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Short communication

Integrating energy storage with wind power in weak electricity grids

Jim McDowall*

Saft America Inc., 3 Powdered Metal Drive, North Haven, CT 06473, USA

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Abstract

Energy storage is required to match wind generation to consumption. This time shifting can be accomplished with several hours of storage, but studies have shown that the economic value of such storage systems is unlikely to support their widespread use. This does not mean that the outlook is uniformly bleak for storage with wind power. This paper discusses storage systems ranging from a few seconds of run time to several hours, and provides a rationale for the use of systems with several minutes of run time to support a high penetration of wind power into weak electricity grids.

Keywords: Alkaline batteries; Energy storage; Lithium batteries; Wind generation

1. Introduction

Wind power has achieved a significant level of penetration in the power generation market in recent years. Most of the installations are tied to strong grids, with the inherent stiffness of the network minimizing quality concerns and making it less important for the wind generation to be matched to consumption. The consensus among experts appears to be that wind generation can increase to around 20–30% of overall generation before the inherently variable nature of wind energy starts to destabilize the grid. Moreover, this figure does not refer to power generation at any one point—during peak loads, for example, but to overall energy production over time. The benefit of greenhouse gas reduction is achieved at the expense of grid planning and predictability.

The situation is worse for weak grids. These are typically electrical islands, which may or may not be linked to a mainland grid, and are frequently characterized by a lack of spinning reserves. In size they may range from tens of kilowatts for a few buildings to a hundred megawatts or more. In such systems, the introduction of wind generation can be destabilizing, even before 20% penetration is reached.

Advances in the power electronics associated with wind turbines have dramatically improved the quality of their output and their ability to ride through voltage sags. Electronic systems cannot, however, cause a turbine to continue producing power when the wind dies. The solution to this problem is energy storage, which can provide sufficient output stability and ramping control to make wind generation compatible with the network and its other sources of generation.

Energy storage can allow wind generation to achieve a high percentage of overall generation in weak grids. Such solutions should be examined now to the greatest extent possible, since the lessons learned could provide valuable insight into actions that can be taken to prevent problems in mainland grids resulting from increasing deployment of wind generation.

2. Energy storage technologies—hours, minutes and seconds

Small-scale renewable energy installations such as standalone photovoltaic systems employ traditional battery solutions exclusively. These include lead–acid, nickel–cadmium (Ni–Cd) and increasingly, nickel–metal hydride and lithium ion technologies. As power and energy levels are scaled up,

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* Tel.: +1 203 985 2712; fax: +1 203 234 7598.
E-mail address: jim.mcdowall@saftbatteries.com.

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other technologies are now being promoted, especially at the extreme ends of the power-energy spectrum, i.e. multi-megawatt systems operating for seconds, and those providing multi-megawatt-hours over several hours.

The following sections will provide a brief overview of energy storage technologies, categorized by their typical run times into hours, minutes and seconds.

2.1. Hours—bulk energy storage technologies

There is already a large installed base of energy storage systems based on water, either in the form of reservoirs on rivers or pumped hydro systems, in which power from the grid is used to pump water up to a (normally man-made) lake or reservoir, allowing the stored energy to be released later by reversing the water flow. On a similar scale of hundreds or even thousands of megawatt-hours, compressed air energy storage (CAES) systems have been proposed, and smaller CAES systems have been operating for many years. In these systems, compressed air is pumped into underground caverns and is fed later into a gas turbine, dramatically reducing fuel consumption. While hydro and CAES systems provide economical energy storage, there are three factors that limit them with regard to the subject topic of this paper: (1) they are geologically limited; (2) their scale does not lend itself to use at the lower load levels of weak grids; (3) they cannot react instantly, but behave similarly to generators (indeed, CAES systems incorporate gas turbines, as mentioned previously).

In recent years, there have been a number of advances in unconventional battery systems, mainly in the field of high-temperature technologies and flow batteries. High-temperature sodium–sulfur (NAS) batteries have been installed in a number of commercial installations [1], and recently a battery of 57.6 MWh was commissioned at an industrial facility outside Tokyo. All of these systems have been heavily subsidized by the developers, however.

Flow batteries represent a dramatic departure from traditional battery technology, in that the power rating is determined by the size of bipolar electrode stacks and the energy is contained in electrolytes that are pumped through the stacks. In this manner, the power and energy are separated from one another. Flow batteries have been limited so far to demonstration systems, such as a recent vanadium redox battery installation, rated at 250 kW and 2 MWh, by PacifiCorp in Utah [2]. Other flow battery technologies proposed include zinc bromine and sodium sulfide-polybromide.

One feature shared by high temperature and flow batteries is their relatively low power-to-energy ratio. This is about unity for most of these technologies, i.e. a 1 kWh battery has a maximum power capability of about 1 kW, and it would generally be uneconomical to engineer them for higher power levels. In contrast, it is not unusual for conventional batteries to be designed for power-to-energy ratios of 10–20.

The most notable conventional battery installation designed for hours of storage was the Southern California Edison Chino facility, powered by a 10 MW/40 MWh lead–acid battery and commissioned in 1986. Results from this system were rather disappointing. Very few people are promoting multi-megawatt-hour conventional batteries because the life cycle costs are inherently uncompetitive.

2.2. Minutes—conventional batteries

While smaller installations with conventional batteries may be engineered for hours of operation, the most promising aspect of this group of technologies related to energy storage applications is their ability to supply significant power levels for several minutes. In this operating mode, they can provide significantly more energy than short-duration devices such as flywheels and supercapacitors (see Section 2.3). Furthermore, they are able to work *with* other generation on the network, rather than in competition *against* it as the bulk storage technologies are attempting to do.

The largest lead–acid battery installed for this purpose was the 21 MW/14 MWh system installed by Puerto Rico Electric Power Authority (PREPA) at Sabana Llana in 1994. Although the system was operationally of great benefit to PREPA there were numerous problems, including premature failure of the battery. This led the US Department of Energy to fund a ‘lessons learned’ study in 1999 [3].

On a more positive note, Golden Valley Electric Authority (GVEA) commissioned its battery energy storage system (BESS) in 2003, using Ni–Cd batteries rated at 27 MW for 15 min. The system was installed on schedule by a consortium of ABB and Saft, and in its first full year of operation prevented some 300,000 customer disconnections in the GVEA service area around Fairbanks, Alaska. The BESS is configured for future expansion and during acceptance testing was discharged for 5 min at the full converter capability of 46 MW. Statistics on the system’s operation are maintained on the GVEA website [4]. Fig. 1 provides an idea of the size of the GVEA installation.

Much development work has been carried out in recent years on the scaling up of nickel–metal hydride and lithium ion batteries, in an attempt to replicate the success of these technologies in portable equipment such as laptops and mobile telephones. The success of nickel–metal hydride has been more evident, with its use in hybrid electric vehicles (HEVs) from Toyota, Honda and Ford. However, this appears to be a matter of timing, much as it was in consumer applications, in which lithium ion appeared about 2 years after nickel–metal hydride and has since become dominant in high-end devices. Many experts in the auto industry acknowledge that the next generation of HEVs will be equipped with lithium ion batteries.

The eventual battery choice for HEVs will have a huge impact on stationary battery systems of many types, including storage with wind energy. In fact, the high-power cycling that would be expected in wind energy systems with fast-acting storage is very similar to the battery duty in HEVs.

Fig. 1. GVEA battery energy storage system.

2.3. Seconds—non-battery devices

The three main storage options for seconds of run time are flywheels, supercapacitors, and systems based on superconducting magnetic energy storage (SMES). The SMES systems are still at the demonstration stage and are grappling with issues such as high cost and strong magnetic fields. Flywheels and supercapacitors (also known as ultracapacitors), however, are now starting to enter the mainstream.

Flywheels and supercapacitors share a number of characteristics that set them apart from batteries. Generally, they

- can be charged at the same rate as they are discharged;
- show minimal temperature dependency over a wide operating range;
- contain very little energy.

These characteristics make the devices well suited to repeated, very short discharges. For example, a 1 MW flywheel system is installed in a demonstration project for voltage stabilization on a New York City subway track [5], and supercapacitors are providing a similar function for a trolley line in Lausanne [6].

These devices are capable of delivering their entire useful energy content over a discharge time of up to about 20 s. This means, however, that a 15 s system must be doubled in size for a 30 s run time, or quadrupled for 1 min. This quickly renders these systems uncompetitive for longer discharges.

3. The value of storage

3.1. Renewable energy time shifting

The California Energy Commission (CEC) recently awarded a series of contracts for energy storage demonstration projects under its Public Interest Energy Research program. Their bidder requirements included a calculation of the value for each proposed project, along guidelines provided by the CEC [7]. Among other applications, these guidelines provided an assessment of the lifecycle financial benefit for renewable energy time shifting at US\$ 655 kW^{-1} and indicated that 6 h of storage is required for this function. On a purely economic basis, then, a complete system with 6 h of storage would have to be installed, commissioned and operated for 10 years at a net present value not exceeding US\$ 110 kWh^{-1} to break even. With today's inexpensive lead–acid batteries already having an installed cost of around US\$ 250 kWh^{-1} for the battery alone, it can readily be seen that bulk storage systems are unlikely to be justifiable for this function. (It is interesting to note that, although the CEC solicitation was ostensibly for bulk storage systems, two out of the three contracts awarded were for systems with seconds of storage, and the third system was rated for 1 h.)

3.2. Transmission upgrade deferral

The picture is considerably more attractive when storage is used to defer an upgrade to a transmission line. In this scenario, system loads are approaching the capacity of an existing transmission line, and ongoing load growth requires that action be taken to prevent an overload. Rather than upgrading the transmission line, energy storage can be used to cover the relatively few and short periods when the line capacity is exceeded. If the upgrade can be deferred for a full year, the financial benefit derived is equal to the annual carrying charges for the cost of the upgrade.

For example, the largest of the Røst islands off the northern coast of Norway has been the subject of two studies [8,9]. The island is linked to the mainland grid by a 65 km long, 22 kV transmission line, which is nearing its capacity limit in serving the 700 inhabitants. The line would cost US$ 5 million to upgrade. If the upgrade can be deferred for 1 year and the utility's carrying costs for money are 10%, the financial benefit is US$ 500k in the first year alone.

In the storage-only deferral scenario outlined in the CEC document, it is assumed that the storage would be moved to another location at the end of 1 year, with the possibility of realizing further financial benefits in other locations. However, a system comprising wind generation coupled with storage could provide a more permanent solution, as discussed later in this paper.

3.3. National perspective on electricity storage benefits

The US Department of Energy (DOE) recently partnered with the Electric Power Research Institute (EPRI) to produce the *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications* [10]. Chapter 2 of the handbook includes a summary of the CEC figures for lifecycle financial benefit in a variety of storage scenarios, primarily for bulk storage applications with between 1 and 10 h of storage, and provides additional discussion of qualitative benefits, implementation challenges, regulatory issues and an overall national perspective on the subject.

Notably lacking from the handbook is an analysis of the benefits associated with short-duration storage, particularly as it relates to weak grids such as the network in which the GVEA BESS is installed. Despite this omission, it can easily be seen from the figures that there is no bulk storage application, with the possible exception of upgrade deferral, that provides sufficient financial benefit to support the cost of a system with hours of storage. Of course, these figures are based on storage applications associated with a strong national grid and it is well worth analyzing the relative merits of long- and short-duration storage with individual applications in weaker grids.

4. Wind generation with storage

Taking the example, if Røst outlined above, it is interesting to explore the possibility of realizing the transmission upgrade deferral benefits using a solution based on renewable wind generation in concert with energy storage.

Placing wind generation on an island like Røst can yield a further financial benefit, since the line losses in this case are 25–30%. Any displacement of energy supplied through the transmission line will avoid this loss and provide an additional value stream. Realizing the upgrade deferral benefit requires generation capacity, so either sufficient energy storage must be installed to provide capacity firming of the wind generation, or a separate generator such as a diesel must be provided. Since the transmission line capacity will be exceeded only occasionally (at least in early years of the deferral), a less expensive standby unit could be used for this function, preferably running on renewable biodiesel.

Energy storage is required to avoid any destabilizing effects from the wind generation on the island's network. The big question relates to how much storage should be installed. The non-battery devices with seconds of run time would provide a 'shock absorber' function, but would be unable to provide bridging power to a standby diesel, so the deferral benefit would be unavailable. The choice of run time for the storage, then, is between a few minutes or around 6 h, depending on the means for providing the necessary generation capacity.

The E7 group of utilities recently carried out a study on the feasibility of using wind power to displace existing diesel generation on the island of San Cristobal in the Galapagos Islands [11]. In addition to examining various configurations of wind turbines, the project team considered three storage options: lead–acid (VRLA) and Ni–Cd batteries with 5 min of run time, and a 6 h NAS battery. The chart in Fig. 2 summarizes the results of their analysis.

The chart shows various combinations of wind turbines and storage. The center bar gives the initial cost of each option, while the outer bars show the percentage of diesel generation displaced. The text box above the center bar gives the cost of generation (US$ kWh^{-1}) both with and without a US$ 1 M subsidy that is under consideration for this project.

The most significant result from the point of view of this paper is that the systems with three wind turbines and 5 min of storage can displace 60% of the existing diesel generation, while the option with four wind turbines and 6 h of storage provides very little additional displacement, at 70%. Another significant point is that the system with the Ni–Cd storage option, while having a higher initial cost, has the same lifecycle generation cost as one with the VRLA option, without the need to replace the battery every 5 years or so.

Applying these results to the Røst system, it is assumed that the short-duration storage would provide up to 15 min of run time. A high-power battery design such as Ni–Cd or lithium ion can provide around 75% of its rated energy over this time period, so each kW of battery rating at the 15 min rate will require an installed capacity of about 0.33 kWh. Six hours of storage will obviously require 6 kWh of capacity per kW of load rating. Even looking at inexpensive (and short-lived) lead–acid batteries at around US$ 250 kWh^{-1} installed, the 5.67 kWh difference between the two options would cost over US$ 1400 per load kW, compared with around US$ 450 kW^{-1} for the installed cost of a diesel generator. It is plainly more economical to use the diesel to provide generation capacity, rather than hours of storage.

Another benefit associated with energy storage systems is in the provision of ancillary services. These include spinning reserves and power system stabilization functions. Many power conversion systems also provide full four-quadrant power capabilities, so full-time VAR support can be provided under most operating conditions.

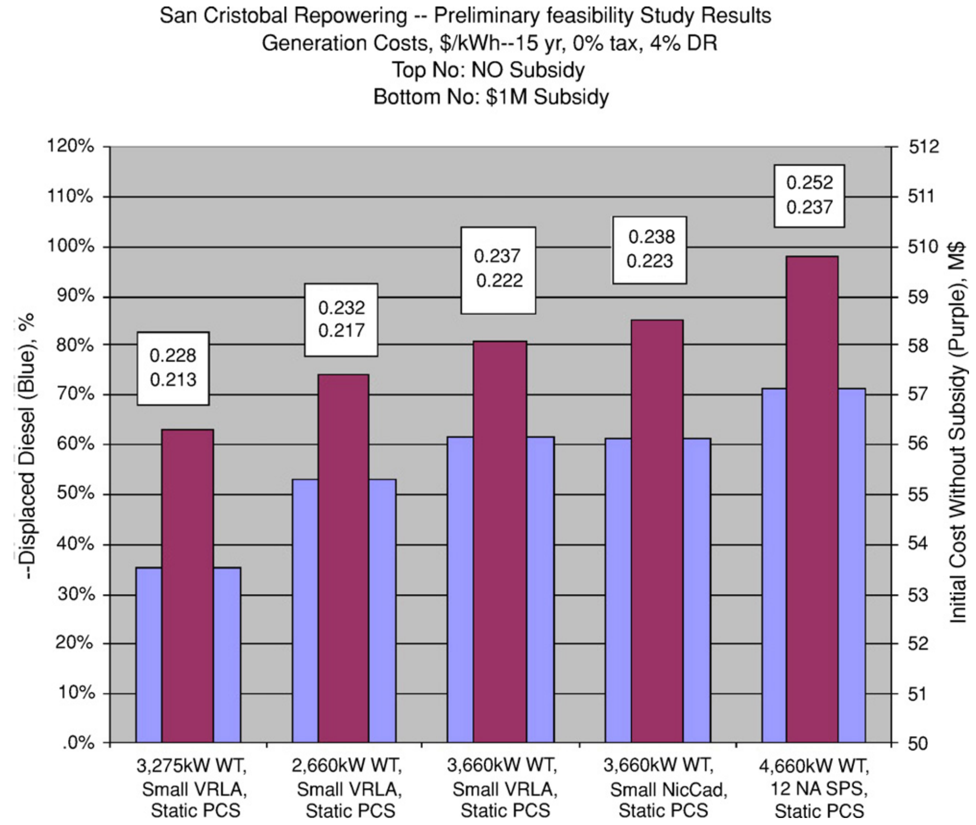

Fig. 2. E7 Galapagos diesel displacement study results.

5. High-power battery technologies

Having established that a battery-based energy storage system with several minutes of run time is optimum for this application, the next obvious question relates to the choice of battery technology. The battery must be capable of delivering a high proportion of its rated energy in a short time. It must also be capable of providing frequent power cycling, often at a partial state of charge. This operation is particularly difficult for lead–acid batteries, often leading to premature failure due to sulfation.

Such problems do not occur with Ni–Cd batteries. Cell designs with sintered positive plates and plastic-bonded negatives (S/PBE designs) provide high power and excellent cycling capability, combined with low maintenance requirements. Of particular importance in this application is the ability of the battery to provide large numbers of shallow cycles, to cope with fluctuations in wind generation output. Fig. 3 shows that S/PBE cells can provide 3500 cycles of 80% depth of discharge (DOD), but, more important, 50,000 cycles of 10% DOD.

The S/PBE Ni–Cd technology provides the required characteristics for this application and is a very good choice for the near term. Longer term, the same developments that make lithium ion a promising choice for HEVs will make this technology an excellent choice for operation with wind generation. In addition to high power and cycling capability, this technology combines high energy-efficiency and small volume and weight with zero maintenance requirements. In a typical architecture that is envisaged for this type of battery, rack-mountable modules are fitted in a 19 in. cabinet. In this arrangement, shown partially in Fig. 4, a complete battery with a capability of 150 kW for 5 min at around 600 V can be fitted in a single 44U cabinet.

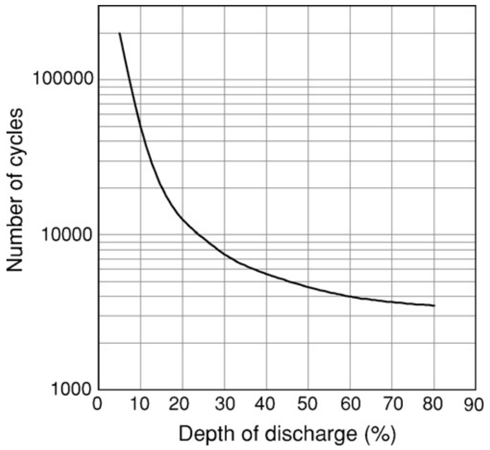

Fig. 3. Ni–Cd sintered/plastic-bonded cell cycling capability.

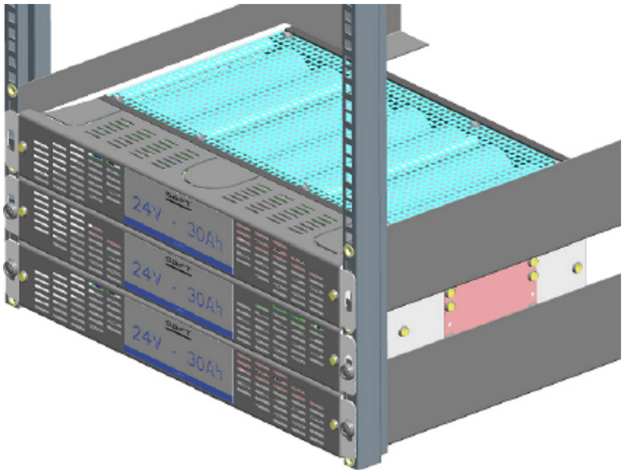

Fig. 4. Rack-mounted modular lithium ion battery.

6. Summary

It has been shown in this paper that battery-based energy storage with several minutes of run time is optimum for stabilizing wind generation in weak grids. This will allow a high level of penetration of this renewable energy source in such networks, while displacing other forms of generation and bridging to alternative power sources when necessary. Value streams that can be realized include deferral of transmission upgrades, avoidance of line losses and provision of ancillary services. Suitable battery technologies include nickel–cadmium in the short to mid term and lithium ion in the long term.

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