Energy Storage – Applications in the Smart Grid

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Abstract— Today, there are many different mechanisms for storing energy, and quite a few mechanisms for converting stored energy into electric energy. Electric utilities must produce electricity on demand, with no facility to warehouse their product. Unlike the telephone system, the electric utilities have no "busy signal" by which to ask customers to come back later and try again. There is no queue line in which electric customers may wait their turn. The operation of an electric utility is a delicate balancing act in which the generation must equal the load, exactly, all of the time.

Keywords-component; Energy Storage, Smart Grid

I. Introduction

Electric energy has been stored for later use for more than a century, by and through technologies still in use today. Energy storage in utility use quantities dates back at least to 1929, when Pumped-storage hydroelectric power was first used commercially. Running generators backwards as motors to pump water into the upper reservoir made it possible to re-use the same water day after day, meeting peak electric demand requirements. Electric energy was required to operate the pumps to refill the reservoir, so there had to be an economical source available. The solution was a conventional power plant nearby that operated most efficiently when fully loaded.

II. The Smart Grid

The "Smart Grid" of the future is a transmission and distribution system with modern devices that can react to situations as they arise, making the system "self operating" and "self healing" from otherwise adverse conditions. To that capability is added a sophisticated communications and control system, so that the operations center and the devices themselves have the information necessary to function reliably and safely.

The smart grid empowers many new generation opportunities, such as solar and wind power. It also enables the grid to accommodate storage opportunities at unconventional places and in unconventional sizes. Energy storage at substations can extend the life of a transformer by helping to level the demand and not overloading the transformer. Community energy storage can reduce loads on distribution lines and allow deferring upgrades or replacements for years. Customer satisfaction metrics, such as SAIDI, can be improved and power quality, voltage sags, and other customer irritants can be reduced considerably.

III. Energy Storage Technologies

There are many different ways to store energy. Energy can be kinetic, chemical, thermal, or some other form of potential energy. A technology for storing AC electric energy has not been discovered yet, however. We have to choose some other energy storage technology and convert that stored energy back into AC electric energy when the energy is needed.

Storing DC electric energy or converting other forms of stored energy into DC electricity has been convenient and the technologies are well developed. Batteries are a mature technology and cars and flashlights have used them for a century.

IV. Electric Energy Storage Technologies

The technologies for storing electric energy incorporate energy conversion as well. Most technologies take electric energy and convert it to some other form of energy, then reconvert it back into the electric energy desired. Because such conversions cannot be done without some loss, making the storage economically sound is a challenge.

One of the older methods for gaining an economic advantage is to store energy when it is cheap and plentiful and release it when the demand is increased and the price is high. Some electric power generation technologies beg for storage as a companion. Nuclear power generating units prefer to operate at a steady pace, and all conventional generating systems have a most efficient operating point. If the demand for electricity drops below the most efficient operating point, then it may become economical to store energy to maintain the overall economic picture. The stored energy may be used when demand rises again, offsetting some more expensive solution, such as purchasing electric power from an outside source.

A. Pumped Storage Hydroelectric Plants

For bulk energy storage in utility grids, pumped hydro power plants dominate, with approximately 100 GW in service around the globe. The earliest application was in 1882 in Zurich, Switzerland. In 1956, a Francis turbine was teamed with a motor-generator and the truly reversible system was born. In the 1990s, an adjustable-speed drive was added and gave the operator control of the electric output by both water flow and electronic speed control.

Worldwide, there are 95 GW of pumped storage hydroelectric power in service. [1] They serve to store electric power as potential energy during times when the cost of powering the pumps is low, and to deliver the energy as electricity when the selling price is higher. The efficiency ratio is about 70 percent. These units also provide ancillary duties, such as voltage and frequency support.

B. Battery Energy Storage

We have had electric batteries for many decades, but the improvements were simple incremental changes for most of that period. The chemistry didn't change much and the packaging got better. In the last 20 years, we have seen improvements to the chemistry, from nickel-cadmium to lithium-ion batteries and beyond. Today, there are more exotic chemistry combinations.

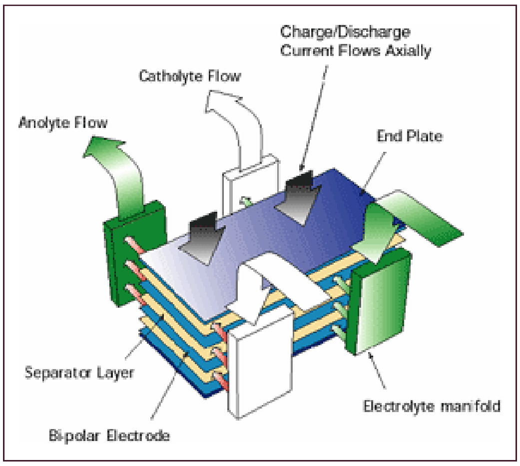

Figure 1 - Zinc-Bromide flowing battery (courtesy Premium Power [2])

Utility-scale battery systems are now in place around the world. One megawatt systems are used in distribution systems as well as in industrial systems. Preventing power interruptions are a common application of battery systems.

C. Lead-Acid Batteries

The very common lead-acid battery has been used by utilities for their own control systems for more than a hundred years. The early urban utilities offered dc voltage to their customers and the electric dynamos were backed up by lead-acid batteries. In utility scale applications, the lead-acid battery is not as practical as it would seem. The application would work best if the batteries could be deep discharged and rapidly recharged many thousands of time, and the present lead-acid technology doesn't permit that. The cells fail due to sulfation of the negative plates, causing them to short out after hundreds of cycles. A failed battery in a string causes the entire battery system to be removed from service. Lead –acid batteries used in computer UPS applications serve for years with very few discharges, thanks to the reliability of the commercial power system.

D. Nickel-Cadmium Batteries.

NiCad batteries have performance closer to the needs of a utility energy storage system. They are reliable and long lived. The charging requirements are very specific and in a large array with a trained operator, they work very well. The *IEEE power and Energy Magazine* featured an installation of 26 MW for 15 minutes that is used in Alaska, the largest utility application of NiCad batteries. They have excellent cycling characteristics. Utility applications such as this can provide both reserve power and voltage control with proper charging control.

E. Lithium Ion Batteries

The lithium ion battery is well known for its application in cameras, computers, and cell phones. The chemistry lends itself to any number of configurations, allowing the battery to be fit to the available space in electronic equipment. They have recently come out as a leader in the electric vehicle market. The batteries are light weight and have a very high power density. That is, the power to mass ratio is high, a desirable attribute for powering an automobile. The technology to make a lighter, safer battery is pushing lithium ion batteries to new heights. The newer designs are finding their way into utility applications.

F. Lithium Iron Phosphate

Lithium Iron Phosphate is a safer battery because the chemistry does not allow oxygen to be released as freely as other chemistries. The cell is less likely to be involved in a fire, even when stacked tightly together. The cost is high because the technology is new, but production increases are expected to lower the cost.

G. Lithium Titanate

Lithium Titanate batteries are lithium-ion cells that employ lithium-titanate crystals on the surface of the anode instead of carbon. The chemistry increases the surface area of the anode more t more than 30 times the surface area of conventional lithium ion cells. According to reports CITE, the result is electrons can leave the anode quickly, making very fast recharging possible.

Electric automotive applications have been proposed, as well as military applications.

H. Sodium Sulfur Batteries

The chemistry of the sodium sulfur battery is a high temperature arrangement. The battery consists of two electrodes of molten sulfur and sodium, separated by a ceramic electrolyte membrane. The process is reversible, giving the battery a long useful lifetime in utility applications. The technology is well suited to a stationary installation with sufficient heating to maintain the 300 degree C temperature required for operation. The design is extensively used in Japan, where the cells are manufactured. Approximately 270 MW of sodium sulfur batteries are installed in support of the power grid in Japan. The technology is finding its way into pilot projects elsewhere in the world.

I. Zinc-bromine Flow Batteries

The zinc-bromine flow battery employs a solution of zinc bromide pumped through a reactor stack, which plate the zinc to the electrolyte surface and creates zinc bromine. Reversing the process dissolves the zinc and restores the battery.

The chemistry is particularly suited to utility operation in that the battery may be completely discharges and left in that state for an extended period, then recharged without loss of life. Unlike other technologies, no heat or other storage conditions apply and the cells have indefinite shelf life. They may be coupled with any electric charging source.

Figure 2 – Zinc bromide flow battery

J. Supercapacitors

The supercapacitor is becoming commonplace in consumer electronics. The supercapacitor has replaced the battery in household appliances that incorporate a clock, such as the microwave oven. The technology incorporates new materials and, while the way a capacitor works has not changed, the capacity certainly has changed. The supercapacitor has low leakage current and may be charged and discharged thousands of times. The next challenge is to combine the units into utility-scale systems.

Figure 3 - Supercapacitors

K. Thermal storage

Converting electricity into heat or cold is a common application. Homes store hot water for use throughout the day and as electric utilities put time-of-use rates into place, the hot water heater will be programmed to heat during low-cost times. Likewise, commercial and industrial users of heat will discover ways to collect and store heat for use later. The thermal energy can be used directly and does not have to be turned bak into electricity.

Storing ice has been a commercial air conditioning mechanism for some time, but that technology will find its way into residential markets. Using ice as a direct cooling agent is more efficient that the air conditioner, as the temperature differential is greater. Modular ice-making systems can make ice during the low-energy-cost periods and use the ice as a coolant directly during the high-cost periods.

L. Flywheels

The flywheel is likely the oldest form of energy storage. The mechanical energy stored in a flywheel can efficiently be used as mechanical energy on the same shaft. Using a motor-generator to spin a flywheel, then to recover the energy as electric energy from the motor-generator is a common frequency-stability strategy. A generator with a significant flywheel can accommodate large changes in load without undue changes in frequency.

Computer systems of the 1960s were equipped with power supplies that had motor-generators and flywheels tin order to isolate them from voltage variations that might disrupt the computations. Some systems used separate motors and generators and changed the frequency for powering the computer.

Today, the heavy steel flywheel is rare. Light fiber composite flywheels are used instead. The energy stored in a flywheel is a function of the mass of the flywheel and a function of the square of the rotational speed. A lighter flywheel can store more energy if it spins faster, and speeds of 30- or 40-thousdand RPMs are common.

Clearly, the electric output of a generator turning that fast has to be converted into the system nominal frequency, and that is done with power electronic systems. The electronic systems take the high-frequency electricity, and make stable, sinusoidal AC voltage available as the output. As the flywheel gives up energy, it slows down. The electronics maintains an appropriate output for many seconds as it winds down.

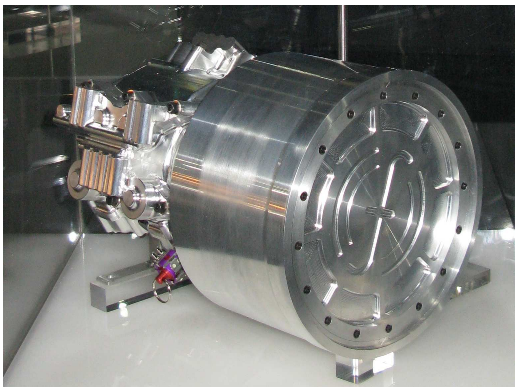

Figure 4 – Flywheel Energy storage system for use in automotive racing

M. Superconducting Magnetic Energy Storage

The superconducting magnetic energy storage system is a newcomer to the market. The energy storage mechanism is an electromagnet. The coil is made from a high-temperature superconductor and, once it is charged, the electricity travels around the coil effortlessly. The term "high temperature superconductor" does not mean room temperature superconductor. The coil is immersed in liquid nitrogen and operates at about 43 K or −230 °C. The high temperature designation distinguishes the material from other superconductors, operating in liquid hydrogen at 20 K or −253 °C.

The magnetic coil carries about 10 times the current that a similar sized copper conductor would carry, and it carries that current in an endless loop. To store energy, the coil is charged with a dc current; to recover that energy, the current is diverted to an electronic module that coverts the dc current into ac voltage and connects it to the grid. The system may be used for voltage support during a voltage sag or to supply current for starting a large machine. As with other storage technologies, the energy must be replaced by recharging the device.

N. Vehicle-To-Grid

The advent of the plug-in electric vehicle means that charging the vehicle battery at home will become a casual occurrence. Little thought is given to the requirements that will place on the electric system, or what benefits might be found in having a high-capacity battery connected to the home electric system. A small number of electric vehicles will make little difference, but a large number in a small part of the system all commanded to charge at the same time may cause loading sand electronic distortion for the power system. To avoid the possibility, automobile charges will be equipped to charge the battery in a "friendly" manner. The units may wait until the evening peak load period passes, or test the battery and determine that a slow charging rate is sufficient. Battery chargers may be programmed to use the lowest cost electricity to charge the battery.

The vehicle battery might be called upon to deliver power back into the residential power system when a low voltage condition occurs. An electric system emergency condition may call upon the vehicle to act as a renewable energy resource for a brief period of time. Vehicle chargers will be equipped to provide for two-way power flow into and from the battery system.

O. Applications to the Smart Grid

The smart grid will have any advantages over the simple grid of yesterday. By including communications links, the grid will be self healing, meaning that problems will be quickly detected and reconfiguring the grid to compensate will be safe and automatic. The Smart Grid will continuously analyse itself, discovering potential problems ad offering options to avoid problems. By performing state estimation in real time and throughout the system, smooth operation of the Smart Grid will be common.

The Smart Grid will also accommodate renewable generation in large quantities. Renewable energy sources are typically variable in nature. Photovoltaic systems have an output that changes, not only from day to night but throughout the day as clouds obscure sunlight from parts of the array. Multiple arrays aggravate the problem by injecting the energy at different geographic places in the grid.

Wind power varies throughout the day and throughout the year. Wind power is exceedingly attractive, but also exceedingly variable.

Electric energy storage on the grid is required to compensate for the variability of the renewable resources. While wind may change dramatically in a matter of seconds, a wind turbine and electric storage system operating as a unit will offer a controllable and reliable energy source.

Electric energy storage may be used as a buffer for variable resources, it may be used to meet the spinning reserve requirements of the operator, and it may be used to improve power quality by mitigating voltage sags ad swells. Electric energy storage may be used to improve power factor on the system, making the grid more efficient and increasing the asset utilization of the grid.

The Smart Grid will include electric energy storage in many forms for many purposes. The different technologies have different economics and different strengths. Each will find a home in the Smart Grid.

[1] Bradford Roberts ,*IEEE Power and Energy Magazine*, July/August 2009, p32

[2] Data and drawing from http://www.premiumpower.com/product/powerblock150.php