The Role of Energy Storage in Development of Smart Grids

Energy storage aspects of the Smart Grid are discussed in this article; various storage technologies are reviewed and the importance of storage systems in electric grid operation is described.

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ABSTRACT | The adoption of Smart Grid devices throughout utility networks will effect tremendous change in grid operations and usage of electricity over the next two decades. The changes in ways to control loads, coupled with increased penetration of renewable energy sources, offer a new set of challenges in balancing consumption and generation. Increased deployment of energy storage devices in the distribution grid will help make this process happen more effectively and improve system performance. This paper addresses the new types of storage being utilized for grid support and the ways they are integrated into the grid.

KEYWORDS | Batteries; community energy storage; energy storage; flywheels; grid storage; smart grid

I. INTRODUCTION

Bulk energy storage has been used for decades in the United States utility grid and now integration of renewables is creating a need for more distributed storage [1]. Current activities in distributed storage systems will be discussed along with a review of market barriers to storage. The technology is broad and various applications require different properties in electricity storage. The basic difference between “power storage” and “energy storage” is key to various applications and will be addressed. Economics of storage will be a major driver of how quickly distributed storage solutions are adopted in electricity grids.

II. GROWING CONCERN

There appears to be general agreement that replacement of fossil fuels as the primary sources of energy for electricity generation and transportation needs to take place over the next few decades. Growing penetration of renewable energy sources and a shift, hopefully, to plug-in hybrid electric vehicles (PHEVs) and all electric vehicles (EVs) will require a much more dynamic electric infrastructure. Beginning with the U.S. Department of Energy (DOE) “Grid 2030 Vision” Conference in April 2003, energy storage emerged as a top concern for the future. In 2007 the DOE convened an Electricity Advisory Committee (EAC) to make recommendations for an energy road map for the United States including energy storage.

The EAC produced a report [2] to the U.S. Congress, which provided a road map development of storage technologies and goals for storage deployment in the United States grid over a ten- (10) year period.

Globally, other nations like Japan and Germany have been working to make larger amounts of energy storage a vital part of their energy plan. Japan has a near-term target of 15% storage in the grid with Germany planning 10% compared to just over 2% in the United States [3].

III. BULK STORAGE FOUNDATION

In each country the majority of the storage that exists today is large pumped hydro facilities typically greater than 200 MW each. These plants are generally located some distance from load centers and can do little to effect potential congestion issues that impact utility transmission and distribution networks during peak demand periods.

Today the total global capacity of pumped hydro storage plants total over 95 GW of capacity with approximately 22 GWs operating in the United States. The original intent of these plants was to provide off-peak base-loading for large coal and nuclear plants to optimize their overall...
performance and provide peaking energy each day. This duty has been expanded to provide ancillary service functions such as frequency regulation in the generation mode. The newer adjustable speed system design allows pumped hydro plants to provide ancillary service (frequency) capability in the “pumping” mode as well, which increases overall plant efficiency. In the United States, filings with the Federal Energy Regulatory Commission (FERC.gov) have been made for additional pumped hydrofacilities. The new plants represent 20 GWs of new storage capacity that could be added to the United States grid [4].

The other basic bulk storage concept is compressed air energy storage (CAES). This system is a peaking gas turbine power plant that consumes less than 40% of the gas used in a combined cycle gas turbine and 60% less than a single-cycle gas turbine to produce the same amount of electric output power [5]. This is accomplished by blending compressed air to the input fuel to the turbine. By compressing air during off-peak periods when energy prices are very low, the plant’s output can produce electricity during peak periods at lower costs than conventional stand-alone gas turbines.

To make the CAES concept work depends on locating plants near appropriate underground geological formations such as mines, salt caverns or depleted gas wells. The first commercial CAES plant was a 290 MW unit built in Huhndorf, Germany, in 1978 and the second commercial site was a 110 MW unit in McIntosh, AL, in 1991 [5]. These units are fast-acting plants and typically can be in service in 15 min when called upon for power. Newer plants currently being designed are based on a simple system approach using advanced turbine technology. Both pumped hydro and CAES systems will be critical to growing demand for storage in electricity grids.

### IV. TECHNOLOGY OF STORAGE

Electricity storage takes many physical forms and is thus governed by different engineering relationships.

- **Flywheel**: \( \frac{1}{2} I \omega^2 \) (0.5 moment of inertia times rotational velocity squared).
- **Super Capacitor**: \( \frac{1}{2} C V^2 \) (0.5 Capacitance times Voltage Squared).
- **Battery**: \( C V \) (Capacity in Ampre Hours times Voltage).
- **Compressed Gas**: \( E = \int V P \, dt \) (This is not as simple as the above, basically a constant times pressure times volume, but depends on isothermal or adiabatic expansion).

As you can see, various physical properties can be used to store energy and especially electricity. The conversion back to electrical energy has an “overhead” associated with it and the round-trip efficiency of the system should be analyzed. Round-trip efficiency is defined as shown in the equation at bottom of page.

This calculation of efficiency is critical to the economic evaluation of electricity storage systems. Basically, what does not come back to the grid must be paid for in some manner. The payment mechanism is in discussion since electricity storage is both an energy load and an energy source. FERC and the ISOs have not completely addressed the rate structures for this type of asset yet.

Table 1 above shows the two main benefits of electricity storage. As mentioned before, one is energy storage for time shifting and power storage for Speed of Response in frequency regulation and spinning reserve. The speed of response benefit is being addressed since a National Laboratory has stated fast response (4 second full power) is worth twice as much as slower response (20-min ramp-up for generation assets).

| Round Trip Efficiency | \( \frac{\text{Energy received at the grid on the primary side of the transformer}}{\text{Energy sent from the Grid on the primary side of the transformer}} \) |
V. DISTRIBUTED ENERGY STORAGE

As mentioned earlier, bulk storage systems can do little to effect energy flow within major load centers. As the growth of electric transportation increases the loading on local distribution feeder circuits; and, grid connected solar systems populate the roofs of homes and buildings, the control of system voltage and reliability will be challenged more than ever before. The concern over how grid operators and utilities deal with these issues has gained global attention. In the United States, the DOE responded in 2009 with a major stimulus program to deploy more types of distributed storage technologies in the 1.0 to 20.0 MW range in addition to the 50 MWs already deployed in the United States at that time.

The greatest effort to demonstrate the use of large batteries as a tool to manage power demand in a utility grid began in the 1990s in Japan with the development of the Sodium Sulfur (NaS) battery system capable of delivering at least six hours of battery runtime on a daily basis. This concept was first demonstrated in the US in 2006 with a 1.0-MW NaS battery deployed in a utility substation as an upgrade deferment device to deal with summer peak loads on a 20 MVA station transformer [6].

By 2010 NaS battery installations totalled 365 MWs worldwide with 300 MWs in service in Japan. In 2009 the world’s largest battery (34 MWs) [5] went into service in support of a wind farm in Northern Japan. Fig. 2 shows a typical NaS battery installation in a utility substation used for peak load management and reliability improvement (outage reduction).

In the United States, American Electric Power (AEP) deployed three 2.0 MW, 14 MW-hour NaS battery systems (as shown in Fig. 2) to demonstrate how intelligent energy storage could be used in meeting “smart grid” goals [7]. The sites were deployed to test battery power as a tool in creation of “self healing” distribution networks where intelligent feeder switching and protective devices could communicate in real time to isolate faults and restore service in seconds without waiting for SCADA commands from the utility control center. This showed how storage could operate “self-powered” islands of grid power in the event of transmission feeder loss.

Advanced battery technologies have been the main focus in distributed storage systems followed by flywheels and supercapacitors. The development of battery systems for transportation will have a benefit for grid applications as prices decline with automotive volume increases. R&D activities in new battery development are very high as transportation and grid support opportunities offer an ever increasing market.

The primary markets for distributed storage systems will be [7], [8]:

- peak-load deduction (peak shaving) at substations;
- storage of off-peak wind energy;
- power “smoothing” for large solar arrays;
- ancillary services (frequency regulation, black start capability);
- transmission and distribution feeder reliability improvement;
- customer feeder load management.

Studies conducted in 2009 to determine the effectiveness of fast-response batteries and flywheels in frequency regulation applications showed these systems could affect frequency control with approximately 40% less energy as compared to fossil fuel plants because of the very fast response time (cycles versus minutes to respond). Based on these findings plants up to 20 MW each (see Fig. 3) are being built in the United States and other countries [5], [9].

In the wind turbine industry supercapacitors have been widely adopted for powering the pitch control of turbine blades and offer back-up energy to safely shutdown a wind turbine if loss of power occurs. Super-caps are being applied as well with small solar arrays to insure smooth power flow as clouds pass over.
Power storage lithium ion batteries are also used for frequency regulation. The PJM ISO has had a pilot system in operation for over two years. It is earning about $850 per day in bidding for the frequency in the “day-ahead market.” This system was independently tested and, as in the flywheel system above, is capable of a maximum capacity (1 megawatt) supply to the grid and four seconds later a maximum capacity (1 MW) storage of electricity. Also, this system has been successfully relocated from a substation in Indianapolis, Indiana to the parking lot of the PJM headquarters just north of Philadelphia.

VI. ENERGY STORAGE AND THE SMART GRID

The challenge in development of a more intelligent electricity network (smart grid) is balancing all of the variables associated with dynamic load control powered from an ever increasing variable (renewable energy) sources. This “balancing act” can be made simpler with small amounts of energy stored throughout the grid. All elements of design from demand response techniques in homes to dynamic loading of transmission lines based on temperature and wind speed will come to bear in a true smart grid design.

A specific example of storage in a smart grid is the concept of placing small amounts of energy storage (1–2 hours) on the feeders of residential areas. The community energy storage (CES) concept deploys 25 kW low-voltage units protecting small groups of homes [11]. In addition to the real power capability, each CES unit power electronic converter (PCS) is capable of producing 25 kVARs for use in voltage control explained later in this section.

The CES units are connected on the low-voltage side of the utility transformer and protect the final 120/240 volt circuits to individual customers. Placing a utility controlled device at the very edge of the grid allows for the ultimate in voltage control and service reliability. Meeting this challenge of even greater control of voltage at the point of customer use is a major departure for traditional utility system control philosophy but is needed to deal with a rapidly changing customer load profile. As more and more sophisticated electronic loads (computers, appliances, etc.) are added by customers who demand greater service reliability; new even larger loads, like PHEV charging units will be added randomly in the grid. On top of these changing load patterns more and more solar arrays on roof tops will introduce a growing amount of energy flowing back into the grid when solar generation exceeds the power demand of the specific customers. Today, a neighborhood with a significant number of solar roofs can generate a fair amount of energy that dissipates back into the utility network during solar peak periods. Since the solar peak precedes the customer load peak by two to three hours each work day it is desirable to store that energy for use when the load grows later in the day. With CES units
located throughout the network, this would allow that excess energy to be captured locally with less line losses and redispached back to the same customers when needed. Another problem that the CES units could deal with during the solar peaks is precise control of the local voltage as clouds pass over. As more and more customers add solar, the voltage can be impacted as clouds pass by. As clouds shadow a large number of arrays, the power output drops very quickly resulting in sudden voltage drops. The power electronics used in the CES devices have the ability to act as instantaneous capacitive VAR compensators to maintain proper voltage and power factor in the local area. The sun can reappear very quickly resulting in the voltage attempting to rise fairly rapidly. The CES electronics would counter this in the same manner as a reactive VAR compensator to prevent voltage sag.

As mentioned earlier, the addition of more and more PHEV loads will affect load demands quite a bit. Most vehicle charging should occur slowly at night but the pattern will be hard, if not impossible, to control. If an abnormal amount of “quick charges” were to take place in a given area, there could be stress on local distribution transformers. The CES units could provide “peak power” in these cases.

VII. STORAGE ECONOMICS


Introduction of a new element (storage) as a major factor in future grid design is not an easy task. Major change in any form requires adjustment of utility business practices and government-run market structures. Storage appears to have many advantages that help the traditional market sectors of generation, transmission and distribution and retail sales of electricity. Most current market structures separate the value proposition of these sectors and make “sharing” of benefits almost impossible. This “demand” for storage and its value to building a more flexible grid is being addressed. Introduction of investment tax credits (similar to wind and solar) are being examined in the United States plus regulators are beginning to consider storage as a separate asset class, which would allow for storage to be considered in utility rate base calculations. These types of charges, coupled with lower costs of storage systems, will accelerate market adoption of storage globally.

The time shift benefit is a purely economic benefit. For instance, there is an economic value of storing wind energy produced at night for use during the day. The energy storage asset must be amortized and the round-trip efficiency of the storage system understood. These two costs must be added to the kWh cost of the night energy produced and compared to the value of the energy used in peak operating times when the stored energy is most valuable.

The economics of fast storage relate to different criteria. Pacific Northwest National Laboratory (PNNL) produced a report stating fast storage is worth as much as twice what slow storage is worth. This is understandable from studying the Beacon figure (see Fig. 6).

Here we can see in Fig. 6 below, the overlap of needs contradicting dispatched generation capacity for frequency regulation. The red sections are time periods when the generator dispatch is working against the area control error (AEC). In these time periods, we have extra cost,
wasted energy and additional carbon emissions. As is also seen in this chart, the blue areas never produce an “out-of-phase” situation with the AEC.

VIII. CONCLUSION

The importance of storage systems in electricity grids is finally receiving the attention of system planners as more storage options become available. As nations around the world continue to increase their portfolios of renewable energy, the participation of storage is increasing. The design of smart grids in the future will take advantage of storage in dealing with more dynamic loads and sources. As market rules are adjusted to take advantage of the benefits of bulk and distributed storage devices, the overall capabilities and reliability of more complex electricity networks should continue to improve as fully integrated “smart grids.”

Acknowledgment

The authors thank Matt Lazarewicz of Beacon Power and Robert Misback of Altairnano Technologies for their contribution to this paper.

REFERENCES


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