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Management of Wind Power Generation with the Attachment of Wind Tunnel

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Abstract

In This study presents a new approach in which a wind tunnel apparatus is used to identify the efficiency of power output by a wind turbine with a 400W rating. Moreover, the study addresses a significant issue concerning the turbulence formed by a natural wind which can be eliminated or reduced with the use of the proposed wind tunnel.

Wind power characteristics that indicate power output versus wind velocity are obtained by performing a number of case studies. The case studies include normal operation of the experimental wind turbine at variable wind velocity values with and without proposed wind tunnel. A certain level of turbulence is formed and the wind turbine power output is measured and recorded for a number of cases.

The statistical t-Test and ANOVA analyses showed that the suggested approach could be useful for wind turbine manufacturers to evaluate the degree that contributes to the variability of renewable energy production. Besides, the results may be helpful to support educational institutions in providing renewable energy awareness in Iowa and in the US by providing adequate information for the selection and handling of the parameters that control the variability of the energy needs.

Keywords: wind turbines, wind tunnels, renewable energy, engineering, wind energy, energy
JEL Classification Codes: C61, C93, Q29

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Introduction

With the diminishing resources of fossil fuels around the world, governments and companies have focused on alternative energy resources. In this regard, renewable energy resources have become major point of interest to stay independent from fossil fuel. Abundant energy from the sun, the wind, plants, and the Earth itself can provide some or all of our facilities' needs for heating, cooling, and electricity (Federal Energy Management Program [FEMP], 2003). On the other hand, renewable resources of energy such as sunlight, wind, tides, and geothermal heat make it possible to keep our environment clean and save it from inevitable future destruction (Leggett, 2006). Using renewable energy both reduces the nation's need for imported fuels, and enhances its security. Renewable energy can also help conserve the nation's natural resources without having any adverse effect on the environment. In wind sector, energy management in wind farms generated from wind turbines has become an important issue (Jobert, Laborgne & Mimler, 2007). Development of wind energy sector will lead to the number of new job openings and this will result in the positive impact to the national economy.

Statement of Problem

The problem of this study is to determine the appropriateness of securing and managing efficient wind power generation through the use of a custom – designed wind tunnel attachment.

Purpose of Study

The several purposes of this study are:

1. To determine the physical specifications for the tunnel attachment apparatus and its components.

2. To predict the overall power output on a monthly basis.

3. To investigate the impact of the wind speed on turbulence and wind power output with and without attachment of the wind tunnel apparatus.

4. To develop educational suggestions for integrating the system into the wind turbine industry.

Need and Justification

Fifty seven percent (57%) of the electricity in the United States is generated by burning coal (U.S. Census Bureau, 1998). By August of 2000 this percentage decreased to forty percent (Milici, 2000). Bergerson & Lave (2007) indicate that more than 50% of electricity is generated from coal; approximately 23% of the total energy is consumed in the US.

In the generation of one kilowatt hour (kWh) of electricity by burning coal, 1kg of Carbon Dioxide (Co2), seven grams of sulfur oxides, nitrogen oxides and particulates, more than 200 grams of ash and waste and trace amounts of several different metals are released (Hyslop, Davies, Wallace, Gazey, Holroyd, 1997) such as hydrogen sulfide (H2S), hydrocarbons ethane (C2H6), Methane (CH4), etc. (Stracher & Taylor, 2004). In 1996 CO2 levels were around 345,000 parts per billion, (Klingenberg, 1996) contrasted to 290,000 parts per billion 100 years ago (Graedel & Crutzen, 1989). Wind energy systems reduce U.S. dependence on fossil fuels, and they do not emit greenhouse gasses (U.S Department of Energy, 2011). The generation of electricity is not, of course, the only cause of record levels of CO2 and other greenhouse gases in the atmosphere, but it does represent a large share (Graedel & Crutzen, 1989).

In much of the United States, wind speeds are low in the summer when the sun shines brightest and longest. The wind is strong in the winter when there is less sunlight available (U.S Department of Energy, 2011). Wind tunnel attachment's ability to capture low speed winds at lower altitudes may decrease the overall cost of the wind turbine.

Being the second largest producer of wind energy in the nation, Iowa has several of these large-scale projects (Iowa Energy Center [IEC], 2000). Today, U.S. wind energy installations produce enough electricity on a typical day to power the equivalent of more than 9.7 million homes (U.S Department of Energy, 2011). The five-year average annual growth rate for the wind industry is now 39%, up from 32% between 2003 and 2008 (U.S Department of Energy, 2011). All of them could benefit from the wind tunnels in securing wind power generation and management as well as prolonging the life durability of wind turbines. This paper intends to make aids available in deciding on how big impact can wind tunnel attachments to wind turbines make and improve the secure wind energy generation.

Hypotheses/Research Questions

Hypothesis 1: The null hypothesis, $H1_0$ is that there is no significant difference in the wind power output means with the use of wind tunnel attachment and it does not affect the energy generation during low wind speeds.

The alternate hypothesis, $H1_1$ is that there is significant difference in the wind power output means with the use of wind tunnel attachment and it affects the energy generation during low wind speeds.

Hypothesis 2: The null hypothesis, $H2_0$ is that there is no significant difference in the wind power output means with the use of wind tunnel attachment when turbulence exists.

The alternate hypothesis, $H2_1$ is that there is significant difference in the wind power output means with the use of wind tunnel attachment with the presence of turbulence.

Organization of the Study

As a first phase of the study, modeling of wind turbine and the wind tunnel attachment apparatus in 3D modeling software by Autodesk 3D Studio Max, version 9 and ProE Wildfire 4.0. The next phase will include the construction of the wind tunnel attachment out of light cardboard material. Pre and Post experiments will be run without and with the use of wind tunnel Attachment and the data will be recorded. Collected data will be analyzed in MS Excel 2007, STATISTICA and Minitab software for comparison reasons. As a final phase the analyzed data will be interpreted for the concluding results.

Limitations/Delimitations

The limitations for the development of this study were as follows:

1. The study was to be conducted only using the Hampden Model H-WPG-1B-CA Wind Turbine manufactured by Hampden Company.

2. The testing was to be done at variable wind conditions.

3. Atmospheric pressure was assumed to be 1kg/m3 for all the times during the experiments.

4. The fan used in the system as wind source has a diameter of 30" with maximum wind speed generation of 15 m/s.

Theory of Wind Speed inside the Wind Tunnel and Experiments

The US Department of Energy's (DOE) National Renewable Laboratory (NREL) tested a 10-meter wind turbine made for the research purposes in the largest wind tunnel in the world (NREL Website, 2000). The primary reason of this test was to understand the aerodynamics of rotating blades of a wind turbine. As a result this understanding would give clear and accurate answers how a wind turbine would behave under various wind conditions (NREL Website, 2000).This wind tunnel was located as a part of National Full-Scale Aerodynamics Complex (NFAC) in NASA Ames Research Center in Moffett Field, (Silicon Valley) California. The tunnel was powered by 18,000 fans that generate test section wind velocities up to 50 m/s (115 mph).

The wind turbine was extensively instrumented to characterize the structural responses and aerodynamics of a wind turbine rotor. The three - week test that measured inflow conditions, airfoil aerodynamic pressure distributions, and machine responses with the rotor oriented upwind and the downwind of the tower was completed in May 2000. The resulting data have been used to improve enhanced engineering models for designing and analyzing advanced wind turbines (NREL Website, 2000).

Description of the System

The proposed system consists of a wind turbine and the wind turbine attachment. A typical wind turbine consists of the rotor (blades and hub), gearbox, conversion system, controls and tower. A wind tunnel consists of the intake contraction (intake), the working section (test section), and the diffuser.

Turbine Specifications for the Proposed Scheme

The output data was obtained using a three bladed model shown below in Figures 1 & 2. As with the original set, the turbine has a rotor diameter of 24 inches made of fiber glass reinforced plastic. In high wind speeds (greater than about 15.8 m/s (35 mph), the turbine will turn out of the wind (known as furling) to protect the turbine from over-speeding. The wind turbine was positioned in the open area where an average wind speed was 5 m/s (11.2 mph) at the time of the experiments. The experiments were carried out in the nature at the B Parking lot of Industrial Technology Department, Cedar Falls, Iowa.

Experimental Layout

The experiments were carried out at the multiple places in nature such as: 1- Parking Lot B of Industrial Technology Department at UNI campus located in Cedar Falls, Iowa with the average of 5 m/s (11.2 mph) wind speed. 2- Parking Lot B of Hillside Residence Halls, UNI Apartments, Cedar Falls, IA with average of 4.5 m/s (10 mph). Artificial wind generation test was run in the Department of Industrial Technology Laboratory ITC 13 of the University of Northern Iowa. Artificial wind speed was generated by an industrial fan to match exact output recorded in natural environment.

The starting wind speed for the wind turbine was 5 mph; the average wind speed collected during the experiment 20 mph produced 100 watts of power on the wind turbine. The maximum wind speed needed to generate the optimum power from the 400W wind turbine was 30 mph. Since the maximum wind speed measured during the experiment was less than 35 mph, the shut-down point or the furl out of the 400W wind turbine was taken from the technical specifications published on the manufacturer's web site (http://val-tecgroup.com).

The shaft power output of the turbine is calculated using the formula (wind power vs. wind speed): $P = 1/2 \rho \Pi r^2 V^3$

where:

P = Power (W)

ρ = Density of the Air (by default in this study air density is calculated as 1kg/m3)

r = Radius of your swept area (m)

V = Wind Velocity (mph)

For example: Electrical power calculated at 10 m/s blowing wind on a turbine whose blades' sweeping area is 2m would be (considering the density of air 1):

P=1/2*1*3.14*22*103=6280 Watts.

The power rating of 6280W is the maximum power in the wind. However, it's impossible to harvest all the power. The Betz Limit tells us that the maximum percentage of power we can harvest from the wind is 59.26%.

Using the Betz limit value, the maximum power output from this experimental wind turbine would be 3721.53 Watts.

The final stage of the experiment took place in the Industrial Technology Laboratory ITC13. The wind tunnel attachment was modeled in 3D modeling software prior to construction and was placed in front of the experimental wind turbine as seen in Figure 1. A 30 inch diameter fan was placed in front of the intake contraction area of the wind tunnel to generate wind speed as shown in Figure 2. Wind speed generation of the fan was controlled by the experimenter to produce exact amount of wind velocity values that had been initially measured in the previous experiments in nature.

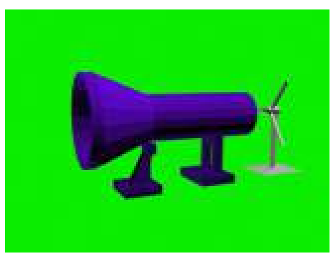

Figure 1. 3D Model of positioning of the wind turbine and the proposed wind tunnel design.

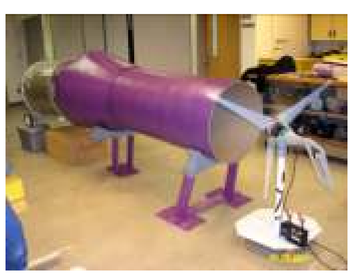

Figure 2. Positioning of the 30inch industrial fan at the wind tunnel intake and the experimental wind turbine.

A t-Test analysis was performed on the difference of the power output change in relation to the wind velocity influenced by the wind tunnel attachment to support the hypothesis that there is a significant difference between the average means of wind power outputs when the wind tunnel attachment was used. A summary of a one-sample t-Test analysis at a 95% Confidence Interval (CI) with alpha level $\alpha=0.05$ with the sample number N=36 for two tail is shown in Table 1. The t-Test yields the mean of the group 1 (power output without wind tunnel attachment) approximately as $M_1=232.71$ while the mean of group 2 (power output with the use of wind tunnel attachment) resulted in approximately $M_2=375.21$. The p-value obtained from the analysis was p=0.0177 lower than the alpha level of 0.05 which indicates that there is a significant difference between the average means of the power outputs with the use of WTA and without WTA being used.

Table 1. *T-Test* analysis for power output.

	T-tests; Grouping: Var1 Group 1: Power Output without WTA Group 2: Power Output with WTA					
	Mean	Mean	t-value	df	p	Valid N
Variable	Group 1	Group 2				Group 1
Output	232.7091	375.2146	-2.42798	70	0.017757	36

Analysis of Variance (ANOVA)

One-way analysis of variance was conducted that examined the effect of the wind tunnel attachment on differences in wind power generation means of two sample groups for statistical significance. The dependent variable, wind speed output, was normally distributed for the groups formed by the WTA (wind tunnel attachment). There was homogeneity of variance between groups assessed by Tukey's test for equality of error variances. Table 2 shows the ANOVA test results for the wind power output without wind tunnel attachment system referred as Group 1, and the wind power output without WTA indicated as Group 2. There was significant interaction between the wind tunnel attachment and the wind power output $F(1, 70) = 5.8951$, $P = .01776$. Simple main effects analysis showed that the power generation of wind turbine significantly increases with the use of WTA.

Table 2. ANOVA for power output with and without WTA

	Current effect: F(1,70)=5.8951, p=.01776 Effective hypothesis decomposition					
Cell No.	Var1	Output Mean	Output Std. Err.	Output -95.00%	Output +95.00%	N
1	Group 1	232.7091	41.50219	149.9356	315.4826	36
2	Group 2	375.2146	41.50219	292.4411	457.9881	36

Data Analysis for Turbulence

To provide a meaningful presentation and interpretation of the data analysis performed for turbulence, two sets of data, thirty six (36) each, were collected for two different cases with wind tunnel attachment apparatus and without wind tunnel attachment making seventy two (72) samples for the wind tunnel power output with the existence of turbulence. All data analyses were completed using the statistical software STATISTICA from StatSoft, Inc.

It was hypothesized that there is significant difference in the mean power output with the use of wind tunnel attachment when turbulence exists. The main idea was to see how much wind power would be generated by the experimental wind turbine with the existence of turbulence by using WTA and without WTA being used The turbulence influenced the velocity of the wind decreasing the wind force hitting the blades of experimental wind turbine. Decrease in the rotational speed of the wind turbine rotor resulted in lower power output compared to how much the wind turbine would generate without the effect of the turbulence. The same experiment was repeated with the use of wind tunnel attachment and the results showed that effect of the turbulence decreased. T-test analysis was performed to see the effect of wind tunnel attachment on the power generation during turbulence and presented in Table 3.

Table 3. *T-Test* analysis for power output with the presence of turbulence.

	T-tests; Grouping: Var1 Group 1: GP1 : Power Output without WTA Group 2: GP2: Power Output with WTA					
	Mean	Mean	t-value	df	p	Valid N
Variable	GP1	GP2				Group 1
Output	232.7091	375.2146	-2.42798	70	0.017757	36

A summary of a one-sample t-Test analysis at a 95% Confidence Interval (CI) with alpha level α=0.05 with the sample number N=36 for two tail is shown in Table 3. The t-Test yields the mean of the power output without wind tunnel attachment indicated as GP1 approximately as M_1=50.89 while the mean of power output with the use of wind tunnel attachment indicated as GP2 resulted in approximately M_2=92.32. The p-value obtained from the analysis was p=0.0116 lower than the alpha level of 0.05 which indicates that there is a significant difference between the average means of the power outputs with the use of WTA and without WTA being used with the presence of turbulence.

Cost Effectiveness

Retrieved wind maps from Iowa Wind Energy Center web site were used to estimate the cost effectiveness of the proposed system. In the month of January 2011 the average wind speed for Iowa was basically calculated by taking the average of all wind speed averages in various locations in Iowa as seen in Table 3.

Table 4. Wind data for Iowa in January 2011

Average Wind Speed	Produced Power	Status
7 m/s	118.24 Watts	Without WTA
8.57 m/s	216.97 Watts	With WTA

MPH	m/s
>19.0	>8.5
17.9-19.0	8.0-8.5
16.8-17.9	7.5-8.0
15.7-16.8	7.0-7.5
14.5-15.7	6.5-7.0
13.4-14.5	6.0-6.5
12.3-13.4	5.5-6.0
<12.3	<5.5

Average Power Calculation for Iowa in January 2011

= (8.5+8.0+7.5+7.0+6.5+6.0+5.5)/7 =7 m/s

As it can be observed in the Table 4, the average wind speed in Iowa for January 2011 was 7m/s and the experimental wind turbine with the capacity of 400 Watts is capable of producing 118.24 Watts. By attaching wind tunnel apparatus to the same wind turbine, the wind speed increases from 7 m/s to 8.57 m/s which, in turn, impacts the wind power generation of the turbine increasing from 118.24 Watts to 216.97 Watts. Based on the data from Cedar Falls Utilities web site (www.cfu.net), the CFU price charges for residential electricity are shown below in Table 5.

Table 5. Cedar Falls Utilities electric price for January 2011 (Modified from www.cfu.net).

Jan-11	RATE
First 800 kWh @	$0.078/kWh
All Over @	$0.060/kWh

National Wind LLC. Published in their website the total amount of wind turbines installed, currently under construction and average potential wind power output. According to the data the Iowa Department of Economic Development (IDED) the total installed wind energy capacity in Iowa is 3670 Megawatts (MW) as of September 2010 (IDED, 2011). The Energy Information Administration (EIA, 2011) reports that an average American house uses 936kWh of energy per month. The total cost of electricity used in January 2011 with the capacity installed and with the CFU prices the calculation will result as follows:

3670 MWh = 3,670,000kWh

The basic rate from CFU will result in 3,670,000* $0.06 = $220,200

Total amount of households that can utilize produced wind energy = 3,670,000 kWh /936 kWh = 3920.94 (3921 households).

The use of wind tunnel attachment increases 3670 MWh to 5720 MWh that results in:

Total amount of households that can utilize produced wind energy = 5,720,000 kWh /936 kWh = 6111.11 (6111 households). Increasing to 6111-3921=2190 more households. Produced energy with the use of wind tunnel attachment can increase the revenue by 5,720,000*.06= $343,200

Another important area for observation is how the wind tunnel attachment system can decrease the cost of energy in Iowa. To calculate how much an average household spends for monthly energy bill we multiply 936 *0.06 = $56.16. An average household in the US spends 56.16 dollars monthly (assuming the lowest rate from Cedar Falls Utility). Considering that the 3921 households spend 56.15 dollars monthly to consume 3,670,000kWh of produced wind energy without the use of the wind tunnel attachment, the monthly price for the household change can be estimated by the following calculation:

Total amount of wind energy produced with the use of wind tunnel attachment is divided by the number of households that need to consume this energy as 5,720,000 kWh/3921 households = 1,459. The extra amount produced 1459kWh – 936kWh = 523kWh will result in saving cost of 523*.06=31.38 dollars. Monthly paid $56.16 - $38.56 savings = will become $17.6 new monthly payment. Thus a household spending $56.16 in monthly basis will decrease its cost to $17.6. Decrease in energy price by CFU is observed as: If a household spends 56.16 dollars monthly for 936 kWh in the rate of .06 cents then the energy rate by CFU must become 17.6 * .06 / 56.16= 0.019 dollars for the same 936 kWh energy usage monthly.

Conclusion

The problems of this applied research study were to determine the strength of the correlation relationship between power output and the wind tunnel attachment. The power of a wind turbine can be increased or decreased by simply attaching a wind tunnel to it. A general rule of thumb is to install a wind turbine on a tower with the bottom of the rotor blades at least 9 meters (30 feet) above any obstacle that is within 90 meters (300 feet) of the tower (U.S Department of Energy, 2011). Wind tunnel attachment's ability to capture low speed winds at lower altitudes may decrease the overall cost of the wind turbine.

Based on the experiment with statistical analysis, attachment of the wind tunnel system on the wind turbine increased the power generation significantly at $\alpha = 0.05$ levels.

Recommendations

Further studies need to be considered on the design on the wind tunnel attachment. The cost effectiveness of the current system was not analyzed therefore; transportation of the wind tunnel to far-distance areas might be costly. Attachment of the wind tunnel system on the wind turbine can be modeled in 3D software program and be simulated to see how different designs of the system may increase the cost effectiveness of the apparatus. The friction force produced by the material used to construct current wind tunnel might reduce if the following are considered for the further studies:

1- Overlapping sections of the intake contraction of the wind tunnel smoothness.

2- The smoothness of the neck (joint area of the diffuser and the intake).

3- Covering inner section of the wind tunnel with epoxy resin to support additional smoothness.

4- Construction of the overall wind tunnel apparatus using aluminum material to decrease the probability of turbulence generation.

5- Adjust the diameter of the diffuser to the wind turbine blade swept area.

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