Catastrophic Failure due to Gyroscopic Effect of Small Scale Tilt up Horizontal Axis Wind Turbines

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1. Introduction

The main aim of wind turbine technology is converting wind energy to electricity. To assure a proper operation the wind turbine has to adapt to any wind conditions, which is in the first order to adjust itself according to the wind direction. It also needs to protect itself from the violence of winds greater than the rated wind speed. All this must happen automatically. Larger wind turbines have computer driven control systems, applying servomotors, hydraulic motors, and all sorts of paraphernalia. Small wind turbines need simple passive controls to a degree as far as possible. Always assume that any moving parts will seize up or wear out.

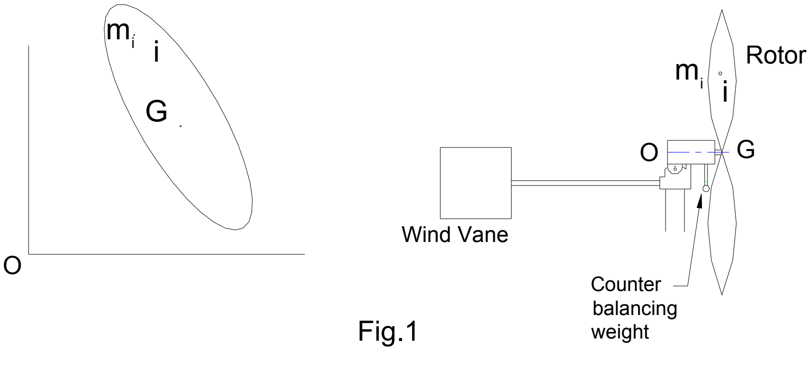
Tilt up method is one simple system to control the small-scale wind turbine. The Wind rotor is pivoted in vertical plane and it could tilt upward due to drag force of the wind rotor, as soon as this force goes beyond the rated condition. Counter balancing weight or spring mechanisms are needed to build the restoring momentum to hold the rotor to the wind, until the wind rotor is tilted up ward with respect to the wind speed. Anyway, this has to be accounted for tilt up systems can exhibit strange gyroscopic movements under turbulent conditions.

2. Gyroscopic effect

Wind rotor is the rotating part of wind turbine consisting of the blade, shaft, and any connecting parts. Since all of there components have mass, then the wind rotor has certain angular momentum. When wind rotor is tilt upward with the sudden increase of wind speed, direction of angular momentum is varied. Then torque is applied on the wind turbine due to the changes of the angular momentum of the wind rotor (Fig.1).

h (O) = Angular momentum of rotor around O.
I = Inertia of rotor around G.
O = Pivoted point of wind turbine.
OG = R.

h (G) = Angular momentum of rotor around G
G = Centre of gravity of wind rotor/Center of the rotor
m_i = Mass of particle at point i in rotor.
Oi = r_i



V, F = Velocity and Acceleration of G relative to the O.

V_i , F_i = Velocity and Acceleration of particle i relative to the G.

Fig. 1: Wind rotor of a small WTGS

$$h(0) = S r_i.m_i.v_i \quad (1)$$

$$h(G) = S (r_i - R).m_i.v_i \quad (2)$$

$$h(G) = S\, r_i.m_i.v_i - R.S\, m_i.v_i$$

$$h(G) = h(0) - R.S\, m_i.v_i \quad (3)$$

From eq - 1

$$dh(0) / dt = S\, v_i.m_i.v_i + S\, r_i.m_i.f_i$$

$$dh(0) / dt = T(0) \qquad (4)$$

From eq - 2

$$dh(G)/dt = S v_i.m_i.v_i + S\, (r_i\text{-}R).m_i.f_i$$

$$dh(G)/dt = T(G) \qquad (5)$$

From eq - 3

$$dh(0) / dt = dh(G) / dt + R.S\, m_i.f_i + V.S\, m_i.v_i \qquad (6)$$

$r_i - R = R_i$, $v_i - V = V_i$ & $f_i - F = F_i$

$S\, m_i.v_i = S\, m_i.(V_i + V)$

$= S\, m_i.V_i + M.V = M.V$ (\ G is center of gravity then $S\, m_i.V_i = 0$)

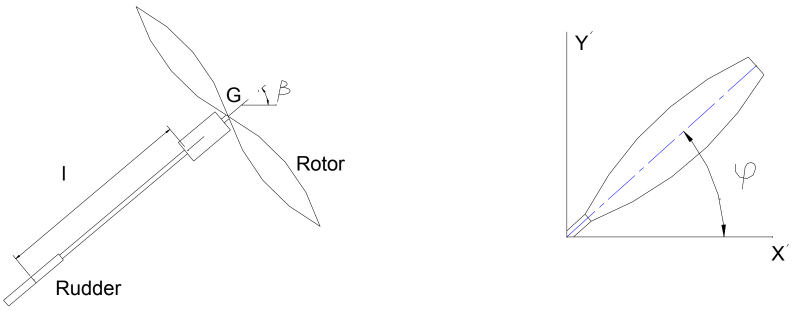
$S\, m_i.f_i = S\, m.F_i + M.F = M.F$ (\ G is center of gravity then, $S\, m_i.F_i = 0$)

$dh(0) / dt = dh(G) / dt + R.M.F + V.M.V$

$T(0) = dh(G) / dt + R.M.F$ ------- 7

3. Applied torque to the wind turbine

The wind rotor tilts upwards and the wind turbine can adjust its position in horizontal plane round the pivoted point O. For definition of the vectorial components of the forces it is assumed that the turbine tilts up by an angle θ, the rotor axis is shifted from the direction of wind speed at an angle β and that the rotor position is rotated against its initial position with an angle φ in rotor plane (Fig. 2).



Wind turbine Inclined to the direction of wind speed.

Position of wind rotor

Fig. 2

A_v = Area of wind vane.

C_{vd} = Coefficient of drag force of wind vane.

C_{vl} = Coefficient of lift force of wind vane.

β = Deviation angle of wind turbine in horizontal plane.

$\omega = d\varphi/dt$ - Revolution of rotor (rad/sec)

Fig. 2: Conditions to define the vectorial components of the forces

V = Wind speed, C_{rd}= Drag coefficient of rotor
A_r = Swept area of wind rotor
$F_d = C_{rd}.A.V^2$, $F_d = C_{rd}.A_r.V^2.\cos\theta.\cos\beta$ Drag force
T_w = Torque due to drag force of wind rotor =
T_w is depend on the wind speed and orientation of wind rotor.
$W = T_c$ Torque due to counter balance weight,
T_c is depend on the counter balancing weight and perpendicular distance from the pivoted point O to the force of counter balancing weight.
Then resistance torque by wind vane is:
$T_{vane} = C_{vd}.A_v.l.\sin^2\beta.V^2 + C_{vl}.A_v.l.\cos^2\beta.V^2$
T_R = Torque by the rotor

The torque by the rotor depends on the wind speed and revolution of rotor. That is the characteristic performance of the rotor.
T_G = Braking torque by the generator.

The braking (load) torque by the generator depends on power out put and revolution of generator. That is the characteristic performance of the generator. To define rectangular three-dimensional vector co-ordinate systems $\underline{i}$ is assumed to be unit vector towards the wind direction, $\underline{j}$ is the vector in the horizontal plane of $\underline{i}$, 90 degrees clockwise deviated as seen from top direction and $\underline{k}$ is the vector pointing vertically upwards (Fig. 3).

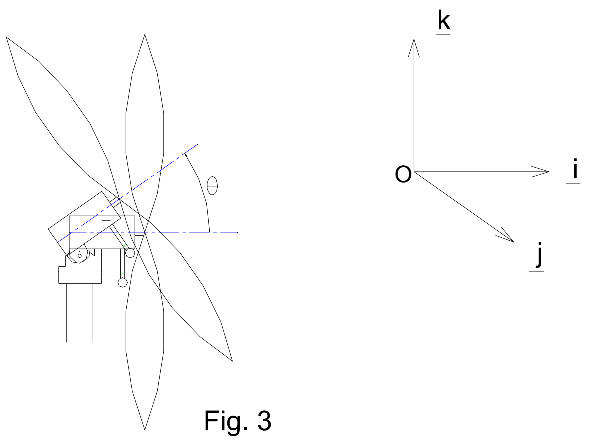


Fig. 3

Fig 3: Three-dimensional vector co-ordinate system of a rotor

$h(G) = h(g)_i + h(g)_j + h(g)_k$
$T(O) = T(o)_i + T(o)_j + T(o)_k$
$T(G) = T(g)_i + T(g)_j + T(g)_k$

From eq -7
$[T(o)_i + T(o)_j + T(o)_k] = d\,(h(g)_i + h(g)_j + h(g)_k) / dt + (R_i + R_j + R_k) . M\,(F_i + F_j + F_k)$

$T(o)_i = d[h(g)_i]/dt + M(R_j.F_k - R_k.F_j)$
$T(o)_j = d[h(g)_j]/dt + M(R_i.F_k - R_k.F_i)$
$T(o)_k = d[h(g)_k]/dt + M(R_i.F_j - R_j.F_i)$

From eq - 5
$[T(g)_i + T(g)_j + T(g)_k] = d\,[h(g)_i + h(g)_j + h(g)_k] / dt$
$T(g)_i = d\,[h(g)_i]/dt$, $T(g)_j = d\,[h(g)_j]/dt$, $T(g)_k = d\,[h(g)_k]/dt$

Then,
$T_R - T_G = T(g)_i.\cos\beta.\cos\theta + T(g)_j.\sin\beta.\cos\theta + T(g)_k.\sin\theta = I.d\omega/dt$ (8)
$T_w - T_c = T(o)_i.\sin\beta + T(o)_j.\sin\beta$ (9)
$T_{vane} = T(o)_k$ (10)

Then, the set of three equations could be expressed by θ, β, φ ,d[θ]/dt , d[β]/dt , d[φ]/dt , $d^2[\theta]/dt^2$, $d^2[\beta]/dt^2$ and $d^2[\varphi]/dt^2$.

$T_R - T_G = F_1\{ \theta, \beta, d[\theta]/dt , d[\beta]/dt , d[\varphi]/dt , d^2[\theta]/dt^2 , d^2[\beta]/dt^2 , d^2[\varphi]/dt^2 \}$
$T_w - T_c = F_2\{ \theta, \beta, d[\theta]/dt , d[\beta]/dt , d[\varphi]/dt , d^2[\theta]/dt^2 , d^2[\beta]/dt^2 , d^2[\varphi]/dt^2 \}$
$T_{vane} = F_3\{ \theta, \beta, d[\theta]/dt , d[\beta]/dt , d[\varphi]/dt , d^2[\theta]/dt^2 , d^2[\beta]/dt^2 , d^2[\varphi]/dt^2 \}$

So, $d^2[\theta]/dt^2$, $d^2[\beta]/dt^2$ and $d^2[\varphi]/dt^2$ could be found by the functions of F_1 {} , F_2 {} and F_3 {} , because initial values of θ, β, φ , d[θ]/dt , d[β]/dt and d[φ]/dt are known. Then all motions of the wind rotor and the turbine could be determine.

4. Cyclic Motion of Wind Turbine.

When the wind speed is increased spontaneously from V_1 to V_2, a simultaneous movement of the rotor tilt up ward will be consequence and wind turbine will be accelerated in horizontal plane due to the vertical torque by gyroscopic action of wind turbine.

<u>*Position A (Fig. 4),*</u>
$T_w > T_c$
$T_{vane} = 0$

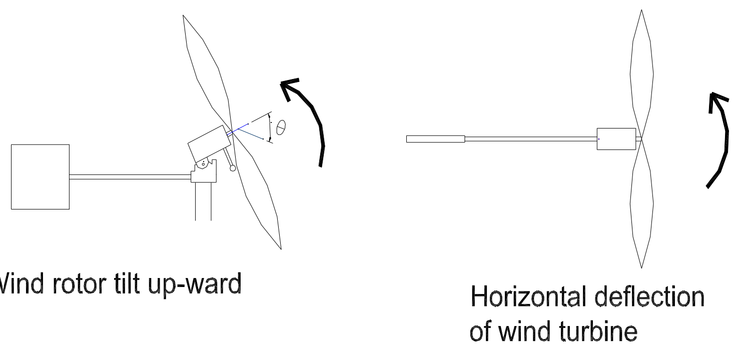


Fig. 4

When the wind rotor tilts up-wards and the wind turbine rotates in its horizontal plane, the effective wind speed is influenced. This leads to a decrease in wind force due to the gyroscopic effect. Wind rotor tilt upward and wind turbine horizontal deflection β will proceed until $T_w = T_c$.
When $T_w=T_c$, wind turbine start to rotate other direction due to torque by wind vane (T_{vane}).

<u>*Position B (Fig. 5),*</u>
$T_w = T_c$ *;* T_{vane} is maximum

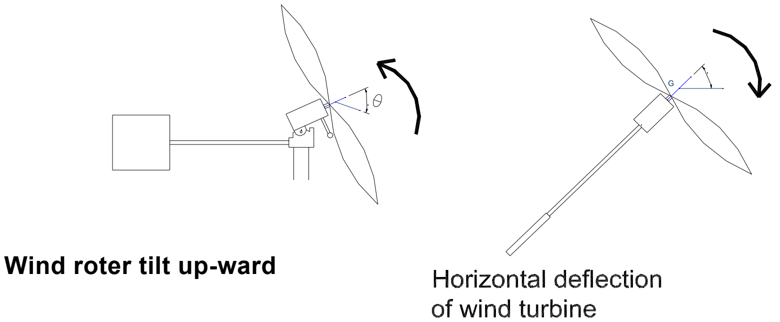
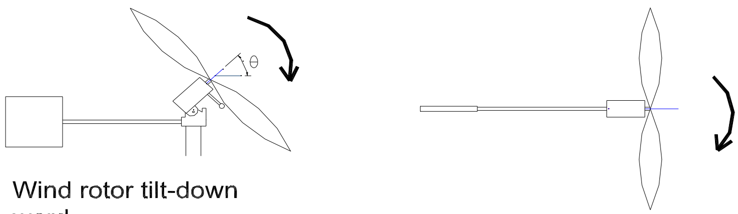


Fig. 5

While wind turbine is repositioning to the wind direction due to the torque of wind vane (T_{vane})., gyroscopic moment is applied to wind rotor in horizontal plane. Then wind rotor tilt upward till (T_c-T_W) balances with the respective gyroscopic moment due to positioning the wind turbine to the wind direction. Wind rotor is tilted up-ward till wind turbine is positioned to the wind direction.

As now $T_c>T_W$ wind rotor start to tilt down-ward.

Position C (Fig. 6)
$T_c>T_{W,}$; $T_{vane} = 0$



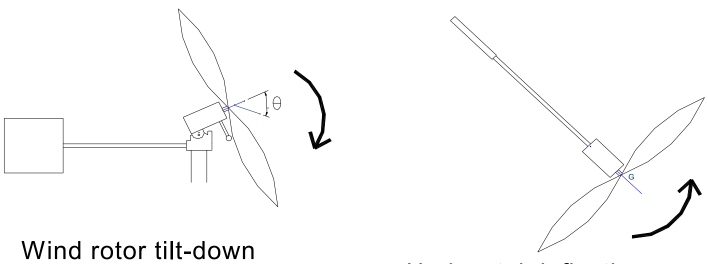
Wind rotor tilt-down ward

Horizontal deflection of wind turbine

Fig. 6

While the wind rotor is tilting downward due to the effect of T_c - T_w , wind turbine starts rotating in the opposite as with respect to the wind direction. Wind turbine deflection in horizontal plane and wind rotor tilt down ward tilt will adjust until $T_c=T_w$.

Position D (Fig .7),
T_c - T_w
-T_{vane} is maximum



Wind rotor tilt-down ward

Horizontal deflection of wind turbine

Fig. 7

What happens at $T_c = T_w$, but wind turbine not in line with wind direction. Then vertical torque is applied to the wind rotor.
$T_v = T_k$

While wind rotor is tilting downwards due to gyroscopic effect by torque $T_{v.}$ Torque (T_w-T_c) is increased due to increasing of effective wind speed of rotor.
Simultaneously wind rotor is tilted downward and repositioned to the wind direction. If the wind turbine move back to the position it had before the sudden increase of wind speed occurred, the sequence of consecutive movement will repeatedly happen until the wind speed is stable.

5. Conclusion

The motions of wind turbines depend on the applied forces. To tilt-up control wind turbines, torque by drag force of wind rotor & counter balancing weight, torque by rotor, braking torque by generator and torque by wind vane make up very complex situation. Then motions are induced corresponding to the gyroscopic effect of rotor by torque (T_w - T_c) , (T_R - T_G) and $T_{v.}$

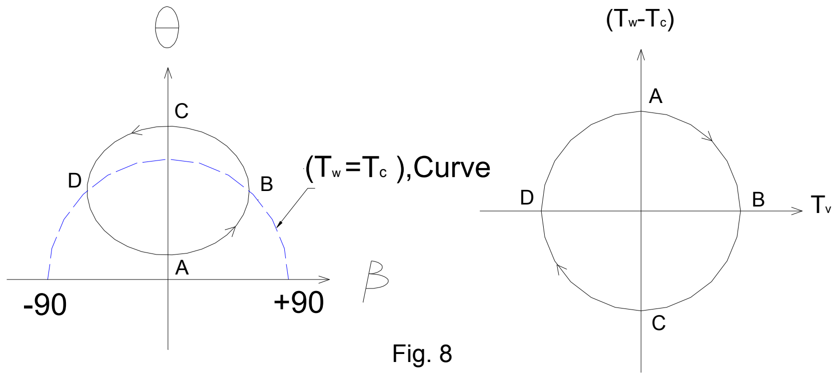


Fig. 8

As soon as wind speed is spontaneously increased or wind direction is suddenly changed, as is common at turbulence conditions, rapid and heavy motions of wind turbines are induced. If the wind turbine comes back to it previous position, when the increased wind speed or change of wind direction still apply, cyclic motion may occur. The dominant rotation of the wind turbine in a vertical plan can cause a deviation in the horizontal plane due to its gyroscopic effects. Gyroscopic torque depends on change of angular momentum of rotor. Change of angular momentum depends on the changing rate of θ,β,φ and the moment of inertia of the wind rotor.

To avoid the cyclic motion under turbulent conditions, one must control the rate of changing of θ and of β by using an energy absorption device for which could be eg; shock absorber. A very effective means is also a reduction of the moment of inertia of the rotor (I). Catastrophic failure may occur when the cyclic motion goes beyond safe level.

6. References

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