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VERTICAL AXIS WIND TURBINES (VAWT) AND COMPUTATINAL FLUID DYNAMICS (CFD): A REVIEW

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Abstract: The use of renewable energies has been raised, over all with the big machines in wind farms. However a small wind turbine market still has the gap. The small VAWT study aims at fulfilling this gap by developing turbines with the ranges between 300W to 500W. These characteristics permit to take advantage of wind in the regions where it has low speed and high turbulence. To analyze the effectiveness of a VAWT, methods of computational fluid dynamics (CFD) are used to simulate various airflows and directions. CFD can be used to numerically predict wind turbine performance which offers a tremendous benefit over a classic experimental technique.

Keywords: tip speed ratio, coefficient of performance, rotor solidity, wind power, turbine power.

I. INTRODUCTION

With an ever increasing energy crisis occurring in the world it will be important to investigate alternative methods of generating power in ways different than, fossil fuels. In fact, one of the biggest sources of energy is all around us all of the time, the wind. It can be harnessed not only by big corporations but by individuals using Vertical Axis Wind Turbines (VAWT). VAWT's offer similar efficiencies as compared with the horizontal axis wind turbines (HAWT) and in fact have several distinct advantages.

Perhaps the most popular type of wind turbine is termed a horizontal axis wind turbine. In horizontal axis wind turbines, a large and heavy nacelle is mounted on the upper end of a robust tower which must have sufficient strength to withstand wind forces, rotational torque as well as being robust enough to support the weight of the generator and electrical equipment associated therewith. A horizontally disposed drive shaft extends from the nacelle and usually has three rotor blades secured thereto. Horizontal axis wind turbines have traditionally been utilized to harness wind energy, but they suffer from drawbacks. For example, current horizontal axis wind turbines have low efficiency due to large gears and transmissions. Parasitic power is consumed by the constant reorientation of the blades into the wind stream. Horizontal axis wind turbines are unable to harness turbulent winds, and are susceptible to damage in high winds

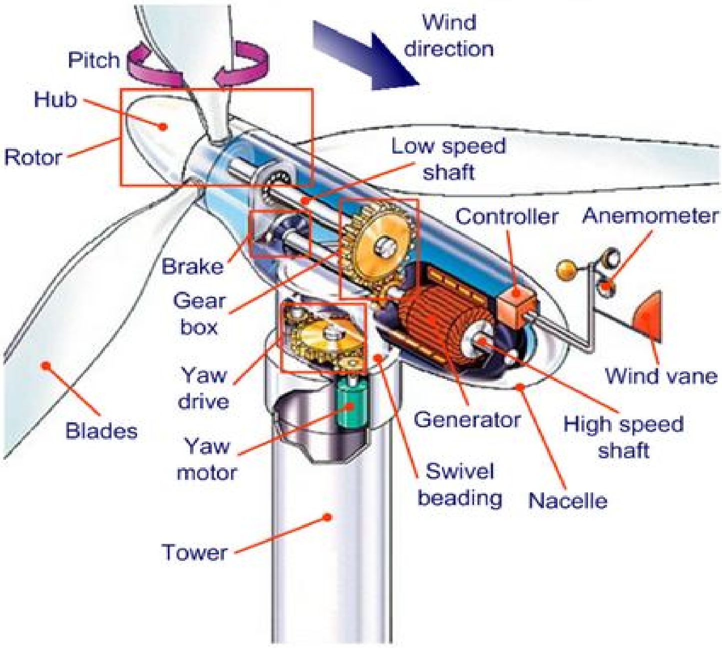

Fig. Horizontal axis wind turbine

In the vertical axis wind turbines, a vertically disposed blades are attached to a vertically disposed drive shaft which is operatively coupled to a generator and associated with electrical equipment with the generator and associated electrical equipment usually being located on the ground near the wind turbine

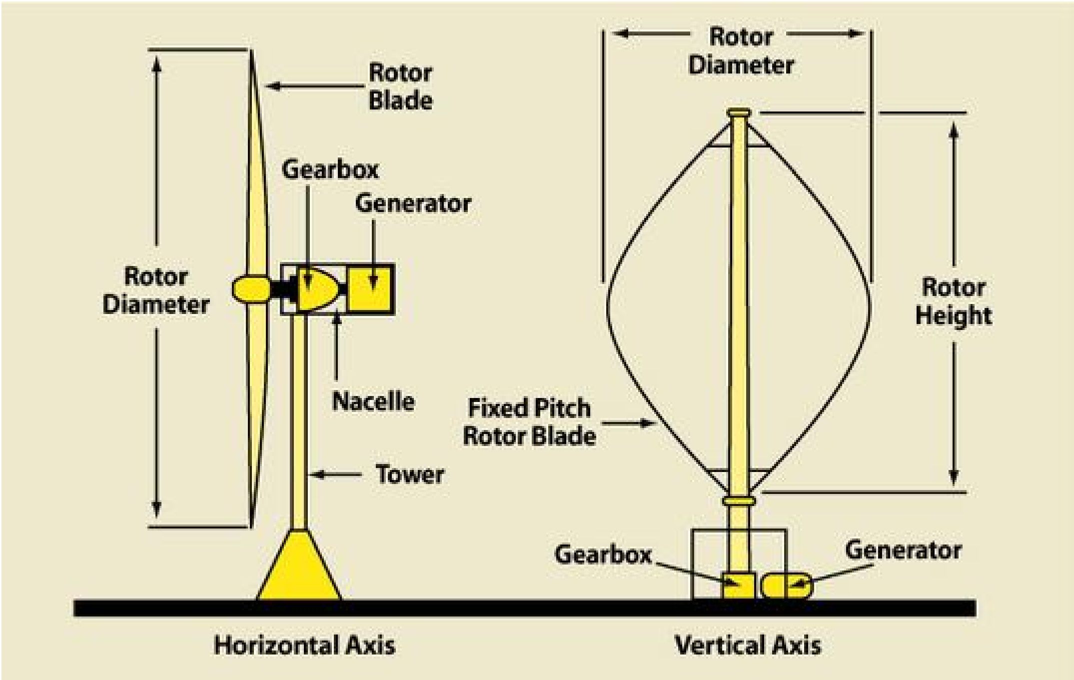

Fig. Horizontal axis and vertical axis wind turbine

Writer believes that vertical axis wind turbines are less expensive for a given power output than horizontal axis wind turbines for several reasons. First, the blades of a vertical axis wind turbine will be less expensive to fabricate than the blades of a horizontal axis wind turbine since the blades of the vertical axis turbine are of a uniform cross-section from end- to-end are not tapered and are not twisted. The blades of a vertical axis wind turbine are also less expensive than the blades of a horizontal axis wind turbine since they can be made much lighter since they can be supported at both ends thereof.

Additional the blades of a vertical axis wind turbine will produce more power than the blades of a horizontal axis wind turbine since the entire length of the blades of the vertical axis wind turbine move at the maximum and uniform velocity through the air and since each blade crosses the wind path twice per revolution.

The tower of a vertical axis wind turbine is also less expensive than the tower of a horizontal axis wind turbine. Since the blades of a vertical axis turbine are never close to the tower. The lower can be supported with guy wires resulting in much lighter construction of the tower. The tower of a vertical axis wind turbine is never subject to a bending moment due to the gyroscopic reaction of turning a rotating mass (the blades) to follow a changing wind direction which is required in horizontal axis wind turbines. The tower of a vertical axis wind turbine is also less expensive than the tower of a horizontal axis wind turbine since the tower does not have to support the weight of complex and heavy generation equipment at the upper end thereof. Further, the tower of a vertical axis wind turbine does not require any nacelle support or yaw drive. In a vertical axis wind turbine, the generator and electrical equipment therefore is located at ground level and since the diameter of the generator is not restrained. The use of a large diameter slow-speed generator will eliminate the need for speed increased gearing.

II. LITERATURE SURVEY

Abdulkadir Ali et al studied the VAWT configuration for two different set of blades (steel made and cardboard made) using partially and fully cowled configuration this analysis resulted in high rotational motion for the partially cowled configuration of the of cardboard made turbine this also resulted in heavier the turbine higher the wind speed will required to generate the rotational motion, the lighter turbine resulted a better performance at all the speeds.

W. T. Chang et al. introduced a innovative devise called as Omni-Directional –Guide-Vane (ODGV) integrated with VAWT ODGV effectively improved the self-starting behavior of the VAWT. At 6 m/s, the rotor rotational speed was increased by 182% at free-running condition and the power output at maximum torque was 3.48 times higher for the ODGV integrated VAWT compared to the bare VAWT.

Huimin Wang et al. studied the two dimensional model of the vertical axis wind turbine two dimensional unsteady flow field was simulated numerically by him at different wind velocity. The analysis resulted in the velocity in the region of wind turbines rotation was much larger than the air flow of the upstream. There is a wake dispersion region in the downstream of the wind turbine, and the length of the wake dispersion region was increased with the increase of the wind velocity, the eddy is much larger in the upper blade's back of the wind turbines rotational part, while eddy is less in the lower blade's back of the wind turbines rotational part. Eddy also exists in the downstream region of the wind turbines rotational part, and the larger velocity of inlet wind, the larger eddy of the downstream flow field. At the same rotational speed, the condition of lower wind velocity has larger total torque coefficient. With the increase of the wind velocity, the variation of the wind turbines total torque coefficient tends to smooth.

Carrigan et al. successfully demonstrated a fully automated process for optimizing the airfoil cross-section of a VAWT. The generation of NACA airfoil geometries, hybrid mesh generation, and unsteady CFD were coupled with the DE algorithm subject to tip speed ratio, solidity, and blade profile design constraints. The optimization system was then used to obtain an optimized blade cross-section for 2 test cases, resulting in designs that achieved higher efficiency than the baseline geometry. The optimized design for the 1st test case achieved efficiency 2.4% higher than the baseline geometry. The increase in efficiency of the optimized geometry was attributed to the elimination of a leading edge separation bubble that was causing a reduction in efficiency and an increase in cyclic loading. For the 2nd test case, the VAWT was given complete geometric flexibility as both the blade shape and rotor solidity was allowed to change during the optimization process. This resulted in a geometry that achieved efficiency 6% higher than the baseline NACA 0015 geometry. This increase in efficiency was a result of the 40% decrease in solidity coupled with the 58% increase in thickness, leading to a slight phase shift in the torque and higher overall peak performance.

S.McTavish et al conducted an assessment of the performance of a novel vertical axis wind turbine using RANS CFD simulations. Steady and rotating validation studies were conducted using experimental data for a Savonius rotor. The static and dynamic torque curves for the Savonius rotor were well characterized. Steady two dimensional CFD simulations were conducted and it was determined that the Aeolun Harvester produces a comparable amount of static torque to existing Savonius rotors. Rotating three dimensional CFD simulations demonstrated that the average dynamic torque generated by this new rotor decays more rapidly with increasing tip speed ratio than the torque output of existing Savonius rotors. Pressure coefficient contours and the local torque coefficient indicate that this rapid decay in torque with increasing tip speed ratio occurs due to stagnation effects acting on the convex side of the outer wall as the blade is retreating. These stagnation effects increase with increasing tip speed ratio and have similar characteristics to the torque production mechanisms observed on Savonius rotors. The verification, validation, and prediction presented in this work demonstrated the applicability of RANS in the development of vertical axis wind turbines. The results of the study, however, have shown that the shape of the inner and outer rotor walls should be the focus of future work as a means to increase the torque generated by the rotor to render it more competitive with existing designs

III. COMPUTATIONAL STUDY

A. Computational Modeling:

The majority of wind turbine research is focused on accurately predicting efficiency. Various computational models exist, each with their own strengths and weaknesses that attempt to accurately predict the performance of a wind turbine. Descriptions of the general set of equations that the methods solve can be found in next chapter. Being able to numerically predict wind turbine performance offers a tremendous benefit over classic experimental techniques, the major benefit being that computational studies are more economical than costly experiments. While other approaches have been published, the three major models include momentum models, vortex models, and computational fluid dynamics (CFD) models. Each of the three models are based on the simple idea of being able to determine the relative velocity and, in turn, the tangential force component of the individual blades at various azimuthal locations

B. Computational Fluid Dynamics.

Due to its flexibility, CFD has been gaining popularity for analyzing the complex; unsteady aerodynamics involved in the study of wind turbines and has demonstrated an ability to generate results that compare favorably with experimental data. Unlike other models, CFD has shown no problems predicting the performance of either high- or low-solidity wind turbines or for various tip speed ratios. However, it is important to note that predicting the performance of a wind turbine using CFD typically requires large computational domains with sliding interfaces and additional turbulence modeling to capture unsteady affects; therefore, CFD can be computationally expensive.

C. Grid Generation.

After the geometry for the VAWT had been defined, the next step is to discretize the computational domain as a preprocessing step in the CFD process. The act of discretizing the domain is termed grid generation and is one of the most important steps in the CFD process. For simple geometries where the direction of the flow is known beforehand, creating the grid is usually straightforward. For flows such as this, high quality structured grids can be used that can accurately capture the flow physics. However, as geometry becomes complex and the flows more difficult to predict with the onset of turbulence and separation, grid generation is no longer a trivial task.

D. Control Equation

As the wind turbines Mach number at work is typically less than 0.3, so the flow around the airfoil could be considered as incompressible flow, the two dimensional incompressible N-S equations and two dimensional continuity equation are used as the control equations.

The two dimensional incompressible N-S equation is expressed in vector as follows:

$$\rho \frac{DV}{Dt} = \rho f - \nabla p + \mu \nabla^2 V$$

Where **V** is the velocity vector, **f** is the volume force vector, μ is the dynamic viscosity.

The continuity equation is showed as follows:

$$\nabla . V = o$$

Compared with the conventional k-ε turbulence model, the content on rotation and curvature is added to the Realizable k-ε model for the calculation of turbulence dynamic viscosity, and the equation of the dissipation rate ε is amended. Therefore, the model been shown that could simulate the flow around a blunt body effectively. Reynolds averaged equations and continuity equations are showed as follows:

$$\frac{\partial \vec{u}_i}{\partial t} + \vec{u}_i \frac{\partial \vec{u}_i}{\partial x_i} = -\frac{\partial \vec{p}}{\partial x_i} + \frac{\partial}{\partial x_j}[v \frac{\partial \vec{u}_i}{\partial x_j} - \rho \overline{u_i u_j}]$$

$$\frac{\partial \vec{u_i}}{\partial x_i} = 0$$

The mode equations of the turbulent kinetic energy k and turbulent kinetic energy dissipation rate ε are:

$$\frac{\partial k}{\partial t} + \vec{u_i} \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_i}\left[\left(v + \frac{v_t}{\sigma_t}\right)\frac{\partial k}{\partial x_j}\right] + \left(\frac{\partial \vec{u_i}}{\partial x_j} + \frac{\partial \vec{u_j}}{\partial x_j}\right)\frac{\partial u_i}{\partial x_j} - \varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho \vec{u_i} \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(v + \frac{v_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + c_1 \rho S \varepsilon - c_2 \rho \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}}$$

Realizable k –ε model has been widely used in various types of flow simulation, which includes

Rotational average shear flow, free flow including jet and mixed flow, flow in pipes, boundary layer flow and backward-facing step flow, the result is consistent with the experimental data.

IV. FUNDAMENTALS AND TERMINOLOGY FOR WIND TURBINE:

A. Wind Power:

The Earth is unevenly heated by the sun, such that the poles receive less energy from the sun than the equator; along with this, dry land heats up and cools down more quickly than the seas do. The differential heating drives a global atmospheric convection system reaching from the Earth's surface to the stratosphere which acts as a virtual ceiling. Most of the energy stored in these wind movements can be found at high altitudes where continuous wind speeds of over 160 km/hr (99 mph) occur. Eventually, the wind energy is converted through friction into diffuse heat throughout the Earth's surface and the atmosphere.

The power contained in a freely flowing wind stream of cross sectional area A (swept area) can be expressed as

Power = (Volumetric flow rate) x (Kinetic energy per unit volume)

P_{wind} = (A V) x (0.5 ρV^2)
= 0.5 ρ A V^3
= 0.5 ṁ V^2

Where, V is the wind speed
ρ is the air density
ṁ is the mass flow rate of wind

Assuming air to be a stable mixture of perfect gases, the air density ρ can be derived from Perfect gas equation as under:

PV = ṁRT
ṁ / V = P/RT
ρ = P/ RT

Where P is the absolute pressure in N/m^2
T is the absolute temperature in K and
R is the gas constant for dry air = 287.1 J/kg K

Strictly speaking, R should be gas constant for moist air, which will vary depending upon the moisture content of the air. The use of gas constant for dry air introduces negligible error in calculations and is a standard practice for computation of air density.

A. **Coefficient of Performance:**

Coefficient of Performance is defined as the ratio of power extracted by a wind turbine to the total power available in the cross sectional area of the wind stream subtended by the wind turbine. It is generally denoted by CP and mathematically, expressed as under:

$C_P = P_{turbine} / P_{wind}$

Therefore, power extracted by a wind turbine can be expressed as

$P_{turbine} = 0.5\, C_P\, \rho\, A\, V^3$

Where A is the swept area of the rotor and
V is the speed of freely flowing wind stream.

B. Tip Speed Ratio:

It is defined as the ratio of tangential or peripheral linear speed at the tip of the blade to the free flowing wind speed. It is usually denoted by λ and is mathematically expressed as under:

$\lambda = \omega r / V$

Where ω is the angular speed of the rotor;
r is the radius of rotor and
V is the speed of free flowing wind stream

C. Rotor Solidity:

Rotor solidity, usually denoted by S, is defined as the ratio of the projected area of a rotor to its swept area.

S = Projected area of rotor / swept area of the rotor

A rotor with a high value of solidity ratio has usually high starting torque but low rotational speed. On the other hand, a rotor with low solidity has high operating speeds making it suitable to be coupled with an alternator for generation of electricity.

V. SUMMARY:

Vertical axis wind turbines (VAWT's) while starting from an inferior position due to lack development over last two decades, do have significant advantages over Horizontal axis wind turbines (HAWT's).

Small scale Vertical axis wind turbines (VAWT) show potential for urban rooftop installation where they can capture the highly unstable turbulent wind flow patterns which are typical in urban environment. Being axis symmetric they are omnidirectional turbines which respond well to changes in wind directions.

For accurately predicting the performance of a vertical axis wind turbine(VAWT) various computational models can be used that can numerically predict the wind turbine performance and offers a tremendous benefit over classic experimental technique.

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