

ADVANCES IN ENERGY STORAGE TECHNIQUES FOR CRITICAL POWER SYSTEMS

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ABSTRACT

Energy storage is an integral part of any critical power system, as this stored energy is used to offset interruptions in the power delivered from either a utility or an on-site generator. Traditionally, capacitors are used for short-term storage (μs - ms) and filtering, batteries are used for intermediate storage (min-hrs), and diesel fuel is used for long-term energy storage (hrs-days). Advances published on the application and use of technology that affects each of these storage intervals are discussed. Particular attention is placed on the role that new battery types, fuel cells, flywheels, microturbines, and ultracapacitors will have on the future of critical power systems.

INTRODUCTION

During the late 1990s, the rise of internet-based companies – those heavily dependent on servers and other computer loads – resulted in an explosion in demand for electrical infrastructure capable of protecting delicate equipment from outages (as short as 1.5 cycles). While these particular companies have suffered a recent downturn, the need for conditioned power continues due to the increased dependence on computer-controlled equipment in fields such as medicine, bio-technology, and semiconductor manufacturing. Even old economy processes like coating, painting, and machining now have a single computer controlling the finishing operation on millions of dollars worth of finished goods (such as the coatings on gas turbine blades).

Uninterruptible Power Supplies (UPSs) are used to improve power source quality as well as protect these critical loads against disturbances, such as frequency shifts, voltage spikes and interruptions. Two typical UPSs with energy storage are shown in figure 1. A double conversion UPS first converts the incoming AC power to DC using a rectifier. An energy storage system would be attached to this DC link. The power to the load is then supplied by an inverter. A line interactive UPS is a simpler, but less effective system, which corrects for voltage sags by injecting current through a shunt connection downstream of a choke.

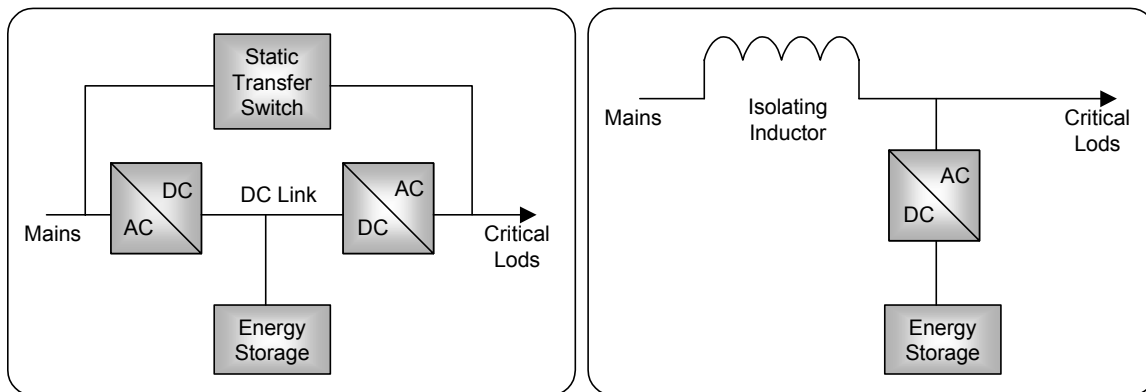


Figure 1. One-line diagrams of a static double conversion UPS (left frame) and a line-interactive UPS (right frame) both coupled to an energy storage system.

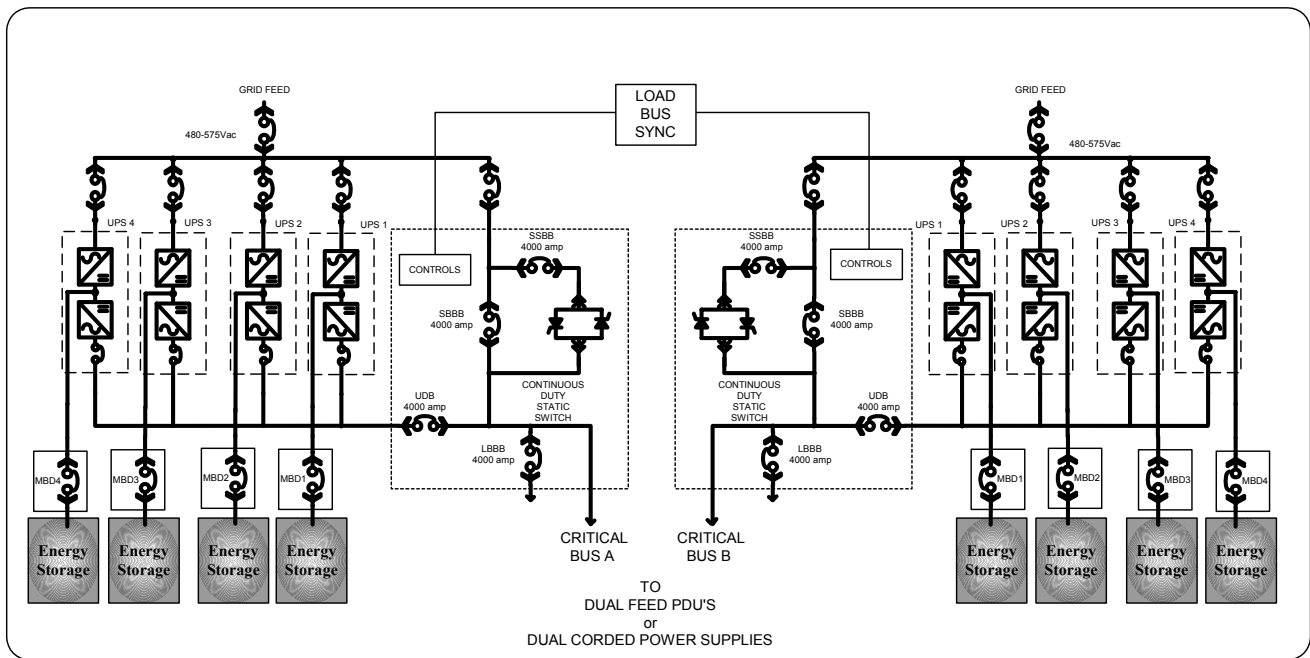


Figure 2. Typical Critical Power System: 2(N+1) Parallel Redundant System

The UPS must at all times be able to make a seamless transition from a utility source to the source of stored energy in case of an outage. Some examples of stored energy sources are batteries, flywheels, superconducting magnets, capacitors, and on-site generators. The most common sources for short-term storage (several hundred milliseconds) and long-term storage (tens of minutes) are capacitors and batteries, respectively, with flywheels gaining ground as the bridge between the utility and a backup generator (5-30 seconds).

A highly-redundant critical power system is shown in Figure 2. In this example, two separate systems provide conditioned power to the loads. This type of system can withstand multiple failures of internal or external components and still deliver uninterrupted power. Obviously the level of redundancy should reflect the cost of an outage, and thus the inherent tradeoffs between cost and reliability.

The energy storage component comprises roughly 30% of the cost and space of the entire critical power system, and nearly 50% of the maintenance cost. As such, considerable research is aimed at enhancing or replacing the existing energy storage systems with ones that are simpler to maintain, cheaper to purchase, or simply more compact. This paper will discuss some recent advances in these energy storage systems.

BATTERIES

Lead-Acid, Nickel-Cadmium, and Sodium-Sulfur batteries are the most commonly used long-term energy storage systems due to their high degree of modularity, low floating charge losses, widespread availability, and lack of moving parts. Lead-Acid batteries are the most prevalent and represent a proven and very reliable form of energy storage. However these batteries contain toxic chemicals that must be monitored and disposed of (or recycled) at a cost that seems to increase each year. In some parts of Europe, it now costs almost as much to dispose of these batteries as it does to purchase them. In addition, the performance and life of the battery is strongly dependent on the frequency of charge/discharge cycles and the ambient temperature. Perhaps the most difficult challenge is that the cell voltage, current limit, and amount of energy stored (Amp-hours) are not independent, often leading to oversized systems.

Most current research is aimed at developing battery systems for vehicle drives. These batteries must withstand numerous discharge cycles, be maintained by a broad range of users, and be more robust to environmental fluctuations. The sodium-sulfur battery is one recent example and, compared to the lead-acid battery, has the advantage of lower weight and smaller external dimensions. Smaller battery systems with significant promise are Nickel Metal Hydride (NMH), Lithium-ion, and Zinc-air. The module sizes are still too small to be used in larger applications, like that shown in Figure 2.

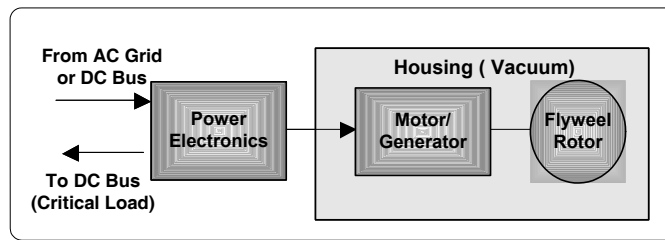


Figure 3. Simplified view of a flywheel Energy Storage System (FESS)

Typical High Speed FESS in vacuum sealed housing

High Speed FESS :
 Rotational Speed >10,000 rpm upto 80,000 rpm
 Flywheel material - Composites, Reinforced carbon fibers
 Magnetic Bearings
 Vacuum housing (10-100 m Torr)
 Specific Energy (1 - 5 Whr/ kg)
 Ride through time as high as 2 hrs (Beacon)
 Losses during Float operation is lower (0.5x of Low Speed)

Figure 4. High Speed FESS. Courtesy of Beacon Power.

Typical Low Speed FESS :
 Rotational Speed < 10,000 rpm
 Flywheel material - Forged Steel
 Hybrid Bearings
 Partial Vacuum housing (50m Torr)
 Flywheel weight ~2x High Speed
 Specific Energy (< 1 Whr/kg)

Figure 5. Low Speed FESS. Courtesy of Active Power.

FLYWHEELS

Flywheels have been an integral part of engine designs for hundreds of years, as they are used to smooth out the operation of cams or cylinders. The Flywheel Energy Storage System (FESS) shown in Figures 3-5 are an adaptation of this concept, coupling a rotating mass with power electronics. In critical power systems, flywheels are used to bridge short-term (5-30 sec) power quality issues or to support the load until a fast-start backup generator can be activated. The energy stored in the flywheel is governed by the following equation:

$$\text{Kinetic Energy stored} \propto \text{Mass} \bullet \text{Radius}^2 \bullet \text{RPM}^2.$$

Increasing the radius or speed can increase the stored energy, but will also increase the internal stress on the material and/or require more sophisticated bearings. As such, two types of flywheels are available in the market: High Speed flywheels (25000-80000 RPM) made of composite material and Low Speed flywheels (2000-10000 RPM) made of steel.

High-Speed Flywheel Storage System

High-speed kinetic storage media operate above 25000 revolutions per minute. The mass moment of inertia, weights and dimensions are relatively small. To reduce friction, the rotor runs in a vacuum and is supported by magnetic bearings. The output frequency of the synchronous generator is in the kilohertz range. A power electronic rectifier/inverter set is connected at the output of the generator. The energy is injected at this point into the DC link circuit of the UPS. The power electronic converter is necessary to correct the large voltage swing at the generator terminals over the speed range; the generator itself is unregulated. The advantages of the high-speed flywheel storage system are its compact size for a given amount of power delivered. Systems suitable for UPS applications are still in the early stages of development

Low-Speed Flywheel Storage System

Low-speed kinetic storage systems operate at speeds up to 10000 RPM. These low-speed systems are considerably larger than their high-speed counterparts for a given amount of stored energy. However the flywheel is made of steel instead of composite materials, and so it is still slightly cheaper to manufacture. Conventional bearings with magnetic support are used to support the large rotor weight, but only a partial vacuum is needed to maintain low frictional losses. These losses combined with the excitation losses result in a float charge, which is roughly double that of the high-speed storage medium.

Like the high-speed flywheel systems, most low speed flywheel systems utilize either a single-stage IGBT or a rectifier/inverter for power transfer. Some operate with an induction or mechanical coupling instead of this DC interface, occupying the triport connection between the AC line and the consumer load. The induction coupling can be used to correct for changing rotational frequency, whereas the mechanical coupling must compensate through power electronics acting as a three-phase exciter winding in the generator. Overall, the advantage of the low-speed flywheel storage system is a rugged construction with tried and tested components. The greatest advantage of flywheels over batteries directly is the ability to predict the amount of energy remaining with pinpoint accuracy.

SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Instead of storing kinetic or chemical energy, SMES devices store electrical energy in a magnetic field. The zero resistance coil passes DC current and stores energy equivalent to $E = \frac{1}{2} \cdot L \cdot I^2$ in its magnetic field. The superconductivity allows the coil to be wound very compactly (with a high flux density of up to 20 Tesla), and consequently a high specific energy density is achievable. The superconductivity also minimizes the resistive losses of the passing current. Since the instantaneous energy content depends on the square of the current, the remaining energy can also be measured very accurately. However, this technique needs requires cryogenic cooling to maintain the superconducting properties of the coil.

The advantages of the SMES lie in its ability to source large amounts of power and to charge and discharge orders of magnitude more times than even the best batteries. It has high efficiency for short-duration storage, and so is well suited to pulse discharges. With a long expected service life and an environmentally friendly construction, there is significant potential for these devices in transmission and distribution applications.

For light industrial or UPS applications, the impact of this technology is less clear. Long-term effects of the stability of the coil components at low temperatures, in conjunction with strong electrodynamic forces, have still not been adequately investigated. SMES-based systems tend to be more expensive and require larger space than other comparable storage media, and are less suited to the continuous standby application. Still, the ability to operate at medium voltage and to discharge up to 3 MW from a single unit shows the promise of this technology.

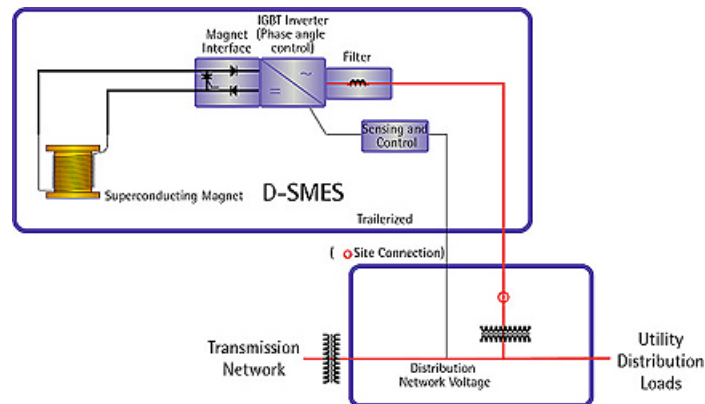


Figure 6. Superconducting Magnetic Energy Storage (SMES). Courtesy of General Electric.

Table 1. Comparison between ultracapacitors and flywheels

	Ultracapacitors	Flywheels
Advantages	<ul style="list-style-type: none"> • High Power Density • Low Environmental Impact • No moving parts • Low maintenance cost • Low standby losses (<0.2% of power rating) • No cooling required • No power or control electronics 	<ul style="list-style-type: none"> • High Power Density • Low Environmental Impact • Many years of experience • Long service life
Disadvantages	<ul style="list-style-type: none"> • Many components to monitor (typically 50-200 cells) • Limited experience • Limited studies on reliability and aging 	<ul style="list-style-type: none"> • Complex power and control electronics • High standby losses (<5% of power rating) • Many components to maintain (bearings, vacuum pump, cooling fans, control sensors) • Potential for catastrophic failure

ULTRACAPACITORS

An ultracapacitor, also known as supercapacitors or electrochemical double layer capacitor, basically consists of two electrodes, a separator and an electrolyte. The electrode made up of a metallic collector, which is the high conducting part, and an active material, which is the high surface area part. The two electrodes are separated by a membrane, the separator, which allows a mobility of the charged ions but forbids an electronic conductance. The most interesting electrodes materials are: metal oxides, carbons and conducting polymers. The electrolyte may be of the solid state, organic or aqueous type depending on the application.¹

Like a battery, the operating voltage of a cell is just a few volts (range: 1,3 to 2,5 volts). However when combined in paralleled strings, modules operating at some hundred volts and storing up to MJ of useable energy can be obtained, and have been demonstrated in laboratory UPS systems.²

As these are typical values for flywheel systems, ultracapacitors naturally lend themselves to be compared with uncoupled flywheel systems, as summarized in Table 1.

The stored energy of the electric field ($E = \frac{1}{2} \cdot C \cdot V^2$) is derived from the capacitance and the applied voltage. Like the flywheel, it is cumbersome to extract all of the energy and so the operation is confined between an upper and lower voltage limit. The total deliverable energy for a given voltage window can be extrapolated from Ragone curves (energy available as function of a constant power load).¹

Considering the technical maturity, the chemical inertness (no redox reactions), the environmental impact (no use of heavy metals), the manufacturing process, the expected performances and costs, carbon based supercapacitors are the most interesting and promising devices for industrial applications. These capacitors don't contain toxic chemicals or any heavy metals that make operation, charging, and disposal hazardous.

MICROTURBINES

Microturbines are small gas turbine generators ranging in size from 30 kW to 500 kW, which include a compressor, combustor, turbine, recuperator, and generator. Microturbines can start in less than 30 seconds, and so can be coupled with batteries, SMES, flywheels or ultracapacitors to complete a critical power system. Microturbines offer a number of potential advantages compared to other technologies for small-scale power generation. Advantages include the small number of moving parts, compact size, low weight, very low emissions, and the compatibility with waste-fuels.



Figure 7. Microturbine

Microturbines are classified by physical arrangements of the component parts: single shaft or two-shaft, simple cycle or recuperated, inter-cooled, and reheat. The machines generally rotate over 40,000 rpm, which can lead to very high stress areas. The compact size, however, allows the use of advanced monolithic ceramic and metallic components that are not yet practical in larger gas turbines. Current microturbine systems have a thermal efficiency of roughly 25% when not accompanied with a heat recovery or combined heat and power module. Present research is focused on increasing this efficiency to 45% by increasing compression ratios and firing temperatures while still maintaining low emissions and ease of use.

Since these units are primarily designed for operation with natural gas, peak shaving, load curtailment, and prime power are reasonable applications. Combined with a UPS and energy storage, these units can be a clean alternative to the more standard reciprocating engine-based systems.

FUEL CELLS

Fuel cells, electrochemical devices that directly convert hydrogen, or hydrogen-rich fuels into electricity without combustion, are another alternative to reciprocating engines. This process is much more efficient than traditional thermal power plants, theoretically converting up to 80% of the chemical energy in the fuel into electricity (compared to the 60% efficiency of combined cycle power plants). Current system efficiencies are closer to 35%. Although their structure is somewhat like that of a battery, the charge duration is extended by the ability to use an external fuel source, mainly hydrogen, stored directly or reformed from other fossil fuels. The technology is developing with a few commercial uses today, but with a promise to emerge as a significant source of electricity in the near future.

Fuel cells have similar structure as battery, with two porous electrodes separated by an electrolyte. Electricity is produced by a chemical reaction between a hydrogen-based fuel and an oxidant (usually oxygen) inside the fuel cell. The general design of most fuel cells is similar except for the electrolyte. Five main types of fuel cells, as defined by their electrolyte, are: alkaline fuel cells, solid polymer fuel cells (Proton Exchange Membrane: PEM), phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells (SOFC). Alkaline and PEM fuel cells operate at lower temperatures (50-260° C) and are mainly designed for use in transportation applications, while the other three operate at higher temperatures (up to 1000° C for SOFC) and are being developed for use in co-generation and large central power plants.

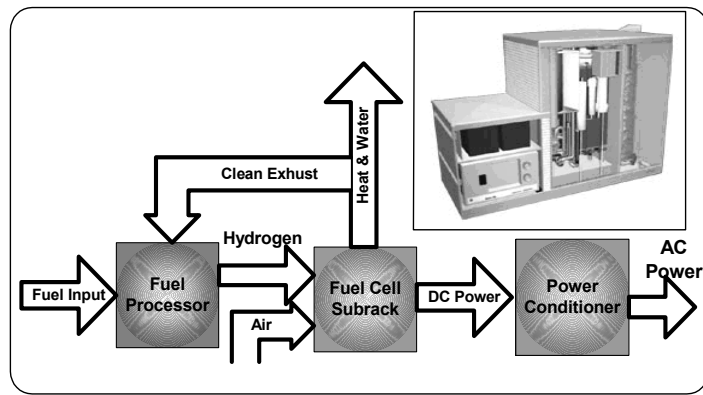


Figure 8. Operation of a PEM Fuel Cell.

SUMMARY

There are many types of energy storage devices used in critical power systems, as summarized in Table 2. Lead-acid batteries are the most popular means of energy storage, providing minutes to hours of ride-through, and are often coupled with diesel gensets to provide the backup power for mission critical applications. However, the high weight and difficulty of disposal of batteries are allowing alternative technologies to gain ground. Among these, low-speed flywheels are making the most progress, being cost effective and suitable for applications where short ride-through time is adequate. High-speed flywheels, ultracapacitors, SMES are also gathering attention, as are alternative battery technologies such as NiCd, NiMH, Li-ion, and Zn-air. The improved energy density and specific energy of these new battery technologies are commercially available in low power range only, but electric vehicles are expected to allow for large-scale manufacturing of higher power devices. Microturbines and fuel cells are also gaining on the traditional reciprocating engine market, as they offer a simple, reliable and clean alternative for longer-term on-site power generation.

Table 2. Features of various energy storage media for 1MW UPS System

Energy Storage Media for 1MW UPS	Chemical Storage media		Electrical Storage media		Mechanical Storage media	
	Sealed lead acid battery	NiCd Battery	SMES	Super capacitor	High speed flywheel	Low speed flywheel
Modules/cells	210	350	1	150	1	1
Voltage/current/speed	420V	420V	4KA	500V	25000-80000rpm	4000 - 10000rpm
Capacity	1100Ah	400Ah	2.5H	200F	6kgm ²	230kgm ²
Ride through time	2min	2min	15s	30s	15s	13s
Losses during floating	500W	250W	24000W	No Data	5000W	10000W
Additional power electronics	Battery Charger	Battery Charger	Transistor Controller	None	Transistor Controller	Transistor Controller
Safety risks type	Leakage of acid	Leakage of alkaline	Loss of superconductivity stray field	Corrosive dielectric	Flywheel delamination	Flywheel Fracture
Maintenance Hour/annum	8	10	14	4	6	4
Service life (years)	5	15 - 20	20	10	20	20
Volume (m ³)	10	22	36	1	1.5	2.5

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