BENEFITS OF ENERGY STORAGE IN POWER SYSTEMS WITH HIGH LEVEL OF INTERMITTENT GENERATION

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ABSTRACT

The world has witnessed increasing growth in wind power in recent years. In 2007, the UK government unveiled a plan for what could be one of the most ambitious expansions in wind power generation the world has ever seen. Through construction of hundreds of offshore turbines, the country hopes to power the equivalent of all the UK's homes by 2020. However, a major problem associated with wind power is its intermittency. Even if it were predictable, it is still difficult to match the generation with demand. This paper focuses on the adoption of energy storage to alleviate the intermittency problem and the extra value which energy storage would add by capturing the wind power during times when transmission lines are congested and transmitting it at other times.

In the paper a methodology is proposed to analyse the ability of energy storage to accommodate the intermittency of wind power generation. The model helps estimate the amount of wind energy that would have to be curtailed and the amount of electrical demand would have been left unsatisfied by using wind power alone. By reviewing a number of reports on development and integration of large scale energy storage in power system, the paper concludes that it is important now for the relevant regulator to develop a mechanism to encourage investment in energy storage. However, the development of such a mechanism requires a clear understanding of the benefits of energy storage, and the level of such benefits in monetary terms. In this paper, models for quantifying the technical, economic and environmental benefits of energy storage in an example power system with high level of wind power generation have been developed. Simulation results based on the model power system show that energy storage is able to mitigate power fluctuation and improve the wind plant capacity factor.

INTRODUCTION

The world has witnessed increasing growth in wind power in recent years. In 2007, the UK government unveiled a plan for what could be one of the most ambitious expansions in wind power generation the world has ever seen. Through construction of hundreds of offshore turbines, the country hopes to power the equivalent of all the UK's homes by 2020. However, the integration of wind power to power systems is confronted with many challenges, including reduction or elimination of power fluctuations, maintaining power quality and voltage profile when connecting to weak grids, prediction of wind power, and changes in the way conventional power plants are operated. The intermittency of wind power may cause imbalance between local power demand and power generation. This in turn may lead to adverse voltage variations and other effects. Feasible solutions dealing with the wind power intermittency problem include better wind forecast and introduction of energy storage systems (ESS). The wind forecast, although much improved, still suffers from problems such as complexity and poor accuracy. The use of energy storage as a power and energy buffer, on the other hand, can smooth the power output fluctuations. Energy storage has been considered as a solution for improving power flows from wind turbine generator, and can potentially make wind a more viable and competitive energy resources.

Cardenas [1] and Kinjo [2] proposed various topologies for the direct pairing of wind power and energy storage technologies. Barton [3] studied the use of energy storage in countering the voltage rise effect. Korpas [4] considered scheduling the storage devices to limit the amount of dump wind energy in a constrained interconnection. Garcia [5] studied energy storage from the point view of sizing and operation to improve the energy penetration of wind in a remote network. Black and Strbac [6] studied the technical and economic implications of wind power and the value of energy storage as a kind of reserve. In conclusion, a great deal of work has been carried out in order to better integrate energy storage into wind power generation system. However, so far few researchers have attempted to analyse systematically the benefits of the adoption of energy storage in mitigating the intermittency of wind generation.

In this paper, a methodology is proposed to analyse the benefits brought by integrating energy storage to wind power system. A comparison study based on various load models is also carried out to better determine the power rating and energy capacity of energy storage. Results are summarised and discussed based on the simulation of a sample power system.

WIND POWER GENERATION

A. Wind power model

The wind distribution can be described mathematically by a typical Weibull distribution. A random variable *v* has a Weibull distribution if its probability density function (pdf) is defined by Equation (1) as follows [7],

$$f(v,c,k) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k}, v>0, c>0, k>0 \qquad (1)$$

Where c is a scale parameter with the same units as the random variable and k is a shape parameter.

Several methods can be used to estimate the Weibull parameter k and c, depending on the required level of sophistication in data analysis. Here the Least-squares Fit to Observed Distribution Method has been employed to calculate the Weibull parameter for a set of wind data during a winter month, as shown in Figure 1, in the Glasgow (Scotland) region. The results of k and c are given in table I.

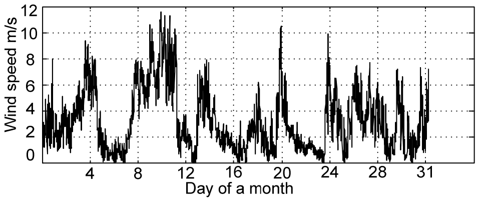


Fig. 1 Wind speed in a typical winter month

Table I Weibull distribution parameters in Scotland (2007)

shape parameter, k	scale parameter, c/ms^{-1}
1.4636	5.428

B. Intermittency

Electricity generated from wind power can be highly variable from hour to hour, from day to day and from month to month. Annual variation also exists, but is not considered as significant. Because instantaneous electrical generation and consumption must remain in balance to maintain grid stability, this variability can present substantial challenges to incorporating large amounts of wind power into a grid system. Intermittency and the non-dispatchable nature of wind energy production can result in higher costs associated with regulation of voltage and power flow. It contributes to requirement for higher operating reserve. At high penetration levels, it could also cause problems to the existing energy demand management, load shedding, or storage.

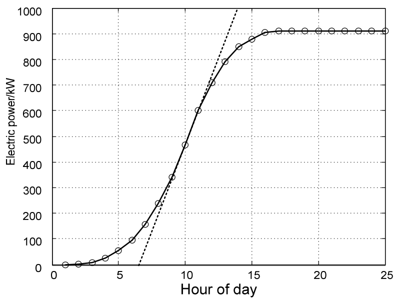


Fig. 2 Electric power output

Fig. 2 shows a typical power curve of wind turbine with a rating of 900kW. It is found the power variation is 153.8kW when there is a 1 m/s change in wind speed at around 10m/s.

C. Mathematical model

The electric power output of a wind turbine is primarily a function of wind speed, as shown below [8],

$$P_w(v) = \begin{cases} 0 & 0 \le v < v_i \\ P_r \dfrac{v^k - v_i^{\,k}}{v_r^{\,k} - v_i^{\,k}} & v_i \le v < v_r \\ P_r & v_r \le v < v_0 \\ 0 & v_0 < v \end{cases} \qquad (2)$$

Where v_i is the cut-in wind speed, v_r is the rated wind speed, v_o is the cut-out wind speed and P_r is the rated electrical power.

ENERGY STORAGE

A. Energy storage technologies

The storage of electrical energy can take place in different ways, i.e. it can be stored as chemical, mechanical or electrical energy. A summary of the characteristics of a list of main long-term duration energy storage technologies is shown in table II [9],

Table II Characteristics of long-term duration energy storage

Characteristics	Technologies			
	Pumped storage	Redox Flow batteries	Compres sed air	H_2 fuel cells
Power(MW)	30-3000	<100	100-3000	<50
Energy(MWh)	<10000	<500	50-5000	--
Efficiency	80%	60-90%	75%	20-40%
Life-time	40 years	10^3-10^4 hours	30 years	10^4 hours
Cost(£/kWh)	21-42	39-60	6-42	--

B. Benefits

The integration of energy storage into wind power generation system could increase system operation efficiency, enhance wind power absorption, achieve fuel cost savings, and reduce CO_2 emissions.

Energy storage provides additional flexibility for the system: at times of low load, energy storage may be used to increase the overall system load by storing energy, whereas the stored energy can be released to the system at times of high load. From a market perspective, this means that energy will be stored at times of low prices (usually low load) and being sold at high prices (usually peak load). Fig. 3 shows the use of energy storage in wind power generation system.

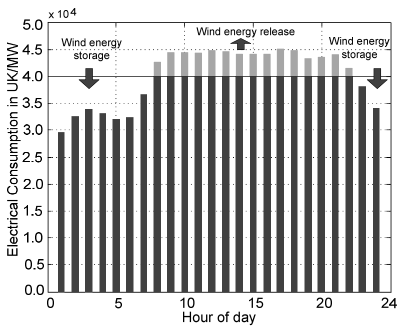


Fig. 3 Impact of energy storage on wind power generation

C. Mathematical model

Since the purpose of this research is to evaluate the ESS performance on a wind farm level, fast transient characteristics of a particular ESS technology is neglected and a generic ESS model is given as,

$$W_{ESS}(t) = \int_0^t P_{ESS}(u)du + W_{ESS}(0) \qquad (3)$$

Where, P_{ESS} and W_{ESS} are the ESS power and energy which are confined by the physical limits, i.e. the ESS ratings. Power losses are also neglected.

CASE STUDY

A. Storage capacity estimation

In order to analyse the benefits of energy storage, the power rating of storage devices should be determined first. Rating of an energy storage system actually includes two elements: "power rating P" (MW) and "energy rating E" (MWh). "Power rating" is the rating of the power conversion unit, while "Energy rating" is the rating of the storage unit. Figures 4 to 6 show the storage capacity requirements to maintain the power balance between wind power and load demand. Figure 7 shows an approximate daily variation in the electricity price in Scotland. The load has been modelled by three categories: constant load, three-level (peak, middle, off-peak) load and actual load model. It can be observed in figure 4 to 6 that load model plays an important role in determining power rating of energy storage.

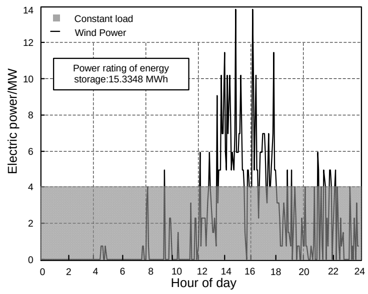


Fig. 4 Energy storage with constant load model

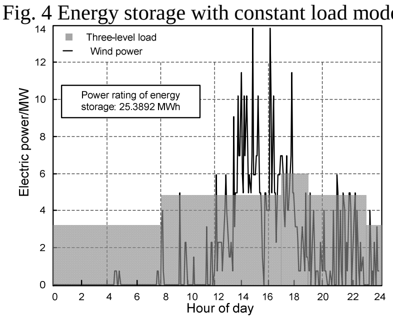


Fig. 5 Energy storage with three-level load model

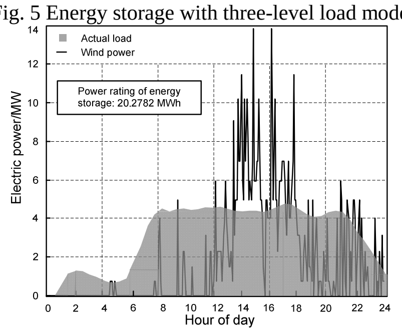


Fig. 6 Energy storage with actual load

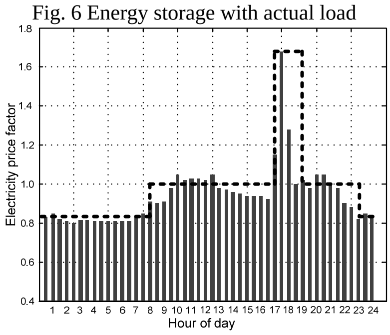
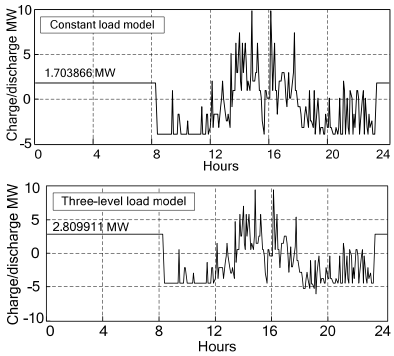


Fig. 7 Electricity prices



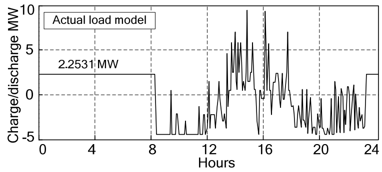


Fig. 8 Energy exchange in storage devices with three load models (+ charging, - discharging)

Figure 8 shows the state-of-charge dynamics of the energy storage in a four-minute time scale, i.e. charging and discharging during off-peak and peak hours, respectively, based on the abovementioned three load models.

Table III Operation of the power system with wind power and energy storage

Load	Source	Energy exchange/MWh		
		constant load	three-level load	actual load
off-peak load 0.00-8.00	Buy electricity & charging	46.554	51.6968	46.825
middle load 8.00-13.00	Discharging	15.028	17.2092	17.229
middle load 13.00-17.00	Charging	11.347	7.9683	9.146
peak load 17.00-19.00	Discharging	2.275	4.9237	2.15919
middle load 19.00-23.00	Discharging	9.3788	11.124	10.03596
off-peak load23.00-24.00	Buy electricity & charging	3.04665	2.4452	2.4491
Cost/£		1984.026	2165.492	1970.926
ESS capacity/MWh		15.3348	25.3892	20.2782

B. Analysis of benefits of energy storage

The application of ESS to wind power can bring many benefits to both power grids and wind power developers. The grid benefits from more friendly wind farms while the developers benefit from increased wind power revenues. In this paper, the benefits of energy storage is modelled as follows,

$$X_{PRO} = X_{SAV} + X_{GEN} + X_{TEC} + X_{EN} - X_{COST} \tag{4}$$

Where,

X_{PRO} Overall benefits of energy storage, £/year

X_{SAV} Benefits of saving and integrating an amount of wind power into existing power system that otherwise not integrated, £/year.

X_{GEN} Benefits result from avoiding the need to add other generation sources, £/year

X_{TEC} Benefits result from improvement in power system performance with wind power due to presence of energy storage, £/year

X_{EN} Revenue related to environmental benefits, £/year

X_{COST} Total cost of energy storage, including capital cost, O&M costs, etc.

Figure 9 shows a typical rural distribution system, with integration of wind turbines and energy storage devices. Details of the system is presented in [10],

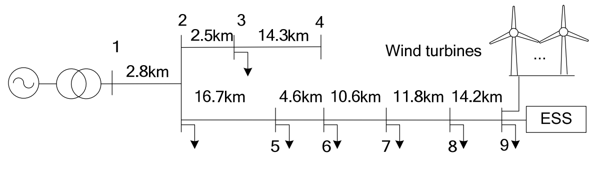


Fig. 9 One-line diagram of a sample distribution system

It is assumed that the wind generators are connected to the end of the distribution feeder. The capacity of the wind turbines is 15 MW (1.5 MW GE wind turbine×10), capacity factor is 0.2423. Wind speed data adopted here is from the measured data in Scotland. For simplicity, the loads are assumed to be proportional to the average national load. The local network is believed to have a greater proportion of domestic and agricultural premises than the national average. Table IV summarises the cost information and other parameters of the energy storage employed here.

Table IV ESS Data

Item	Value
Discharge energy price £/MWh	50
Energy related cost £/MWh	1,500
Balance of plant cost £/MWh	25,000
Fixed O&M cost £/MWh.year	1,250
Charge/discharge efficiency	86.5%
Life time year	20

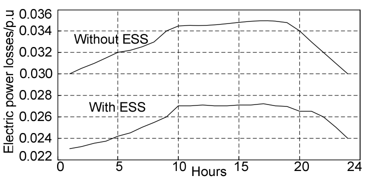


Fig. 10 Electric power losses with/without energy storage

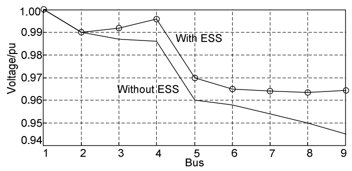


Fig. 11 Voltage profile with/without energy storage at peak load

Figures 10 and 11 show the average daily losses and voltage profile at peak load, respectively. Since the losses of a distribution system can be expressed as a function of the current flows over time, which is in turn a function of load and generation. Storage could provide flexibility to adjust these two parameters by shifting either load or generation to other times of the day. Energy storage helps to shift wind and load between different periods thereby help to improve the voltage profile.

The overall benefits of energy storage is therefore calculated by equation (4), $\boldsymbol{X_{PRO}}$ = £ 3,045/year. The figure should be significantly higher if the ROC incentives are included.

Where,

X_{SAV} = Energy price(£/MWh)×Discharged energy by storage devices (MWh).

X_{GEN} = energy prices of the avoided plant × ESS power ratings.

X_{COST} = fixed charge rate × total capital cost of ESS(£) + fixed operation and maintenance cost (£/MW.year).

The ESS operation follows the following scheme,

1. During any time period, the surplus wind farm power is diverted into the storage,
2. During any time period, where there is a power deficit, the stored energy is released from the ESS.

CONCLUSIONS

This paper proposed a methodology to analyse the benefits of energy storage in wind power generation system. The problem was formulated based on, and the prospoed methodology was applied to, a typical rural distribution feeder with wind generators. The benefits were obtained from the calculation based on actual measured wind data. Results show that energy storage has the potential to improve system operational performance such as reducing power loss and improving voltage profile in the case of high penetration of wind generation.

It is also concluded that load models play an important role in determining the power rating/capacity of storage devices. It can be concluded from the investigation that it is important now for regulators to develop a mechanism to encourage investment in energy storage. The paper indicated clearly that it is already financially viable to have energy storage systems when penetration of wind generation is high and the financial benefits should improve if the price of energy storage falls as anticipated and ROC incentives are included.

REFERENCE

[1] R. Cardenas, R. Pena, G. Asher, and J. Clare, 2004, " Power smoothing in wind generation systems using a sensorless vector controlled induction machine driving a flywheel ", *IEEE Trans. Energy Conv.*. vol. 19, 206-216.

[2] T. Kinjo, T. Senjyu, N. Urasaki, H. Fujita, 2006, "Output levelling of renewable energy by electric double-layer capacitor applied for energy storage system", *IEEE Trans. Energ. Conv.*. vol. 21, 221-227.

[3] J. P. Barton and D. G. Infield, 2004, " Energy storage and its use with intermittent renewable energy ", *IEEE Trans. Energy. Conv.*. vol. 19, 441-448.

[4] M. Korpas and A. T. Holen, 2005, "Operation planning of hydrogen storage connected to wind power operating in a power market ", *IEEE Trans. Energ. Conv.*. vol. 21, 742-749.

[5] R. S. Garcia and D. Weisser, 2006, " A wind-diesel system with hydrogen storage: joint optimization of design and dispatch ", *Renewable Energ.* vol.31, 2296-2320.

[6] M. Black, G. Strbac, 2007, "Value of Bulk Energy Storage for Managing Wind Power Fluctuations", *IEEE Transactions on Energy Conversion.* vol.22, 197-205.

[7] Stevens MJM, Smulders PT, 1979, "The estimation of the parameters of the Weibull wind speed distribution for wind energy utilization purposes", *Wind Engineering*. vol.3, 132-145.

[8] B. M. Jatzeck A. M. Robinson D. O. Koval, 1999, "Estimation of the Optimum Rated Wind Velocity for Wind Turbine Generators in the Vicinity of Edmonton, Alberta", *Proceedings of the 1999 IEEE Canadian Conference on Electrical and Computer Engineering.* Alberta, Canada, 1335-1338.

[9] AL Susan M.Schoenung, James M. Eyer, Joseph J. Iannucci, Susan A. Horgan, 1996, " Energy Storage for a Competitive Power Market", *Annual Review of Energy and the Environment*, vol. 21, 347-370.

[10] F. Katiraei, C. Abbey, and R. Bahry, 2006, "Analysis of voltage regulation problem for a 25-kV distribution network with distributed generation", *Proceedings of IEEE Power Eng. Society General Meeting.* Canada, 8-12.