Next Generation Wind Turbines- Changing the view of Wind

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Abstract: In the last decade, there has been an increased focus on moving away from fossil fuels for energy needs and adopting renewable energy sources. More than a century of innovations in wind turbines has brought wind power generation costs at level with fossil fuels. From the period 2004 to 2013, the total installed capacity of wind power stations across the world went up from 48GW to 318GW, an increase of more than 550% (REN21). Having grown in leaps and bounds in the last decade, wind power seems to be our best bet to meet the energy demands of the future. This paper examines key innovations in this field that will feature in the next generation turbines and drive wind power into the future.

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1. Introduction

The last few decade have witnessed a rapid advancement of renewable energy technology due to factors like the gradual depletion of coal and oil, the impending fears of climate change and the role of fossil fuels in exacerbating the situation. As a result of these, across the planet, there is an increased focus on moving away from fossil fuels for energy needs and adopting renewable energy sources. The United Nations Framework Convention on Climate Change, which started in 1992 and most recently the Paris Agreement of 2015 are notable drivers in this realignment (UNFCCC).

Amongst all renewable energy technologies, wind power presents the most compelling case for capital and intellectual investment. Wind power systems involve many more technological factors than other systems which opens up the scope for innovation to increase efficiencies. In the last decade alone, wind turbine technology has become far more efficient, quiet, and sophisticated cutting down costs by nearly 80% (NCWE). From the period 2004 to 2013, the total installed capacity of wind power stations across the world went up from 48GW to 318GW, an increase of more than 550% (REN21). Moreover, with almost 125 years of contributions from inventive minds, wind technology is now in an advanced state of maturity and commercialization, making it our best bet for the immediate future.

2. Wind Energy overview and current status

Modern wind power systems incorporate large scale wind turbines that have a primary purpose of 'feeding the grid', featuring blade lengths up to 150ft and towers upto 200ft high. A typical wind system generates enough to electrify an entire municipality of 500-600 average homes. A wind farm is a group of wind turbines in the same location used to produce electricity. A large wind farm may consist of several hundred individual wind turbines and cover an extended area of hundreds of square miles. For a typical wind turbine, an estimation of the electrical power generated (P_e) can be arrived at using the following equation:

$$P_e = \left(C_r C_t C_g\right)\frac{\rho A v^3}{2}$$

where A = swept area of turbine blades, in m^2

ρ = air density, in kg/m^3
v = wind speed, in m/s
C_r = efficiency of the rotor system (between 0 and 1)

C_t = efficiency of the transmission (between 0 and 1), and

C_g = efficiency of the electrical generator (between 0 and 1)

A single turbine with blades of length 150 ft (45.72 m) will sweep an area A equal to 6566.93 m^2. Using typical values of ρ (=1.225 kg/m^3), typical wind speed at a suitable wind farm site (estimated 15 m/s) and a typical overall efficiency, i.e. $C_{total}(= C_r C_t C_g)$ of the system to be 0.4, the electrical power generated (P_e) calculates to be 5.43 MW. This is an indicative figure and useful only as an estimate, but this simplified mathematical model reveals the order of power available from a single wind turbine. Another fact revealed by the model is that, all other factors remaining constant, the output power has a cubic dependence on the wind speed. This is interesting and is very useful in site selection for wind farms. A location where wind speeds differ by only 10% will have a wind power potential difference of almost 33%. This makes wind speed measurements an important consideration in wind turbine design. This essay shall explore the importance of wind speed measurements in a later section.

In the basic layout of a typical wind turbine, there is a wind capture device consisting of blades, mounted either on a vertical shaft (called Vertical Axis Wind Turbines) or a horizontal shaft (in case of Horizontal Axis Wind Turbines). Oncoming wind pushes against the aerodynamically shaped blades and creates lift on individual blades, which are coupled in such a way so as to produce rotation of the shaft on its primary axis. The other end of this shaft is connected to an electric generator that converts the rotation of the shaft to electrical energy by virtue of electromagnetic induction. There is a braking system that can be invoked in extreme conditions and prevent over speeding of the turbine. There is a control and monitoring system, typically in the form of electronic circuits and computer interfaces to operate the turbine. All the systems are housed in a nacelle. The nacelle and the blades are mounted on a tower, typically a rigid structure which provides stability to the system and can be moved to re-orient the turbine towards wind direction.

3. The future of wind turbines

The challenge in wind power generation has always been to build systems that are cost-effective, durable and efficient. The conventional approach to tackle this challenge is to improve productivity of the wind turbine itself. This entails increasing the output by making larger scale turbines that generate more power and optimising the aerodynamic design of blades, electrical design of generators and other components to reduce energy losses and increase the efficiency of power conversion. These rely heavily on advances in other technological fields, such as material science, manufacturing technology, transportation, construction, etc.

The other approach to this challenge involves innovative thinking and design optimisation of the wind power generation system as a whole, such as improving configuration and layouts of wind farms to increase wind harvest, optimising site selection, and tackling problems of intermittency. A lot of these efforts rely on improvements in control systems using advanced methods of data capturing and data modelling and improved prognosis and health monitoring. With the advent of big data in the recent decades, novel approaches have appeared which would drive this technology into the future.

The following sections shall provide an illustration of both of these approaches and demonstrate how the wind turbines of tomorrow will be better poised to completely replace fossil fuelled power plants.

Magnification of Turbine Size – Longer Blades and Taller Towers.

The longer a turbine's blades, the more wind it captures and the more electricity it creates. However, a longer blade need to be stiffer in order to bear not only its own structural load but also the very large aerodynamic loads that occur during operations. This constraint presents a trade-off that is now being tackled. Sandia National Laboratories is currently leading the development of Segmented Ultralight Morphing Rotor (SUMR) that features a longer, segmented blade capable of morphing its shape, or bending, to reduce the aerodynamic load on the blade (Ichter et. al., 2012). In high winds, the SUMR blades morph their shape to align with the wind direction making them less vulnerable to damage. In low winds, the blades fan out for maximum wind energy. This design reduces peak stress and fatigue on longer rotor blades and makes their deployment structurally feasible. The proposed blades would be longer than 650 ft and capable of generating at least 50-MW power. In comparison with the largest blades currently operationalised, the Vestas 164 (generating 8MW with 260ft long blades), this is 2.5X longer and has 6X more output.

To make longer blades, GE has come up with a new lightweight blade design by wrapping very strong architectural fabric around a metal space frame. From a materials standpoint, GE is replacing the traditionally fiberglass with light and stiff carbon-fibre in the construction of blades, so they lose pounds and gain strength – this would enable much bigger blades (Wood, K.).

Another major issue with deploying longer blades is to have taller towers necessary to erect them. Traditionally, steel sheets are used to erect the towers. These are shipped over land to the wind plant site. For larger towers, this would pose logistical issues, increasing costs and sometimes infeasible, if the shipping route passes under bridges. To tackle this, the National Renewable Energy Laboratory (NREL) of the United States has pioneered a spiral welding process to build taller steel towers onsite itself, using steel pipes which are easier to transport (Cortell et al., 2014). Another approach is to use corrugated steel segments to assemble towers onsite - which would require up to 30 percent less metal. An alternative approach draws from the construction industry and proposes the use of concrete to build the tower. Due to easy transportation of raw materials to the plant, concrete towers can be erected onsite from scratch.

4. Design optimisations in wind turbine components

The wind that hits the blade hub is wasted, but GE is developing a turbine that features a dome at the hub. This ecoROTR turbine, instead deflects the hub wind out to the blades. Although the performance increase is only 3 percent, but on the scale of a wind farm with hundreds of turbines, this adds up to a significantly larger installed capacity (GE Reports, 2015).

NREL has led the development of new gearbox technologies that replace roller bearings with journal bearings - to improve gearbox reliability and lifespan, while reducing size and weight (Halse, C., and Keller, J., 2014) On the other hand, Siemens has come up with a completely gearless design for its 7 MW turbine. The absence of gears eliminates mechanical losses and points of failure or repair, thereby reducing operation & maintenance (O & M) costs. Further, the direct drive technology renders the turbine highly compact whilst reducing its mass. By lowering mass, towers and foundations supporting nacelles may also be engineered using less steel, thereby saving on manufacturing costs. Reducing turbine mass would also enable Siemens to build taller wind turbines (Seimens Industry).

5. Methods: smarter turbines and plants

Intelligent wind turbine R & D is focussed on smart rotors that have on-blade sensors to monitor loads and active control surfaces analogous to those used in aircraft wings that use this feedback to reduce loads, increase lift and thereby decrease operating and maintenance costs. The SUMR discussed previously in this essay is an example of a smart morphing rotor. GE's wind farm model uses embedded turbine sensors to gather and analyse data in real time on factors such as temperature, misalignments or vibrations and relays feedback to a network that makes configuration adjustments to improve efficiency for peak power generation.

Wind measurement is another important challenge. Measurements of wind velocity of incoming wind before it hits the turbine can be fed to control systems that can carry out real-time optimisation of turbine configuration and reduce aerodynamic loads. However, the degree to which such techniques can reduce loads by reacting to turbulence depends on how accurately the incoming wind field can be measured. Traditional wind measurement on a farm is done by fixed steel met masts. Borrowing from advances in surveying techniques, the Carbon Trust is deploying Light Detection and Ranging (LIDAR) technology to completely transform wind measurement on wind farms. LIDAR gives a more detailed picture of the wind resource over a larger portion of the wind site. In information terms it is the difference between taking a still photo compared to having a three dimensional video with full sound. The economic implications are enormous since wind measurement accounts for about 45 percent of an average wind farm's overall project cost (Carbon Trust).

It's not just the turbine that's getting smarter. NREL is concentrating on using intelligent plant-wide controls to model wind flows and optimise the plant as a whole system, instead of on a turbine-by-turbine basis. In a farm configuration, the wake or turbulence behind one turbine adversely impacts the operation of the turbines downstream. This approach aims to optimise the power output of the entire farm, e.g. yawing a turbine perhaps by a degree or two, could steer the wake away from turbines in the next row, which might decrease the power output slightly for that particular turbine, but increase production of an entire subsequent row (Fleming et al., 2013).

6. Sitting of offshore wind turbines

Offshore wind turbines have always been more productive than their in-land counterparts, due to constant availability of flowing winds. However, as we move deeper into the sea, the costs to install and maintain support structures and foundations becomes increasingly prohibitive. To improve offshore foundations, Sandia is exploring the development of floating wind turbines. These innovations follow the oil industry very closely, which have been using floating oil rigs for a while now (Bloomberg). Instead of using large fixed steel piles or lattice structures, they are developing less-expensive spar-buoy, tension leg and semi-submersible floating wind platforms that maintain stability and motion control.

7. Tackling the issue of intermittency

Wind is an intermittent work horse, since it does not blow all the time, and also does not blow the same way all the time. Due to this, a wind turbine would generate more electricity when winds are favourable and less or no electricity when winds are absent. The electric grid on the other hand requires a regular, smooth supply of electricity. GE is bridging this gap by using a short-term, grid-scale battery storage system paired with a smart system that analyses trends and is able to predict when power will be needed and when the wind will be blowing (GE company, 2013). The Predictable Power App lets the operators know how much energy can be expected and when (GE-Energy). It is also able to micromanage the orientation of turbines for optimal rotation. Still, turbines will produce energy at times that the grid is unable to use it. The battery system attached to the turbine allows it to feed excess electricity into the batteries, converting it to electrochemical energy that the grid can use upon request, with nearly immediate turnaround time. With these innovations, reliable, steady wind energy is becoming a reality, driven by the power of predictive analytics and big data.

As more of these next generation turbines hit the grid, the reliability of renewable energy increases, making it a feasible backbone to the electric grid. By some estimates, global installed wind capacity could grow to 2,000 GW by 2030 and meet almost 19 percent of global electricity demand. These innovations will certainly help the wind energy industry to get there.

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