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Richard F. Post

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R. F. Post
Lawrence Livermore National Laboratory

Introduction

Efficient and cost-effective means for storing electrical energy is becoming an increasing need in our electricity-oriented society. For example, for electric utilities an emerging need is for distributed storage systems, that is, energy storage at substations, at solar or wind-power sites, or for load-leveling at the site of major consumers of their electricity. One of the important consequences of distributed storage for the utilities would be the reduction in transmission losses that would result from having a local source of load-leveling power. For applications such as these there are three criteria that must be satisfied by any new system that is developed to meet such needs. These criteria are: (!) high “turn-around” efficiency, that is, high efficiency of both storing and recovering the stored energy in electrical form, (2) long service life (tens of years), with low maintenance requirements, and, (3) acceptably low capital cost. An additional requirement for these particular applications is that the system should have low enough standby losses to permit operation on a diurnal cycle, that is, storing the energy during a portion of a given day (say during sunlight hours) followed several hours later by its use during night-time hours.

One answer to the spectrum of energy storage needs just outlined is the "electromechanical battery". The E-M battery, under development for several years at the Laboratory and elsewhere in the world, has the potential to solve the above energy storage problems in a manner superior to the electro-chemical battery in the important attributes of energy recovery efficiency, cycle lifetime, and amortized capital cost.

An electromechanical battery is an energy storage module consisting of a high-speed rotor, fabricated from fiber composite, and having an integrally mounted generator/motor [1,2,3]. The rotor operates at high speed, in vacuo, inside of a hermetically sealed enclosure, supported by a "magnetic bearing", that is, a bearing that uses magnetic forces to support the rotor against gravity. Magnetic bearings are a virtual necessity for the E-M battery in order to achieve long service life, and to minimize frictional losses so that the battery does not

lose its charge (run down) too rapidly. These considerations mitigate against the use of conventional mechanical bearings in the E-M battery for most applications.

The Laboratory has pioneered the development of a new form of magnetic bearing to meet the special requirements of the E-M battery: the "ambient-temperature passive magnetic bearing." [4,5] Simpler, and potentially much less expensive than the existing "active" magnetic bearings (ones requiring electronic amplifiers and feedback circuits for their operation) development of the ambient-temperature passive magnetic bearing represents a technological breakthrough.

Beyond its use in the E-M battery, the ambient-temperature magnetic bearing could have important applications in replacing conventional lubricated mechanical bearings in electrical machinery. Here the gains would be two-fold: reduced frictional losses, leading to higher motor efficiency, and, of equal importance, the elimination of the need for lubricants and for routine replacement of the bearings owing to mechanical wear. Thus an added benefit from a vigorous pursuit of our electromechanical battery concepts could be its impact on many other areas of industry where rotating machinery in need of improved bearings is involved. If perfected, passive magnetic bearings would seem to represent an almost ideal replacement for the mechanical bearings in many types of industrial electrical machinery.

Returning to the issued of energy storage, the E-M battery itself has much to contribute in the area of improving the efficiency of stationary energy storage systems. For example, many electrical utilities utilize "pumped hydro" energy storage systems as a means of improving the utilization of their "base-load" power plants. That is, electrical energy is stored during off-peak hours for delivery at times of peak usage. These pumped hydro systems employ upper and lower reservoirs, between which water is shuttled to store and recover the energy. Of necessity, pumped hydro storage facilities are located in mountainous areas, usually far, both from the urban centers where power uses are concentrated, and from the sites of the power plants themselves, increasing the transmission line losses that subtract from the useful energy. More importantly, pumped hydro systems themselves only return from 65 to 70 percent of the electrical energy input required to pump the water from the lower reservoir to the upper one. Thus, including the extra transmission losses from distant

siting of the facility, of order 40 percent of the input electrical energy is wasted in every cycle of use of the facility. For a (typical) pumped hydro system capable of accepting 5000 Megawatt-hours of input energy, this would represent a direct loss of 2000 Megawatt-hours of electrical energy per diurnal cycle of use.

Contrast the above situation with that offered by the E-M battery. First, banks of such batteries could be used at locations throughout the electrical grid, thereby reducing transmission losses. Second, instead of a 65 to 70 percent turnaround efficiency, E-M batteries have demonstrated turnaround efficiencies in excess of 90 percent. The long-term payback of such an increase of efficiency is obvious: Over a 20-year period (the expected life of a well-designed E-M battery), the cost savings from replacing an overall 60 percent efficient 5000 Megawatt-hour storage system with a distributed energy storage system with 90 percent turnaround efficiency is substantial: For a system cycled 300 times in a year, with electrical energy valued at, say, $0.10/kwh, the 20-year savings would amount to $900 million. This amount of money is comparable to the original cost of the pumped storage system itself.

From these examples It seems clear that the development of the E-M battery, and its companion technology, the ambient-temperature passive magnetic bearing, could have a major impact on diverse electrical-energy-intensive activities of our modern civilization.

Requirements for "Bulk-Storage," EM Batteries Intended for Diurnal Use

Economic factors and the nature of the charge-discharge cycle for E-M batteries intended for use in a diurnal cycle imply that some special requirements must be met. In such a cycle the charging of the storage system might occur during "off peak" hours, followed by a several-hour period before discharge during the hours of peak demand. This requirement puts strict bounds on the allowable parasitic energy losses from the storage system between charging times and discharge times. In addition, one can list several other requirements on such a system, both technical and economic, that need to be satisfied if bulk-storage systems employing E-M batteries are to fulfill their promise. In the

program being described each of these issues has been considered and technical approaches to addressing them have been defined. There follows a list of the specific requirements that bound and shape the development program outlined in this document.

- Modularity to allow for flexibility of application (commercial, residential, etc.).
- Low “standby” losses to allow for efficient use in diurnal cycles.
- High turnaround efficiency to minimize cost of energy losses occurring during charge and discharge.
- Minimum internal heating upon charging and discharging to reduce heat-transfer problems in the vacuum envelope.
- Employment of lowest-cost materials (magnets, fiber composite, etc.) wherever possible, to minimize capital cost.
- Amenability to mass-production methods, including a sealed-off vacuum envelope and low-cost rotor fabrication means.
- Near maintenance-free operation and long service life.
- As small as possible a “footprint” for each module to minimize the cost of housing a storage system composed of such modules.
- Insensitivity to seismic events.

In the next section we will describe some of the new and special features of our proposed modular E-M batteries aimed at satisfying the special requirements listed above.

New Elements in the Flywheel Energy Storage Picture

Flywheel energy storage has been practiced, in one form or another, for millennia. What has made a new look at this old technique worthwhile has been the synergistic development, in the last few decades, of new materials and technologies. The first of these is the progressively accelerating development of high-strength fibers for use in fiber composites, coupled with new automated fabricating techniques. Flywheel theory shows that, contrary to intuition, the most cost-effective materials from which to make the rotor are the "light-yet-strong" materials - the fiber composites.

A useful figure-of-merit for the storage of energy in the material of a flywheel is given by the ratio of the strength of that material to twice its density. This figure-of-merit represents the amount of kinetic energy stored per kilogram of the material, were it to be formed into a flywheel in the form of a thin ring and spun up to its breaking point. Table I lists this quantity for various materials, both metallic and fibrous. As can be seen, even the best steel is vastly inferior to the cheapest fiber (ordinary E-glass fibers).

Table I

Material	**Max Stress**	**Density**	**Umax**
E-glass (20° C.)	3.5 GPa	2540 kg/m^3	190 W-hr/kg
S-glass (20° C.)	4.8	2520	265
Kevlar (20° C)	3.8	1450	370
Carbon fiber	7.0	1780	545
(Maraging steel)	(2.7)	(8000)	(47)

Of course the actual amount of energy that can be stored in an E-M battery module per kilogram of its total weight will be substantially lower than the peak values indicated in the plot. That is, one must include the effect on the weight of the rotor of limiting the allowable composite stress levels to achieve a long service life, then include the weight of the housing and the generator/motor and its bearings. It appears, nevertheless, that for those special applications where it is important to achieve the highest possible energy density at high power levels, achieving a specific energy approaching 100 Whr/kg and a specific power of 10 or more kilowatts/ kg from a module should be possible with care in the design. This amount of stored energy per kilogram is three times that for a conventional lead-acid battery and the specific power levels are also much

higher. For bulk-storage systems, the issues are different, and so the approaches to be taken will be different.

The second element, critical for the development of the modular E-M battery concept, is the availability of cost-effective permanent magnet materials, and of new design principles for their use. These materials form an essential element in the passive magnetic bearing system being developed at the Laboratory. They have also been essential in implementing the integrally mounted generator/motor that coupled the energy from the flywheel rotor to the outside load in the high-power E-M batteries developed at the Laboratory in the late 1990s [6,7,8]. Both the LLNL passive bearings and this novel generator/motor borrow the design of their permanent-magnet arrays from magnet design principles pioneered by Klaus Halbach of the Lawrence Berkeley Laboratory for use in guiding particle beams in accelerators.

As noted above, it appears to us that the special requirements of a diurnal-use energy-storage system require a change in philosophy for the design of the generator/motor of the E-M battery. We believe that this crucial task should be performed by a generator/motor employing electrostatic principles, rather than the electromagnetic principles that have guided our work to date. While not suitable for the fast-discharge, high -peak-power , applications that were addressed in our earlier E-M battery development program, the electrostatic approach appears ideal for the slow (hours-long) charge and discharge cycles, the requirement for operation in a vacuum environment, and the need for very low parasitic losses in bulk-storage applications.

Early work on electrostatic generator/motors was performed by Professor Trump at MIT, proving out the principles involved. We have improved on Trump's pioneering work through the development of a new generator/motor configuration, one that seems ideally suited for the use at hand, and one that is simpler to implement than Trump's original configuration. With an electrostatic generator/motor not only will the conversion efficiency be higher than the electromagnetic generator, but also the power output is easier to control (through control of the exciting voltage) . Also, turning off the exciting voltage between times of charging and the (hours later) times of discharging will drop the

parasitic losses from the generator/motor system to zero, something not possible with a generator/motor based on the use of permanent magnets for excitation.

The third critical element required for implementing the modern E-M battery is the development of new solid-state components, including microprocessor chips and power-electronic components. Power-conditioning circuits using these elements provide an efficient and cost-effective means for converting the variable-frequency, ac output/input of the E-M battery module to ac-mains frequencies. Finally, recent developments in vacuum technology are of great assistance in arriving at practical designs for the vacuum enclosure of the E-M battery module.

The end result of these several developments is viewed as making practical, in the next few years, the design and mass-production of multi-kilowatt-hour energy-storage modules that can perform, at competitive costs, every important function of an electro-chemical battery of equivalent capacity, but with greatly improved lifetime, and energy recovery efficiency.

Status of Prior E-M Battery Development at the Laboratory

In the late 1970s and early 1980s there was a government-funded effort at the Laboratory exploring materials aspects (high-strength fiber composites) of flywheel technology. Following a hiatus of about 10 years, work was resumed at the Laboratory, aimed at exploiting the new concepts outlined above. This work resulted in the development of prototype E-M batteries with outstanding power output and energy recovery efficiency. From a rotor about the diameter of a large coffee can, electrical powers in excess of 100 kilowatts have been extracted, at turnaround efficiencies measured to be well in excess of 90 percent.

This particular technology has been licensed to a local company whose goal has been to develop units meeting a special commercial need. The need: high-power units for UPS and power- conditioning applications.

IV) Elements of a Development Program for Bulk-Storage E-M Batteries

Because of the extensive prior developments in EMB-related technology already carried out at the Laboratory the development of a commercially viable EMB for bulk energy storage can be defined clearly. What follows is one possible scenario for such a development. It involves a series of steps, at the end of which an EMB suitable for manufacture will have been designed and prototyped.

Step 1: Define the targeted parameters of an EMB (energy-stored, capital cost/kwhr, etc.)
Step 2: Choose materials (composite, magnet material, etc.) that are to be employed in the prototype EMB.
Step 3: Choose the configuration (rotor, bearings, generator, etc.) of the prototype EMB.
Step 4: Launch parallel programs to design and fabricate critical components (rotor, generator, magnetic bearings, etc.)
Step 5: Where feasible, perform tests of these components separately, using appropriate test stands.
Step 6: Design, fabricate and test one or more prototype EMB's based on the work of the previous steps.
Step 7: Use the information obtained in Step 6 to refine the design, including making the design suitable for mass-production.

V) Summary

New materials, new technology, and new design concepts have prompted a re-examination of flywheel energy storage systems. In this context the development of an economically competitive, modular, "electromechanical battery" could have a major impact. When developed, E-M batteries would have a wide range of possible applications, including contributing to increased efficiency in the electrical utilities, facilitating the use of renewable energy sources, such as solar and wind-powered systems, and providing energy continuity for stand-alone systems that rely on wind or solar energy. A companion development at the Laboratory, the ambient-temperature passive magnetic bearing, could find many other applications in industry, for example, in enhancing the efficiency, and reducing the need for maintenance, of electric motors.

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