. 11



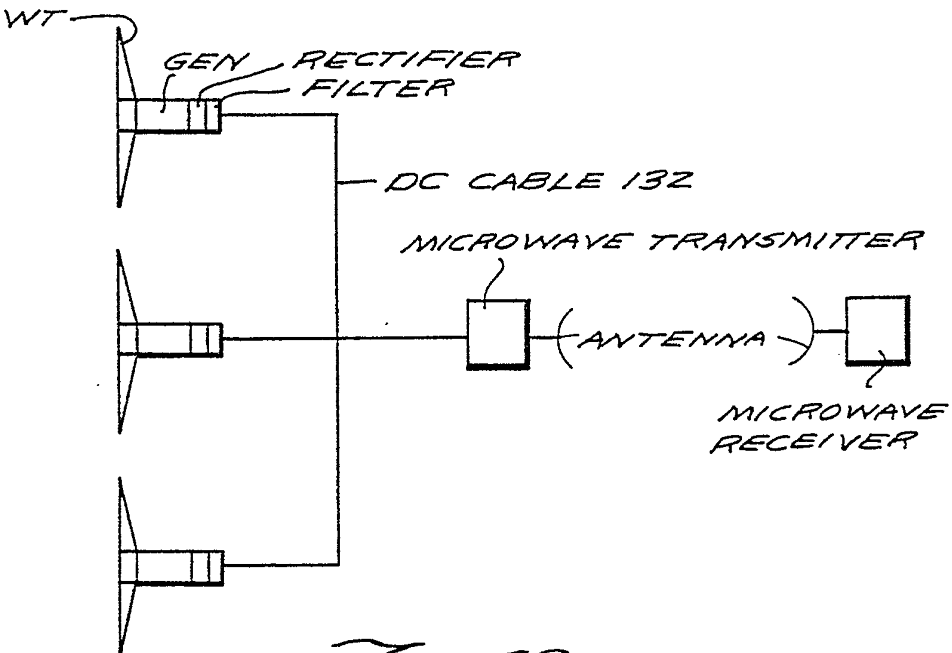


Fig. 12

INTERNATIONAL SEARCH REPORT

International Application No PCT/US80/00690

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int. Cl.3 B64B 1/50 F03D 9/00 F01D 25/28 F03B 7/00
U.S. Cl. 244/33 290/55 415/7 416/86

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	244/33,153R; 290/44,54,55; 415/2,7, Dig 8; 416/85,86

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
A,P.	US, A, 4,166,596, Published 04 September 1979, Mouton, Jr. et al.	1-65
A	US, A, 4,073,516, Published 14 February 1978, Kling.	1-65
A	US, A, 4,070,131, Published 24 January 1978, Yen.	1-65
A	US, A, 3,924,827, Published 09 December 1975, Lois.	1-65
A	US, A, 2,017,961, Published 22 October 1935, Ferral.	1-65
A	DE, C., 69,848, Published 07 May 1892, Rodeck.	1-65

* Special categories of cited documents: [15]

"A" document defining the general state of the art

"E" earlier document but published on or after the international filing date

"L" document cited for special reason other than those referred to in the other categories

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but on or after the priority date claimed

"T" later document published on or after the international filing date or priority date and not in conflict with the application, but cited to understand the principle or theory underlying the invention

"X" document of particular relevance

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
22 September 1980	10 OCT 1980
International Searching Authority [1]	Signature of Authorized Officer [20]
ISA/US	Charles E. Frankfort Charles E. Frankfort

Form PCT/ISA/210 (second sheet) (October 1977)