ENERGY STORAGE SIZING AND PLACEMENT ON AN ISLANDED GRID WITH HIGH PENETRATION OF WIND

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This study seeks to find a cost effective energy storage solution to reduce grid frequency variation due to high penetration of wind in an islanded grid. Energy storage systems are able to meet the fast ramp rates required to stabilize fast fluctuations from wind; however, its high cost remains a drawback for utility or customers seeking to utilize it. This paper documents a simple way of sizing an energy storage system, in terms of capacity and rated power output that will reduce frequency variations due to high wind penetration. Also, a short study on the effect of energy storage systems does on congestion of transmission lines was done.

Keywords: short-term energy storage, wind energy, sizing

INTRODUCTION

The utilization of energy storage systems to reduce rapid power fluctuations from renewable sources like wind has been discussed widely in recent years. Certainly, there is potential for energy storage systems (ESS) to be an effective solution for mitigating effects of variable power sources like wind. However, ESS remains a cost-prohibitive solution, especially at lower levels of wind penetration.

The installed cost of an ESS is a function of its storage capacity (kWh) and rated power (kW) [1]. The study performed aimed to find the appropriate selection of energy storage systems, taking into account its sizing (both capacity and power) and cost of installation.

A factor not usually taken into account is the placement of ESS on a grid. Depending on the application of the energy storage system, it could be placed near load centers for customer side power quality services or closer a wind farm for renewable energy firming services.

In this study, the main application of the energy storage system is in the firming of renewable sources; specifically wind, as well as regulation services (i.e. regulating grid frequency). The placement of the ESS on the grid is such that it yields the least impact on grid congestion. It should be noted that the ESS is not used for congestion relief.

ESS is not a cost-effective solution at lower levels of renewable penetration. A simple isolated grid model of a utility in Colorado was used as the basis of a test system with the main source of renewables from wind.

MODELING

Wind Energy

This study assumes that a significant amount of generation would be from wind, specifically around 25-30% of total load (MWh). The wind data used in this study was taken from the National Renewable Energy Laboratory (NREL) Wind Technology Center at Boulder, CO [2].

Using a wind turbine model, power output from a single wind turbine can be calculated. To simulate power output from a large wind farm, power output from multiple wind turbines were aggregated at the electrical output [3]. A low-pass filter was added to the dynamic model in order to take into account the physical and electrical inertia of the wind turbine [4]. A simple block diagram of the dynamic model of a wind turbine is shown in Fig. 1.

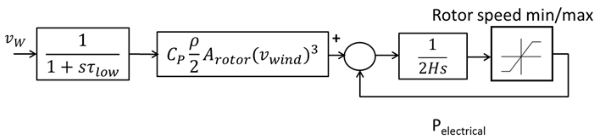

Fig. 1 *Dynamic Model of Wind Turbine with Filter*

A study on the power spectrum of wind turbines by J. Apt [4] shows the frequency range of wind farm power fluctuations. Fig. 2 shows the power spectrum of several wind farms situated in the Midwest region. It should be noted that the power spectrum is inaccurate at higher frequencies due to the fact that the original data is sampled at 5-minute intervals. However, results at the lower frequency range are comparable to the results found by J. Apt.

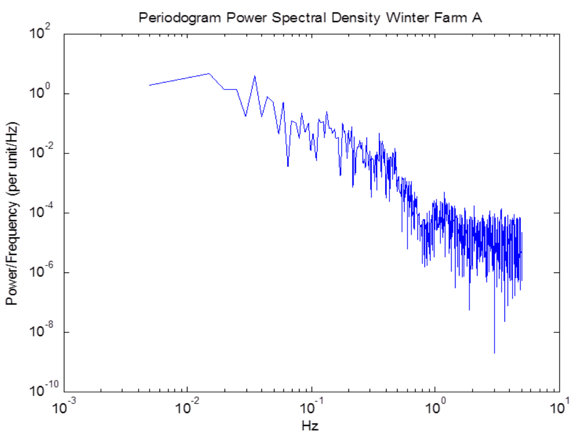

Fig.2 *Power Spectral Density of Wind Farms in the Midwest*

Since the main application of the energy storage system is to reduce the fluctuations from wind, the power spectrum of wind provides information regarding the design of the ESS. J. Apt has outlined in his paper stating that the design of a power source required to compensate for the wind fluctuations essentially has to match the fluctuations of the wind at high frequency. Hence, the ramp rates of the energy storage systems have to match that of the wind fluctuations with a much lower power output as would be required from a large conventional generator like a gas-fired generator.

Load-Frequency Model

To test the efficacy of the energy storage system, a dynamic load-frequency model of the isolated grid was modeled. This model of the test grid has four sources of generation: a baseload reheat steam turbine, a combustion turbine and the output from the wind farm and the energy storage system. Individual models of the generators were based on simplified IEEE dynamic models [5]-[6]. This dynamic model of the test grid is shown in Fig. 3.

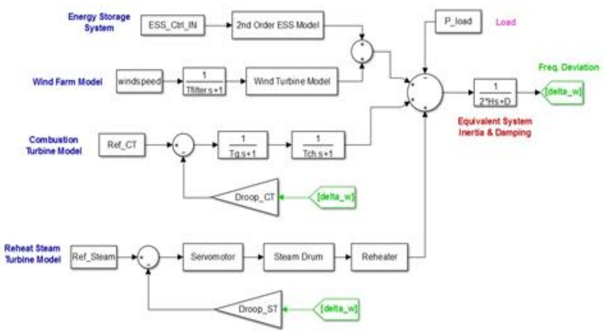

Fig. 3 – *Simple Load-Frequency Model of Test Grid*

The energy storage system was modeled as a second order plant. A PID controller is used to control the output of the ESS. The load-frequency model was modeled in Matlab and Simulink.

12-Bus Power Flow Model

To simulate the power flow of the test grid, a reduced order of an electrical grid of a utility in Colorado was modeled into a 12-bus system. The modeling was done with the student version of *PowerWorld Simulator v.17*. Fig. 4 shows the one-line diagram of the 12-bus system.

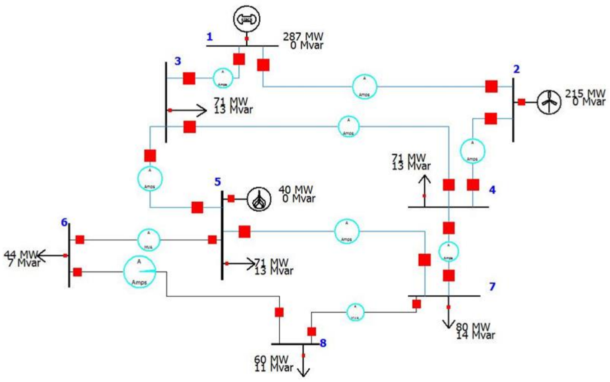

Fig. 4 – *12-Bus Power Flow Model of Test System*

The baseload plant, which is a coal plant, is situated at Bus 1, which is also the slack bus. The wind farm at Bus 2 is located away from the load centers (Buses 3-8). There is a small peaker plant (around 50-70 MW) placed at Bus 5.

First, a base case scenario of the power flow simulation was done on the 12-bus system excluding the energy storage system. The base case transmission line congestion was found and is denoted as the percentage of the line limit utilized. Table 1 tabulates the base case results.

Table 1: Base Case Line Congestion

From	To	Line	MVA Limit	% Limit Used
1	2	I	450	5.2
1	3	II	300	45.7
2	4	III	300	79.2
3	4	IV	500	2.2
3	5	V	250	26.9
4	7	VI	250	67.2
5	6	VII	250	21.0

It should be noted that the above results were calculated using data during the winter week data and at the point where the load was the highest.

Input Data Sets

Two different data sets were used in simulation and both consists of a 250-minute time slice of a winter and summer day in 2011 of a utility in Colorado.

The power output from the wind farm is at a 1-minute resolution, as given by NREL's wind test site in Boulder, CO. However, the load data is sampled and recorded at a 5-minute resolution. To match the resolution in both the wind and load data, while fully acknowledging the loss in data precision, the load data is held constant within the five minute intervals. Fig. 5 illustrates the point as shown.

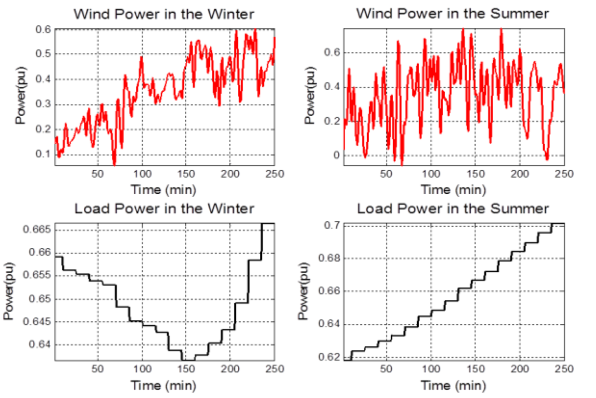

Fig. 5 – *Wind and Load 250-min Data Set for Winter and Summer 2011*

Table 2 shows the load consumption (MWh) and average wind penetration during the 250-min time slice. During simulation, a system base of 600 MVA is used to convert to a per unit system.

Table 2: Input Data Set for 250-min Time Slice

	Load (MWh)	% Wind Penetration
Winter	~1500	~30
Summer	~1640	~29

RESULTS

Grid Frequency Regulation

First, the base case of the system was obtained, with the base case consisting of the load-frequency model of the test grid without any energy storage system installed. The resulting grid frequency deviation from nominal (i.e. 60 Hz in North America was calculated.

Fig. 6 shows the grid frequency variation of the base case scenario using the summer data set.

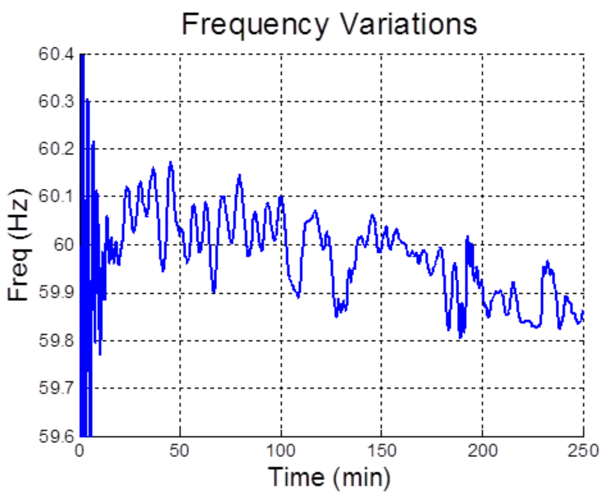

Fig. 6 – *Frequency Variations for Summer Base Case*

The next part involves placing a generic energy storage system within the load-frequency model (i.e. the test grid). The ESS rated power output and capacity is incrementally increased and the maximum frequency deviation is recorded and shown in Table 3.

Table 3: Frequency Deviation with Increasing ESS Size for Summer Case

P_{max} (MW)	E_{max} (MWh)	Cycles	∆Freq (Hz)
No ESS			0.398
7.1	0.38	36	0.377
14.2	0.77	36	0.357
21.3	1.53	36	0.336
28.4	2.30	36	0.315
35.5	3.07	36	0.295
42.6	3.84	36	0.276
49.7	4.60	36	0.269

Frequency variations for the winter data set were calculated and the results found are shown in Table 4 and Fig. 7.

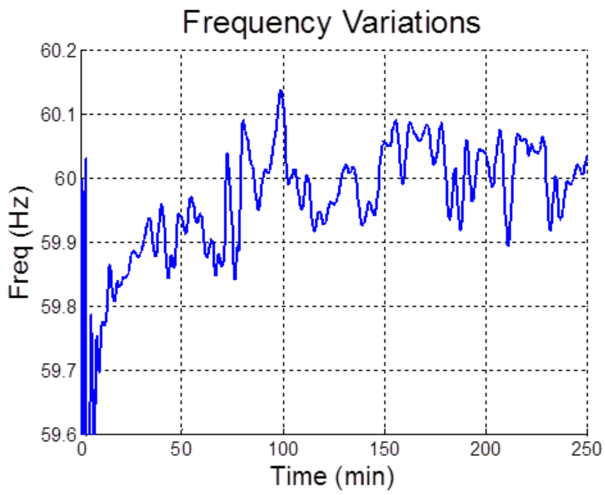

Fig. 7 – *Frequency Variations for Winter Base Case*

Table 4: Frequency Deviation with Increasing ESS Size for Winter Case

P_{max} (MW)	E_{max} (MWh)	Cycles	∆Freq (Hz)
No ESS			0.440
6.1	0.54	30	0.420
12.3	1.07	30	0.400
18.4	2.14	30	0.380
24.6	3.21	30	0.360
30.7	4.28	30	0.340
36.9	5.35	30	0.320
43.0	6.42	30	0.312

By increasing the capacity and rated power output of an ESS plant, the frequency deviations decrease, as can be seen in Fig. 8 for the winter base case.

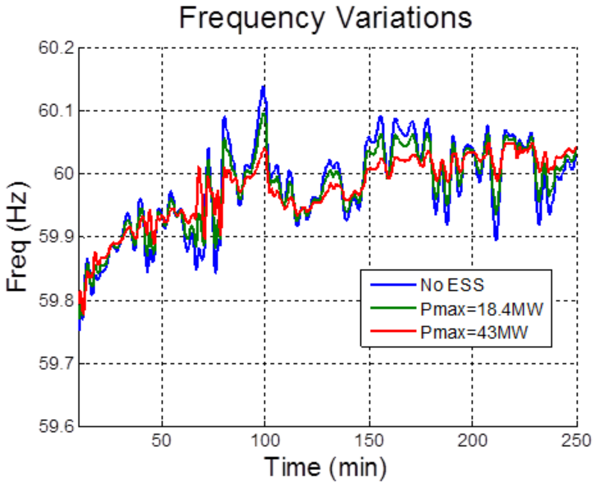

Fig. 8 – *Frequency Variations with Increasing ESS P_{max} for Winter Case*

The important question here is not the fact that by increasing the capacity of an ESS reduces frequency deviation but the balance between sizing and cost of the ESS.

Using cost information from SANDIA's recent energy storage handbook [1], some rough estimates of cost data could be found. It should be noted that some of the technologies listed in the handbook are still in the pilot and laboratory testing stage and so the costs estimates do come with an accuracy range.

Table 5 shows the cost estimates as used in this study for a select few energy storage system technology. Long-term storage systems like compressed-air energy storage (CAES) and pumped hydro were not taken into account as the main application of ESS here is to stabilize frequency variations due to fast fluctuating wind.

The cost estimates in Table 5 only takes into account cost of ESS suitable for renewable integration and frequency regulation. The depth of discharge (DoD) is the average values found in the handbook. The range in Table 5 is the upper and lower limits of total installed cost, which depends on the technological state of the ESS, i.e. a commercial system has a lower range as there are multiple installed systems that has proven reliable in terms of cost estimates ESS technology like the Zinc Bromine system however is still in laboratory testing stage, hence the higher range.

Table 5: Cost Estimates based on SANDIA's Energy Storage Handbook

Type	**Cp $/kW**	**Ce $/kWh**	**DoD (%)**	**Cycle**	**Range (%)**
Sodium Sulfur	2,565	233	80	4.5k	±5
Flywheel	1,295	4,319	100	25k	-15 to 25
Lithium-Ion	616	1,110	86	4k	-25 to 10
Vanadium Redox	1,709	412	100	10k	-25 to 25
Adv Lead-Acid	1,044	1,905	29	16k	-25 to 40
Zinc Bromine	732	302	100	2k	-20 to 25

Using results and data from Tables 3-5, the following total installation cost for different types of ESS was calculated and tabulated in Table 6. The rated power output, PESS and capacity of ESS is in MW and MWh respectively. The costs are found in $million. The installed cost was found with the following equation (1):

$$Installed\ Cost = \left[\left(\frac{C_E \times E_{ESS}}{DoD}\right) + (P_{max} \times C_p)\right] \times Lim_{up} \quad (1)$$

Table 6 – Total Installed Cost for Different ESS

P	**E**	**NaS ($)**	**Fly ($)**	**Li-Ion ($)**	**VR. ($)**	**Pb Acid ($)**	**Zn Br ($)**
10	2.5	28	30	10	23	38	10
20	3.3	55	50	18	44	60	20
20	5.0	55	59	21	45	75	20
30	7.5	83	89	31	68	113	30
40	10	111	119	41	91	150	40

Looking at Table 6, there are no clear winners in when weighing the cost-benefit analysis. Although Zinc Bromine systems turn out to be much cheaper than the rest, it should be noted that it is still in development phase and a grid installation is still years in the future [1].

For high powered (MW) and low capacity (MWh) ESS, a flywheel system is a good match since it allows high cycling rates. Advanced Lead-Acid and Zinc Bromine systems are relatively new technology with some characteristics still in the testing stage. For medium capacity and medium power output, a Sodium Sulfur and Lithium-Ion system is a good choice. However, it should be noted that those systems have relatively low cycle life as compared to flywheel systems.

ESS Placement

A short study was done to find the optimal placement of the ESS on the grid. As mentioned in the power flow model section, a base case system without any ESS was found, specifically existing transmission line congestion.

The power flow cases were simulated for both summer and winter data sets at the highest loading (MW) time, which corresponds to the highest congestion times. A 50 MW ESS was placed at the different buses (except the slack bus, Bus 1) and the new transmission line congestion was compared to the base case. Fig. 9 shows the “best fit” bus placement for the ESS system.

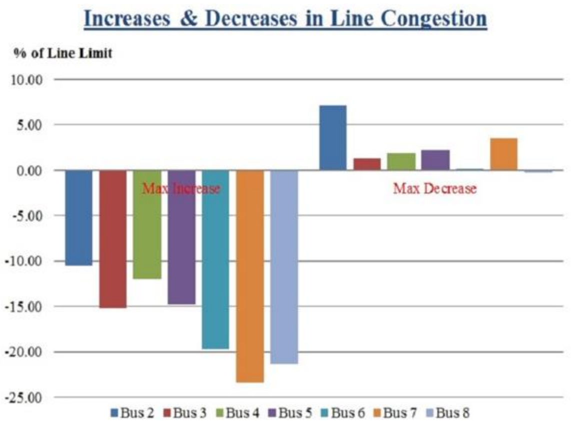

Fig. 9 – *Increase and Decreases in Line Congestion*

Since the choice of placement of the ESS is the one with the least impact on line congestion, Bus 2 yields the least impact. It causes the least increase in congestion and actually on some lines, alleviates line congestion.

Bus 2 is the bus at where the wind farm is situated. Note that the power flow was done for only a single time step, which is where the load is at the highest and with corresponding wind power output at that time.

CONCLUSIONS

This study has shown that there are no clear winners of an ESS, in terms of meeting a high capacity as well as high power output. Sizing of an ESS depends highly on the application of the ESS, in this case, regulating grid frequency variations due to high wind penetration. In an isolated grid, the detrimental effects of >25% wind are stronger due to reasons such as lower system inertia and smaller baseload plants. However, this study also showed that an ESS, properly sized could reduce frequency variations. Placement of the ESS depends on the grid in question and for this case, it was the optimal place is at the wind farm bus.

FUTURE WORK

Future work will include more detailed optimization techniques like linear programming methods to find optimal sizing value. Only installed cost of energy storage system is taken into account for this study, but future study will find more detailed cost analysis that includes levelized cost of electricity (LCOE) and net present value (NPV) of the energy storage system.

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Frank Barnes received his B.S. from Princeton University in electrical engineering in 1954 and his M.S. Engineer and PhD from Stanford University in 1955, 1956, and 1958. He joined the University of Colorado in 1959 and appointed a Distinguished Professor in 1997. He was elected to the National Academy of Engineering in 2001 and received the Gordon Prize 2004 for innovations in Engineering Education from the National Academy. He is a fellow of IEEE, AAAS, and ICA and served as Vice President of IEEE for publication. In the last four years, he has been working on energy storage and the integration of wind and solar energy into the grid and the effects of electric and magnetic fields on biological systems.