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Analytical Evaluation of Solar Enhanced Magnus Effect Wind Turbine Concept

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Abstract- With the environmental concerns increasing and the fossil fuels diminishing, the push for more efficient devices to extract power from renewable resources has much increased. In the present study, a novel wind turbine is introduced that utilizes the Magnus Effect. This turbine employs spinning cylinders instead of blades, and has the capability to attain an aerodynamic efficiency that is higher than the conventional wind turbines. On top of the wind effect, due to convenient cylindrical surface, the cylinders can be covered with solar cells, hence a second source of renewable energy. Analytical basis for the performance of this turbine is constructed in the present study, and initial estimates of performance parameters under different conditions are made.

Keywords Magnus effect; spinning cylinders; insolation; Betz limit; power extraction.

Nomenclature

a	=	*Induction factor*
C_l	=	*Section lift coefficient*
C_p	=	*Power coefficient*
I	=	*Insolation (W/m²)*
L	=	*Lift force (N)*
M	=	*Torque with respect to the rotor hub (Nm)*
N	=	*Number of blades*
R_c	=	*Radius of the cylinder (m)*
R_t	=	*Radius of the rotor; span of the cylinder (m)*
Re	=	*Reynolds number based on the diameter of the cylinder*
V_{wind}	=	*Ambient wind speed approaching the turbine (m/s)*
V_∞	=	*Ambient air speed approaching the section (m/s)*
$\dot{W}$	=	*Power (W) (generated, extracted, solar)*
β	=	*Angle between the V_{wind} and V_∞*
θ	=	*Angular position around the cylinder surface*
υ	=	*Kinematic viscosity of air (m²/s)*
ω_c	=	*Spin angular speed of the cylinder (rad/s)*
ω_t	=	*Rotational speed of the rotor (rad/s)*

1. Introduction

Renewable energy is an inevitable part of an environmentally friendly and sustainable future. Wind turbines and photovoltaic solar panels currently form the backbone of the renewable energy sources worldwide. In order to increase their efficiency, much research is under way. Still, the solar and wind energy cannot be delivered from their innate limitation: “no wind-no wind power” and “night time-no solar power”. Fortunately, these two energy sources are not mutually exclusive, i.e. they can coexist, and even if one is not there, the other can be harvested. In this study, a novel, hybrid wind turbine is introduced, which utilizes the Magnus effect.

The main idea of this novel wind turbine is that, instead of blades, spinning cylinders are used, which rotate due to the Magnus effect [1, 2]. Since the Magnus effect can result in C_l values that are much higher [3] than that of a conventional wing profile (1-1.5), improved efficiencies [4-9] are possible.

Using a cylinder instead of a conventional wing brings another advantage. The topology of a cylinder is suitable for being covered with solar cells. Thus, the same wind turbine can harness the energy of the sun and wind both at the same time. Even if there is no wind, solar panels can generate power, and even if there is no sun, the wind energy can be harvested. It should be noted that the solar cells have no impact on the aerodynamic performance of the wind turbine; rather, they just produce electricity.

This novel wind turbine needs power to spin its cylindrical blades. Depending on the spinning speed, this energy is going to change. Therefore, a careful drag force and torque calculation needs to be done in order to optimize the energy harvesting, while spinning the cylinders. Another optimization is needed for the solar aspect of this device. When the turbine is at a low-wind or no-wind setting, it may be more efficient to align it not according to the dominant wind but according to the direction of the sunlight.

The proposed wind turbine also brings structural challenges due to the gyroscopic forces that will be generated as a result of the lateral rotation of the rotating cylinders (Fig.1). Based on such analyses, a variable-thickness cylinder may be needed for structural integrity.

In the present study, the derivations of basic formulas regarding the aerodynamic and solar performance of this wind turbine are presented. Based on this analytical knowledge, variation of the performance under different conditions is analyzed.

2. Methodology

For the basic aerodynamic analysis of this wind turbine, an inviscid, incompressible flow model is utilized. Accordingly, the C_l for a spinning cylinder in uniform flow and the stagnation angles are given by;

$$C_l = \frac{\Gamma}{R_c V_\infty} = \frac{2\pi R_c \omega_c R_c}{R_c V_\infty} = \frac{2\pi R_c \omega_c}{V_\infty} \quad (1)$$

$$\theta_{stagnation} = arcsin\left(-\frac{\omega_c R_c}{V_\infty}\right) \quad (2)$$

Since the spinning cylinder in this case is at the same time rotating around one of its ends, a velocity triangle forms (Fig.1), by which the governing flow direction and its magnitude can be calculated by;

$$V_\infty = \left[V_{wind}^2 + \omega_t^2 r_t^2\right]^{1/2} \quad (3)$$

$$cos\beta = V_{wind} / V_\infty \quad (4)$$

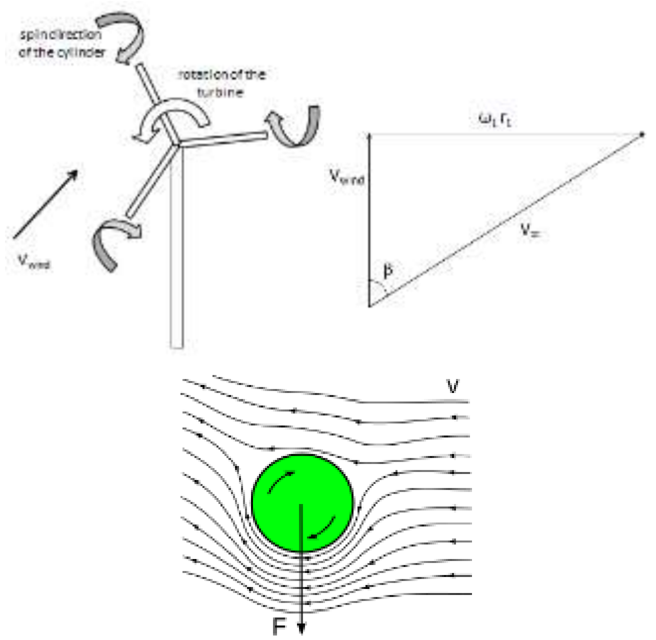

Fig. 1. Representation of the velocity components at a cross-section of the spinning cylinder.

The lift force here is going to be normal to the governing flow direction, not the wind. Therefore, using this velocity triangle, the component of the lift in the rotation plane and the subsequent moment due to the lift at that section can be found as;

$$dM = dL_{in\ plane\ of\ rotation} r_t = dL\, cos\beta\, r_t \quad (5)$$

This moment must be integrated along the span, in order to obtain the overall torque and the resultant power generation. In performing this integral, there are a number of factors that need to be considered. First of all, in a wind turbine, one can have more than one blades, hence multiple cylinders. Second, as can be remembered from the stream tube analysis of a wind turbine, actual wind speed that the turbine sees is less than the wind speed due to the expansion of the stream tube. Therefore, instead of the V_{wind} term in the above formulae, one must use V_{wind} (1-a). With these in mind, the net power extraction can be formulated as;

$$\begin{aligned}\dot{W}_{gen} &= M\omega_t = N\int_0^{R_t} \frac{1}{2} V_\infty^2 \left(2R_c\, dr_t\right) C_l\, cos\beta\, r_t \\ &= N\left(\omega_c R_c^2\right)\left(\omega_t R_t^2\right)\pi V_{wind}\left(1-a\right)\end{aligned} \quad (6)$$

Independent of this result, the same power extraction can be estimated using the rate of kinetic energy decrease in the stream tube, which gives;

$$\dot{W}_{extracted} = \frac{1}{2}\left(\pi R_t^2\right) V_{wind}^3 \left(1-a\right)^2 4a \quad (7)$$

Equating Eq. (6) and Eq. (7), a second-order polynomial for the value of “a” is obtained;

$$a^2 - a + \frac{N\omega_c\omega_t R_c^2}{2V_{wind}^2} = 0 \quad (8)$$

The power coefficient of the turbine based on “a” can be obtained from;

$$C_p = 4a\left(1-a\right)^2 \tag{9}$$

In this regard, one can insert the value of 1/3 into Eq. (8) and Eq. (9) for “a”, and study the consequences. It is known that this value returns Betz limit when inserted into Eq. (9). So, the same process for Eq. (8) can tell under what co Betz limit can be reached with the Magnus effect wind turbine. Accordingly, one can obtain the following relationship;

$$\omega_{c,\,Betz\ limit} = \frac{4V_{wind}^2}{9NR_c^2\omega_t} \tag{10}$$

Another limit for the performance of Magnus effect wind turbine is the union of the stagnation points at certain rotational speed. Although in practice, the cylinder can be accelerated to higher speed and can achieve higher C_l values, in this study, the union of the stagnation points is going to be assumed as the limit, since it desired to extract energy from the wind rather than to create lift. The union of the two stagnation points in inviscid flow happens when the free stream velocity (V_{wind}) is equal in magnitude to the tangential speed at the cylinder surface (w_cR_c). When this happens, the two stagnation points unite at the angular position *3Π/2*. However, in case of a wind turbine, the relative magnitude of the free stream is changing along the wing span, as indicated in Fig. 1 and in Eq. (3) and Eq. (4). So, the union of the stagnation points cannot be achieved everywhere at once, but it first occurs at the root section, and that is the limit assumed in this study. Accordingly;

$$\omega_{c,\,stagnation\ union} = \frac{V_{wind}}{R_c} \tag{11}$$

In order to calculate the required torque to spin the cylinders, one can make use of the following formula [10] to calculate the torque per length, and then integrate it along the wing span;

$$C_T = \frac{T}{2V_\infty^2 R_c^2} = \frac{2\pi}{\sqrt{R_e}}\left(\lambda^{-0.5} - 0.522\lambda^{-2.5}\right) \tag{12}$$

where $\mathrm{R_e} = {V_\infty 2R_c}/{\nu}$.

The limitation of Eq. (12) is that it is valid between Reynolds numbers of 200 and 1000, and the torque coefficient decreases with Reynolds number. The Reynolds numbers tried in the present study reach values up to 10^5, and should have C_T values that are much less. Still, due to lack of data, three times the result from equation (12) is assumed for calculations. Upon integration, one can multiply the result by the rotational speed of the blades and by the number of blades in order to obtain an expression for the power required for spinning the cylinders;

$$T = 2\ R_c^2\, C_T\ \omega_c N\left(V_{wind}^2 R_t + \omega_t^2 R_t^3 / 3\right) \tag{13}$$

Aside from the wind aspect of this turbine, there is the solar power aspect. As a rough estimate, it can be assumed that the cylindrical blades of the turbine cover a projective area that is equal to a rectangle. This rectangle has an area of $2R_cR_t$, which continuously rotates and changes its incidence angle. This area belongs to a single cylinder, and the other cylinders must be accounted for in a complete analysis. Nevertheless, an average performance over a rotation of the turbine can be estimated, and this number can be used to infer the solar power generation. One effect of the rotation of the turbine and the spin of the cylinders is that a portion of the cylinders is always going receive sunlight through the normal direction, but in general, the incidence angle is going to change continuously for a given cell.

For stand-alone PV applications, it is necessary to know the incident solar radiation on an inclined surface. Since a round-type PV system (for simplicity in calculations, a dodecagon type PV panel of which details are given in Fig.2, will be considered) will be taken into account in the objected design, it will act as PV panel using a fixed tilt and fixed azimuth angles provided by single axis tracker system. So, it is quite straightforward to calculate the direct-beam radiation on a given tilted surface by providing the position of the sun and orientation of the plane. As given in Fig.1, If it is assumed that the efficiency of a flat type panel with an exact tilt and best azimuth angle is “1” by taking into account the number of cells as 120, the efficiency of the dodecagon type PV panel can be calculated as;

$$P_{eff} = \left(\frac{1}{12}.1\right) + \left(\frac{1}{12}.\sin 60°.2\right) + \left(\frac{1}{12}.\sin 30°.2\right) \tag{14}$$

By following the methodology explained in [11], the efficiency of the panels covering the cylindrical blade surfaces can be estimated as 0.3.

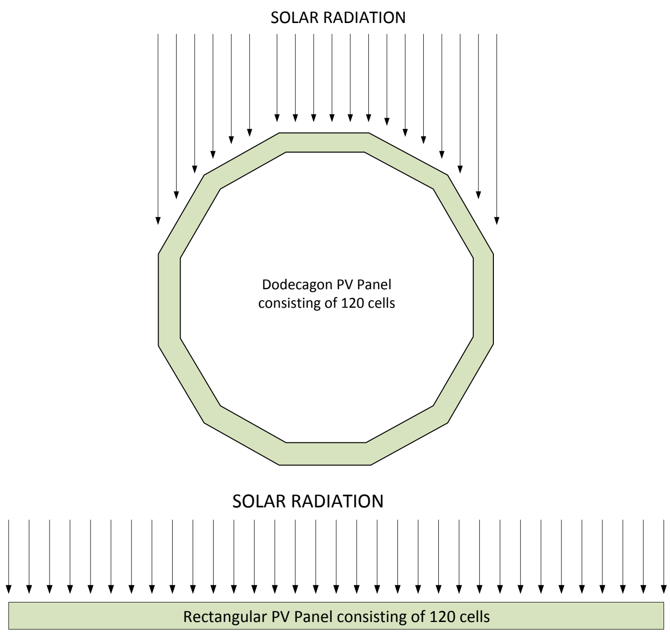

Fig. 2. Comparison of an approximate blade surface and a flat surface with insolation in the normal direction.

It means that the efficiency of both systems intersect where azimuth angle of flat or rectangular type solar panel is 17.45°. So, within the same design area; rectangular type solar panels provide better energy output than that dodecagon –type PV panel design between 17.45° and 90° azimuth angles. That is, the cylindrical surfaces are going to generate 30% of the power that would be generated by a flat surface that is receiving the sunlight in the normal direction and that has the same projected area as the cylinders.

Another effect of the rotation and spin of the cylinders is that each pixel of solar cells is going to receive the sunlight at an alternating angle, resulting in an alternating magnitude of insolation. The impact of this alternation on the solar cell performance must be explored. In the present study, effects of alternation of insolation are going to be neglected.

It also must be noted that solar cells not looking towards the sun are going to receive indirect insolation, and this is going to reduce the power generation. For a realistic estimate, this portion of the generation must be accounted for. However, for this initial analysis, the portions of the cells that are directly receiving the sunlight are going to be assessed.

Considering the above explanations, the solar panels on the Magnus Effect wind turbine would generate solar power according to the following expression;

$$\dot{W}_{solar} = 2(2R_cR_t)\,{}^{I}\!/_{2} = 2R_cR_tI \qquad (15)$$

Up to here, the energy aspects of this novel turbine have been discussed. Of course, when the dual-axis rotation of the cylinders is taken into account, on top of centrifugal one, gyroscopic acceleration must be considered. However, a structural analysis in context of this double-loading is not going to be included in the present study.

3. Results

Eq. (7) can be plotted for a wind turbine consisting of 3 blades with 4 seconds of rotor period and 15 m/s wind speed at sea level conditions. In Fig.3, the values of C_p at different cylinder radii are shown. The calculations show until the Betz limit is reached. As this figure indicates, thicker cylinders can achieve high efficiency at lower spin speeds. On top of this, thicker cylinders are better for harvesting more solar energy. At low wind speeds, the wind turbines do not rotate until above 3-3.5 m/s. In particular, at these low wind or no wind settings, these turbines can generate minor amounts of power instead of idling.

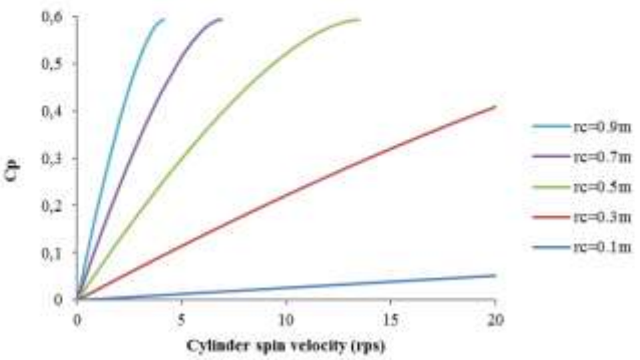

Fig. 3. Variation of power coefficient with cylinder spin velocity at different cylinder radii.

One such case has been presented in Fig.4, where a wind turbine with 15 m rotor radius is exposed to a 3 m/s wind. Although the power coefficient for wind energy is different for different cylinder radii at the same spin velocity, the power coefficient was assumed to be similar to a conventional wind turbine, i.e. C_p = 0.35, only for the preparation of Fig.4. However, increase of cylinder radius means more surface area for solar power. As a result, the solar power generated from a net insolation of 150 W/m^2 increases with the cylinder radius. The reason for linear increase, instead of a square relationship, with cylinder radius is that for the solar power, the projected area of the rotor is employed, not the actual surface area.

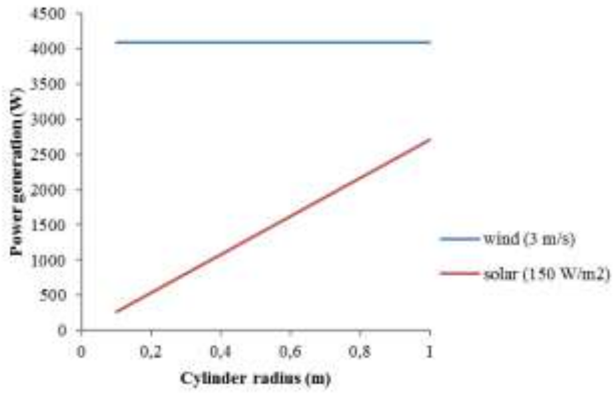

Fig. 4. Comparison of the solar and wind components of power generation at low wind speed.

How much rotation is needed for power generation at low wind speeds, or at any wind speed for that matter depends on the cylinder radius. For an estimate of the upper limit for power generation and to compare with a conventional wind turbine, a sample case is formed for a wind speed of 15 m/s, rotor radius of 10 m, and a rotor period of 3.33s. Under these conditions, a conventional wind turbine with an aerodynamic efficiency of 0.4 would generate approximately 260 kW power at sea level. A Magnus effect wind turbine at the same conditions, however, when run at settings to reach the Betz limit and to unite the stagnation points, can provide 385 kW power. The settings for the latter case are shown in Fig.5. It is seen here that the same high aerodynamic efficiency can be obtained by changing the number blades, and choosing the cylinder radius and cylinder rotation rate according to the design limitations.

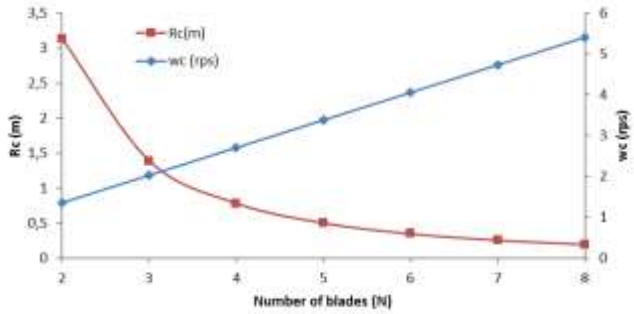

Fig. 5. Variation of settings for maximum efficiency in a Magnus effect wind turbine.

For the same cases, the power required to spin the cylinders is plotted in Fig.6. Considering the fact that conservative values are presented, for the same case, the Magnus effect wind turbine can provide a net power output between 323-352 kW. This means a net increase of 63-92 kW (i.e. 24- 35 % increase) compared to a conventional wind turbine.

Another aspect of these cylindrical blades is that the C_l value decreases with radial position in the rotational plane. This is due to the fact that the overall speed that the cylinder cross-section is exposed to is increasing. This also means that the stagnation points are continuously moving away from each other. This effect is shown for a sample case in Fig.7, where the rotor radius is 15m, cylinder radius 0.3m, wind speed 15m/s, rotor rotation period 4s and cylinder rotation period is 3s, approximately. Along with the increasing separation between the stagnation points, the suction peaks on either side of the cylinder rotate along the span. This latter effect is due to the change of the free stream direction along the wing span, as seen in Fig.1. The final picture of pressure distribution along the span is that there is a spiraling path, on which there is a negative pressure gradient. That is, a flow is likely to be induced in the span-wise direction, and it may affect the overall aerodynamic performance of the Magnus effect wind turbine. This situation can be controlled by using interim plates and/or endplates [3].

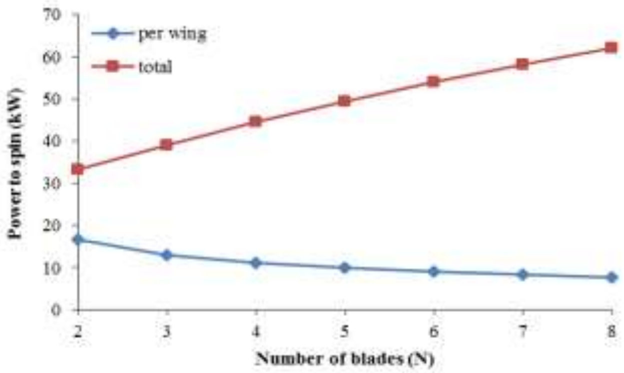

Fig. 6. Required power for spinning the cylinders for the cases shown in Fig.5.

It must be noted that Betz limit can be achieved without necessarily increasing the rotation rate of the cylinders. The comparison of the behavior the two factors, is shown in Fig.8. For a sample case at 5 m/s wind speed at sea level and with 3 blades, it is seen that when the cylinder radius exceeds 0.5 m, it is possible to obtain the highest efficiency at lower rotational speeds.

The exact numbers for these factors eventually depend on the design criteria, which include the structural and also electrical factors. In any event, the solar energy can help with the power needed to spin the cylinders. However, a calculation of the power needed to spin the cylinders must be performed in order to see the net result, and compare with the conventional wind turbines.

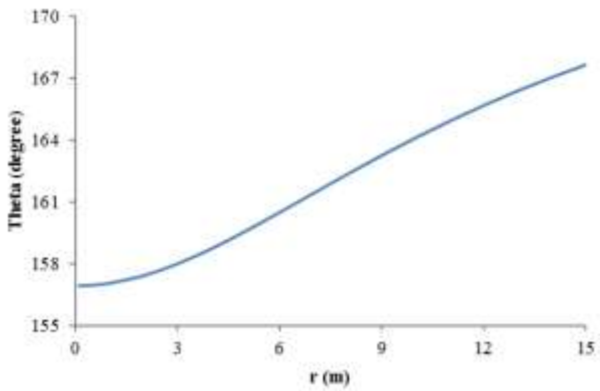

Fig. 7. Variation of angular separation of stagnation points along the span.

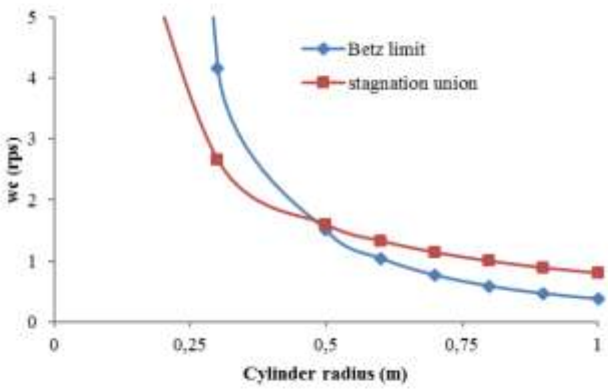

Fig. 8. Conditions for reaching the Betz limit and union of stagnation points at 5 m/s wind speed.

4. Conclusion

In the present study, initial analyses of a novel wind turbine and the derivation of the relevant formulae are done. This turbine utilizes the Magnus effect, and so, uses cylinders instead of streamlined blades. Detailed simulation and experimental studies are needed to better establish the performance parameters of this turbine and to reveal the structural challenges to realize it. At the first step, these turbines can enable high aerodynamic efficiency close to Betz limit even at low wind speeds while bringing in ease of manufacturing. For a sample case studied in this article, 24 – 35 % increase in power generation is estimated. Sizing studies of these turbines can provide designs that are suitable for small power generation units in urban settings, while commercial size turbines can still be deployed for high power generation demands. For better performance estimation of these turbines, better torque estimates need to be done for high Reynolds number settings. Solar power cells covering the surface of the rotating cylinders provide minor power, which can be utilized within the turbine itself to spin its cylinders. Thus, the net power output from the Magnus Effect wind turbine can be increased.

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