

Power Delivery in a Digital World

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Nine Nines for a Digital World

Our technological world has, to a large degree, become a digital world. Gone are the giant wheels, the clanking chains, and puffing engines of Victorian technology. 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. We have developed a digital economy based on information rather than on raw power.

Of course the digital economy still needs power, and specifically electric power. In fact information based technology is estimated to consume some 13% of the U.S. power output - a figure which may grow to 50% by 2020. But digital devices not only need energy, they need a continuous supply of high quality power. They cannot tolerate the micro outages, voltage sags, surges, or frequency shifts 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. A miss is as good as a mile! Ideally, digital technologies would like to have better than 99.999 999 947 percent reliability. This is 9 nines! It corresponds to one cycle per year. The grid can only supply about 99.9% reliability - 3 nines!

The Economics of Naught

Reliability is not only a technical requirement for digital technologies it is an economical necessity. 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! Estimates for total losses of U.S. industry from outages range from 30 billion dollars upwards. 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. The point is that down-time of electricity supply is not equal to down-time of the system served. So, 10 five cycle outages are much worse than one 50 cycle outage. As many as 1500 power quality events have been recorded in one year at an Internet provider's site. In any case, while the cost of power is determined by the economy of power production, the price 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!

Energy Storage, the Key to Reliability

Seamless waveform continuation, when a power quality event occurs, can only 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.

A wide portfolio of energy storage options is becoming available to the digital consumer. Chief among these is chemical storage by batteries. The traditional lead acid (LA) battery. Because of their widespread use in automobiles, they are

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inexpensive and have fairly well known operating characteristics. The 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. A mobile 2 MW system is installed at a major polymer extrusion plant to provide seamless power for 15 seconds. The ability to avoid the disastrous effects of micro-outages and voltage sags leads to a payback period of about one year. Larger versions of this system, which was developed (in part) with funding from DOE, are being installed at an increasing number of sites. 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 anywhere 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. While only relatively small systems exist in the U.S., a 120 MWhr facility is under construction in the U.K.

And Further Options

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, at a substation in the foothills of Mt. Fuji, provides 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 power 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 power 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.

Energy Storage and DG

Energy storage is not alone in providing reliability for the digital economy. Power can also be generated on site. In fact, it is expected that 20% of new generation will be distributed generation (DG) by 2010. A number of effective alternatives are emerging for providing distributed generation. Diesel gensets have evolved into compact generators satisfying all but the most stringent air quality requirements. Gas driven reciprocating engines are available and new, even cleaner technologies such as microturbines and fuel cells are fast becoming economically viable. Because they run on natural gas, they can utilize a continuous flow of energy parallel to the electric grid. When used in an N+1 or N+2 conformation, they can provide reliable standby power for extended outages. However, DG technologies are not able to provide instant power when power quality events occur. They are also not very effective in responding to rapid load changes. At the very least, enough storage is required to allow the backup generator to come on line. Beyond that, the optimal mix of energy storage and DG should be determined for each application based on load characteristics, power supply pricing (both gas and electricity) and system cost amortization. Distributed generation and energy storage are complementary. Together they can provide the required reliability and furnish peak shaving benefits as well.

Energy Storage combined with distributed generation can benefit both the user, by providing reliability, and the grid, by providing spinning reserve. Reserve capacity in the U.S. is now down to a low 10%. This is a serious liability which potentially impacts the stability of the entire grid and can lead to major outages such as those during the hot summer of 1999. If contracts can be arranged by the customer to provide spinning reserve for the grid, this could lead to a significant reduction of the cost of reliability. Unfortunately the monetary value of such auxiliary services is not yet well determined. But spinning reserve as a commodity is likely to be important once substantial restructuring has been achieved.

Restructuring and the Grid of the Future

Restructuring the electricity market will convert power delivery from a vertical monopoly under state regulation into disaggregated utilities allowing market based decisions. Eventually there will be gencos devoted entirely to electricity production, transcos dedicated to effective power transmission, and discos interfacing with the customers. Independent System Operators (ISOs) will be responsible for balancing the grid. But beyond this, real time pricing and the requirement for premium power will create entirely new entities which can be considered as ‘utilities’ also. Aggregators will combine individual customers to negotiate optimal prices and to sell ‘load as a resource’ to the grid. Large customers will, in effect become their own utilities assuring power quality for themselves by adequate storage, and long term backup by local distributed generation. Because the same devices can also be used for peak shaving to decrease demand charges and as spinning reserve for the grid, reliability can be made more cost effective for the customer. Alternatively, these functions could be performed by ‘utilities’ contracting for a specified degree of reliability with equipment placed at the customer’s site but not owned by the customer. Insurance contracts could then effectively cover any residual power outages, effectively bringing reliability to 100%.

The grid of the future and its related management structure, driven in large measure by the digital economy, will become much more complex. But at the same time, by replacing a centrally oriented radial grid with a distributed web, the resulting structure has the potential to become self-regulating to an appreciable degree. Power delivery of the future will be characterized by distributed generation, distributed storage, and distributed intelligence. The grid of the future will combine the physical characteristics of Kirchhoff’s law with the monetary complexity of the stock market and the intricacies of the Internet into a vast, non-linear structure providing power for a digital world.