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Increasing Wind Turbine Efficiency by Reducing Tower Shadow Effect and Scouring Effect

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Abstract

This work is intend to minimize the tower impact on the turbine blade aerodynamics, structural behavior and the oscillating nature of the frequency so called tower "shadow effect". A horizontal axis wind turbine always has some form tower support structure, either lattice or tubular structure. Smaller machines tend to be supported on lattice structure whereas larger once use cylindrical tubes, made of either steel or concrete. Both the type of structure offers resistance to the flow causing velocity and pressure fluctuations in the near vicinity of tower and this fluctuation is pronounced to certain region called wake region.

The pressure and velocity deficit, unsteady vortex shedding causes 3p fluctuation or flicker effect and deteriorate power quality in connected power networks. Moreover, this causes a fatigue loading on the blades. Thus an attempt is made to minimize the turbine blade interaction with the wake region. CFD is found to be good technology that can be utilized to analyses and optimize such a kind of complex problems. Having greater amount of advantages over proto based experimental techniques; CFD is applied to understand the intricate insight of the problem.

Keywords: Tower shadow effect, scouring effect, wake region, turbulence.

Introduction

There is a continuous decline of availability nonrenewable sources such as coal on which world electrical power production rely on. But the demand for electrical power increases very drastically. This leads to the utilization of renewable sources on a large scale wind power among others. Percentage of electrical power generated or wind plants is rapidly growing every year all over the world and thus the impact of such plants on the power grid is becoming increasingly important. The connection of the wind turbines on the distribution network may affect grid power quality. This is the reason why so much attention has recently been paid to the issues associated with operation. One of the most important problems in the construction of wind turbine is its tower itself.

Every wind turbine is mounted on a supporting structure. The structure may be circular, mono pile or a complicated truss work called lattice structure. These structures resist the fluid movements in the upwind direction causes a flow separation and unsteady vortex filled wake region behind the tower. This causes the turbine blade to undergo a fluctuating wind load, which is dynamic and called tower shadow effect. This causes quick changes of mechanical power called 3p-frequency in the case of 3 blade turbine, contribute power loss, flicker effect, dynamic loading on the structures of wind turbine blades.

In this project a novel approach is taken to minimize the wake region thus by delaying the flow separation.

CFD has lot of advantages such as reducing the cost and time span involved in design phase. Having advantages such as insight, foresight, impends to replace the proto based experimental techniques very soon. CFD is utilized in this project to understand the flow nature and to compare the modifications.

A Brief History Of The Development Of Wind Energy

Since antiquity, mankind has been using wind energy; it is thus not a new idea. For centuries, windmills and watermills were the only source of

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motive power for a number of mechanical applications, some of which are even still used today. Humans have been using wind energy in their daily work for some 4,000 years. Sails revolutionized seafaring, which no longer had to make do with muscle power. In 1700 B.C., King Hammurabi of Babylon used wind powered scoops to irrigate Mesopotamia. Aside from pumps for irrigation or drainage, windmills were mostly used to ground grain. Thus, we still speak of "windmills" today, even when we are talking about machines that do not actually grind, such as sawmills and hammer mills.

But the wind turbines that generate electricity today are new and innovative. Their success story began with a few technical innovations, such as the use of synthetics to make rotor blades. Developments in the field of aerodynamics, mechanical/electrical engineering, control technology, and electronics provide the technical basis for wind turbines commonly used today. Since 1980, wind turbines have been becoming larger and more efficient at rates otherwise only seen in computer technology.

The Physics of Wind Energy

A wind turbine or wind power plant is a device that converts kinetic energy from the wind into electric current. Mechanical energy is simply created when the wind turbine blades spin and a generator is turned, thus producing electricity.

The Aerodynamics of Wind Turbines

The power coefficient of a wind turbine's rotor blade is calculated according to the laws of air foil theory. As with the wing of an airplane, air passing over a rotor blade creates an aerodynamic profile with low pressure above the wing, pulling the wing up, and overpressure below, pushing it up.

The difference in pressures exerts a lift on the wing vertical to the direction in which the wind is blowing and creates resistance in the direction of the wind (incident flow). For a wind turbine's rotor blade rotating around the rotor axis, the incident flow is the result of the geometric addition of wind velocity v and the circumferential speed u, which increases in linear fashion the longer the blade is. In other words, the lift exerted on the rotor blade is not only the result of wind velocity, but mostly out of the blade's own rotation.

Speeds at the tip of the blade are thus very great. Current wind turbines have rotor tips travelling at velocities six times faster than the speed of the wind. The tip speed ratio is thus lambda = 6. The rotor tip can then be travelling at velocities of 60 m/s to 80 m/s.

The energy that the rotor harvests is equivalent to the lifting force in the swept area minus the resistance force in the swept area. The forces applied in the direction of the axis drive the rotor, which then not only harvests the energy of the wind, but also exerts a load on the tower and the foundation.

Controlled Power: Nominal Capacity And Control

If we speak of a 1.5 megawatt wind turbine, we are describing the generator's maximum output -- its nominal capacity. 1.5 megawatts is equivalent to 1500 kW or 2,039 horsepower. The turbine generates that much power at a specific wind velocity. This nominal wind velocity is generally between 11 and 15 m/s (equivalent to 40-54 km/h).

Wind turbines begin generating power at the cut-on speed of around 2.5-4 m/s and cut off at wind velocity of 25-34 m/s. Modern control technology is used when wind turbines are connected to the grid to ensure a “soft”, gradual transition. If the wind is too strong, output is reduced to ensure that a constant level of power is fed to the grid. Modern turbines also switch off slowly during storms to prevent power output from disappearing suddenly. This gradual transition helps prevent disturbances in transit grids.

Types of Wind Turbines

Wind turbines can be separated into two types based by the axis in which the turbine rotates. Turbines that rotate around a horizontal axis are more common (HAWT). Vertical-axis turbines are less frequently used (VAWT).

Types of Towers

- Guyed wind tower
- Lattice tower
- Tubular Tower
- Tilt up wind towers

Computational Fluid Dynamics

Computational fluid dynamics (CFD) is the science of predicting fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena by solving the mathematical equations which govern these processes using a numerical process.

Governing Equations of CFD

Applying the fundamental laws of mechanics to a fluid gives the governing equations

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for that fluid. The conservation of mass equation and the conservation of momentum equation are combined along with the conservation of energy equation to form a set of coupled, nonlinear partial differential equations. It is not possible to solve these equations analytically for most engineering problems. However, it is possible to obtain approximate computer-based solutions to the governing equations for a variety of engineering problems. This is the subject matter of Computational Fluid Dynamics (CFD).

Conservation of mass:

Rate of increase of mass in fluid element equals the net rate of mass flow into the element.

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

For incompressible fluid flow…,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

Conservation of momentum:

Momentum is conserved in x, y, z direction & from the Newton's second law (F=ma) the momentum equations in all three direction is derived as,

$$\frac{\partial(\rho u)}{\partial t}+\nabla\cdot(\rho u\mathbf{V})=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+\rho f_x$$

Conserved in X direction

$$\frac{\partial(\rho v)}{\partial t}+\nabla\cdot(\rho v\mathbf{V})=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+\rho f_y$$

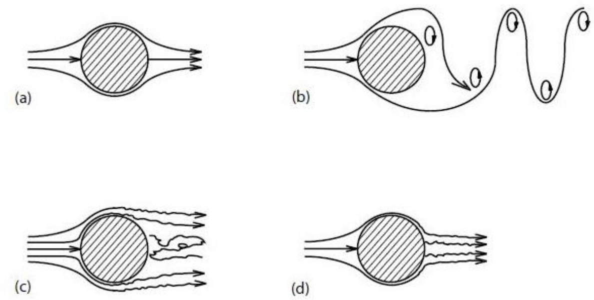
Conserved in Y direction

$$\frac{\partial(\rho w)}{\partial t}+\nabla\cdot(\rho w\mathbf{V})=-\frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+\rho f_z$$

Conserved in Z direction

Numerical Modelling of Tower Shadow

Turbulence contributes highly to the fatigue loading of wind turbines, and in real life it is present nearly everywhere. Turbulence is hard to predict with its' random, irregular and chaotic rotations originating from surface friction, temperature differences and mixing of fluid flows to mention some. In a lot of experiments he flow is kept laminar to isolate the phenomena of interest. For the purity of the experiment this is ok, but the behavior of the flow will often differ when it is changed into a turbulent flow. In the following, turbulence will be discussed in the context of flow around a circular cylinder (wind turbine tower). For cylinders placed in a fluid flow, the separation point will shift downstream the cylinder wall giving different wake behavior as the flow changes from laminar to turbulent.



(a) attached laminar flow, (b) laminar vortex street, (c) turbulent boundary layer, and (d) turbulent boundary layer with late separation

Observations

Two types of HAWT model has been considered for CFD analysis to study the tower shadow effect as shown below.

1) HAWT with tower
2) HAWT without tower

Power Calculation From The Simulation

	Torque (n-m)	**Power (KW)**
With tower	**62508.717**	**163.647**
Without tower	**104812.21**	**274.397**

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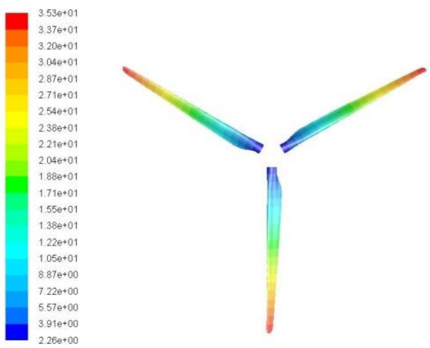
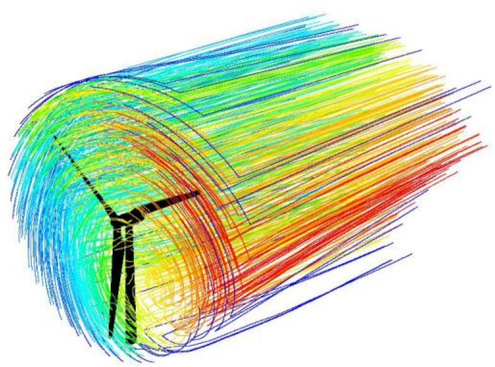
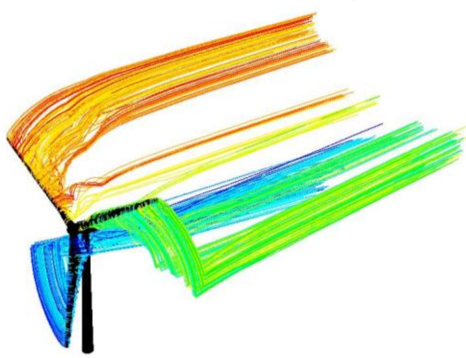
HAWT 3d view(FIGURE-1)



Velocity magnitude m/s(FIGURE-2)



Wind flow around the turbine blades(FIGURE-3)



Wind flow near individual blades(FIGURE-4)

Conclusion

The study is attempted to understand the underlying physics behind tower shadow effect. The torque indicates the loss in power due to wind shadow effect is considerably large. Though this cannot be completely removed as any wind turbine needs a support without which it is almost impossible to work, it may be hoped the shadow effect can be reduced to some extent. The effect of tower on the wind energy generated can be seen as velocity deficit caused by tower in near vicinity of the tower and in the form of wake region. The difference of undisturbed and disturbed wind velocity without tower and the one with it causes this undesirable energy loss. Delaying earlier separation reduces the extent of wake region and this can be achieved by stream lining the tower. This still has some amount of difficulty in it in various aspects and this forms the scope of the future work.

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