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A SIMULATION SOLUTION OF THE INTEGRATION OF WIND POWER INTO AN ELECTRICITY GENERATING NETWORK

Thomas F. Brady

Department of Engineering Technology
1401 South US 421
Westville, IN 46391, USA

ABSTRACT

To effectively harness the power of wind electricity generation, significant infrastructure challenges exist. First, the individual wind turbines must be sited and constructed as part of a wind farm. Second, the wind farm must be connected to the electricity grid infrastructure and the power generated managed accordingly. Due to its stochastic nature, wind energy cannot be controlled; it must be managed. The integration and management of wind power within the highly complex, interconnected electricity infrastructure of the United States presents numerous policy making and decision analysis scenarios. The purpose of this paper is to develop a simulation framework for analyzing the integration of wind power into the generation system of a utility company. An analysis of public domain wind data is presented and specifics of how to transform this data into a compact, efficient representation suitable for simulation modeling is presented. Finally, performance metrics relative to wind effects are discussed.

1 INTRODUCTION

Despite accounting for less than one percent of the electricity generated in the United States(Gagnon 2005), wind power is one of the most rapidly growing and discussed sector of the United States energy system. Wind farms are being constructed rapidly throughout the country. There are currently fifty seven large wind projects under review or construction in the midwest alone. While wind power is touted as 'free and green', the integration of wind energy into the electric power infrastructure of the country presents numerous challenges.

The most significant wind power challenge is that wind turbines generate electricity only when the wind speed is above a certain threshold. Practical, cost effective means of storing, or inventorying electricity do not yet exist. Thus, wind power investments are feasible not as stand-alone items, but as components of an integrated power generating system that include fossil fuel, nuclear, and other renewable forms.

Wind is the classic example of a stochastic variable. As such, electricity generated from wind can be analyzed as stochastic phenomena. The purpose of this paper is to describe the issues involved with integrating wind power into a typical utility company serving a captured market area and to present the framework of a simulation solution. The simulation framework focuses on the capture and representation of wind data for a particular region in the state of Indiana and the operational policies of managing wind power integration. This paper is organized in the following fashion. Section one presents an introduction to the problem scenario. Section two presents a brief literature review. Section three presents a short discussion on the process of electricity generation and the development of a simulation model with the objective of analyzing operational wind policy decisions. Section four presents an approach for capturing public domain wind data and transforming such data into a useable, efficient format for use within a simulation model. Section five presents the conclusions and recommendations.

2 LITERATURE REVIEW

Literature pertaining to wind generation relevant to the theme of this paper is focused on the concepts of policy and operational uncertainty. Wind power has been effectively used in Europe for decades and is considered a mature technology for electricity generation. As the volatility of fossil fuel prices and the political and economic instability of fossil fuel producing regions increases, the search for alternative fuels in the United States has intensified. Increased awareness of environmental concerns such as global warming and the steady increase in electricity demand have also contributed to a renewed emphasis on finding additional, cleaner sources of electricity generation, such as wind power.

The policy aspects of power generation relative to wind power focus on conservation and pricing issues. Electric power in the United States is largely a regulated industry in which governmental units control pricing. Utilities set up generating assets in captive territories and the subsequent rates they charge to consumers are primarily set based on traditional capital recovery-type scenarios since the construction and operation of power plants is a large capital intensive industry. Additionally, fuel costs and the transportation of such fuels are highly variable and contribute significantly to the rate paid by consumers. The introduction of wind assets into a power generation system present challenges to regulators, utilities, and consumers. (O'Neill 2007) presents a comprehensive look at the electricity environment from the standpoint of integrating wind power while (Olsina 2007) presents modeling and analysis viewpoints of integrating wind power into deregulated marketplaces.

Operational uncertainty is a factor relative to the consideration of wind power as a component of an electricity generation system. Wind power is available only when the wind speed is above a certain threshold which makes the availability and control of wind-based electricity entering the power grid uncertain at best. Forecasting and control mechanisms become critical, integral components to any power generating system that includes wind. (Barth 2007) lays out several models that demonstrate scheduling issues and pricing considerations in German markets that include significant wind farms. (Boronico 1997), (Fosgerau 2008), and (Olsina 2007) present models and analysis of stochastic systems in which demand is highly variable and use marginal cost analysis to set minimum capacity levels for service providers. (Koch 2003) and (Slootweg 2002) present evidence of the effects of stochastic wind conditions on the stability of the power grid in Germany. They point out that wind turbines 'interact with the power system in a way that differs from conventional generators' and suggest methods for analyzing and integrating large wind farms into national power grids.

(Harper and Thurston 2009) provide an excellent description of the environment facing an individual utility. They describe the decision process the utility faces as it attempts to match demand with capacity in a real-time environment. Of most interest to this paper is the development of a game theory approach to solve the problem of how to determine which generating assets to use at a given time. They present a scenario of a given set of generation assets such as gas turbines, hydro units, nuclear units, etc. each with a given capacity that can be switched on and off at a given node in an electricity grid. This paper presents a simulation representation of the decision scenario faced by grid managers.

Literature specific to wind power tends to focus on the concept at a macro level. Analysis of integrating wind into the power grid is looked at from a country or regional aspect primarily in terms of searching for upper bounds on the amount of electricity that can be generated from wind. Policy aspects of power generated from pricing and incentives to construct and operate wind power aspects are also presented from regional or political perspectives. Little if any literature exists on the operational aspects of integrating wind power into the electrical power grid from the perspective of a single utility serving a distinct customer region. Thus, this paper focuses on the issues of integrating wind power into the electricity generating system of a single utility and the development of a simulation-based solution framework for policy analysis.

3 ELECTRICITY GENERATION AND SIMULATION

Electricity demand in the United States continues to grow. This demand is erratic and cyclical, making it difficult for a utility to predict. Large spikes occur when the population wake up and return home from work. The intermittent use of appliances such as dishwashers, refrigerators, washers and dryers, and plasma television sets contribute to the variability in demand that a utility experiences on a minute by minute basis. Electrical load leveling policies are being investigated and in some cases incentivized by utilities as part of efforts to smooth out the load.

Electricity generation in the United States is a heavily regulated entity. Prices are generally set by local governmental entities and are essentially based on capital recovery principles over long time horizons based on the economic life of power plants. Utility companies generally serve a local base of customers that include both residential and industrial. The electricity generation capacity of a utility is generally sized according to the load they serve. Electric power is delivered via a set of transmission lines that are interconnected to form a national grid. When a utility cannot serve demand, it must 'buy' power off the grid. The ability to instantaneously 'buy' power essentially serves the classic function of inventory. The price of power bought off the grid is based on spot pricing and can be very costly for a utility, thus necessitating the careful matching of electric generation to demand.

For a local utility to cover its cost of capital and provide a fair return to its stakeholders within the framework of a regulated pricing structure, it must carefully match its generation capability to the market it serves. Coal fired power plants are economical on a large scale and can serve a large base load, but do not respond well to variable demand spikes. Gas-fired turbines are economical for short term reactions to demand spikes and are often matched to coal-fired operations to provide quick response capability. Thus, the key operational decision for a utility is when to vary the mix of output from its generation assets based on load variability. With a coal-fired plant and a gas turbine, the output can be controlled and managed. When a wind power asset is introduced to the mix, the decision-making process concerning generation mix becomes more complex.

Figure one graphically depicts a simulation model constructed of a local utility company. The right side of the screen depicts electricity demand entities representing commercial, industrial and residential sources. The left side of the screen depicts the electricity generating entities. In this model, a single coal-fired system is paired with a wind farm. The two bar graphs in the middle represent a real time view of the demand and supply of electricity and consist of summation of individual entity attribute values.

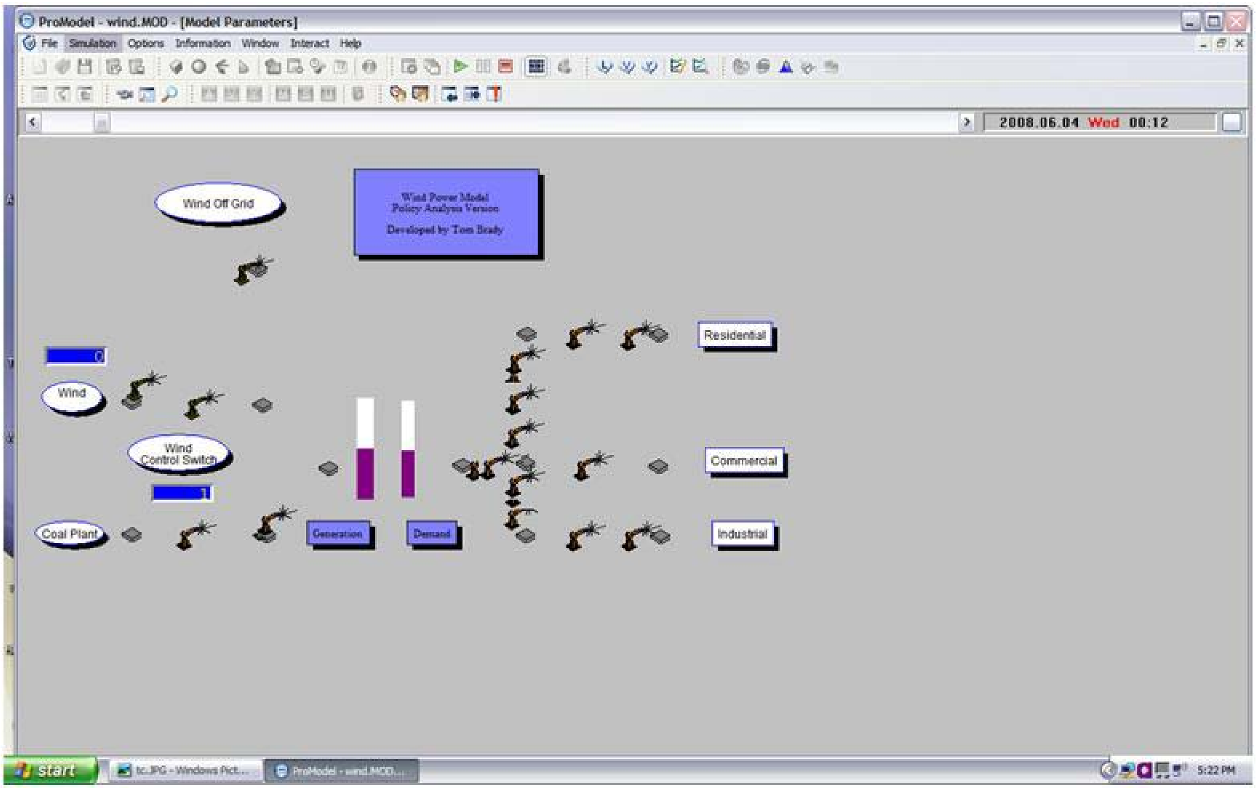

Figure 1: Electricity Generation/Consumption Simulation Model

The job of the utility dispatcher is to monitor the demand and supply situation and make decisions about when to ramp up or down the coal boiler, when to allow wind power into the system, and when to purchase electricity. The purchase of electricity is not currently modeled in this scenario. Internal to the model is a switch that controls the amount of wind power that is added to the "supply" side of the model. This switch, and the associated logic controlling it constitute the major decision variables of the simulation. The current logic simply monitors the difference between supply and demand of electricity. If the wind is blowing at a speed high enough to generate electricity and supply is lower than demand, the wind power is added to the supply side. If the supply is greater than the demand, the wind power is passed onto the grid at large or switched off. A second level of decision making will involve ramping decisions for the coal boiler that are related to the current status of the wind.

One of the most difficult aspects of modeling electricity systems is the representation of demand. Electricity demand is highly stochastic and localized. The local attributes of the market area with respect to the residential population, commercial entities, and industrial base all contribute to the variability of electrical demand. Furthermore, electricity demand variability exists on a second by second basis, with highly varying loads occurring seemingly at random. The author was able to obtain from the local utility a data file consisting of electrical demand captured at five second intervals for a period of six months. From a model validation perspective, the most accurate method of representing this demand in simulation format would be to read in the demand at five second intervals. However, this method would impact the run-time performance of the model. After an analysis of the data, the decision to represent the data for electricity demand to the simulation model in the form of a state transition matrix was made. Details of this approach are discussed later in this paper with respect to representing wind data. The transition matrices for electricity demand and electricity generation from a coal boiler are shown in Tables 1 and 2.

Table 1: Electricity Load Data

	-2	-1	0	1	2
-2	26.80%	51.00%	20.70%	1.10%	0.40%
-1	7.10%	42.50%	42.50%	7.50%	0.40%
0	1.30%	19.20%	51.40%	24.20%	3.90%
1	0.30%	4.70%	28.70%	44.40%	21.90%
2	0.00%	0.80%	7.20%	31.70%	60.30%

Table 2: Electricity Generation Data

	-2	-1	0	1	2
-2	11.60%	12.20%	17.50%	19.50%	39.20%
-1	14.10%	14.80%	16.00%	18.70%	36.50%
0	16.90%	12.80%	19.50%	18.90%	31.80%
1	18.10%	15.30%	18.60%	18.30%	29.70%
2	21.20%	15.50%	18.50%	17.40%	27.30%

The time horizon for the simulation model is six months, primarily due to the fidelity of the events and the quick transitions of the wind, demand, and generation data entities. The model is currently in the validation stage. Realistic, accurate decision making scenarios for the coal boiler ramping are also being developed. The utility being modeled has contracted for a given level of power from a wind farm currently under construction. Delays in the construction of the wind farm have extended the design and analysis phase of the simulation model.

Performance measures of interest in the model relate to the balance of electricity supply and demand. Constant ramping of the coal boilers exerts unwanted strain on the physical equipment and the coal handling systems supplying the boilers. Thus, the variability in coal boiler output is a key metric supplied by the simulation model. The most important performance metric generated by the simulation is the expected contribution of the wind power. While many engineering estimates exist, simulation provides the only means to generate an accurate estimate that takes into account the variability of demand, the wind speed, and operational decisions made about coal boiler ramping. Having a simulation model of this type will allow the utility to optimize its decision making concerning wind power integration from a total system perspective. This will allow them to make more informed, cost effective decisions about how to integrate wind power into their electricity generating portfolio.

4 REPRESENTATION OF WIND DATA IN A SIMULATION MODEL

Wind data is available in public domain format from numerous sources, including federal, state, and municipal governmental entities and television and radio stations. Figures 2 and 3 display wind speeds recorded at Michigan City, Indiana for January 1, 2007 and the entire 2007 year. This particular data set is provided by the US Coast Guard and is reported at five minute intervals. The wind speed reported is in miles per hour and represents the mean speed during the five minute interval. A cursory search of public domain wind data produced a range of collection times between five seconds and one hour. A majority of wind turbines being installed in the United States today require a sustainable four mile per hour wind speed to generate electricity. Most regions in the country will exhibit patterns similar to these. The magnitudes of the speed and the distances between the peaks and valleys determine the potential contribution of power to a given utility.

Within a simulation model, wind can be represented in detailed fashion as an entity in a subnetwork or simply as a global variable. In terms of validation, the most accurate method to represent wind in a simulation model is to use an external file of actual wind readings. When the time horizon of a given simulation model is in months or years, the sheer volume of processing a wind file with entries representing seconds or minutes can significantly impact the execution time of the model.

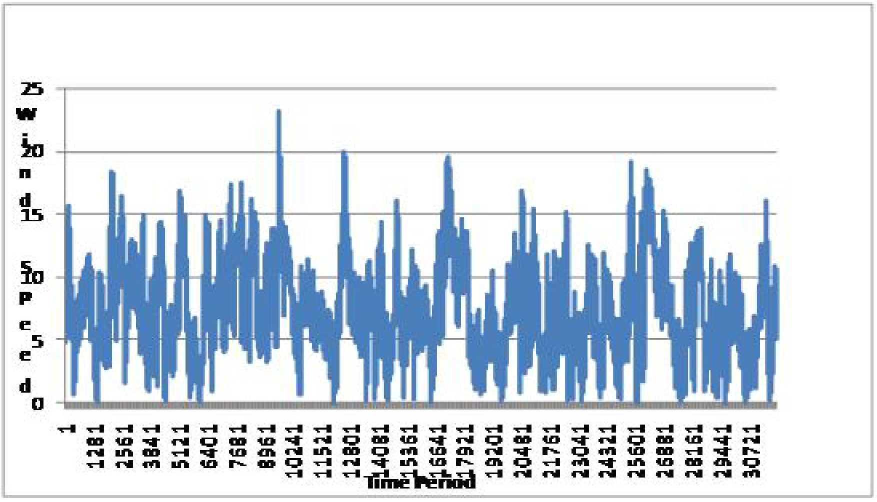

Figure 2: January 2007 Wind Speed in Michigan City, Indiana

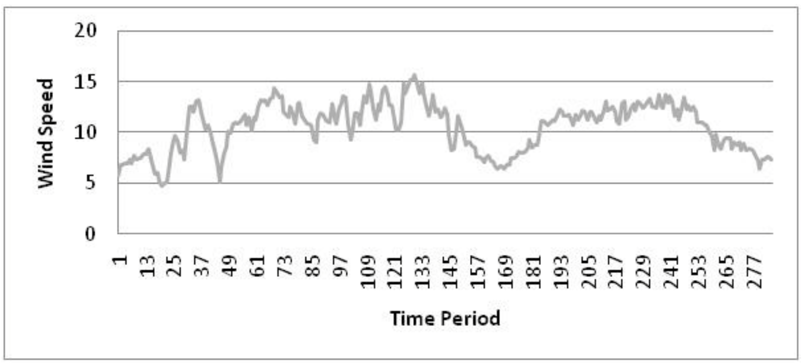

Figure 3: 2007 Wind Speed in Michigan City, Indiana

An alternative method of representing wind speed within a simulation model involves transforming actual wind speed data into a predictive equation using regression or time series models The accuracy and verification of this type of approach are directly related to the mean square error of the predictive equation. As the variability of the wind in the region modeled by the simulation increases, caution must be exercised by the analyst in using this method. If a good fit of the data can be achieved, the combination of a time series equation and the simulation time clock can be a very efficient method for generating wind data within a simulation model. (O'Neill 2007) and (Slootweg 2002) discuss the difficulties in developing accurate time series-based models from raw data.

Another method of representing wind speed within a simulation model is to fit the wind speed data into a discrete or continuous distribution using commercially available software. Extreme caution should be used if contemplating using this method. A histogram generated from the wind speeds shown in Figure 3 produced a nearly perfect bell curve. Repeated draws from this distribution on a periodic basis could lead to significant bias, particularly in a long run time model. Actual wind speeds ebb and flow liberally over time; thus the generation of an outlier from a distribution during a simulation run would not be representative of the real system.

When modeling wind speed as a component of a simulation model, the change in speed from one state to another should be the primary focus when developing a representation of wind. A simple, tractable method for accomplishing this is to use a state transition approach. Using this approach, the generation of a wind speed in a simulation model will more accurately mimic the true wind distribution over time. Table 3 illustrates a state transition matrix that was developed from the wind data displayed in Figure 3. State 0 represents the average wind speed while the other states represent deviations from the average. The interval for each state is 2 mph. The intervals and the average were determined from a statistical analysis of the most recent yearly wind data for the region. A two step approach is required to implement this technique for generating wind status within a simulation model. Global variables representing wind speed and current state must be declared and updated on a periodic basis. The update interval must be related to the frequency of the wind data set. Step one requires updating the current state of the wind. A random number can be generated and parsed according to the transition matrix and the current state updated to the new state. The wind speed variable can then be set to the average wind speed for the state plus an error term. This error term can be a random variable representing the standard deviation of the overall change in wind speed.

Table 3: Wind Speed Transition Matrix

	-2	-1	0	1	2
-2	5.78%	9.56%	26.89%	31.08%	26.69%
-1	1.45%	6.42%	30.40%	44.59%	17.14%
0	0.24%	2.59%	45.53%	47.48%	4.17%
1	0.31%	3.86%	48.40%	44.49%	2.94%
2	3.78%	15.62%	42.78%	29.97%	7.85%

5 CONCLUSIONS

As consumer demand for electricity increases and society demands for greener electricity production intensify, wind power is emerging as a popular alternative. Due to the enormous demand for electrical power, wind generation sources will never replace conventional forms of electricity production. Thus, utilities are challenged to integrate wind farm power into their generation assets and continue to provide uninterrupted power to their customers.

This paper discussed the electricity generation environment and showed how a simulation model can provide an analysis framework to support the optimization of operational decisions concerning the integration of wind power into a single utility company's electricity generation network. The model can be used provide boundary conditions on the decision to switch the contribution of wind and coal boiler generation modes. The optimal switching control policy will be a function of the wind patterns, fuel costs, generation asset mix, and market demand conditions for the given region.

This paper also discussed how to convert raw wind data into representations that can easily be implemented in simulation models. A logical extension of this paper will involve sensitivity analysis of the decision making parameters as well as the integration of other forms of electricity generation. This will require an expansion of the decision logic. An interesting extension to the model would be the optimal sizing of a wind farm.

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AUTHOR BIOGRAPHY

THOMAS F. BRADY is the Department Chair of Engineering Technology at Purdue University North Central;. He received his Ph.D. in Industrial Engineering from Purdue University. His research interests include simulation optimization, large scale systems simulation, and modeling methodology. He is a member of IIE, INFORMS, and SABR. His email is <tbradyjr@pnc.edu>.