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A State of the Art Review of Energy Storage Alternatives for Mission Critical UPS & CPS Power Systems

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Abstract

This paper will examine the state of the art in commercially viable DC energy storage for uninterruptible and continuous power systems (UPS and CPS). Specifically, lead acid batteries, nickel metal hydride batteries, lithium ion batteries, low speed flywheels, high speed flywheels and ultracapacitors will be examined in detail. Cycle / "hits" resistance, temperature tolerance, reliability/availability ratings, maintenance & support requirements, space requirements, environmental impacts, and return on investment (ROI) issues are presented for major DC storage systems currently available and commercially viable. Regrettably, it is not practical to review the hundreds of emerging products and technologies, so we will limit this study to the top eight as we see them.

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Uninterruptible Power Supply (UPS) systems have become commonplace in commercial, industrial and government business operations today. While the AC side of UPS development has not changed significantly in recent years, DC energy storage (the "battery") is witnessing dynamic advances in emerging new & improved technology. Why? Battery failures account for more UPS system failures than all other non-personnel related causes combined. Still, batteries, as in lead acid (LA) batteries, far & away outsell other DC energy storage options. One well publicized market study has annual LA battery sales approaching $1 billion in conventional UPS system sales alone, with a similar number for telecom-based applications.

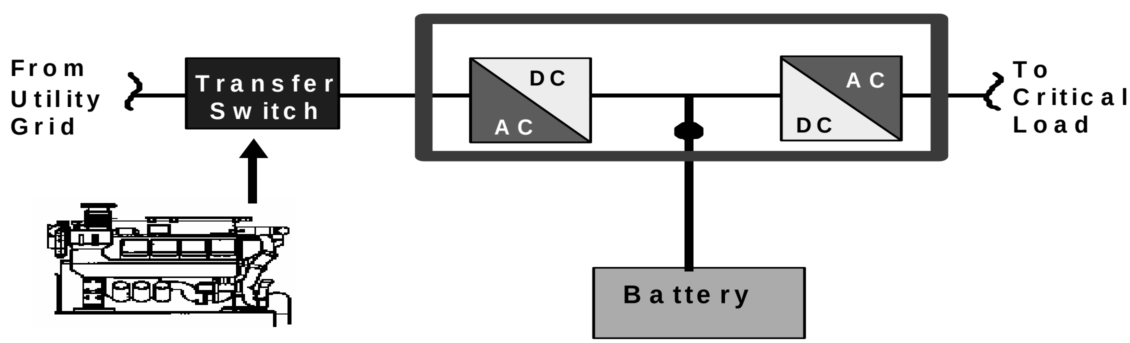


Figure 1 Critical Power System using UPS, battery, genset & ATS

Conventional LA batteries can be had in a variety of formats but the most accepted & used types are high rate discharge rectangular plate Sealed or Flooded LA batteries. In both cases lead, along with Calcium, Antimony or other alloys, make up the bulk of the plates. Concentrated Sulfuric acid is the common electrolyte. The charge-discharge process involves formation of explosive hydrogen. Air conditioning is an absolute must since service life drops 50% for every 12-15 degree temperature rise, and they don't like to be cycled a lot. Finally, IEEE, in their draft guideline 1184, recommends oversizing all LA batteries by 25% to allow for loss of capacity inherent in these designs. That is about as far as the similarities go in LA batteries, so let's discuss the differences.

Flooded Lead Acid (FLA) Batteries

Flooded batteries, also know as vented or wet cell batteries, have been the first choice for Tier 3 & 4 Data Center UPS system designers as well as other high criticality UPS applications for decades. These battery systems are normally quite reliable and typically last 2/3 to ¾ of their 20 year (pro rata) warranty period. The normal failure mode is shorted rather than open cell, in sharp contrast to their sealed LA cousins. This is important because a 15 minute single string FLA system will typically loose a minute or less with a short circuit failure (caused perhaps by sediment buildup). The result on uptime/availability is not in any way critical. But there are ways to experience open circuit failure in FLA cells. Post seal leaks, case cracks caused by plasticizer loss with aging, perhaps aggravated by seismic events, incorrect installation grease case damage, extreme plate growth, and other events can cause loss of electrolyte. When this occurs, the result is immediate and catastrophic because FLA batteries are almost always designed in <u>single</u> string configuration. Regular maintenance is an absolute must for these systems.

FLA batteries are very large and heavy, typically weighing perhaps 500 lbs each. Separate and very large battery rooms must be built with a wide array of support equipment. This routinely includes spill containment & neutralization, air exchange systems (for hydrogen build-up), cooling systems, eye washes & showers, hydrogen detection systems, perhaps fire suppression and monitoring systems as well. The installed cost of such systems is many times the cost of sealed (SLA) batteries. But then again, so to is expected reliability.

Sealed Lead Acid (SLA) Batteries

Sealed LA batteries, sometimes called recombinant or (incorrectly) "maintenance free", are available from dozens of manufacturers. For UPS application, most common by far are gelled electrolyte and VRLA (Valve Regulated LA) types with design life of five (5) years. These batteries may be warranted for 5 or 10 years by regardless of warranty, typical useful life routinely falls between three and five years. Much (3 to 4X) more expensive 20 year pro rata sealed products are also available with useful lives about twice the common SLA type.

SLA batteries are the product of choice for small UPS, low bid and/or non-critical applications. Since they are so inexpensive on first cost, these batteries outsell their more reliable FLA counterparts by 3 to 1 worldwide. They are typically half the size & weight of FLA, and usually (but not always) escape local code requirements for spill containment or air changes. By definition, these products are sealed, allowing no possibility of water adds. During charge and discharge electrolysis, hydrogen is generated which is trapped and recombined with generated oxygen to form water. This process is very efficient but not 100% so. Some generated gases are lost to overpressure release through integral valves, thus leading to a major and unsettling failure mode of SLA batteries – dryout. Dryout is an open circuit condition causing loss of the entire string for any single cell loss. Almost as problematic as dryout failure itself is the fact that it is impossible to predict exactly when a cell will fail. Because of this, great care must be taken in design and use of SLA batteries for medium to high criticality applications. First and foremost, do not use single string designs. Always have at least one redundant string for all expected load conditions. Next, never let these batteries push the far end of their service life. End of life for SLA batteries follows a bath tub curve. After minimal failure in years 1 – 3, failures rise near exponentially in years 4 & 5. During this period, some published reports show string MTBF on a VRLA-backed UPS system as low as 2000 hrs. Although nearly as expensive as adding another string, it may be worth considering battery monitoring which trends impedance or conductance as well as voltage to get at least some hope of failure prediction.

Fig. 2a 20 yr FLA batteries on racks

Fig. 2b 10 yr VRLA batteries in cabinets

Nickel Cadmium Batteries

NiCad Batteries have been around for quite a while and today come in both vented & sealed versions, as well as in a variety of plate materials & designs. Much more expensive than LA batteries, NiCad batteries are therefore relatively uncommon but not rare in UPS application. NiCad's do a better job than LA cells on cycling, temperature withstand, energy density (space), predictability, and overall reliability. They make excellent candidates for genset start for these reasons. However they are not the equal of their Nickel Metal Hydride cousins in the majority of those respects. They also have environmental issues because of the cadmium present. OSHA labels cadmium "extremely toxic" noting several deaths when welders unsuspectingly inhaled off-gases. This makes any possibility of a fire in a battery room a life-threatening concern. Finally, many NiCad types experience "memory" effect, a major problem in UPS service since most discharges are very light.

Figure 3 - NiMH System

Nickel Metal Hydride Batteries

Thousands of NiMH batteries have been in electric hybrid vehicle service for several years. As with Lithium Ion, NiCad, and other higher end UPS DC technologies, Nickel Metal Hydride (NiMH) batteries cost much more than SLA batteries on first purchase. However, the characteristics of NiMH appear to make it particularly good for UPS application. Tests indicate an almost limitless cycling ability (hundreds of thousands) in conventional short hit UPS service without impact to service life. Temperature, a killer with LA UPS batteries, also has little effect. With conventional VRLA batteries, the projected 4 or 5 year design life will be cut to less than one year if temperatures hit 100 degrees F, a condition the UPS itself is designed to operate in comfortably. NiMH batteries, like NiCad, can operate at 104 degrees F continuous with minimal impact on life.

NiMH chemistry is such that unpredictable open circuit failures, common to SLA cells, do not appear to be an issue. Ultimate cell failure is typically projected at least 10 years out, and is preceded by a long warning impedance rise. Additionally, NiMH cells can be designed with redundant strings/modules, so DC reliability may equal or even exceed that of flooded batteries for many applications.

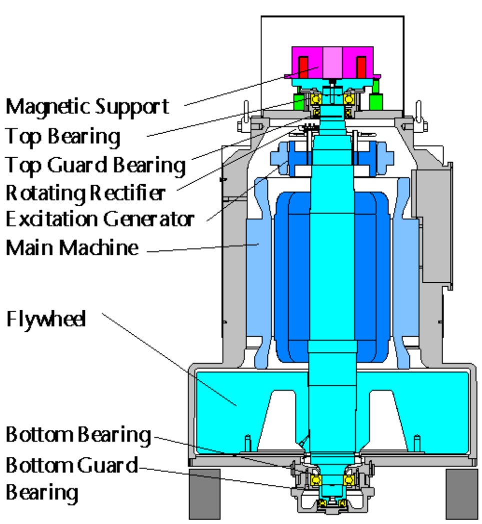
Some new NiMH UPS products are packaged as a complete system. Batteries, system monitoring, charging, all required support are included. This can include a comprehensive 5 or 10 year full warranty/service contract. They are extremely compact, taking 40% to 75% the footprint of already small SLA cells, and just 10% to 25% that of FLA batteries. Other benefits include lighter weight, complete elimination of explosive hydrogen, explosive lithium, lead or cadmium hazard/recycle, or acid spill issues, and complete insensitivity to UPS ripple on the DC bus. Perhaps one of the more intriguing benefits of this new UPS DC technology is the end cell volt (ECV) limits. Unlike LA batteries, which don't like to go much below perhaps 25% of nominal voltage, NiMH can run down at full power well below half nominal without impacting service life. For genset-backed UPS users, this means you can now buy a (smaller) 30 second battery instead of a 3 minute battery for many applications. And these systems are modular and scaleable, so if things change, and 15 minutes reserve time is required or perhaps greater KW capacity, the system can be scaled up. Most mission critical application systems included both redundant string and built in battery monitoring.

Flywheels

Flywheels are mechanical rather than chemical energy storage systems designed for minimum of 12-15 seconds reserve time and typically used with reliable & often redundant diesel generation backup. A great deal of development & refinement has been done in the flywheel industry in recent years. Today, both low speed and high speed flywheels designed for UPS application are commercially available. These devices will run anywhere from two to four times as much as SLA batteries on first cost, for the great majority of UPS applications but many also promise higher reliability, service life and predictability. They also can offer significant advantages in applications that are space-critical, higher ambient temperature, or high cycling in nature. During the Dot Com explosion around the new millennia alone, over a hundred flywheel-based UPS & CPS systems were installed in multi-MW configurations.

In order to use flywheels successfully, several things have to happen. First, the diesel electric generation system must be designed, installed, commissioned and maintained to mission-critical standards. This means redundant gensets in some cases, or redundant start systems on non-redundant gensets in others. Monitoring of charging & block heater circuits, regular testing perhaps including fuel testing is recommended. While there is continuing debate about 15 seconds being enough time for conventional Tier 3-4 criticality applications, there is no doubt that in today's business economy, 15 minutes for "soft shutdown" is not an option. The onus for all UPS DC power technologies has moved from reserve time to absolute power continuity.

Fig. 3 Low Speed Steel Flywheel
Courtesy of Piller Inc, NY



Low Speed Flywheels

These are arbitrarily defined as running at less than 10,000 RPM. Necessarily, these devices employ higher mass (weight) to deliver required energy and power. All the commercially available versions use steel flywheel construction rather than exotic materials. The designs vary widely from vertical to horizontal, from CPS-engine integrated to discrete DC flywheel only. One commonality and sore spot of all these systems is dependency on mechanical bearings. Most designs use magnetic bearings as well but it's the mechanical ones that are problematic. Scheduled or unscheduled bearing changeouts anywhere from 2 to 6 years are common. These changeouts require the system to go offline for as much as 4 to 8 hours which is clearly less than ideal. Low speed flywheels (LSF's) have dominated the MW UPS/CPS flywheel application range to date. There, they are extremely compact energy storage devices, but that is definitely not the case at say 20 to 100 KVA ranges currently. While they are not inexpensive to purchase or maintain, the energy density is tough to match.

High Speed Flywheels
These are relatively new entrants to the UPS DC energy storage field. Here, the power & energy is derived more proportionately from speed than mass. These designs benefit from complete elimination of active mechanical bearings, relying upon non-contact magnetic bearings only for all normal operations. The advantage of this design to mission critical facilities is a tremendous improvement in availability (the number of "9's") resulting from elimination of bearing changeouts (or battery changeouts) and the associated downtime. There is also minimal maintenance on the projected 20 year service life of these systems for the same reason. Some of the high speed flywheel systems make use of new carbon fiber composites or similar exotics. Other designs use steel-based components. While steel has millions of run-hours in similar turbine application, the jury is still out on performance of exotics over time.

High speed flywheels (HSF's) are normally designed for 500KVA/KW UPS application and below, while low speed versions court the MW applications as mentioned prior. However, the field is converging with at least one high speed flywheel maker scheduled to offer a 750KW single machine version in 2006.

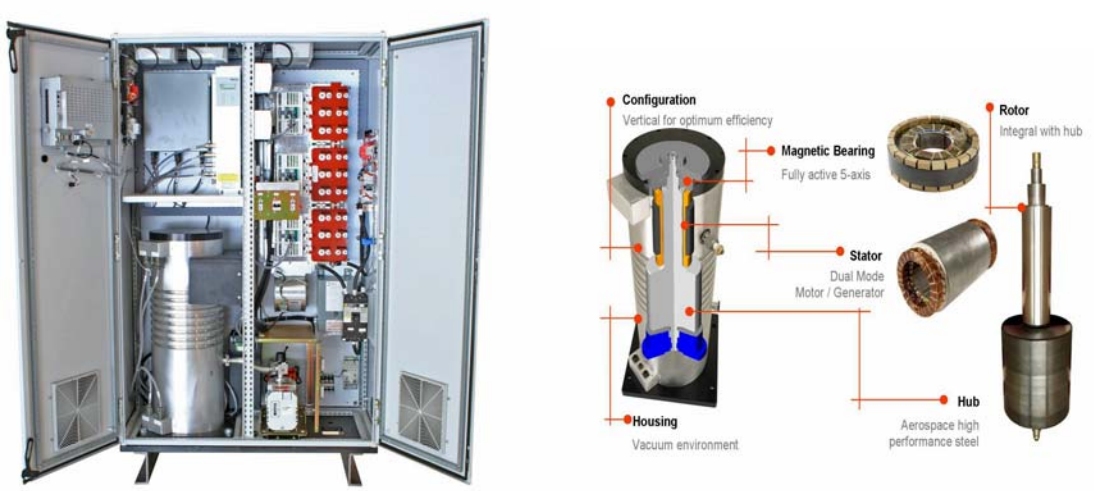


Fig. 3 High Speed Steel Flywheel
Courtesy of VYCON, Cerritos CA

Lithium Ion & Lithium Polymer Batteries

As with NiMH cells, Lithium (Li) batteries are near maintenance free, high cycle capable, do not generate hydrogen, and are half the size and weight of SLA batteries. Also like NiMH, these cells have predecessors in laptop computers, cell phones and electric vehicle applications. Initial cost is about the same between the two as well. One worry here is the rash of recalls and product explosions associated with Lithium and Lithium ion batteries in particular. Lithium is unstable in air and in many (but perhaps not all) battery designs, there is considerable risk which can only be tempered with proof of time. But the biggest issue with this otherwise very promising technology is service life, which to date is just ½ to ¼ that of NiMH, FLA and other battery types. The combination of high cost, low service life, and safety issues limits use of these products in UPS applications. However, much development continues so the future may change.

Ultracaps

Ultracaps (UCs), also called supercaps, have been on the front screens of emerging technology watchers for some time now, but are more interesting with recent price drops. Field beta testing in hybrid vehicles, rail and windmills, has led to the marketing of UC's for stationary applications, namely UPS systems & 48VDC telecom. Although most if not all UC makers have essentially no UPS installations at this time, a soon to be introduced 48VDC version is making its way through test with higher voltages to follow.

As with most emerging battery technologies and flywheels, UC's cost much more than LA UPS batteries on first purchase. UC's have a very high cycling ability (hundreds of thousands) in conventional short hit UPS service without impact to service life if duty cycle is low. Temperature has a sharp effect on service life cutting it roughly in half for every 10 degree © rise (a bit like LA batteries). Still, at operating temperatures in the 25 degree © range, one major manufacturer contends the product "should go 10 years without needing replacement or maintenance". At 40 degrees ©, they believe it should make five years or so. Not withstanding these claims, standard warranty is only one year from most manufacturers.

Although ultimate cell (cap) failure is typically projected at least 5 if not 10 years out, the failure mode is open circuit from electrolyte dry-out. This is a great concern because in normal UPS application, some 200 Ultracaps must be linked in series to hit the 500+VDC operating voltage of common UPS buses. If any one of these goes open circuit, like SLA batteries, that entire string is lost. For high availability Tier 3 & 4 applications, this may take them out of consideration unless redundant strings become very affordable. There are currently no documented claims on MTBF available.

Ultracaps from the primary US manufacturer are normally sold in 6 cap 16VDC module units (akin to a 12V battery). They will likely be more compact than LA batteries for some 15 second applications, but less so for other applications. Other benefits include lighter weight and quick changeout/MTTR potentially. However, one area of concern is safety. While Ultracaps do allow for elimination of explosive hydrogen, explosive Lithium, lead recycle, or acid spill issues, some Ultracaps substitute Acetonitrile for acid. Acetonitrile is highly flammable, even explosive under a variety of conditions. It also has toxicity issues when inhaled, ingested or contacted. While at least one vendor has designed a reasonable containment system for their caps, in the large quantities required for major data center protection, there could be, and we suspect will be, lingering concern.

Economics 101

OK, we've looked at key performance issues. Now let's look at costs & ROI (Return On Investment). Realistically, we need to examine installed cost over at least a five year if not a ten year period. Hands down the least expensive DC system for UPS you can buy is SLA battery, initially. Nothing comes close. At a nominal 100 to 150 KVA UPS range and 5 to 15 minutes reserve time, the installed pricing of cabinet-mounted SLA batteries is routinely under $20,000 in the USA. However, not many reliability experts would dare specify SLA/VRLA batteries for medium to large UPS application without redundant strings, expensive ohmic monitoring, and frequent changeout (3-4 years typical). This SLA hardening treatment triples, quadruples, or quintuples initial costs, depending on ROI period. Because of this, another solution with a "high" installed cost of say $50,000 in this case, may very well be the less expensive overall.

When looking at 5 or 10 year ROI or LCC (Life Cycle Cost) periods, include everything. Minimally, this means initial cost, freight, rigging, electrical installation, air-conditioning or air change installation & operating costs if applicable, cost of space, maintenance costs including bearing changes and battery changeouts as applicable, monitoring equipment costs, extended warranty protection costs, utility costs of running any support equipment, lead or HAZMAT recycle costs, spill containment and eye wash if applicable, etc.

Summary

There is no perfect "battery" or UPS DC system. Each technology has its pluses and minuses. If you need a short term, inexpensive solution for lesser criticality loads, SLA battery is the clear choice. But if reliability and high availability is mandatory, better look elsewhere. For high cycling or high temperature issues, NiMH, NiCad or flywheels are worth considering. If space or weight is key, look at any of these, but definitely skip FLA. If mission-critical reliability & availability regardless of cost is the goal, then NiMH, FLA, perhaps NiCad, and flywheels in some cases, should all be examined based upon application and that site's provable genset availability. Below we have assembled a simple comparison matrix. In the left column you will find the features, parameters and shortfalls most commonly examined by UPS system designers. On the top row you will find the eight (8) candidates reviewed herein. We have deliberately not added any conclusive winner section because every application is different, and the sub-categories & vendors number in the hundreds. You may need to seek the services of a qualified consulting engineering firm or power quality systems expert if the choices in your case are not straightforward.

	SLA	**FLA**	**NiMH**	**NiCad**	**Li Ion**	**LSF**	**HSF**	**UC's**
Installed cost	A	C-D	C-D	C-D	C-D	C	C-D	C
Service life	F	A	A	A	D	A	A	C
Availability	D	A	A	A	D	C	A	B-C
Failure mode	F	B	A-B	A-B	B	B	B	D
Cycle ability	F	D-F	A	A-B	A	A-B	A	A
Temp withstand	F	F	A	A	A	A	A	D
Space / weight	B	F	A	B	A	B	B	A
Maintenance	C	D	A	B	B	D	A	B
Environ/Safety	C	D	A	C	C-D	A	A	C-D

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Dennis DeCoster is Managing Principal / Principal Site Engineer of Mission Critical West Inc., Redondo Beach, CA. Mr. Decoster's articles & publications have been featured in Power Quality Magazine, IEEE-IAS, Pure Power, Availability.com, the Power Quality Conference, Consulting-Specifying Engineer, several battery conferences, and many other forums. He can be reached by email for questions or comments at dd@mcwestinc.com or at www.mcwestinc.com on the net.