Iterative Analysis of Wind Turbine Design Utilizing Digital Modeling

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Abstract

When developing a system for power production it is of interest to be able to optimize design features to create the maximum electrical power output. It is expensive to both create physical models of these power systems and iterate upon them to improve on design aspects. Digital models are useful in this case as they are inexpensive to run and easily changed on the fly. Researchers at UNC Charlotte have developed a model of a 100 kW rated wind turbine to explore how the design features of rotor diameter and gear ratio affect the performance of such a system. The digital model uses an input of National Renewable Energy Lab (NREL) wind resource data over a range of 3 years between 2004 and 2006 with a fixed blade pitch, and air density. The model finds given the wind resource data that a gear ratio of 20.6 and rotor diameter of 17.86m are optimal. This model allows engineers to estimate power generation with an input of wind speed from a database to determine the best design parameters before construction begins. The model can be further developed to include economic factors such as levelized cost of energy to ensure feasibility from a cost and performance standpoint.

Introduction and Literature Review

Renewable energy is defined as any energy resource that is replenishable on a human time scale and includes energy sources such as solar energy, wind energy, ocean energy, and biomass. Over the past few decades renewable energy has gained a much larger share in countries's energy portfolios for two main reasons. Those being the negative effects of using carbon based energy sources on Earth's climate and the benefits that come with having a varied energy portfolio such as increasing national security by reducing the reliance on electricity imported from other countries. Researchers have studied the impact of renewable energy's positive impacts on energy security of nations and environmental health.

During tumultuous times in geopolitics nations heavily reliant on fossil fuels can be heavily disadvantaged if they are a net energy importer and may have to pay unfavorable rates for natural gas or cut into strategic reserves earlier than forecasted. Geopolitical events such as the 1973 oil embargo, Iraq war, and Russo-Ukrainian are all examples of energy paradigms shifting and the impacts of each can be dampened by a country if they have a diverse energy portfolio.

Khan et. al. performed a Granger causality analysis on renewable energy and energy security using historical data between the years of 2001 and 2022. That identified that renewable energy did have a positive impact on energy security, particularly during times where supply chains are disrupted. Østergaard et. al. present a review paper describing the current state of several renewable energy technologies such as attempting to increase photovoltaic energy output in high temperatures by cooling them with small nozzles that emit water droplets on the surface. Efforts to identify wind and wave resources in various areas of interest for power generation across the globe. As well as the integration of battery and hybrid storage for intermittent renewable energies such as solar and wind.

Li et. al. [3] characterized the behavior of a Wave Energy Converter (WEC) utilizing a thorough testing regime including wave tank testing and free decay tests to quantify the heave response bandwidth of a dual body heaving buoy. This allowed for the optimization of a WEC for energy capture under different sea states based on wave period and height data.

Kim et. al. [4] explored the design of a dual body WEC that leveraged multiple frequency modes to maximize energy capture across a wider range of wave periods. This study used wave tank testing to determine the Response Amplitude Operator (RAO) across a range of wave periods.

The benefits of renewable energy on the environment and energy security are known but the technology has continually taken strides to be cost competitive with fossil fuels. Gross et. al. [5] points out that with any technology, the more it is applied and constructed the faster and cheaper it gets. The paper explains that learning by doing can decrease costs as lessons are learned and best practices are identified in processes. In the case of wind an emphasis on good site characterization and wind resource characterization has been able to identify areas best suited for a wind farm. Offshore wind development has proven to have the best wind resource and is an area of great interest. Turbines have also increased in size while reducing in weight/kW allowing for bigger farms and increased energy output for cheaper. Additionally to reduce intermittency of wind farms a tandem effort of using battery or hydrogen storage with the turbine can create a stored energy during off-peak hours, which can then be redistributed when demand requires additional power. As material scientists make breakthroughs allowing for larger wind turbines to be created and intermittency is reduced it creates an environment where wind farms are cost competitive with oil and gas.

Wind energy is one of the more scalable and exciting technologies to develop from interest in renewable energy and works by capturing kinetic energy from the wind and transforming it into electricity. The power in the wind can be described by the equation P(w)=(½)*V^3*ro*A where A is the swept area of the turbine, ro is the density of the air, and V is the velocity of the wind. The power of the wind equation can be equated to the mechanical power generated by a wind turbine which is described by the equation P=Tw with some factor of losses due to factors such as friction. Where T is the torque on the input shaft of a wind turbine and w is the angular speed of the input shaft. There are many design factors that go into altering the values of T and w to create an optimal turbine system. Two of these factors are the gear ratio (G) which can alter the torque value and angular speed and the rotor diameter (D) which can alter the swept area of the turbine. The objective of any electrical power plant is to meet grid demand and generally produce as much power as possible for as cheap as possible. The research presented here aims to optimize a wind turbine system to create as much power as possible for as cheap as possible by modifying the G and D parameters using a modeled 100kW turbine system in MatLab.

Methodology

A model was developed in Matlab to evaluate different parameters for a 100kW wind turbine given real world wind data. Combinations of model parameters were evaluated to maximize total energy output over a period of three years, while ensuring the turbine remains within its rated power capacity of 100kW. Data spanning a continuous three-year period between 2004 and 2006 is imported from the National Renewable Energy Laboratory (NREL). This data is read from a CSV file, and the wind speed values are extracted from the dataset and a time vector is established to plot wind speed and power. The flowchart shown in figure 1 provides a general overview of the process used to approximate the optimal parameters for the highest capacity configuration.

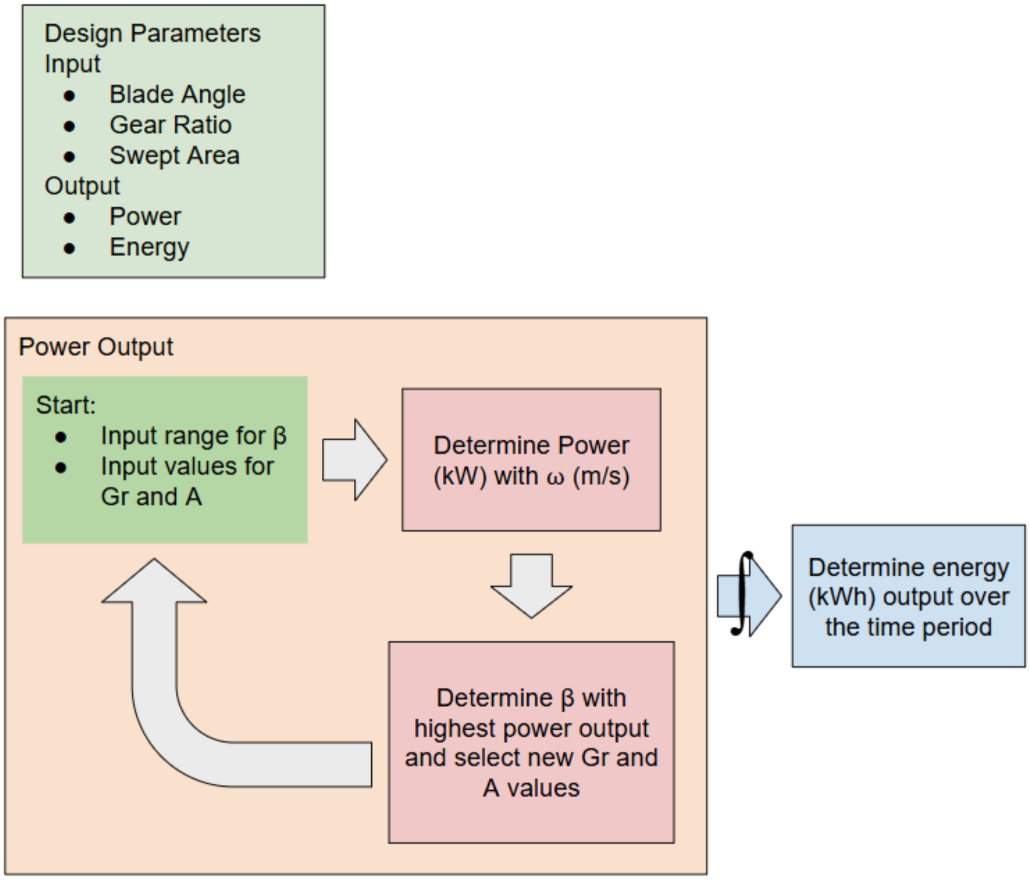

Figure 1: Flowchart for designing a wind turbine for maximum energy capture

An initial range for rotor diameter and gear ratio were defined with intermediate values set in 0.1 increments. This model was run iteratively and the range was reduced after each iteration to center the output values and use smaller increments. After two iterations, the gear ratio showed negligible change and was set constant for further iteration. The blade pitch angle, a parameter that influences aerodynamic efficiency, is held constant at 2.2 degrees. The model also defines air density as 1.27 kg/m^3 and generator rotational speed as 1800 rpm, for aerodynamic calculations.

A series of two nested if statements were used to evaluate the performance for each gear ratio and rotor diameter configuration. For each configuration, the blade-tip speed is calculated using the generator speed and gear ratio, which is then used to compute the tip-speed ratio (λ), a non-dimensional value that compares blade-tip speed to the incoming wind speed. This value is crucial for estimating the turbine's aerodynamic efficiency.

To estimate the power coefficient (Cp), the script uses a semi-empirical formulation based on the Heier model, which is a common approach in wind energy analysis. The Heier model uses a set of empirical coefficients and an intermediate variable λ_i to determine Cp as a function of tip-speed ratio and gear ratio while any negative Cp values are replaced with zero to maintain physical realism, as negative power coefficients are non-physical.

This model is then able to calculate the instantaneous power output of the wind turbine at each time step using the standard power equation that accounts for air density, rotor swept area calculated from rotor diameter, wind speed cubed, and the power coefficient. The total energy output over the three-year simulation period is then computed by summing the instantaneous power values and multiplying by the duration of each time step (600 seconds, or 10 minutes). To ensure the turbine does not exceed its design limitations, the script includes a conditional check that filters out any configuration where the maximum instantaneous power output exceeds 100,000 watts (100 kW). While the different configurations are being calculated, the model continuously saves the optimal combination to be recalled after all values have been evaluated.

After completing the optimization process, the script outputs the optimal rotor diameter and gear ratio and two plots are generated. Wind speed every ten minutes (figure 2) is shown over the three year period, and power output given the optimal parameters are shown. These two plots are used to visualize the variability and range of wind resources over time as well as the relationship between wind speed and power generated.

This model provides a rapid and low cost estimate for wind power parameters. This allows for the estimation of optimal parameters while still remaining at a relatively low computational cost. This is particularly valuable in the early stages of wind turbine development, where physical prototyping is expensive and time-consuming. Furthermore, by identifying optimal design parameters that maximize energy capture without exceeding rated capacity, the model supports the creation of more efficient and reliable wind turbines.

Results

The recorded wind speed data shows significant variation during the three year period and ranges between 0 and around 25 m/s. Figure 2 shows the wind speed in m/s every ten minutes and this data was used to calculate both the maximum wind power for a swept rotor area and the power captured by the wind turbine.

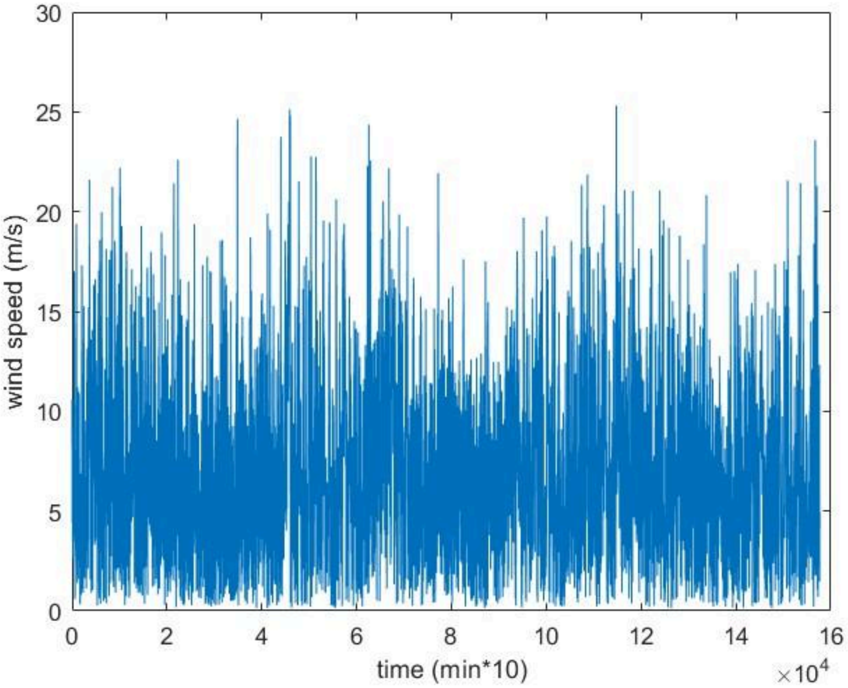

Figure 2: Wind Speed vs. Time from 2004 to 2006

With the gear ratio and rotor diameter parameters, the blade tip speed was calculated to determine power coefficient using the Heier approach. The output of this power remained within the 100kW range and is plotted every 10 minutes during the three year period in figure 3.

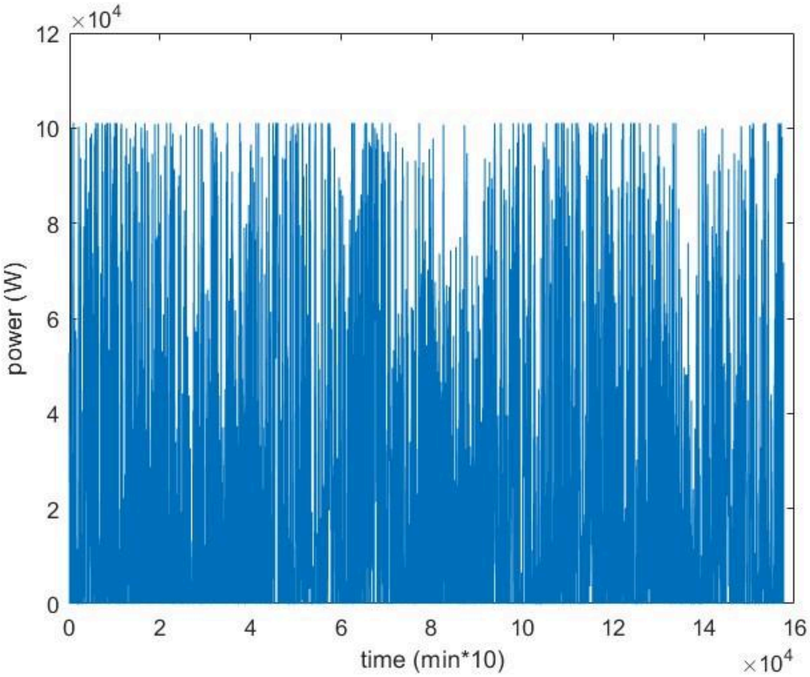

Figure 3: Power Output vs. Time from 2004 to 2006

Across the given range of input parameters, the optimal values were recorded. A gear ratio of 20.6 and a rotor diameter of 17.86 meters was found to produce the maximum energy output across 3 years while remaining within 100kW.

Conclusion

The digital wind turbine model developed by researchers at UNC Charlotte highlights the critical role of computational tools in improving the design and performance of renewable energy systems. By simulating a 100 kW rated wind turbine and analyzing how variations in rotor diameter and gear ratio influence energy output, the model enables engineers to identify optimal configurations without the financial and logistical burden of building physical prototypes. Leveraging three years of wind resource data from the National Renewable Energy Laboratory (NREL), the model provides a flexible and cost-effective platform for exploring how site-specific wind conditions interact with key design parameters. This capability is essential for accelerating the development cycle and improving the accuracy of performance predictions prior to construction.

Beyond its technical contributions, the model serves as a valuable tool in the broader effort to reduce the cost of renewable energy systems. Lowering the capital and operational costs associated with wind energy is crucial not only for economic competitiveness but also for enhancing national and global energy security. As the world transitions away from fossil fuels, affordable and reliable renewable energy infrastructure reduces dependence on imported energy sources and insulates communities from geopolitical instability and market volatility.

Additionally, by supporting the expansion of low-emission energy sources, tools like this model contribute directly to the reduction of greenhouse gas emissions, helping to mitigate the environmental impacts of climate change and decrease air pollution that affects public health.

Looking ahead, the model's adaptability offers opportunities for even more comprehensive design optimization. Integrating economic considerations such as levelized cost of energy (LCOE) into the simulation framework can provide a more holistic view of both technical performance and financial viability. In doing so, engineers and decision-makers can better align wind turbine design with broader sustainability and affordability goals. Ultimately, this digital modeling approach represents a step forward in creating smarter, cleaner, and more resilient energy systems that benefit both society and the environment.

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