

Wind Energy and Power System Inertia

Lisias V. L. Abreu, *Member, IEEE* and Mohammad Shahidehpour, *Fellow, IEEE*

Abstract—Wind is an abundant, clean, robust, and compelling resource for generating electricity. It has also become the fastest growing type of renewable generation in the United States. However, the low inertia of a wind-dominant power system could be troublesome in power system operation. This paper presents reasons that make wind energy an important energy source in electricity markets. It also discusses suitable markets for wind energy, means of improving the wind energy combined with flywheel, and financial aspects of pricing the reliability of wind farms.

Index Terms—Wind energy, electricity restructuring, power system operation, system dynamic stability.

I. INTRODUCTION

THE wind energy generation units evolved from small and isolated units to large-scale facilities which are interconnected with the power grid. Whether a wind turbine generator (WTG) is large or small, stand-alone or grouped as wind farms, the penetration of wind energy in the electrical grid is increasing rapidly. Today, the commercial capacity of WTG is up to 5 MW and the power industry envisions future wind farms beyond 1,000 MW. Figure 1 shows that wind energy in 2005 exceeded 9 GW of installed capacity with an average annual growth rate of 27% [1]–[4]. The European Wind Energy Association (EWEA) believes that by 2020, wind energy could provide 6% of US electricity which is a share similar to that of today’s hydroelectric generating plants [5]. The engineering issue is whether the presence of wind generation significantly changes the average inertia of power

systems. Of course, the exact answer to this problem is subject to particular characteristics of individual power systems. One way to address the problem with inertia is to combine wind energy with high inertia energy storage systems. Improvements in the flywheel energy storage (FES) technology have demonstrated that it is especially appropriate to combine other technologies with wind energy to manage power system inertia [6]–[10]. Using kinetic energy as storage, the FES technology offers high steady inertia and good efficiency which improves the power quality and allows wind generators to participate in ancillary services markets.

The issue with inertia could also be handled by electricity price which is driven by frequency. Any sudden decline in generation will increase the market price temporarily. A faster frequency drop, e.g., after a major contingency, could cause a spike in price. However, the wind energy participation in energy markets could be limited by the price of wind energy as an intermittent supply and the willingness of market participant to pay for wind energy to replace peaking units. This paper discusses the reasons that make wind energy the fastest growing energy source in the world. It also presents markets that wind energy is suitable for nowadays. Furthermore the paper shows how WTG can be successfully combined with energy storage systems. At last, the paper discusses advantages and disadvantages of turning the WTG inertia into a market problem.

II. WIND ENERGY BENEFITS

The following items discuss wind energy as an attractive power generation technology.

A. Environment

Wind energy offers many advantages which explain why it is the fastest growing resource for electric power generation in the world. Wind energy is safe, clean, and abundant. Unlike coal, gas, oil and nuclear fuel, wind energy produces no emission such as carbon dioxide or hazardous waste. In addition, wind energy helps reduce the environmental damage and climate changes caused by fossil power generation. In 2004, wind power generation worldwide saved 63 million tones of carbon dioxide, the main greenhouse gas [11]. Unlike conventional technologies, environmental impacts of wind energy are relatively small. Problems with wind energy such as noise, visual impacts, erosion, birds and bats killed, radio interference, and TV shadow flicking were greatly reduced by introducing technological developments and properly siting of wind plants.

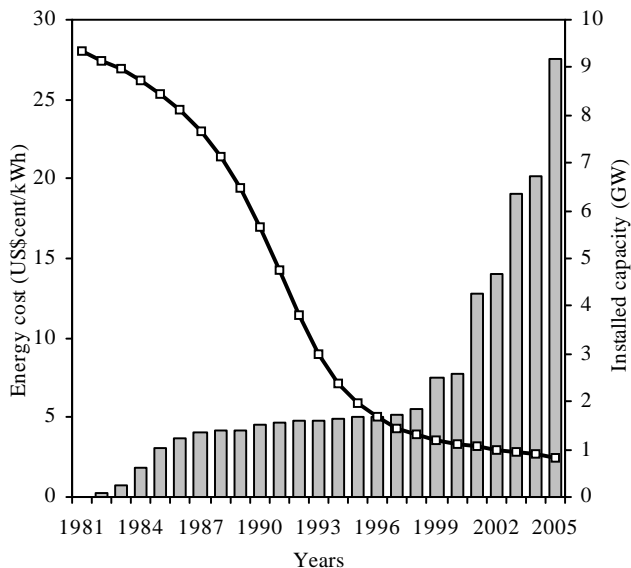


Fig. 1. U.S. wind installed capacity and average energy cost. Sources: DOE & AWEA 2005

B. Economics

Wind energy has always been clean and renewable but not a cost-effective source of power generation. According to the U.S. Department of Energy (DOE) and the American Wind Energy Association (AWEA), in the last 25 years, the cost of generating electricity by wind has dropped by 90% due to technological advances and financial incentives such as renewable energy production tax credit (PTC) and renewable portfolio standards (RPS). The new provisions turned wind technology into one of the most affordable types of renewable energy and very competitive with coal and gas-fired power plants.

Recent WTG technologies made the generator size grow from 10 kW (five meter rotor diameter) to more than 5,000 kW (more than 120 meter rotor diameter). Since the total cost is expressed as a function of WTG's rated capacity, large scale systems are more cost-effective, with lowest costs per kW achieved by wind farms. Thus, in general larger turbines produce more energy in smaller land footage and reduced maintenance per MW capacity.

A wind system investment has three main components: purchased price of electricity, cost per kWh, and payback period. The purchased price of electricity is a market-based factor and depends, among others, on market characteristics and subsidies. The cost per kWh of a wind system includes initial installation costs (e.g. tower and turbine equipment purchase, foundation, wiring, utility interconnection equipment, delivery and installation charges) and operation and maintenance expenses. It may include additional energy costs for inflation, interests paid on borrowed money, insurance, utility buy-back, state and federal tax benefits, and wind turbine resale value.

When utility-scale turbines were installed initially, wind-generated electricity cost as much as 30 cents per kWh and with technologies available today, costs have dropped to 4 to 6 cents per kWh, depending upon the availability of wind resource and financing of particular projects [2]. It is important to note that the cost of wind energy varies widely depending upon the wind speed at a given project site. The energy utilized from wind is proportional to the cube of wind speed, so a slight increase in wind speed results in a large increase in electricity generation. Moreover government financial subsidies established to encourage the development of clean and renewable energy and diversification of energy sources have sensibly helped promote wind energy. In the U.S., tax credits such as the renewable energy production tax credit (PTC) and the renewable portfolio standards (RPS) motivated most of the U.S. new wind additions over the last few years.

At the federal level, PTC was approved in 1992 and extended through December 2007 before its expiration in December 2005. PTC provides 1.9 cents per kWh tax credit, with annual inflation adjustment provision, for electricity generated with wind turbines over the first ten years of operation. Meanwhile, states increased their promotion of wind energy through RPS and other incentives including loan

guarantees, grant programs, tax exemptions, net metering, and green-power purchasing programs. More specifically RPS required that an additional 1% of the nation's electricity come from new renewable energy sources by 2005 and increase slowly each year thereafter, until renewable energy provides 10% of the national electricity supply by 2020. It also required utility companies to have a percentage of renewable energy in their portfolios and sell it at a cheaper rate to customers.

C. Independency of primary energy source

Wind is the motion of air masses produced by the irregular heating of the earth's surface by sun. The earth's surface made of different terrain topographies, roughness, vegetation and water formations transfers the absorbed heat to the air causing local and global differences in the air temperature, density, and pressure. These differences consequently create forces that push air masses around for balancing the global temperature or, on a much smaller scale, the temperature between land and sea or between mountains.

In addition, wind is a renewable energy source because it is produced as long as the sun shines on the earth. It is a significant resource because it is free and abundant. Unlike conventional energy sources, wind is a virtually permanent and a domestic energy source in the United States which is also regarded as one of the largest resources in the world. With less dependence on fossil fuels, wind energy could bring more security by avoiding rapid price fluctuations, long term fuel price and supply risks as well as economical and political issues caused by the dependence on imports from other countries.

D. Modularity

Wind energy turbines (WTG) have come a long way since the prototypes of 25 years ago. Today's WTG are modern state-of-the-art technologies, modular and very quick to install. Turbine size ranges from a few kW to 5 MW and more. Wind energy has the innate characteristic of being modular which means WTG are separated modules that can be arranged, reorganized, replaced, interchanged and have their number lessened or increased easily within wind farms or distributed in the power grid. Most applications of WTG are in wind farms which can be installed as demand expands, thus reducing investment risk. They can be installed quickly if required in response to energy market conditions.

There are other benefits for having modular characteristics. Wind farms also have a relatively small probability of overall plant outages due to equipment failure. Furthermore, wind energy is very useful in remote areas where access to transmission lines is limited or in areas where transmission lines are congested.

III. WIND ENERGY MARKETS

Utilities would supply power plant capacity to meet expected customer demand at all times and maintain reserve margins. Even with wind forecasting uncertainties, wind energy has been traded in the following markets.

TABLE I
RTO'S SUGGESTED MARKETS FOR WIND ENERGY

Services Provided	PJM	MISO	ISO-NE	SPP	ERCOT	NYISO	CAISO
Bilateral transactions	■	■	■	■	■	■	■
Real-time market	■	■	■	○	■	■	■
Locational pricing	■	■	■	○	■	■	■
Hourly pricing	■	■	■	○	■	■	■
Congestion pricing	■	■	■	○	■	■	■
Loss pricing	■	■	■	○	■	■	■
Day-ahead market	■	■	■			■	
Locational pricing	■	■	■			■	
Hourly pricing	■	■	■			■	
Congestion pricing	■	■	■			■	■
Loss pricing	■	■	■			■	
Ancillary market	■	◆	■	◆	■	■	■
Regulation market	■	◆	■	◆	■	■	■
Capacity market	■		■			■	◆

■ Existing ◆ Cost-Based ○ Projected for 2006

A. Retail Markets

The 1978 Public Utility Regulatory Policy Act (PURPA) requires utilities to connect with and purchase power from small wind energy systems. Wind power suppliers may sell power directly to local utilities. Additionally, retail wheeling markets allow wind power suppliers to supply electric energy to customers which are located beyond local utilities' operating region. Wind plants will then be connected to local utilities' transmission or distribution systems for delivering electricity to end users in other electric utilities' retail service territories.

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The energy market is operated much like a stock exchange, with market participants establishing a price for electricity by matching supply and demand. This market uses locational marginal pricing that reflects the value of energy at specific locations and times for delivery. If the lowest-priced electricity can reach all locations, prices will be the same across the grid. When there is transmission congestion, energy cannot flow freely to certain locations. In that case, more-expensive electricity is ordered to meet the demand. As a result, locational marginal price (LMP) is higher in congested locations.

The day-ahead market is a forward market for electricity to be supplied hourly in the following day. The next day hourly LMPs are calculated based on generation offers, demand bids, and scheduled bilateral transactions. It is expected that the

day-ahead wind forecast will have a mean absolute error of 10-15% of the wind farm rated capacity [12]. Wind energy suppliers may participate further in this market as wind forecast accuracy continues to improve.

The real-time market determines the energy price during the delivery day for one hour or less periods. It balances power errors between the day-ahead schedule and the actual load. Based on actual grid operating conditions, LMPs are again calculated for these time intervals with an expected mean absolute error of 5% [12]. Wind energy suppliers participate in this market as well since the one-hour-ahead wind forecast accuracy continues to improve.

C. Capacity Credit Market

The capacity credit market design allows wind power suppliers to sell uncommitted capacity as well as additional dispatch production of energy. Capacity credit market participants submit bids to buy or offers to sell indicating maximum amounts and prices that they are willing to pay. The market operator processes bids and offers by clearing the auction-based market at a capacity clearing price. Then market participants will be designated to produce or consume certain amounts of energy in given periods of time. Wind energy producers are able to participate in this market since they can commit their production as long as necessary.

D. Ancillary Services Markets

Ancillary services are the support for the reliable operation of power systems. Under normal conditions, regulation and load following are the two services required to continuously balance generation and load. Basically, a positive or negative difference of generation and load plus losses will be reflected in the respective decrease or increase of nominal system frequency. Thus, regulation is represented by momentary adjustments of certain electric generators or loads equipped with Automatic Generation Control (AGC). In interconnected systems, regulation helps maintain the 60 Hz interconnection frequency, manage differences between actual and scheduled power flows among control areas, and match generation and load within a control area. Load following is the use of electric generators or loads to follow hourly load fluctuations.

Modern wind farms are capable of providing instantaneous reserves as long as the wind blows and thus participate in regulation markets. Most of wind farms could participate in load following markets and others participate in supplemental reserve markets, subject to improvements in the dynamic performance of wind-based systems. The following sections of the paper will discuss how a combination of wind energy and flywheels with better market rules could make electricity markets, such as ancillary services, attractive to wind suppliers.

IV. WIND ENERGY IMPACTS ON SYSTEM INERTIA

The issue of inertia is particularly important for high wind power penetration levels in synchronized systems. System inertia can be defined as the total amount of kinetic energy

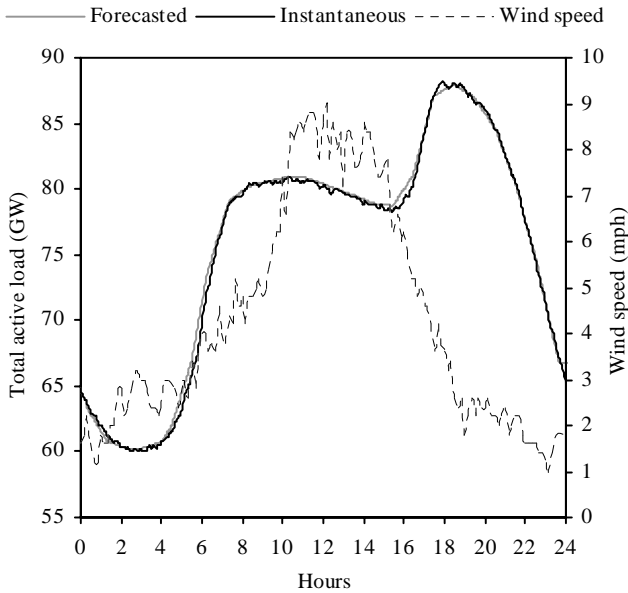


Fig. 2. Forecasted load and instantaneous demand in the PJM Interconnection area and average wind speed in Pittsburgh-PA in a typical winter day. Sources: PJM and NOAA's National Weather Service 2005

stored in all spinning turbines and rotors in the system. When an unbalance occurs between generation and demand, the inertia would limit the rate of change of frequency. The rate of change of frequency is very important because a slower change in frequency guarantees sufficient response time for controllers due to frequency unbalances.

Wind speed varies in all time scales with particular effects on power systems. For the operation of power systems, large-scale wind power production variations from day to day, hour to hour, and minute to minute are of critical importance. Wind gusts cause second to minute variations with sufficient time for frequency control. Weather pattern variations can be included in the hourly wind power production for real time load following. Daily cycle, seasonal cycle, and annual variations provide proper time scale for day-ahead scheduling.

It has been observed that standard fixed speed wind turbines with directly connected generators contribute to power system inertia with the inertias of generator and wind turbine rotor. On the other hand, standard variable speed wind turbines control grid power independently and thus decouple the generator torque from grid frequency. This gives variable speed wind turbines virtually zero inertia in power systems. Since most wind turbine generators are connected to the grid based on non-synchronous interfaces, e.g. power electronic converters, frequency deviations of power systems will be directly correlated with wind variations [13]–[15].

The high impact of intermittent wind energy generation has already been reported by certain control areas where there is a direct correlation between larger frequency deviations and larger amounts of wind in the system [16]. The frequency deviations are smaller when less wind is on the system and deviations increase as more wind is placed on the system. Thus, from the dynamic stability point of view, the penetration

of wind energy is characterized by smaller damping and inertia constants of the grid. With high penetration of wind power, the system will be unable to absorb unbalances due to the intermittent nature of wind without risking the stability, power quality, or frequency control. This lower system inertia promotes opportunities for storage systems, such as flywheels, to be combined with wind farms in system operation. Among other strategies for increasing system inertia is the implementation of a pricing mechanism that would drive investments on generation storage systems or other generation units with higher inertia.

V. WIND ENERGY AND FLYWHEEL

Wind power may supply electrical energy to a grid with environmental and economical benefits, fuel independency, and higher modularity characteristics, but it cannot ensure itself as a continuous supplier of electricity. The following paragraphs will show how wind system inertia can be improved with flywheels technology and how it influences the wind participation in energy and ancillary services markets.

No individual power plant is totally reliable and a wind farm alone may not be at the desirable reliability levels. For instance, a wind plant may not be able to supply a scheduled amount of load due to an unexpected shortage of wind nor sell energy in the real-time market due to sudden increases in demand. Likewise, a wind plant will not be able to store energy due to additional wind or an unexpected drop in system demand. Combining wind turbine generators with flywheel technology could provide a means for storing the surplus energy and improve wind plant's inertia. In other words, it could result in a smoother output, preventing instantaneous power oscillations due to unexpected wind variations, which wards off some risks of energy markets and allows power plants to participate in ancillary service markets.

After a contingency, the wind system inertia on the grid may not stabilize the frequency in the same way as that of synchronous generator. Even with larger size wind turbine generators and larger blade lengths, which could result in higher inertia, one cannot count on such units to maintain or improve the system inertia [17]. Consequently, penetration of

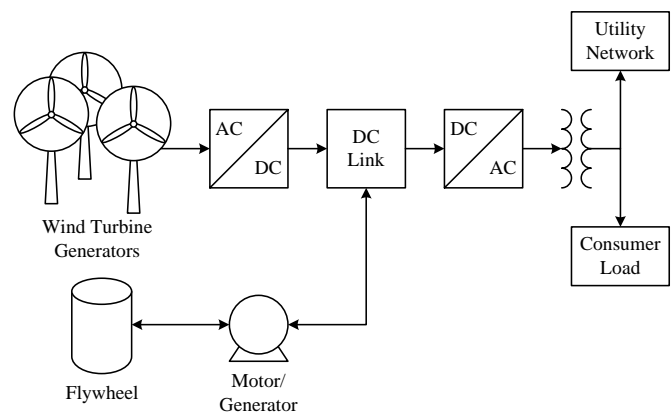


Fig. 3. Wind turbine generators and flywheel energy storage system

wind turbine generators could significantly affect the power system inertia. Although wind generator technologies can support speed governing output control, it may be difficult to add this technology to wind facilities already installed and not designed specifically for speed governing. And more, the actual wind turbine generator control systems do not respond to the frequency drop by increasing its output. Thus, the capabilities of wind turbine generator to bring frequency back up to nominal value rapidly could be very limited. These problems make flywheel energy storage (FES) systems very suitable for combining with wind turbine generators.

A flywheel system is a kinetic spinning mass rotating at very high speeds (more than 20,000 rpm) coupled to a motor/generator (see figure 2) to store energy that is instantly available when needed. It draws electrical energy from a primary source, e.g. electric grid, and stores it in a high-density rotating flywheel. The rotating mass slows down as energy is drawn from FES, and speeds up as FES is charged. Flywheels compete with other energy storage technologies such as superconducting magnetic energy storage systems (SMES) for power applications requiring units of MW capacity for one or two seconds, and batteries in power applications when the backup time needs to be longer than 15 seconds.

The first commercial flywheel proposed in 1973 was a 10 MWh directly connected to power grid which stored kinetic energy when spinning at very high speed [18]. The proposal could not be implemented due to the dynamic stability and structural integrity of rotating mass in very high speeds. Even with huge potential markets for flywheels, e.g. wind energy applications, the largest available flywheel is around 400 times smaller than the one proposed in 1973. However, research is being carried out all over the world to enlarge the commercial flywheel capacity [19].

The application of flywheel energy storage systems with wind turbine has never been more appropriated. This combination allows wind energy suppliers to participate in ancillary services markets, e.g. spinning reserve market. In addition, no spinning reserve requirements have been explicitly established for wind generation yet. The adoption of flywheel technology by wind energy suppliers could definitely mitigate the risk of bidding into energy and ancillary services markets by reducing power output oscillations due the unpredictable wind characteristics.

VI. FREQUENCY BASED PRICING

The dynamic performance problem of the combination of wind farms with flywheels could be managed as a market issue. The economical and physical constraints of a combined wind and flywheel have generally been treated in disjointed processes. Power generation and consumption in power systems will change steadily to maintain a normal frequency. Accordingly, market prices would fluctuate based on market demand for energy. The link between economics and demand equilibrium can be improved by varying the real-time market

price corresponding to instantaneous system needs using the concept of wide open load following (WOLF) [20].

The WOLF pricing is illustrated in Figure 3. In frequency based pricing scenarios, power imbalances will force electricity prices up or down temporarily. As an example, wind power generation is priced at 10 \$/MWh once the market is cleared at 60Hz. An unexpected increase in the load would make the frequency decrease to 59.98 Hz and the price to go up temporarily to 25 \$/MWh. Accordingly, wind energy producers will have to make a decision for participating in this risky market or in other markets that are economically more stable.

The market-based strategy would drive up investments on wind energy in power systems. Allowing prices to be driven by frequency will improve reliability indices and customers and generators can then make operating decisions based on dynamic prices. The decisions will affect reliability indices which will affect the price [21]. Thus, pricing will provide another feedback to improve the reliability and the economics of the electric industry.

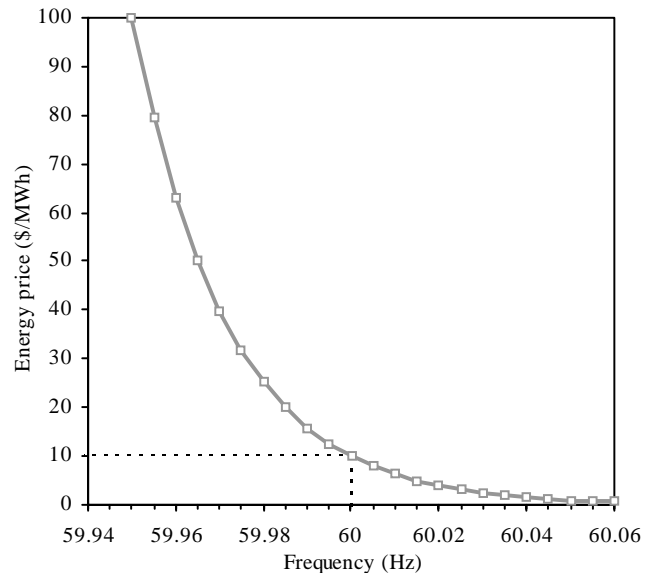


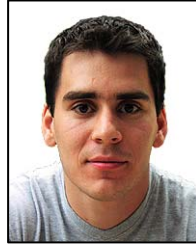
Fig. 4. Exponential curve used by wide open load following to turn the wind inertia problem into a financial issue

VII. CONCLUSION

This paper discussed issues like environmental, economical, fuel independency and modularity benefits that make wind energy the fastest growing energy source in the world. It also presented that the retail, energy, capacity credit and ancillary services markets are suitable for wind energy. Additionally, the paper showed that wind turbine generators can be successfully combined with flywheel energy storage systems. At last, the paper discussed how the dynamic performance of the system can be improved by turning the inertia deficiency problem into a financial issue.

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Lisias V. L. Abreu (M'05) received the B.S. degree from Universidade Federal de Goiás, Goiânia-GO, Brazil, in 2003 and M.S. degree in electrical engineering from Universidade Estadual de Campinas, Campinas-SP Brazil, in 2005. Presently, he is working toward the Ph.D. degree at Illinois Institute of Technology, Chicago, IL USA. His research interests include renewable energy, power systems restructuring and reliability. He can be reached at <http://www.ece.iit.edu/labreu>.



Mohammad Shahidehpour (F'01) is a Full Professor in the Electrical and Computer Engineering Department and Director of the Electric Power and Power Electronics Center at the Illinois Institute of Technology (IIT), Chicago. He can be reached at <http://www.ece.iit.edu/ms>.