Wind power generator using horizontal axis wind turbine with convergent nozzle

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This paper introduces the wind power generator using horizontal axis wind turbine with convergent nozzle. This paper brings a detailed theoretical and practical study of air concentrating nozzle and the optimum nozzle dimensions have been analyzed in detail. Commercial CFD software which is used for the nozzle with different tapering angle has also been analyzed. The length of the nozzle was varied to study its effect on the increase of wind speed for constant inlet and outlet nozzle areas placed at different distances from the wind tunnel. The results of the new wind turbine performance characteristics using concentrating nozzles have also been outlined. We have practically deliberated and constructed a wind power generator, established on this nozzle duct furnished with the optimal nozzle.

Keywords: CFD software, Wind energy, Horizontal axis wind turbine, nozzle parameters, convergent nozzles, low wind speed.

Introduction

Wind energy is the non-depletable, non-polluting source of energy. In addition, due to concerns for environmental issues, the development of renewable and green energy is strongly expected. Among the sources, wind energy has developed swiftly, however in contrast with the overall demand for energy, the scale of wind power usage is minimal. Therefore, a new wind power system that generates higher power output even in regions where irregular and lower wind speeds patterns are expected is strongly preferred. The geometrical design of the rotor has progressed from the cylindrical type to be twisted, spiral and other shapes. Though the efficiency of energy transformation is low for conventional Savonius rotor, its high start-up torque and simple mechanical structure are two major beneficial factors that suggest a potential opportunity for this kind of rotor. Though wind power generation plays a vital role in the green power generation, it has disadvantages as its output is lower compared to thermal and nuclear power generation. Gilbert and Foreman*2 examined a diffuser-augmented wind turbine (DAWT) in which the power is augmented by focusing the wind energy using a diffuser. Diffuser-Augmented Wind Turbine is in fact a kind of Horizontal Axis Wind Turbine that has a shroud or duct wrapped around its rotor. The shroud is a conical structure with larger diameter in the downstream region when compared to the upstream one. Until recently the rotor was positioned near upstream of the shroud. A compact type brimmed diffuser has been developed for a small and mid-size wind turbines. A long diffuser with a large brim is highly modified and the combination of a diffuser shroud and a brim is obtained. Power augmentation of compact “wind-lens turbines” is 2–3 times as high as compared to a bare wind turbine. Boundary layer effects on the flow pattern inside and above a model wind farm is studied under thermally neutral conditions using wind-tunnel. To characterize the turbulent flow structure at different locations, cross-wire anemometry is used. Spalart-Allmaras turbulence model is used to simulate the turbulent flow features near the rotor blade. The torque coefficient of the rotor is fitting in terms of its magnitude and variation through the rotational cycle. Along the height of the rotor, distinct spatial turbulent flow patterns vary with the upstream air velocity.

The annular airfoil generates an inward radial lift force. This lift force is accompanied by a ring vortex which by the Biot-Savart law will induce a higher velocity on the suction side. In effect, this higher velocity increases the mass flow through the rotor plane. As noted by various scientists like Lewis*7 et al., the bound vorticity increases the effective area in front of the rotor and consequently the “swallowing” capacity of the complete system. The undisturbed free stream flow will in turn provide the extra momentum for the exhaust rotor wake.

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flow to recover from the velocity deficit caused by the energy extraction of the rotor. Another reason is that the mixing causes the wake to have an additional expansion and thus provide the rotor wake flow with more volume. More wake, volume for the same mass flow through the diffuser will result in lower exit pressures behind the rotor and therefore results in more suction. For normal wind turbines this mixing effect is rather small due to the tip vortices emanating from the blade tips. As noted by van Bussel, these tip vortices effectively act like roller bearings, preventing the outer flow from mixing with the wake flow. But another advantage of the DAWT configuration is that the tip vortices created at the blade tips are expected to be significantly less due to the close proximity of the diffuser wall. Therefore, the mixing potential behind the exit plane of a DAWT is expected to be higher than for a normal wind turbine.

Yu et al. performed an experimental investigation in which a single inverted delta tab was attached to the trailing edge, at an angle of 45 degrees pointing downstream, of a splitter plate in a two stream mixing layer. This configuration was found by Foss and Zaman in earlier research to be the most effective way of promoting mixing with delta tabs. Detailed flow measurements were performed with an X-hot-wire probe and various static pressure orifices in front of the delta tab. Analysis of turbulent flow was found in the delta tab that stream wise vortex formation and subsequent mixing effect were stronger and more intense when the tab was tilted into the high speed side. Yu et al., used a three component fiber optic laser-Doppler anemometer to investigate the flow and adopted the suggestion pioneered by earlier researchers to explain the mechanism behind these stream wise vortices emanating from the tab.

The concept behind the nozzle ducted wind turbines is to line up the flow of air. This often means optimal performance with simplicity in design and operation. Aerodynamic modeling is used to determine the optimum tower height, control systems, number of blades and blade shape. Because of the prompt progress in the aerodynamics, smaller and economic proposals are continually introduced and they frequently endure the common function to induce a greater velocity rather than more air flow, which results from the statistics that the dynamic energy of the wind is proportional to the cube of its velocity.

Hence, the main purpose of this paper is to reorganize the relation between duct shapes and wind velocities, and to organize the design parameters of duct geometries for the ultimate increase of velocity, and to promote the efficiency of ducted wind turbines. The design resulting at last will be practically tested to prove its efficiency.

Wind Nozzle Design

Our proposed method of improving turbine efficiency is to put a duct around the turbine, often termed as Nozzle Augmented Wind Turbine (NAWT), an improvement to the conventional open rotor Horizontal Axis Wind Turbine (HAWT). NAWTs employ a duct around the HAWT that decreases in the area as it extends after. The purpose is to increase the mass flow through the blades and hence increase the power extracted for a given rotor size. The Wind Nozzle concept is a ducted rotor design. In contrast to an open rotor, such as the Bergey Turbine the rotor is enclosed in a duct. The Wind Nozzle also utilizes an increased blade number and does not need an additional tail to keep it aligned into the wind.

The current configuration utilizes a nozzle to increase the power produced by an open rotor turbine. This concept combines several concepts into a functionally attractive design to eliminate the need for higher wind velocity and larger height. This design improves efficiency by accelerating the wind through turbine blades and carries more dynamic energy.

One such method of improving turbine efficiency is a nozzle augmented wind turbine (NAWT) as an improvement to the conventional horizontal axis wind turbine (HAWT). A nozzle augmented wind turbine (NAWT) has a bucket-shaped duct that surrounds the wind turbine blades and this enhances the turbine to run more efficiently than traditional open-bladed systems by extracting more energy from the wind.

In nozzle type arrangement the inlet diameter is larger than the outlet diameter; due to this the air velocity at the inlet is low. When it comes to the outlet, the velocity gets increased due to a reduction of area, at the same time air starts to flow in all directions. In order to bring the air in the horizontal direction cylinder is connected at the outlet side of the nozzle. So the air is concentrated to the narrow path of the cylinder with increased velocity.
In nozzle type wind turbines this principle is used to increase the wind velocity. From Figure 1 the velocity of air at the inlet is \( V_1 \). This wind is concentrated to the cylinder with a velocity of \( V_2 \). Due to the Bernoulli’s principle velocity of air at the cylinder is greater than the inlet velocity \( (V_1) \) by using nozzle type wind turbines. The diameter of the nozzle of its inlet is \( D_1 \); Diameter of the cylinder at its outlet is \( D_2 \). Tapering angle is denoted as \( \theta \). Length of the nozzle and the cylinder is \( L_N \) and \( L_C \).

In case of conventional wind mills, blades are directly driven by wind. When wind velocity decreases the blade speed also decreases. This decrease in the blade speed is insufficient to produce power but in nozzle type wind mills the velocity of the air is increased by the nozzle and it operates at low wind velocity also. So we can generate power even at low wind speed. This nozzle utilizes a decreased number of blades and does not need any tail to keep it aligned into the wind. Studies on NAWT show that a sucking effect can be produced according to the Bernoulli’s principle and this significantly increases the wind speed inside the duct and substantially enhances the efficiency of the wind turbine.

NAWT equipped with an aerodynamically designed nozzle demonstrated power augmentation for a given turbine diameter and wind speed by a factor of about 5–6 is compared to standard micro wind turbine. Our NAWT design is also safer due to the shroud with no lunar or solar flicker, blade/ice throw and is avoidable to birds and bats. Even more attractive is the potential for operational flexibility afforded by the nozzle, enabling the useful power generation at lower and higher wind velocities, and simpler control features.

**Analysis of nozzle velocity**

The relation between velocity and radius in free vortex is obtained by putting the value of external torque equal to zero or the time rate of change of angular momentum is moment of momentum must be zero. Consider air particle of mass ‘\( m \)’ at radial distance \( r \) from the axis of rotation having a tangential velocity \( V \). Then,

\[
\text{Time rate of change of angular momentum} = \frac{\partial (mVr)}{\partial t}
\]

Integrating we get

\[
mVr = \text{constant} \quad \text{or} \quad Vr = \frac{\text{cons} \tan \frac{r}{m}}{m} = \text{constant} \quad \ldots (1)
\]

**Equation of motion for vortex flow**

Consider a wind element ABCD shown in Figure 2 (shaded), rotating at a uniform velocity in a horizontal plane about an axis perpendicular to the plane of paper and passing through \( O \).

Let \( r \) = Radius of the element from \( O \)
\( \Delta \theta \) = Angle subtended by the element at \( O \)
\( \Delta r \) = Radial thickness of the element.
\( \Delta A \) = Area of cross section of element

The forces acting on the element are

(a) Pressure force, \( p\Delta A \), on the face AB.
(b) Pressure force, \( (p+\frac{\partial p}{\partial r}\Delta r)\Delta A \), on the face CD.
(c) Centrifugal force, \( \frac{mV^2}{r} \), acting in the direction away from the centre \( O \).

Centrifugal force = \( \rho \Delta A \Delta r \frac{V^2}{r} \)

Now, the mass of element = mass density \( \times \) volume
\[= \rho \times \Delta A \times \Delta r \]

Equating the forces in the radial direction, we get

\[(p+\frac{\partial p}{\partial r}\Delta r)\Delta A \rho \Delta A \Delta r = \rho \Delta A \Delta r \frac{V^2}{r} \]
Cancelling $\Delta r \times \Delta A$ from both sides, we get

$$\frac{\partial p}{\partial r} = \rho \frac{V^2}{r} \quad \ldots (2)$$

Equating (1) gives the pressure variation along the radial direction for a forced or free vortex flow in a horizontal plane. The expression $\frac{\partial p}{\partial r}$ is called pressure gradient in the radial direction. As $\frac{\partial p}{\partial r}$ is positive, hence pressure increase with the increase of radius ‘r’. The pressure ‘p’ varies with respect to r.

$$p = \rho \frac{V^2}{r} \frac{\partial r}{\partial r} \quad \ldots (3)$$

Consider two points 1 and 2 in the air (wind) having radius $r_1$ and $r_2$ from the central axial respectively as shown in Fig.2.

Integrating the above equation for the points 1 and 2, we get.

$$\int_{r_1}^{r_2} \frac{\partial p}{\partial r} = \int_{r_1}^{r_2} \frac{\rho c^2}{r^2} dr$$

$$\frac{p_2}{pg} + \frac{p_1}{pg} = \frac{V_1^2}{2g} + \frac{V_2^2}{2g} \quad \ldots (4)$$

Equation (4) is Bernoulli’s equation. Hence in case of free vortex flow Bernoulli’s equation is applicable in the nozzle velocity is increase in the pressure decrease.

**Design Analysis of Nozzle Using CFD**

The tapering angle plays a key role in determining the output wind velocity of nozzle. Hence it is important to choose this angle properly while designing the nozzle aerodynamically. With the help of the well-known CFD software FLUENT (by ANSYS) we analyzed various tapering angle and which has the maximum constant output velocity. The constant wind velocity of 27.309 m/s is obtained by the input wind velocity of 5 m/s when it is applied in the nozzle wind turbine with the taper angle of 38.66 degrees. Here the range of the output velocity is constant, and hence no oscillations are present and it is shown in Figures 3(a). The diameter of the front end of the cone is 2m. The diameter of the rear end of the hollow cylinder is 0.4m. The length of the hollow cylinder is 0.4m and that of the tapering length of the cone is 1m. The total length of the nozzle wind turbine with tapering angle 38.66 degrees is 1.4 m.

Combined with the wind turbine, the frame structure and the enhanced nozzle shape of the duct design, a model of the ducted wind turbine was designed and manufactured. This turbine consists of a rotating part, and the completed installation is tested for its practical use.

The crucial dimensions of the structure decided are as follows: the work consists of two diameters, the outlet small diameter is 0.4 meters and the inlet large diameter is 2 meters and the overall height is 3 meters. The ratio of the inner and outer diameter of the turbine has to be designed in the ratio of 5:1. We adopted turbulent wind powered permanent magnet synchronous motor for the experiment. The nozzle design is thus economically and dimensionally compromised due to machine capabilities and cost considerations. The nozzle shape is illustrated as in Figure 3(b), it is concluded that any new profile can be derived from scaling known optimal results. Despite the trivial difference between the experimental and typical designs.

The stationary part consists of the turbine, the nozzle and their supporting structure, while the rotary part includes a nozzle with a window and a set of rollers providing the rotating abilities for the nozzle to orientate its inlet toward the wind. All the features mentioned above tie as the final design of the nozzle wind turbine, a corresponding CFD model in FLUENT was established to verify the final design. Due to the manufacturing limitations, the wind speed is increased by a factor of 0.95 rather than 1.6 of the optimal nozzle in Figure 3 (b). The vibrant energy of the passing airflow is raised by 5 times with respect to input velocity and it should also be noticed that the outer halves of the blades divert most of the dynamic energy.

Since the final design of the nozzle duct is verified, the detailed mechanisms are designed and assembled in the CFD Fluent software and the whole installation is realistically set up as shown in Figure 3 (b).

**Testing of Nozzle Augmented Windmill**

The nozzle augmented windmill which we designed and implemented is tested for the analysis of the speed (rpm) versus wind velocity (m/s) in our laboratory with the help of blower fans. Table 1 shows the characteristics of the nozzle augmented wind turbine, that wind velocity is directly proportional to the speed of the rotor. The change in
wind velocity directly affects the speed of the rotor. A set of readings is taken comparing the output wind velocity of the windmill and speed of the rotor.

The voltage generated by the nozzle augmented wind turbine for various rotor speeds shown in Table 2. The output wind power obtained from nozzle type wind turbine is compares with the wind power obtained from open type model no: bsl-yz-500W. The comparison is literally discussed in the figurative illustration is shown in Figure 4. The illustration clearly explains the efficient, increase in output wind power with the increase in velocity. The comparison shows that there is a 40% increase in output power in nozzle type proportionately when compared to open type.
Conclusion
The Nozzle Augmented system has been reported to have a greater efficiency than the HAWTs based on the structural design. The above illustrated graphs show the performance of the nozzle augmented wind turbine for various wind velocity and its power generation capacity. Thus, it is clear from the results and discussion that the proposed system can generate more power at the lower wind velocity than the conventional horizontal axis wind turbine.

In this nozzle augmented system the length of the blades are made shorter and the nozzle is made up of mild steel because of cost considerations. In nozzle augmented system, the output power depends upon the tapering angle of the nozzle and the wind flow at the inlet. Hence, if it is possible to determine more accurate tapering angle and if the nozzle is designed for a larger diameter it is possible to generate more power. The nozzle augmented system works effectively where the wind velocity is even. In future with the help of large nozzle and standard ratings of alternator the nozzle augmented system can be mounted to generate more power than the conventional systems.

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