RELIABILITY AND POWER - VISTAS FOR ENERGY STORAGE

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Historic Preamble

About half a century ago, electrical energy and its delivery system were an immense technological success story. With the formation of the rural co-ops, electricity now served virtually every citizen of the United States. The transmission system spanned the continent from coast to coast. Gleaming fossil fuel plants provided inexpensive energy. Soon these were joined by nuclear power plants. In the near future, it was thought energy would be so cheap and plentiful that metering would become unnecessary.

It didn't last. Concern for nuclear safety came first, eventually halting new development of such power plants. Then it was realized that fossil plants spewed out huge amounts of chemical pollutants endangering vast tracts of forests. Greenhouse gases posed problems of even larger scope. At the same time, construction of new transmission lines almost came to a standstill. On the other hand, consumption of electrical energy continued to grow steadily.

Today, electricity supply has become a major problem. Region wide outages have become commonplace. Rolling blackouts make newspaper headlines like hurricanes - only more frequently. And industries have become much more vulnerable to even the shortest outages. The worst occurrences seem to be restricted to California, but experts see no reason why the problem shouldn't spread to other states.

The current energy crisis not only concerns the amount of energy, but the availability of energy as well. *Where* and *when* energy is reliably supplied is as important as *how much*. This is where energy storage comes in. The problems of the electricity industry become opportunities and challenges for energy storage: The reliability needs of the digital economy, excessive price volatility, and transmission congestion are drivers for extensive deployment of energy storage. Of course, energy storage will not solve all our energy problems. But energy storage will become a necessary and powerful tool in mitigating the effects of an overburdened electricity delivery system.

Reliability for a Digital World

Our technological world has, to a large degree, become a digital world. Digital controls are everywhere. The production lines of high tech manufacturing plants are controlled by digital switches. Mass transportation relies on digital devices for scheduling and ticketing. Telecommunication has become digitized. Financial transactions, from bank statements to the complex activities of the stock market, are carried out in binary mode. The Internet and web based e-commerce have vastly accelerated the transformation from analog to digital devices.

But digital devices not only need energy, they need a continuous supply of high quality power. They cannot tolerate the micro outages, voltage sags, or surges which occur so frequently on the grid. The vulnerability of digital devices is inherent. Analog devices are tolerant to small fluctuations and can easily be made self-correcting. Digital devices, on the other hand are either right or wrong. Ideally, digital technologies would like to have better than 99.999 999 947 % reliability. This is 9 nines! It corresponds to one cycle per year. The grid can only supply about 99.9% reliability - 3 nines!

Reliability is not only a technical requirement for digital technologies, it is an economical necessity. Estimates for total losses of U.S. industry from outages range from 30 - 150 billion dollars. Outages are obviously immensely expensive for industries from cellular communication to brokerage operations, running into millions of dollars per hour. Digitally controlled manufacturing processes are equally vulnerable. A single large polymer extrusion plant may lose half a million dollars a year from short-term outages alone. A credit card company may lose 10 million dollars per minute in missed revenue. The competition is just a mouse click away! But quoted $/hr figures for outages are somewhat misleading. Actually, much of the damage is done in the first few cycles when controls trip. An outage of a few cycles may take four hours to clean up. While the price of power is determined by the economy of power production, the cost of a power outage is determined by the value of the product. As a result, power quality is becoming as important as power quantity, and the cost of "no power" is almost priceless in the digital economy!

Seamless waveform continuation when a power quality (PQ) event occurs can best be provided by electrical energy storage. It is instantly available power that counts! No auxiliary generator can be brought on line with even remotely sufficient speed. Most outages last only from a few cycles to a few seconds. A design period of 15-30 seconds is adequate for most PQ storage applications. After that, either the power returns, or the system can be shut down in an orderly fashion. If an outage persists for longer periods, during a rolling blackout for example, storage could still furnish the required electricity, but it needs a storage device designed for energy content. Alternatively, any of a variety of distributed generation options can be used, such as gensets, fuel cells, micro turbines or reciprocating engines. The actual mix must be determined in each case by the load requirements, the power quality pattern, and the fuel and mortgage costs. In all cases, energy storage is a required, essential component.

As an example, a 2MW system, installed at a major polymer extrusion plant, provides seamless power for 15 seconds. The system utilizes lead acid batteries with carefully integrated power electronics. 15 seconds is just long enough to bring into play a quickstart genset. Together, the system is able to ride out power quality events as well as longer blackouts. The payback period turns out to be one year!

Factories and digital facilities whose requirements cannot be met by the reliability of the grid are becoming ubiquitous. Large internet hotels are springing up in almost every major city. We can try to make a rather rough estimate of the total market potential. Taking our cue from the estimate of economic losses from power quality events, and assuming a one year payback, we find a potential market of 30 - 150 billion dollars. This may well be off by a factor of 10, but even so, it represents a very sizable market.

The Power of Arbitrage

It is a fundamental fact that machines function best at a constant pace, but humans work in diurnal cycles. At night, when the load is small, energy is available for a low price. During daytime peaks, the rate is higher. In addition, severe hot or cold weather will magnify the load very considerably. These consumption peaks above the average fluctuations are particularly irksome for utilities, because they have to bring expensive peaking units into play. As a result, energy providers impose a heavy demand charge.

In recent years, this situation has become more and more aggravated as electricity consumption increased to such a degree that peak demand pushes dangerously close to the limit of capacity reserves. The system has to draw on marginally effective sources of supply, and spot prices soar. This price volatility has become exacerbated by the fact that many transmission lines are also burdened to their limit. As a result, even though cheaper electricity is available elsewhere, it cannot be imported in sufficient quantities. When this severely stressed system faces an unexpected event, such as a power plant going off line, it becomes unstable. Rolling blackouts, if not the collapse of an entire regional grid, are the result.

Electricity restructuring was intended to allow market forces to make the electricity supply system economically self-correcting. Time of day pricing is intended to give major customers strong incentives to readjust their load pattern. Unfortunately, this has not worked out so far. Some of the price volatility is indeed passed on to the consumer, but the market is very inelastic and shows little response. Customers complain bitterly about high prices, but, generally, they continue to consume. In some cases, "load as a resource" has indeed lead to unexpected solutions. Aluminum smelters in the Northwest, for example, have found that it is more profitable to close down and sell their guaranteed, low priced power back to the utilities.

Energy Storage presents an excellent opportunity to allow commercial and industrial customers to take advantage of this situation. However, what is required for such applications are storage systems with fairly substantial energy content. Energy storage would have to carry the load for some 650 hours a year or a maximum of 5 hours at a time. Power quality benefits would become available as an extra bonus. Using fairly conservative assumptions, one finds a rather impressive 460 GW potential market! Taking into account reasonable estimates for peak/off peak price differentials and annualizing appropriately, one finds a benefit of some 875 $/kW for energy storage in this application.

The economic incentives for such load management are very likely to become even better. As ISOs become more aware of this huge available resource, we can expect new contractual arrangements to be put in place to allow the customer to actually sell back unused load. Municipalities or utilities may also offer more direct incentives. For example, the Los Angeles Department of Water and Power has initiated a 5-year effort to help its largest customers to lower costs and energy consumption by installing energy storage systems. Participating customers are eligible for an initial incentive of $400 per kilowatt demand reduced from on-peak hours, while utilizing low priced night time energy. In addition, the city will provide up to $10,000 for engineering services and half the actual cost of commissioning. As a result, a 3-year payback is expected for the customer. Peak reduction will allow the utility to deploy it=s resources in a more effective way and reduce NOx emission in the Los Angeles basin.

Alternatively, utilities can also use arbitrage themselves to mitigate the deleterious results of price spikes. For example, weekly peak loads in the New England Power pool vary by some 50%. But, for the same time period, weekly peak spot prices vary by 10,000% ! As a result, 90 hours of operation are responsible for one sixth of the wholesale cost in one year. Under such conditions of very high price volatility, a utility employing 200 hours of storage per year with a maximum of 4 hours at a time could avoid peak prices while increasing reliability with expanded capacity reserves. The total market potentially available amounts to some 200 GW. With reasonable assumptions for peak prices and other parameters, one finds a benefit of 550 $/kW installed.

It is obvious from these considerations that there is a vast potential for the deployment of energy storage to take advantage of temporal fluctuations in demand and supply price. Even moderate market penetration will go far towards increasing demand/supply elasticity and thus allowing restructuring to fulfill its aim of economic optimization. Effectively, this will lower wholesale market prices for all consumers. Of course, other load shaping options, such as distributed generation or direct load reduction, must also be considered. Energy storage will be successful only if it is the most economical solution for given local conditions and requirements.

Thinking Big

While many future applications of energy will be as a distributed resource, larger projects may be closer to central generation in spirit. Here is a small sampling of such projects. Some of them are already operating successfully; some may take a long time until realization.

As an example, the world's largest battery system is installed in Puerto Rico, where it provides spinning reserve as well as voltage and frequency control for the island's grid. At 20 MW and 14 MWhrs, the system can deliver both power and energy. Although the tropical location makes extra demands on the lead acid batteries, it has been decided to double the capacity of the system in the near future. Eventually, the facility may grow to 60 MW.

A smaller system was installed on the Alaskan island of Metlakatla, forming an effective minigrid. A 1 MW/1.4 MWhr valve regulated lead acid battery system shields the island's town from the frequent momentary brownouts due to the very variable load of the local sawmill. It has been suggested to join this system via an underwater cable to the nearby town of Ketchikan. This would allow replacement of some of Ketchikan's dirty diesel generators by the clean hydropower of Metlakatla.

An interesting potential storage project arises from a special problem in the New England ISO. The region is linked to Québec by a high voltage DC transmission line. Nominally, 2000 MW could be imported over this line. However, if this line were to fail, voltage collapse could occur in nearby New York and New Jersey unless extra spinning reserves could be brought into play almost instantaneously. Since only 1200 MW of reserve capacity are available, the DC line is under utilized by 800 MW. Instead of building a power plant of this capacity and idling it, a corresponding energy storage plant would be vastly more cost effective.

Another good opportunity for energy storage occurs in one of the regional utilities in Japan. Their generation mix is made up of nuclear, fossil, and liquefied natural gas. During nighttime, the demand can be satisfied entirely by nuclear which, of course, has a completely constant output. In fact, the extra available energy is put into pumped hydro to use for daytime peaking. However, nighttime load is not constant, showing about 260 MW fluctuations. To guarantee load frequency control, this extra demand has to be supplied as needed. About 160 MW of this can be supplied by variable speed pumped storage. The extra 100 MW are currently provided by fossil power plants operating at minimum level. Energy storage could obviously provide a much better, flexible and non-polluting alternative. Payback period is estimated at some 7 years.

Opportunities for large storage applications also arise from renewable energy sources. Wind farms are essentially non-dispatchable because output fluctuates unpredictably. As a result, they cannot really participate in the high priced spot market. Typically, spot market bids are required 24 hours in advance, with a penalty of 250% for non-deliverance. Coupling wind farms with energy storage would allow the industry to sell blocks of power at premium prices. With wind projects in the hundreds of MW in the near future, this will present a great challenge and opportunity for energy storage.

A Portfolio of Solutions

Energy storage systems already offer a variety of options for digital reliability. Increasingly, systems are also becoming available offering enough energy for peak shaving and arbitrage. Chief among the options is chemical storage by batteries, in particular the traditional lead acid (LA) batteries. Because of their widespread use in automobiles, they are inexpensive and have fairly well known operating characteristics. Variations on the LA theme are the valve regulated LA battery, which is sealed and needs less maintenance, and gel batteries, which are becoming popular in Europe. Stationary systems range from the huge 20MW/15 min system in Puerto Rico to a 1 MW/ 1 hr system on Metlakatla Island in Alaska and typical telecommunication applications at 4kW/4 hrs. An essential feature for successful application of LA batteries and, indeed, any energy storage is the careful integration of appropriate power electronics.

The family of flow batteries presents a very interesting feature. They can decouple power and energy. A central battery unit provides power, but total energy is furnished by a reservoir of rechargeable electrolyte, which can be as large as one pleases and situated anyplace convenient. Zinc-bromine batteries are available off the shelf and have been deployed widely. Again, integrated power electronics are essential to successful applications. Vanadium redox batteries, developed in Australia and Japan, have found application up to 3 MW. Sodium bromide batteries have received considerable interest recently. A 120 MWhr facility is under construction in the U.K. Large facilities are also planned in the U.S.

Among the advanced batteries, the sodium sulfur battery deserves special mention. Developed in Japan, this battery operates at high temperatures, but extensive tests have shown the safety of the containment under extreme conditions. Twenty systems totaling about 16 MW and 124 MWhrs have been installed. The largest of these installations can provide 6 MW for 8 hours. It can also supply active and reactive power to mitigate voltage sags and frequency fluctuations. Lithium ion, lithium polymer, and nickel metal hydride batteries have been developed mainly for automotive use. They may find wide application if California and perhaps other states continue their mandate for zero emission vehicles. These advanced batteries offer vastly decreased footprint and excellent maintenance characteristics. However, they tend to be much too expensive for large-scale applications. Efforts are underway to test installation of used vehicular batteries for load leveling and power quality control. A wide secondary market would reduce the effective cost very considerably.

Besides batteries, flywheels are increasingly attracting interest. They are able to charge and discharge rapidly and are little affected by temperature fluctuations or discharge patterns. They have good footprint, lower maintenance, and a long life span, although energy loss is faster than for batteries. Flywheels are particularly suitable for power quality control, but as yet no large-scale applications of the technology have been made. High temperature superconducting flywheels are under development with funding from DOE. Such systems would offer inherent stability, minimal loss, and simplicity of operation.

Supercapacitors store electrical energy by charge separation in porous high surface area electrodes. They are capable of very fast charges and discharges and apparently are able to go through a large number of cycles without degradation. Although these claims are impressive, no large-scale system has been fielded yet.

Superconducting magnetic energy storage (SMES) stores energy in the magnetic field generated by a loop of endless current. Power is available almost instantaneously, there is no loss, and there are no moving parts. Energy content is, however, small and the cryogenics can be annoying. Several 1 MW units are used for power quality control throughout the world. An interesting recent development was the deployment of a string of distributed SMES units in northern Wisconsin to enhance stability of a transmission loop. The line is subject to large sudden load changes due to the operation of paper mills and has the potential for uncontrolled fluctuations and voltage collapse. Besides stabilizing the grid, the 6 SMES units also provide increased power quality to customers served by connected feeders.

Conclusions

Opportunities for profitable application of energy storage are indeed vast. In the immediate future, reliability and the digital economy seem to offer the most favorable market. In the long run, load leveling and arbitrage are promising fields for larger storage systems. The increasing variety of technology options, which is becoming available, will have a sizable share in making the electrical grid of the future reliable and economic.

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