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MODELING WIND TURBINES IN THE GRIDLAB-D SOFTWARE ENVIRONMENT

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ABSTRACT

In recent years, the rapid expansion of wind power has resulted in a need to more accurately model the effects of wind penetration on the electricity infrastructure. GridLAB-D is a new simulation environment developed for the U.S. Department of Energy (DOE) by the Pacific Northwest National Laboratory (PNNL), in cooperation with academic and industrial partners. GridLAB-D was originally written and designed to help integrate end-use smart grid technologies, and it is currently being expanded to include a number of other technologies, including distributed energy resources (DER). The specific goal of this project is to create a preliminary wind turbine generator (WTG) model for integration into GridLAB-D. As wind power penetration increases, models are needed to accurately study the effects of increased penetration; this project is a beginning step at examining these effects within the GridLAB-D environment. Aerodynamic, mechanical and electrical power models were designed to simulate the process by which mechanical power is extracted by a wind turbine and converted into electrical energy. The process was modeled using historic atmospheric data, collected over a period of 30 years as the primary energy input. This input was then combined with preliminary models for synchronous and induction generators. Additionally, basic control methods were implemented, using either constant power factor or constant power modes. The model was then compiled into the GridLAB-D simulation environment, and the power outputs were compared against manufacturers’ data and then a variation of the IEEE 4 node test feeder was used to examine the model’s behavior. Results showed the designs were sufficient for a prototype model and provided output power similar to the available manufacturers’ data. The prototype model is designed as a template for the creation of new modules, with turbine-specific parameters to be added by the user.

INTRODUCTION

In recent years, the use of wind generated power, as both a centralized source of power (such as wind farms) and as a distributed resource, has rapidly increased. As wind power penetration increases, the negative effects upon the transmission and distribution systems can no longer be ignored; they must be modeled and examined in further detail [1], [2], [3]. Additionally, recently developed technologies, including Grid-Friendly™ appliances and other distributed energy resources (DERs) are being incorporated into existing power systems and by extension, into existing and newly developed software simulation environments. The effects of these new technologies become particularly important as more of these technologies are deployed within the electricity infrastructure. The goal of this project is to develop a preliminary wind turbine generator (WTG) model to be incorporated into one of these new software systems, GridLAB-D.

GridLAB-D is a new simulation system developed for the U.S. Department of Energy (DOE) by the Pacific Northwest National Laboratory (PNNL) in collaboration with industrial and academic partners. GridLAB-D is a unique simulation environment, in that it is a generalized simulation environment that is specifically designed to be used with multiple processors. Based on the architecture of GridLAB-D, the transmission power flow solution technique implements the Gauss-Seidel method [4], while the distribution power flow technique is implemented with the forward and backward sweep (FBS) method. GridLAB-D finds quasi-steady state time series solutions that, when put together, approximate the time-varying, non-dynamic solution. The FBS method is described by Kersting [5], and further information and description of the software’s capabilities, and the reasons behind its creation, are provided by the designers [6]. DOE initiated this software with the intent to eventually release it as open-source software to facilitate...
As wind passes across the turbine blades, the kinetic energy is converted into mechanical power. According to Betz’ law, a maximum of 59% of this power can be extracted \[8\]. However, actual applications are typically less efficient than this. The power extracted from the wind by the turbine can be expressed as

\[ P_m = P_{\text{wind}} \times C_p(\lambda, \beta), \]  

where \( P_m \) is the mechanical power extracted by the turbine blades and \( C_p(\lambda, \beta) \) is the coefficient of performance, or the fraction of power that is extracted from the wind. The tip speed ratio, \( \lambda \), is the ratio between the turbine blade tip speed and the wind speed, and the pitch angle, \( \beta \), is the angle of attack of turbine blades. Only a few manufacturers openly supply tables that give the coefficient of performance for any given integer wind speeds. In the cases where a manufacturer’s table was available, a tenth order polynomial interpolation function was generated in Matlab to give a continuous function to estimate the manufacturer’s data at all wind speeds. In cases where performance data was not available, the method described by Justus \[9\] was used.

According to Justus, and further explained by Malinga \[3\], at any given pitch angle an approximation of performance can be given by

\[ C_p = \begin{cases} 
C_{pm} \times \left[ 1 - F \left( \frac{u_{m}}{u} - 1 \right)^2 - G \left( \frac{u_{m}}{u} - 1 \right)^3 \right], & u_{c} \leq u \leq u_{r} \\
C_{pr} \times \left( \frac{u_{r}}{u} \right)^3, & u_{r} \leq u \leq u_{f} 
\end{cases} \]  

Wind speed, \( u \), determines the coefficient of performance for any given turbine model, and is divided into two distinct regions, below and above rated wind speed, \( u_r \). The cut-in wind speed, \( u_c \), and the cut-out wind speed, \( u_f \), are the boundary values which determine the operating range of the turbine model. \( C_{pm} \) and \( C_{pr} \), respectively, are the maximum values of the coefficient of performance and the coefficient of performance value at rated wind speed, while \( u_{c} \) is the wind speed at which the maximum \( C_{pm} \) occurs. \( F \) and \( G \) are coefficients which can be found by applying the boundary conditions. By using manufacturer’s data for cut-in, cut-out and...
rated wind speeds and power output at rated speeds, an estimated coefficient of performance function can be generated to approximate the performance of a real turbine. This method only fully applies to fixed pitch turbine systems, where the pitch angle of the blade is constant. In a variable pitch turbine, the blade pitch is adjusted at a given wind speed to gain the highest achievable coefficient of performance value. This means that the Justus model is not entirely accurate for variable pitch turbines at lower wind speeds; however, it is sufficient for the model at this stage of development, and can represent either pitch style, regardless of generator type.

The coefficient of performance gives the percentage of the power that can be extracted from the wind. The total power for extraction available in the wind is given by

$$P_{\text{wind}} = \frac{1}{2} \rho A u^3. \tag{3}$$

A is the area swept, $\pi r^2$, by the turbine rotors in meters squared, and $\rho$ is the density of the air passing across the turbine. Air density is affected by atmospheric conditions, such as temperature, pressure and elevation, and can alter the power output by as much as 40% for a given turbine and wind speed. At this time, the climate model within GridLAB-D does not support all the necessary climate components, including air pressure, so air density was calculated assuming constant standard pressure and using imported TMY2 temperature data. Future versions of GridLAB-D will support these features, and functions were put in place to eventually use location-specific data to determine air density.

A certain amount of mechanical power is lost in the drive train gearbox. The blade and hub assembly on a wind turbine will typically spin at 12–18 revolutions per minute, while to deliver AC power at a nominal frequency of 60 Hz, the generator shaft needs to spin at 1 200–1 800 rpms. The gearbox steps up the rotational speed of the shaft but also incurs mechanical losses due to friction. Cotrell [10] shows that a 1% loss of rated power per stage due to viscous friction losses is a reasonable assumption. Aguglia [11] describes the gearbox losses as

$$\eta_{\text{gear}} = 1 - q \times 0.01 \times \frac{P_{\text{gear rated}}}{P_m}, \tag{4}$$

where $q$ is the number of gearbox stages on the shaft. The total extracted mechanical energy into the generator can now be given as

$$P_m = \frac{1}{2} \rho \pi r^2 C_p(u) \eta_{\text{gear}} u^3. \tag{5}$$

Mechanical power extracted can be determined as a function of wind speed and current atmospheric conditions for any given wind turbine.

One final adjustment was made to calculate the extracted power. Most meteorological data is measured at 5 to 15 m height, as is the case with the TMY2 data; however, wind turbines are significantly taller. Wind shear near the ground, which is affected by the roughness of the local terrain, significantly reduces the wind speed at lower levels. A correction factor,

$$U_{\text{adj}} = U_{\text{ref}} \times \left( \frac{z_{\text{ref}}}{z_0} \right)^{\frac{1}{k}} \tag{6}$$

used by the European Wind Atlas [12], was used to adjust the wind speed as measured at 10 m to approximate the strength of the wind at the height of the wind turbine. The measured wind speed, $u_{\text{ref}}$, at height $z_{\text{ref}}$ is adjusted to the turbine hub height, $z$, through the use of a roughness length factor, $z_0$. The roughness length factor is a unit-less correction factor that approximately describes the amount of wind shear at a given location due to local terrain. For example, over water, $z_0 = 0.0002$, while over rough agricultural land, $z_0 = 0.4$, and can have a sizeable effect on the amount of power generated at the turbine hub height.

### Converted Electrical Power

Mechanical power supplied by the wind is converted to electrical power through a synchronous or induction generator. Permanent magnet synchronous generators (PMSGs) have been the commonly used form in general applications; however, doubly-fed induction generators (DFIGs) have become increasingly popular, as they have the ability to not only absorb reactive power, but they also provide reactive power to assist in voltage stability [13]. DFIGs are essentially induction generators with complex feedback loops that can control the reactive power output of the generator. Since induction generators will always absorb reactive power and cannot provide it, they are not widely used without additional hardware, such as shunt capacitors. DFIGs were created as an alternative to this problem, and are becoming more popular since they are generally cheaper and lighter than corresponding PMSGs. This project began the process of creating a PMSG model with limited control systems, and took the first steps in modeling an induction generator for future use as a DFIG.

### Synchronous Generator

The PMSG was modeled using a balanced Y-grounded circuit, but has the capability to be implemented with unbalanced generator parameters. The per-phase model is shown in Figure 2. $V_{\text{phase}}$ is the voltage from one terminal to neutral and is determined by the bus line voltage. The circuit is solved through an iterative process, in which the final desired output is the current supplied to the grid.
Active power output was found by determining the losses in the circuit due to the resistive elements subtracted from the converted mechanical power. Reactive power was determined by a specified control mode. At this stage of development, a constant power factor control mode was used to determine the desired reactive power output of the generator. The power factor can be adjusted, within the limits of the generator's capabilities, to deliver or absorb reactive power as needed to meet the requirements of the control mode. The controller will be implemented at a later time using an external control module. Further development will also include constant potential and constant power modes, depending upon the application. These control modes can be considered analogous to generalized versions of common generator dispatch methods.

**Induction Generator**

The induction generator was also modeled using a balanced Y-configuration; however, unbalanced loading was not fully tested. The per-phase model is shown in Figure 3. Similar to the PMSG, \( V_{phase} \) is determined by the bus voltage, and \( I_{phase} \) is the desired output. The circuit is solved with the two-port matrix

\[
\begin{bmatrix}
V_{phase} \\
I_{phase}
\end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} V_{rotor} \\
I_{rotor}
\end{bmatrix},
\]

where the matrix elements are given by

\[
\begin{align*}
a & = 1 + Z_{st} / Z_c \\
b & = Z_r + Z_{st} + Z_{st} \cdot Z_r / Z_c \\
c & = 1 / Z_c \\
d & = 1 + Z_r / Z_c
\end{align*}
\]

In this case, \( V_{rotor} \) is a representation of the voltage across the resistor which represents the power converted, not an actual potential. For development purposes, a constant power mode was used to generate the maximum amount of active power available at the terminals. Reactive power was then found for that level of active power. The circuit was once again solved iteratively, and per unit values were used.

**RESULTS AND DISCUSSION**

Four test turbines were designed: a generic 1.5 MW induction generator, a generic 1.5 MW synchronous generator, a 1.65 MW PMSG representation of a Vestas V82 turbine, and a 2.5 MW PMSG GE turbine. Vestas V82 wind turbines, which actually use DFIGs, were represented as PMSGs within the electrical portion of the model for testing purposes. GE and Vestas are the largest suppliers of wind turbines within the United States [14] and had the most data publicly available, making them the easiest to model at this stage. For this reason they were selected as two of the turbines to be included at this stage of development.

Initially, all of the models were tested as stand-alone modules. They were connected to a constant voltage infinite bus, where the constant voltage was held near the generator's rated terminal voltage. Both active and reactive power was then measured as a function of wind speed at standard air density and temperature. Where applicable, the outputs were compared to manufacturers' data (Figures 4–5). The generator and turbine specifications used are presented in Table 1. The Vestas V82 provided similar results to its manufacturer's data, except at high wind speeds (Figure 4a), where slight polynomial perturbations can be seen which were due to the low order polynomial interpolation of coefficient of performance data. Later implementations may employ other forms of interpolation from manufacturers' data to reduce the error at higher wind speeds. The GE 2.5 MW, on the other hand, provided similar results to its manufacturer's data at high wind speeds, but consistently provided lower power output at lesser wind speeds (Figure 4b). As discussed before, this is due to the use of the generalized, fixed pitch, coefficient of performance model to determine the percentage of mechanical power transferred. GE wind turbines use variable pitch blade systems, which increase the coefficient of performance at lower wind speeds and can provide a higher cut-off wind speed. This illustrates the advantages of using, variable pitch wind turbines with active control over fixed pitch turbines: more power can be consistently provided at lower wind speeds. Figure 5a illustrates the output of a fixed pitch, 1.5 MW PMSG wind turbine as a general model, while Figure 5b shows...
the active power output and reactive power absorption of a fixed pitch, 1.5 MW induction generator wind turbine. Since both these turbines represent generalized models, there is no data to compare. The models can be adjusted to represent almost any size turbine and it is up to the user to redefine them as needed for specific applications.

In Figure 5, the induction generator active power is similar to that of a synchronous generator. The PMSG provides reactive power at similar curves to the active power, since it is controlled at a constant power factor of 0.95. However, in the induction generator, reactive power is continuously absorbed, somewhat independent of the wind speed. For this reason, induction machines are no longer commonly used as generators without additional shunt capacitors; however, the results in Figure 5 are consistent with an induction generator configuration. Further development of the wind turbine model will include DFIGs, which do not always consume reactive power and can actually provide reactive power when needed. This is one of the primary reasons they are finding widespread acceptance within the industry.

Table 1. The generator and turbine specifications used for testing the models.

*In reality, Vestas uses a DFIG, but a PMSG representation was used.

**Ten minute cut out speed.

Figure 4. (a) Active power for Vestas V82 compared to manufacturer’s data. (b) Active power for GE 2.5 MW compared to manufacturer’s.

Figure 5. (a) Active and reactive power generated by the generic 1.5 MW PMSG. (b) Generic 1.5 MW induction generator, including active and reactive power.
The PMSGs were also tested on a variation of the IEEE 4 node step-down test feeder (Figure 6) with an unbalanced load. The wind turbine generator was attached to node three. The secondary voltage on the Y-Y-connected transformer was changed to the rated voltage of the generator, and the unbalanced, constant power load was reduced to a level stable for that voltage. The entire feeder was then run using wind and temperature data from Tulsa, OK at one hour time step increments. Figure 7 shows the magnitude of the voltage of the three phases at the load, measured at each time step, and the corresponding power and wind speed at each step. As the wind turbine supplies more power to the system, the strain on the load voltage decreases and the voltage increases accordingly. Phase C has the largest load, and correspondingly, has the lowest voltage returned of the three phases.

CONCLUSION

Generic and manufacturer-specific aerodynamic models were created to simulate the mechanical power extracted from wind data provided by TMY2 sources, with sufficient corrections for atmospheric conditions, hub height and mechanical losses. Preliminary designs were created for both synchronous and induction generators to extract electrical power. These prototype models were tested against publicly available manufacturers’ data and against a variation of the IEEE 4 node test feeder.

The model in this project created a generalized, first-run prototype, but further work is needed to accurately model the wind turbines that are available. The goal was to create a template for future designers, which can be used to create highly accurate, time varying models of specific turbine designs. The main future tasks will include the creation of a DFIG model, as these generators become more widely used, and the creation of more accurate control and dispatch methods. Future work will also include the integration of further atmospheric and location specific data, to account for variability in air density, especially at different geographical locations. Finally, more accurate models should be created to represent coefficient of performance data. For cases where data is not available, a variable pitch approximation should be designed, which, although case-specific for individual turbines, will provide a better approximation than a fixed pitch model.

New tools, such as GridLAB-D, coupled with models for new and existing technologies, are needed as more advanced technologies are integrated into the electricity infrastructure. As new technologies are created, such as Grid-Friendly™ appliances or plug-in hybrid vehicles, the effect of their integration will need to be studied in more accurate, time-sensitive detail. An open-source, next generation, power simulation system, like GridLAB-D, allows for a wider user base, faster and easier creation of simulation modules, and can assist in the integration of new technological capabilities.

ACKNOWLEDGEMENTS

This work was conducted at PNNL under a project funded by DOE. Thanks go to PNNL, Battelle and DOE Office of Science, for sponsoring and supporting the Science Undergraduate Laboratory Internship Program, an invaluable research experience. Special thanks to Kevin Schneider and David Chassin for their guidance and mentoring during the duration of this project and to Matt Hauer and Bo Yang for their constant support and assistance.
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