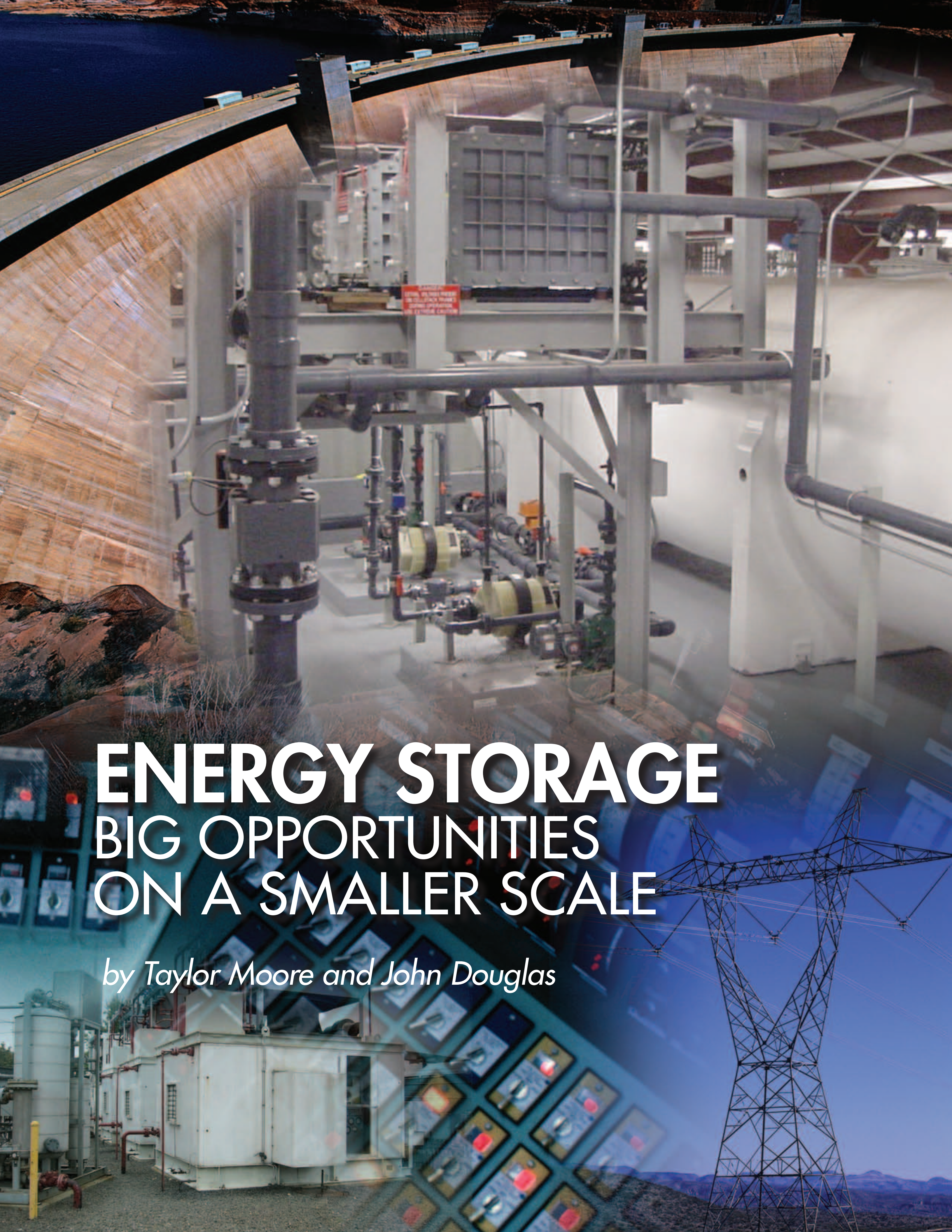


ENERGY STORAGE
BIG OPPORTUNITIES ON A SMALLER SCALE

by Taylor Moore and John Douglas

The Story in Brief

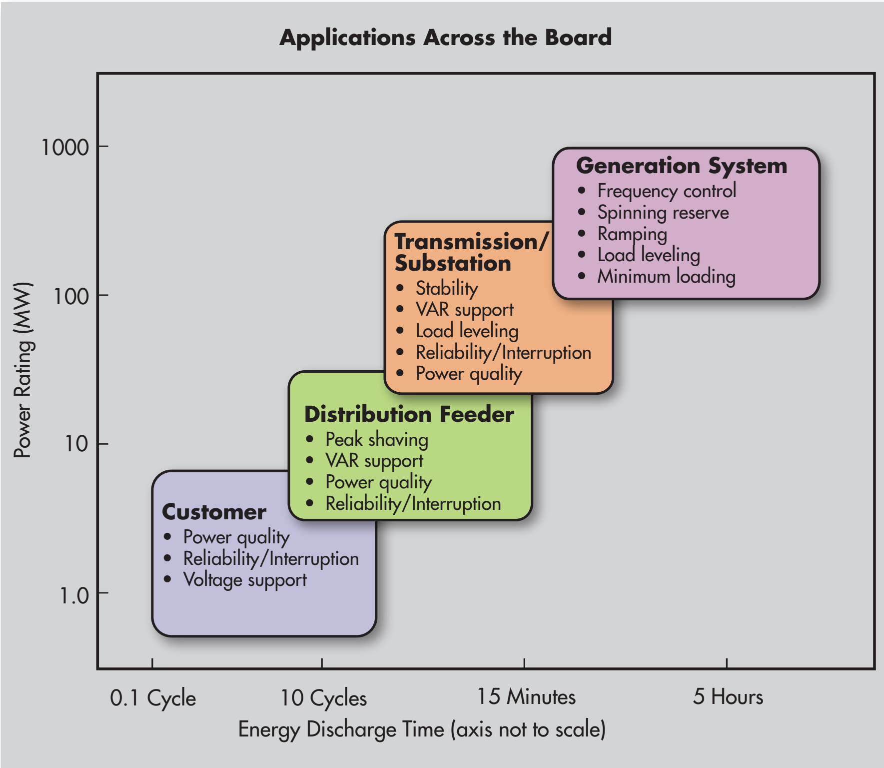
For decades, energy storage research was focused mainly on large-scale technologies for utility load leveling—storing cheaper, off-peak generation to serve customer load during hours of peak usage. While such installations can still make economic sense in favorable locations, a number of smaller storage devices that have been developed and demonstrated over the last ten years are substantially broadening storage applications for a wide variety of utility issues. Advanced batteries, ultracapacitors, high-efficiency flywheels, and superconducting magnetic storage have the capability to increase efficiency, reliability, power quality, and asset value across the entire electricity path, from power plants to customer premises.

Most visions of the electricity system of the future have included widespread, large-scale energy storage as a key component, and with good reason. Theoretically, the ability to store electric power in bulk could take care of some of the most difficult challenges in the electricity business, allowing the system to provide digital-quality power with rock-solid reliability using mostly baseload generation plants. These capabilities would result from overcoming the only major limitation on electricity's super-flexible form value: the need to use it the instant it is generated.

Yet despite these potential advantages, energy storage provides only about 2.5% of total electricity capacity in the United States, nearly all of it from pumped-hydro installations used for load shifting, frequency control, and spinning reserve. In sharp contrast, some 10% of all electricity produced in Europe is cycled through a storage facility of some kind, while Japan stores 15% of the total electricity it generates. These disparities reflect, in part, more-attractive sites for pumped hydro in both areas overseas and—particularly in Japan—higher electricity prices and a greater difference between peak and off-peak prices.

That's the problem: economics. Current bulk storage technologies involve physical scale and cost that have generally removed them from consideration in an industry whose commodity price has largely resisted inflation. In most cases where bulk energy storage would be useful in this country, it has simply been cheaper to build peaking combustion turbines to provide reserve generating capacity that can be dispatched when needed. Nevertheless, the prospects for storage on a smaller, less-capital-intensive scale—roughly tens of kilowatts to tens of megawatts—are bright indeed. A variety of new, intermediate-scale storage technologies are looking increasingly attractive for meeting a different set of utility needs, just as power industry restructuring is reshaping the economics of the services such devices would provide.

Many of the new potential applications are related to transmission and distribution system operations, and some technologies are also uniquely positioned for end-use applications as a demand-response tool. The Federal Energy Regulatory Commission (FERC) has defined a variety of what it calls ancillary services—services needed to support the delivery of power to customers while maintaining system reliability and for which the provider can seek compensation through restructured electricity markets. Energy storage is particularly well suited to provide at least two of these ancillary services: system regulation and spinning reserve. Regulation services involve supplying electric energy in real time to compensate for rapid changes in system load; spinning reserve restores the balance of supply and demand on a system after the sudden loss of a generator or power line or a sudden, unexpected increase in load. In



With the development of new intermediate- and small-scale technologies, energy storage can provide a broad range of benefits in applications that span the entire power continuum, from power plant to customer site. The choice of appropriate technology—advanced batteries, flywheels, ultracapacitors, or superconducting devices—depends primarily on the power capacity and discharge time required for the application.

addition to these power delivery benefits, energy storage may provide ancillary services that are not explicitly connected with current markets—for example, it may provide dynamic reactive energy (measured in volt-amperes reactive, or VARs) to the transmission system when needed.

To analyze the emerging business cases for using energy storage under various circumstances and to create a unique resource for comparing the specific technologies involved, EPRI and the U.S. Department of Energy have published the *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications.* A major conclusion of the research reported in this handbook is that, "while storage is not yet the universal solution for the ills of the electric delivery system, as more experience is gained and as technologies improve, storage may one day be ubiquitous in our power systems." A companion volume, the *EPRI-DOE Handbook Supplement of Energy Storage for Grid Connected Wind Generation Applications,* published a year later, has added coverage for wind energy applications.

An Expanding Role for Storage

By far the largest application of energy storage in today's electric power systems is the use of pumped-hydroelectric facilities to provide daily load shifting. The United States currently has 150 such facilities in 19 states, providing a total of 22 GW of generation capacity. Typically, these facilities consist of two reservoirs at significantly different elevations, connected by large penstocks and with a power-generating station between them. Electricity from a conventional power plant is used to pump water from the lower reservoir to the higher one during off-peak hours; gravity pulls the water back to the lower level through a hydroelectric turbine when additional energy is needed to help meet peak system loads. Such facilities range in size from hundreds of megawatts to over 2 GW and are capable of discharging at full power for 8–10 hours. Scarcity of suitable surface topography that is environmentally acceptable, however, is likely to inhibit further significant domestic development of utility pumped-hydro storage.

Another well-proved bulk storage technology for daily load shifting is compressed-air energy storage (CAES), which uses electrically driven compressors to charge an underground reservoir during off-peak hours. When needed, air is discharged from the reservoir into an expansion turbine connected to a generator. When electricity is used for the compression cycle, the fuel normally used by a simple-cycle combustion turbine plant is reduced substantially. One CAES plant, rated at 290 MW, has been operating in Germany since 1978 and is currently being used to provide spinning reserve and to store off-peak power from a nearby wind farm. Another facility, rated at 110 MW and having a maximum discharge period of up to 26 hours, was built and installed in 1991 by the Alabama Electric Cooperative with EPRI participation. More recently, several bulk storage CAES projects have been proposed to take advantage of salt caverns in Texas and an underground limestone mine in Ohio, but none of the plans for these plants have come to fruition yet. To advance the state of the art, EPRI is exploring the use of above-ground pipelines to store compressed air for CAES applications. Such pipes, similar in size and pressure to those used to transport natural gas, could be sited within an existing transmission right-of-way.

At a much smaller scale, lead-acid batteries have also been used for bulk storage. Indeed, one of the earliest uses of such batteries was to supplement the output of utility generation plants for meeting peak loads. As the size of utility grids grew, however, this application became less common because of the relatively high cost of the batteries. During the 1980s and '90s, a 17-MW battery facility in Berlin, West Germany, a 10-MW facility in Southern California, and a 20-MW plant in Puerto Rico were built to demonstrate the continued technical and economic feasibility of lead-acid batteries for load shifting and grid support. The Berlin project reached payback in approximately three years, operated for seven years, and was decommissioned only after reunification in Germany eliminated the need for the plant's frequency-regulation services. The facility in Puerto Rico provided similar services on the small island grid. According to Steve Eckroad, EPRI program manager for energy storage, "All three of these projects inspired a 27-MW battery facility with similar functionality in Fairbanks, Alaska, that uses a different battery technology—nickel-cadmium. The Fairbanks plant has operated successfully for over two years, providing spinning reserve and local voltage support, thus saving the local utility customers from numerous outages."

While new centralized bulk storage applications are constrained by economics and siting issues, smaller distributed energy storage (DES) options are expanding the role of energy storage into other areas of the electricity value chain, with T&D applications and end-user solutions appearing to be particularly promising. "The benefits of storage are greatest at the customer level, when you consider the value of the reliability that storage makes possible," says Dan Rastler, EPRI program manager for distributed resources. "The locational value of distributed storage could also benefit utilities in supporting the grid and helping to reduce grid congestion and other constraints." However, he adds, "Our research has shown that utilities would be much more able to monetize the value of distributed storage assets than a customer would."

The lack of suitable mechanisms for either utilities or customers to reap tangible monetary benefits from investments in storage remains one of the leading regulatory and economic issues impeding more-widespread deployment of energy storage. In some states, for example, electric utilities can no longer participate in the power supply business; they are allowed only to manage power delivery. But since a storage device is neither a generator nor a traditional part of the "wires" business, it remains unclear how a utility would be able to recoup the money spent installing one on its T&D system. And if a customer installs a storage device on his own property, the tariff treatment it would receive is also unclear. In one state, such a use of storage might be rewarded as a demand reduction effort by the customer. In another state, it might be considered an exiting strategy to avoid grid service and result in a standby charge to the customer.

"Industry restructuring is helping create a new demand for energy storage, particularly in T&D applications" says Eckroad. "New technologies will facilitate these applications, but significant regulatory questions need to be resolved before their true potential can be realized." Adds Rastler, "One area the EPRI program will be working on is to help inform all stakeholders in the policy debate of the value of electricity storage to electric utilities, to end-users, and to society. We will be working to shape a win-win-win strategy to enable the emerging energy storage technologies to contribute value to the electricity system."

Advanced Storage Plants

A variety of new storage technologies have recently been either commercialized or demonstrated at commercial scale. The priority applications for these technologies are concentrated largely on optimizing the existing T&D infrastructure or providing new ways to deliver premium-quality power to customers—or preferably, both. These devices will probably not be used for bulk storage and central-station load shifting any time soon. Rather, they offer a way to make T&D systems more reliable and responsive to customer needs by supplying ancillary services and enabling utilities to defer more capital-intensive infrastructure investments.

"The choice among candidate storage technologies comes down to a question of how much energy you need to store and how long you need to use it to supply power," says Robert Schainker, EPRI director for strategic planning. "Bulk storage

Pumped-hydro facilities such as TVA's 1.6-GW Raccoon Mountain plant represent the most mature option for large-scale utility applications like daily load shifting. There are currently 150 such U.S. facilities operating in 19 states; however, high construction costs and a scarcity of suitable surface topography are likely to severely limit further development of pumped-hydro storage in this country.

allows you to arbitrage large quantities of electric energy between different times and places. Distributed energy storage enables you to shore up your system by supplying smaller amounts of energy when and where it's critically needed."

One DES option—advanced batteries—builds on the industry's long familiarity with lead-acid batteries but improves on that technology's equally familiar shortcomings, such as limited deep-cycling lifetime and high maintenance requirements. In comparison with other advanced storage technologies, the great advantage of batteries is their inherently high energy density, which results from their use of chemical rather than physical processes to store energy.

A leading competitor for DES applications is the sodium-sulfur battery, which is offered commercially by NGK, Ltd., under the trade name NAS. This technology is based on a high-temperature reaction between sodium and sulfur, separated by a ceramic electrolyte—a configuration that has excellent stability, robust cycling, and minimal on-site maintenance requirements. As early as the 1980s, Tokyo Electric Power Company (TEPCO) had selected this type of battery as an alternative to growing reliance on central-station pumped-hydro storage. TEPCO has already installed several NAS units in the 1–6-MW range to provide load leveling and uninterruptible power at the substation level. The first NAS battery demonstration in the United States was hosted in 2002 by American Electric Power, with the cooperation of EPRI and other partners. AEP is now following up that demonstration with the installation of a 1.2-MW NAS battery at a substation where growing load will eventually require substation and/or feeder upgrades. The battery will defer those upgrades for a few years, after which the plan is to move the unit to another substation. Meanwhile, New York Power Authority (NYPA) plans to install a 1.2-MW, 6-hour NAS battery on Long Island to provide peak shaving for one of its mass transit customers. Although initial cost remains an issue, NAS manufacturing capacity is expanding and should lead to lower prices, making this technology increasingly attractive for T&D applications.

Other advanced batteries now being developed for use in plug-in hybrid electric vehicles (PHEVs) may have the potential for stationary applications as well—either on the grid or at customer locations. Both nickel–metal hydride (NiMH) and lithium ion (Li-ion) batteries have demonstrated energy storage capacities much higher than those of conventional lead-acid batteries of equal weight and can live through 5–10 times as many deep-discharge cycles. If PHEVs are successfully demonstrated and become commercially popular, the costs of NiMH and Li-ion batteries could be reduced by as much as 80% over a relatively short time, making them more affordable for stationary uses. One particularly intriguing possibility is the use of a PHEV as a backup power unit in the home. The vehicle would normally be charged through a simple electrical hookup in the garage; designers say that the charging unit could be configured to automatically feed electricity from the vehicle batteries back into the house wiring to cover basic electricity needs during a local power outage. Recent EPRI research suggests that advanced Li-ion batteries could result in crossover DES applications.

For long-duration discharge applications, a more fundamental departure from traditional battery design is being considered—so-called flow batteries. Generically, these batteries utilize active materials contained in the fluid electrolyte rather than in solid electrodes. The advantage of this design is that the battery's energy rating depends on the volume of the electrolyte, while the power rating depends on the size of the reaction cell stacks. As a result, the cost of extending the discharge time of a flow-battery system depends only on the size of the tanks used to hold the electrolyte, which is low in comparison with the cost of changing the number of cells in traditional battery systems. Thus, flow-battery systems are especially attractive for applications that require energy delivery for several hours. The corresponding disadvantage is that flow batteries tend to be complex systems with pumps, plumbing, and other auxiliary components.

Large-scale battery storage was demonstrated in the mid-1980s at Southern California Edison's Chino facility, which offered 10 MW of power with a 4-hour discharge capability using lead-acid batteries. Such projects paved the way for more-advanced battery projects, including a recently built 27-MW, 15-minute-discharge nickel-cadmium installation in Fairbanks, Alaska.

Sodium-sulfur batteries, offered commercially under the trade name NAS, have shown great promise for utility applications in the 1–6-MW range. Based on a high-temperature reaction between sodium and sulfur, the NAS battery features excellent stability, robust cycling, and minimal on-site maintenance. Shown is a 6-MW unit installed at a substation in Ohito, Japan.

Flow batteries of two types—the vanadium redox battery (VRB) and the zinc-bromine battery—are now available from developers as commercial prototypes. In the VRB, the positive electrolyte tank contains vanadium ions with a valance of +4, which lose an electron to the positive electrode during charge-up, shifting the valance to +5. The negative electrolyte tank contains vanadium ions with a valance of +3, which gain an electron during charge-up and go to +2. These reactions are reversed during discharge as the electrolytes circulate through opposite sides of a reaction cell, separated by an ion-exchange membrane. There have been several VRB demonstration projects at utility scale. In 2003, for instance, PacificCorp installed an 8-hour, 250-kW VRB facility on a distribution feeder in Moab, Utah, designed for peak shaving and voltage support to defer a feeder upgrade.

Superconducting Devices for Fast Discharge

The most advanced nonbattery energy storage system at the megawatt-capacity scale is superconducting magnetic energy storage (SMES). This technology directly exploits recent advances in superconducting materials and cost reductions in power electronics. Energy is stored in the magnetic fields produced by continuously circulating current in a dc superconducting coil. Because there are none of the thermodynamic losses inherent in the conversion of stored chemical energy (batteries) or mechanical energy (flywheels), SMES devices have very high efficiency—theoretically as high as 95% in large installations. Although extensive design and development programs have been conducted to design large-scale (10–100-MW) SMES units, substantial cost reductions will be necessary before bulk storage applications are economically feasible.

For fast discharge at high power levels, SMES is very attractive. There are several commercial "micro-SMES" applications at the 1–3-MW level, capable of discharging more than a kilowatthour of energy in a second or so. Micro-SMES units typically provide protection against voltage sags for sensitive industrial equipment. In addition, a commercial product—the D-SMES, from American Superconductor—is designed to provide reactive power for voltage support on distribution lines, with real power injection also available to help customers ride through system disturbances. SMES units could be scaled to much higher power levels to inject tens or hundreds of megawatts into transmission systems to provide dynamic stability.

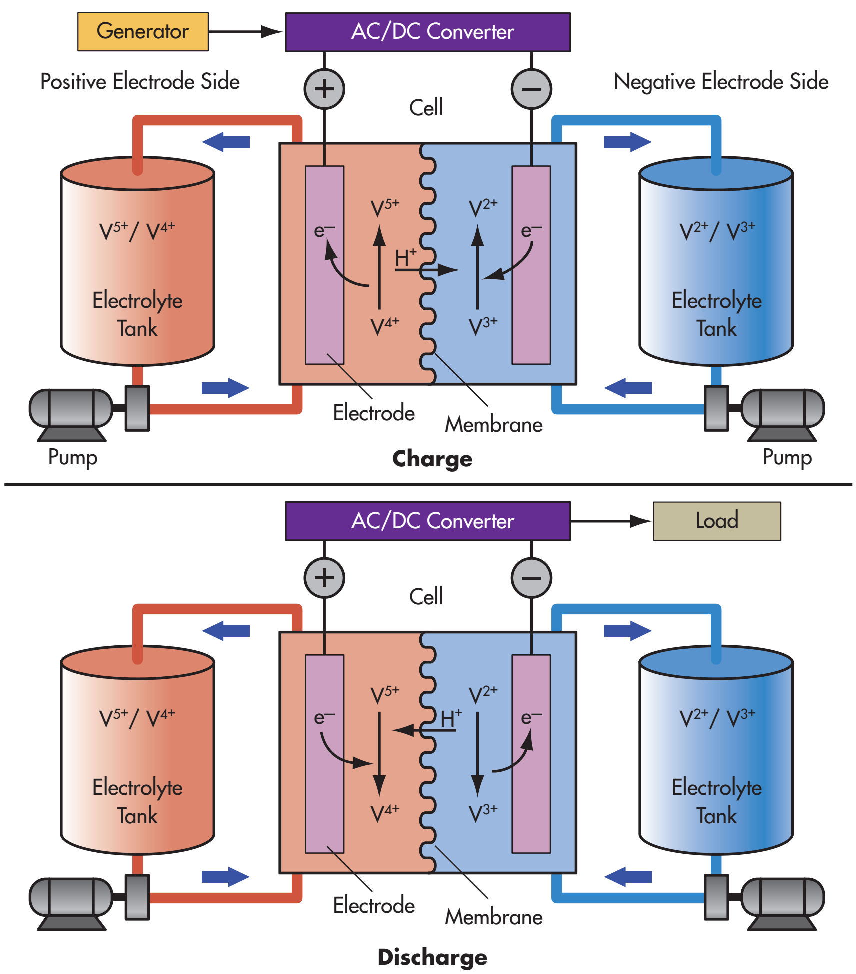
A new superconducting device to be deployed at the transmission system level is now being prepared for service at the Tennessee Valley Authority. Called the SuperVAR dynamic synchronous condenser and manufactured by American Superconductor, this device will increase grid reliability, help stabilize grid voltage, and help maximize transmission capacity. Like SMES, the SuperVAR is based on superconductors, but in a rotating machine configuration rather than a static coil. Dynamic synchronous condensers serve as "shock absorbers" for the grid by dynamically injecting or absorbing reactive power to minimize sudden and large voltage fluctuations. Two 12-MVAR condensers are scheduled for delivery to TVA in late 2006 and early 2007. This planned installation is following successful demonstration and accelerated-life testing of an advanced prototype SuperVAR unit at a steel mill connected to the TVA transmission grid, which helped smooth more than five million voltage sags and surges that accompanied 2300 steel mill melt cycles.

"In today's digital economy, keeping voltage levels constant and stable is vital," said Terry Boston, TVA executive vice president of power system operations, in an American Superconductor news release. "That's what our customers expect, and we believe that's what this new product will help us deliver. We believe SuperVAR machines will help protect TVA's transmission system from voltage fluctuations and help ensure continued delivery of affordable, reliable power."

Other Emerging Technologies

At the submegawatt to megawatt level, two modern versions of technologies that have evolved substantially from nineteenth century origins are competing to provide voltage support and short-term ride-through capability. Flywheels have been present in power systems for more than a century, since the time when they were used to smooth the output of generators driven by steam-piston engines. Now low-speed versions with heavy steel wheels

The storage potential of flow batteries, such as the vanadium redox battery, resides in the fluid electrolyte rather than in expensive electrodes. Thus, the discharge time can be upgraded by simply using larger electrolyte tanks. When the battery is being charged, the V^{4+} ions in the positive half-cell are converted to V^{5+} ions when electrons are taken up by the positive electrode, and electrons from the negative electrode convert the V^{3+} ions to V^{2+} in the negative half-cell. During discharge this process is reversed, resulting in a voltage to load.



have penetrated power-conditioning markets, while lighter, high-speed versions with magnetic bearings are beginning to find commercial application. Similarly, double-layer electrochemical capacitors first found widespread application by supplying small amounts of backup power for computer memories and are now being scaled up for utility applications.

The major advantage of flywheels over batteries is that they are capable of several hundred thousand full charge-discharge cycles and thus have a much better cycle life. During charge-up, a flywheel is accelerated by an electric motor, which later acts as a generator during discharge. Low-speed flywheels are usually designed for high power output, while high-speed units can be designed to provide either high power or high energy storage. The most common power quality application is to provide ride-through of interruptions up to 15 seconds long or to bridge the shift from one power source to another. Flywheels have also been used for demand reduction and energy recovery in electrically powered mass transit systems. For example, NYPA recently tested a commercial-grade flywheel in a New York subway station for storing electricity from regenerative subway braking.

Multimegawatt flywheels have been installed by power-quality-sensitive customers such as communications facilities and computer server centers, and commercial systems can be used for reactive power support, spinning reserve, and voltage regulation as well. Beacon Power Corporation completed acceptance testing of a flywheel demonstration unit built under contract to the New York State Energy Research and Development Authority and DOE, and the system was installed and connected to the grid at a demonstration host site in Amsterdam, New York, in March. The unit was enhanced to also provide uninterruptible power to the site, as well as to provide reactive power to help stabilize voltage to electrical equipment. Another Beacon flywheel system is undergoing testing and evaluation in San Ramon, California, in a project for the California Energy Commission.

In addition to supporting flywheel system demonstrations in New York and California, Beacon reports continuing progress toward development of a next-generation 100-kW, 15-minute flywheel that will be the core of an integrated, full-power commercial electric storage system. A prototype is expected to be ready for testing in late 2006.

Electrochemical capacitors, also known as ultracapacitors, store energy by means of an electrolyte solution between two solid conductors, rather than by the more common arrangement of a solid dielectric between the electrodes. This arrangement gives the devices much greater capacitance and energy density than conventional capacitors and also enables them to be made very compact. Like flywheels, ultracapacitors have been used in power quality applications, such as ride-through and bridging, as well as for energy recovery in mass transit systems. EPRI is currently evaluating several new membranes and materials that, when configured as ultracapacitors, could potentially offer significant opportunities for energy storage.

National Benefits of Storage

With all the new technologies, products, and projects that are under way, it is not surprising that EPRI's energy storage program is sharing in the upsurge of activity and the early stages of industry investment in new applications for electricity storage. "Utilities are beginning to show a lot more interest in electricity storage to spawn a variety of technology solutions for distributed-resources deployment, renewables integration, and T&D management," says EPRI's Eckroad. "And we're seeing increased collaboration with DOE, as exemplified by the recent coproduction of the all-inclusive handbook on storage applications and benefits. Member funding for EPRI's program has risen by 150% from 2005 to 2006. The activity in the storage technology area in the last few years has been exciting."

Flywheel storage modules, such as this 100-kW, 15-minute unit from Beacon Power, can be ganged in parallel to provide storage on the multi-megawatt level. Beacon is demonstrating a flywheel storage system in Amsterdam, New York, to provide frequency regulation and reactive power.

In a project funded through the Technology Innovation (TI) program, EPRI is also working to accelerate cost and performance breakthroughs in integrated, customer-sited storage systems. Collaborating with Alliances for Discovery—a public interest, nonprofit organization specializing in collaborative innovation—and the Institute for Engineering and Management at Case Western Reserve University, EPRI will provide technical leadership toward the development of small-scale electric energy storage systems (auxiliary power units) that could be sited at residences, commercial establishments, and industrial facilities for a capital cost of less than $150/kWh. Though managed and funded separately, this TI work will be closely linked to R&D in EPRI's core energy storage programs.

The *EPRI-DOE Handbook of Energy Storage* provides some startling figures on the potential economic benefits of energy storage for the United States as a whole. The benefits of reducing financial losses from power quality problems, for example, could amount to nearly $23 billion over the next ten years, while the benefits of time-of-use energy cost management could exceed $32 billion.

"In the broadest sense, storage devices may be the most important element of power systems in the future," the handbook concludes. "Storage devices, if inexpensive enough and reasonably efficient, would be of highest value if placed at or near customers with variable loads. The second-best location is on utility feeders, followed by substations and the transmission system. If these devices are operated for the common good, the high-voltage wires could be nearly base-loaded and the reliability of the system as a whole would be much improved."

A major challenge in achieving these benefits, however, will be to ensure that storage technologies are smoothly integrated with existing power systems. "It is particularly important that we take all these technologies and hook them together in a way that optimizes their benefit to the system as a whole," says Steve Gehl, technical executive for EPRI's Energy Technology Assessment Center. "What we need to do is demonstrate the flexibility that storage provides to the power system, develop technologies that take advantage of that flexibility, and facilitate their integration."

Background information for this article was provided by Steve Eckroad (seckroad@epri.com), Steve Gehl (sgehl@epri.com), Dan Rastler (drastler@epri.com), and Robert Schainker (rschaink@epri.com).

Further Reading

EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications. EPRI. December 2003. Report 1001834.

EPRI-DOE Handbook Supplement of Energy Storage for Grid Connected Wind Generation Applications. EPRI. December 2004. Report 1008703.