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Comparison Of Energy Storage And Electric Conversion For Bridging Power Applications

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Abstract

A high value-application for energy storage is the protection of critical end-use equipment and industrial processes. One category of this protection that has been applied, with several different energy storage technologies and interesting circuit configurations, is **bridging power**. There are at least a dozen bridging power products available in the 25 kW to 2,500 kW size range. These use low and high speed flywheels, lead-acid batteries, ultra capacitors and magnetic storage technologies. This paper provides an overview of bridging power applications, identifies key functions, and compares the power and energy performances of these systems with respect to different energy storage and conversion technologies.

Introduction

Usually the objective of the bridging power system is to carry the critical load away from an out-of-spec or failing power source, and to a stable alternate source. Several key functions are required to accomplish this objective. These are rapid isolation from the failing source, recovery using local storage, energy conversion, synchronization, paralleling and soft transfer switching between the primary and alternative power source. Optional functions that may add value to this application are; additional power conditioning and filtering, full-time reactive and real power stabilization, harmonic cancellation, control and dispatch of distributed generation, interconnection protection and load control. Figure 1 shows each of the basic functions in a generic circuit configuration.

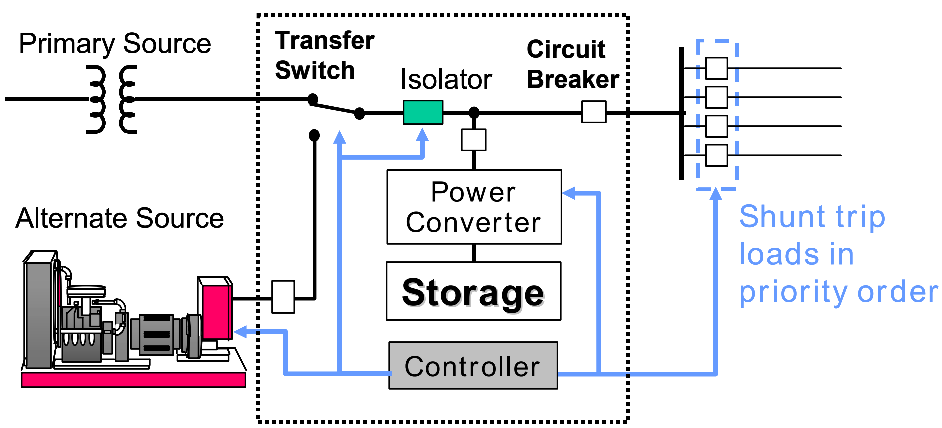

Figure 1 Generic Circuit Configuration for a Bridging Power System

In this paper the generic functional blocks of several commercially available bridging power systems are described. Measures of performance for these various functions are identified. Different elements that provide for the same specific functions inside bridging power systems are then compared using these measures. Storage element comparisons are power and energy density, round trip efficiency, speed or dc voltage ranges, and method of electrical conversion. System-level comparisons include standby losses, voltage and frequency regulation, as well as some of the added value functions described above. Issues of storage containment, cost per k-WH, life, and application are discussed. The bridging power system application is defined as:

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Bridging Power Application – system provides continuous real and reactive, regulated, and conditioned power support during a switching transition from one power source to another.

Typically, the bridging application transfers the facility load from a primary power source, normally the commercial utility power source, to a secondary source, normally a stand-by engine generator set. In addition, the application includes the transfer back to the primary source after power is restored, and these transitions must be seamless without causing any disruption to the source, load or facility. Characteristics of the available bridging power systems are:

- Interruption protection within cycles
- Bridging power to alternate source for last for seconds
- Synchronized control for paralleling and seamless transfer
- 3-phase systems range from kWs to MWs at low to medium ac voltage
- Interconnection protection and load control may also be provided

Another application of the short-term storage may be a full-time dynamic stabilizer. This is a special case where the storage system acts as an interface to compensate for lack of power delivery capability in the local power system. So the stabilizer provides transient response features like voltage stabilization and overload capability. These may be essential for distributed generation (DG) applications as shown in figure 2, where system transitions would otherwise cause voltage variations. Potential system advantages, besides soft transfer of load, are increased inrush and pulse-loading capacity. In order to provide these advantages the interface system must allow parallel, fulltime operation of the load and generators while providing supplemental energy during transients.

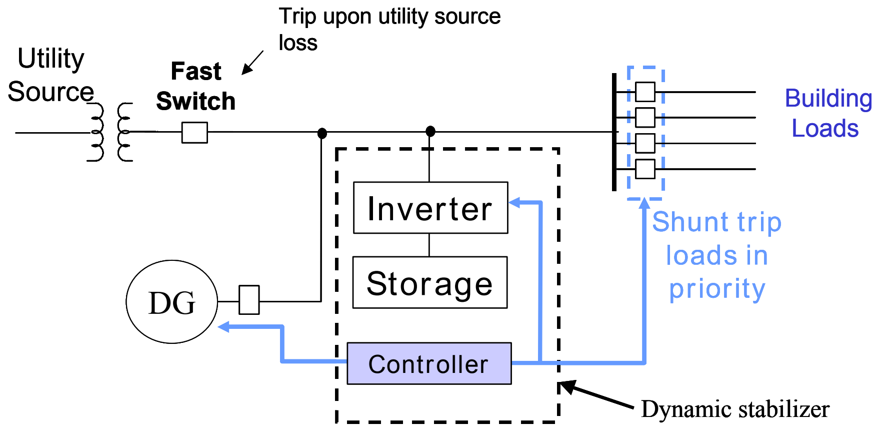


Figure 2 Short-term Energy Storage Based Dynamic Stabilizer in a DG Application.

Bridging Power System Technologies

The past decade has been a period of great innovation in energy storage and the next decade promises even greater advances. Driven in part by increased interest in short-term ride through storage applications for power electronics and related power quality applications several new energy storage technologies are now entering or will soon enter commercial service. These technologies include advanced battery technologies, composite high-speed flywheels, ultracapacitors, and improved superconductive magnetic energy storage devices (SMES).

Lead-Acid Battery-Based Bridging Power Systems.

Despite all of the battery technology research, the lead-acid battery still remains the primary energy storage technology in use today. The cost for lead-acid batteries, typically lowest among storage options, depends greatly on the “cycle duty” and application for which it is designed. Batteries may be for starting duty (automotive), UPS duty, marine applications, or deep-cycle industrial applications (fork lift types). The main concern with lead-acid batteries is shorter life due to environment and the number of deep discharges. The cycle life of a battery is the number of discharge/charge cycles it can take before its performance degrades to an unacceptable level.

Some applications do not require any deep discharge at all. For example, with a car battery, the process of starting the car only discharges the battery by a few percent in the few seconds required for a normal start. This 60-72 month car battery is well understood and low cost. Other batteries, such as those for a forklift are deeply (more than 50%) discharged/recharged on a daily basis. Batteries designed for deep periodic discharges are heavier and more expensive. Automotive batteries purchased in bulk can cost less than \$50/kWh of capacity whereas deep-cycle batteries can cost anywhere from \$100-1,000/kWh depending on the technology employed. Automotive batteries usually will not last more than 100 deep discharges whereas deep-cycle batteries can last for up to 1,000 deep discharges.

A cranking type battery is nearly ideal for bridging power applications because the short duration of use 15-30 seconds, is also a relatively shallow discharge. Bridging power systems using this approach have been quite successful. For example the PureWave™ (also called AC Battery) module shown in figure 3 is being used for bridging power system up to 20 MW and is available in a 250 kW module. Shown in figure 3 is one 250-kW module, rated at 480 V, three-phase and with a capability for a 30-second bridge between primary and alternate power sources.

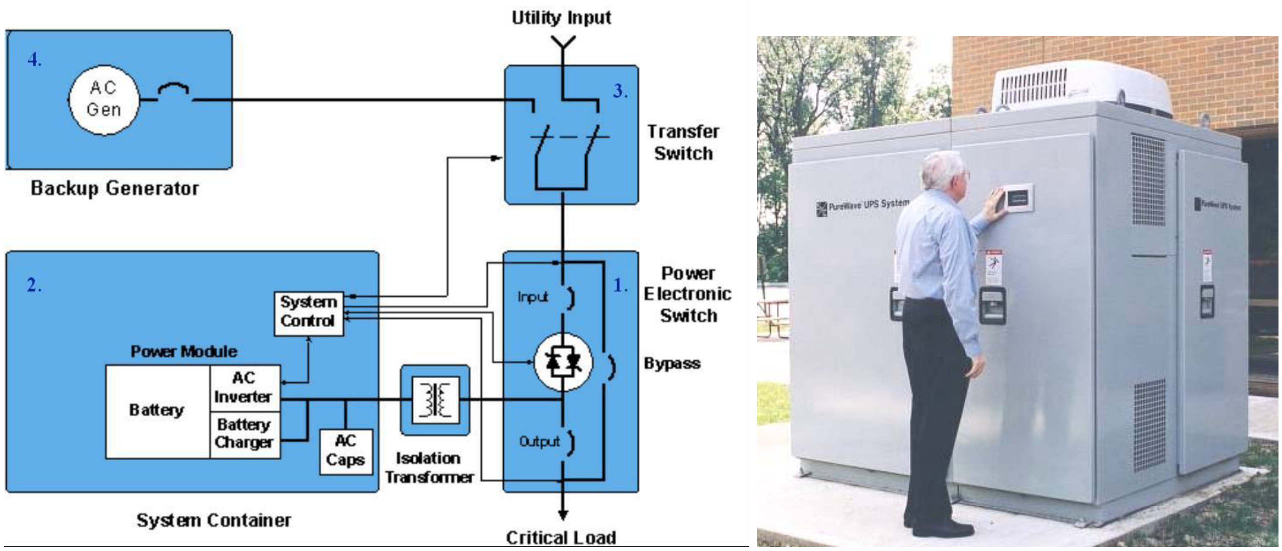


Figure 3. One line and Packaging of Soft-Transfer Interface System using Battery Energy Storage (courtesy of S&C Electric)

Key functions are shown in the one line as numbered blocks. Block 1 provides the rapid isolation from grid faults, bypass and short circuit protection. Block 2 includes the short-term battery storage and power conversion functions as well as overall system control with synchronization and paralleling. Power conversion in this case is provided by a one-minute rated PWM inverter system. The inverter running time limitation is related to heating of output inductors. Block 3 provides transfer from one energy source to another, and block 4 represents the alternative source of power.

Since temperature also impacts battery performance and life, it must be maintained according to the manufacturers' specifications. For lead-acid batteries, manufacturers usually recommend that the battery be kept as close to 25°C as possible. Higher temperatures will shorten the life significantly and low temperature at the time of use will reduce the capacity. The solution applied for the example system is an insulated and air-conditioned enclosure for the battery and the power electronic components.

Battery storage will have shorter lifetimes and higher charge/discharge losses than other choices for short-term storage. With limited duty, proper equalization and air conditioning we should expect greater than 7-year battery life. The system efficiency is limited by chemical conversion or coulomb losses, which always limits the round efficiency to around 75%. This loss occurs only during recharging after a power quality event and therefore probably only involves a couple hours per year. The more important loss is standby which occurs more than 360 hours per year. For this system standby losses are about 1 .5%.

Low- and High-speed Flywheel Bridging Systems.

Flywheels are also well suited for the short-term bridging power application. A number of new flywheel systems, both low-speed and high-speed, are being commercialized. Several companies are introducing products that can provide from 15 to 250 kW modules and several kWh of energy storage. Companies like Holec, Piller, Precise and SatCon offer low-speed systems while Active Power, Beacon, and Urenco have high-speed flywheel products. Flywheels have very long cycle life compared to batteries and can be more cost effective in bridging power applications. As costs come down, this market is expected to grow.

Flywheels are "charged" and are "discharged" via the shaft on which they are mounted using a suitable motor/generator system. Since the speed is variable a permanent magnet generator with inverter, a synchronous generator with a clutch, or unique technologies like the written pole system are used to make up for the speed change. The objective is to have sufficient stored energy to ride through voltage sags and momentary service interruptions. Flywheels for motor-generator sets are often specified to provide sufficient ride-through capability to perform load transfer to auxiliary power sources prior to system shutdown due to under speed on the flywheel. The auxiliary power source may be another utility feeder or on-site backup generators. Backup generators can usually be online within 5-10 seconds. Primary applications include power quality support of sensitive manufacturing processes, computer facilities, and other critical loads.

Motor/generator/flywheel-based power conditioning systems are available in power ranges from about 10 kVA up to more than 1 MVA. Typical applications allow for 1 to 10 seconds of load ride-through capability depending on the size of the load carried and the flywheel mass selected. Some larger flywheel and/or specialized systems (written pole motor/generators) can even allow for up to about 30 seconds of ride-through capability. The actual ride-through time available on a flywheel system is inversely related to the system loading at the moment of utility voltage interruption. A flywheel rated to provide 2 seconds of ride-through capability at full rated load should be able to provide about 10 seconds at 20% load. Some manufactures such as Active Power have target the UPS battery market with a flywheel that substitutes for the battery unit as in the Cat UPS, shown in Figure 4.

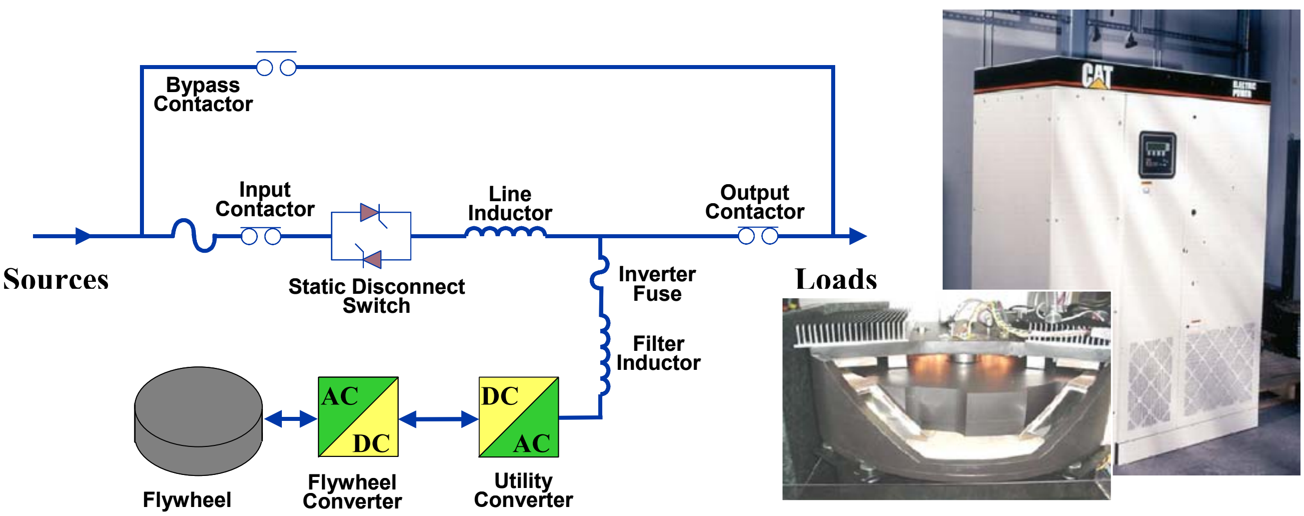


Figure 4. A 250-kW Cat UPS provides the bridge between normal utility power and an on-site generator

Figure 5 shows a physical comparison of the pulse-type ultracapacitor from ESMA and a conventional cranking type lead-acid battery. The functions for these products are similar to the battery type bridging system. Power is provided from either the normal or alternate source via an open transfer switch. If either source fails the line inductor or static protect the load on the left with bridging power provide by the flywheel and power conversion system. In this case power conversion involves both an alternator and power electronic inverter. In addition to these functions some added power conditioning is possible with via the converter filter inductor that shapes output current and the series line inductor, which allows for continuous voltage regulation and wave shaping to the load relative to the normal source voltage. A low-speed configuration that uses electro-mechanical linkages between a low-speed flywheel and the output is shown in Figure 5

Power:	1670 kVA
Discharge duration:	12 sec
Input voltage:	480V
Available energy:	5.6kWh
Output voltage:	480 – 600, 3Ø ac, 60 Hz, 4-wire
Recharge time:	48 sec
Weight:	43,198 lb.

Speed range	3600 – 1800 rpm
Total weight	10,850 lb.
Rotor weight	5,960 lb.
Magnetic bearing force Resultant bearing load Bearing change	24,000 N 3,000 N 70,000 hours
Output rating Nominal / Maximum	1100 kW / 16 sec. 1650 kW / 10 sec.
Output voltage	405 – 550 VDC
Efficiency / losses	99% / 11 kW

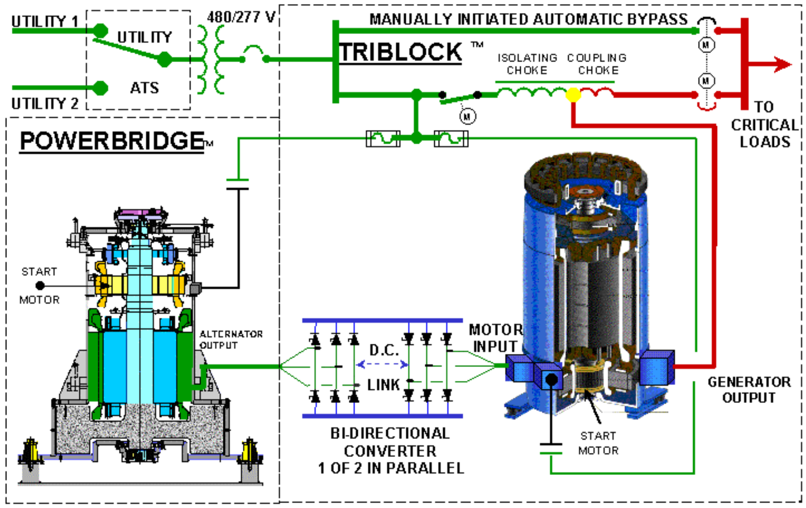


Figure 5. Product Spec and One-Line Diagram for Piller Power Bridge™ with TriBlock™ UPS

Ultra-Capacitor Product Applications

Ultracapacitors are generally best suited for the very short-term applications such as inrush current mitigation lasting a few seconds and momentary ride through as in the case of voltage sags lasting only a few cycles. However substituting a traction-type ultra-capacitor for the lead acid battery can also provide a straightforward bridge power or voltage stabilization application. Ultracapacitors can have a cycle life that is 1-2 orders of magnitude better than lead acid batteries. They also have a much high power density (albeit a lower energy density) and are better than 98% efficient in the charge/discharge cycle. For the same volume about 1/3 the ride through time is possible with conventional products. The advantage of the capacitor is 4-5 times the power capability, with high tolerance for temperature variations and longer life. They can also be charged faster than batteries. A comparison of batteries, ultracapacitors, and flywheels is shown in table 1.

Table 1. Comparison of Storage Bridging Power Systems

Parameter	Lead-Acid Batteries	Flywheels (1)	Ultra-Capacitors
Power @ 15s W/kg	20 – 330	10 – 130	120 – 1200
Energy @ 15s kJ/kg	10 – 6	10 – 6	10 – 6
Energy Range kJ/kg	93 – 6	10 – 2	12 – 2
Discharge Time Range	90 – .25 minutes	2 – 200 seconds	60 – 1 seconds
Recharge Time Range	Hours to Minutes	Minutes to Seconds	Minutes to Seconds
Roundtrip Efficiency (2)	70-80%	95-98%	97-99%
Typical Cycle Life	2,000 cycles	10,000 cycles	100,000 cycles
Cost \$/kJ Range(3)	\$.1 - 1	\$1 – 4	\$5 – 40
Technology Status	Mature	Available	Emerging

1. **Flywheel performance, cost, and weight includes the generator and containment**
2. **Assumes a slow recharge for best-case efficiency**
3. **First cost over rated discharge time range from longest (lowest cost) to shortest time (highest cost)**

Many of the available ultra capacitors contain materials that are much more benign from an environmental perspective. The main issues right now hindering widespread adoption of ultracapacitors are cost and lack of application experience. Ultracapacitor's initial capital cost is 10-times more than lead acid batteries for long duration type applications but when life cycle costs are considered the factor is only 3-10 time more expensive. Furthermore, for short duration applications, they are *already cost competitive* due to their higher power density and other attributes. As costs come down for ultracapacitors, it is possible in the future that they will challenge batteries for even long duration applications. Some of the specific characteristics of these two technologies are shown in Table 2.

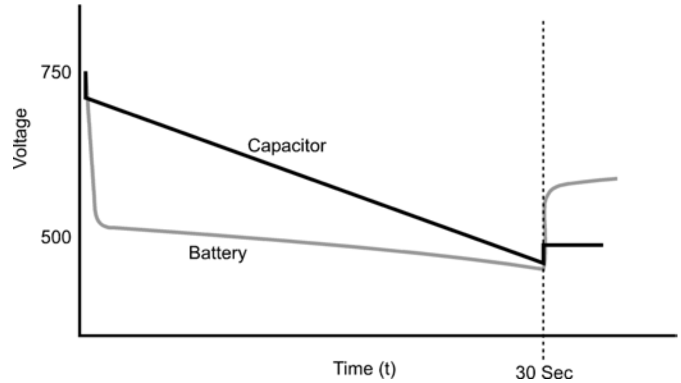


Figure 6. Physical Packages of Delco 1150 Cranking Battery and ESMA EC-402 Pulse type Ultra Cap as well as the Discharge Curves for each Technology (cap is shown without its metal cover)

Table 2. Characteristics of ESMA Pulse Type Ultra Capacitor and Delco DELPHI-E cranking battery

Characteristics	ESMA 30 EC 402	Delco 1150
Operating voltage window, V	42-21	11.5-7.2
Minimum voltage at no current, V	10	7.2
Energy stored in V operating window, kJ, not less than	220	300 (9.7 A-H)
Capacitance, F, not less than	330	N/A
Internal resistance, Ohm, not more than	0.009	.0115 (CCA=625)
Weight, kg, not more than	40	27
Overall dimensions (L× W× H), mm, not more than	570×180×262	330x170x240
Operating temperature range, C	-50 / +50	0 to 26 (65 –100%)

Super Conducting Magnetic Storage (SMES) Systems

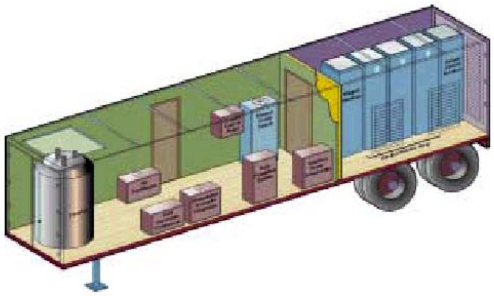
The most common superconductivity application currently employed in the power field is the low-temperature application, operating at 4.2° Kelvin and often referred to as a micro-SMES system. These can typically store about 1 to 10 mega joules of energy and are used to support loads from 100 kW up to several megawatts for 1 to 10 seconds during power quality disturbances. This duration of power support is sufficient to prevent many common voltage sags and momentary interruptions from affecting critical loads and to allow backup generation to come on line prior to exhaustion of the SMES energy.

This energy storage approach does not need a superconductor to work. Storage can be accomplished with conventional non-superconducting magnet coils. However, the physical size would be much larger and the losses and costs so high as to make it not practical for any commercial application. Superconductivity makes it possible to use very small wire and reduces the losses mainly coming from the refrigeration, ancillary magnet control, and converter switching circuitry. In fact it is the superconductivity that makes short-term magnetic storage commercially feasible.

One of the big advantages of SMES over battery energy storage is equipment life and maintenance costs. Battery life is inversely related to the depth of discharge and number of discharge cycles. Depending on the type of battery and the temperature of its environment, it may be able to handle only 500 to 1,000 deep discharges prior to needing replacement. If the battery is required to perform a deep discharge once a day, its life may be as short as only a few years. SMES systems suffer no degradation of this nature and they can be charged rapidly and discharged without much concern over shortening the system life. The fact that SMES systems can be rapidly charged at a much faster rate than batteries is an advantage also in applications where the unit is required to rapidly absorb system energy--such as in dynamic braking, frequency control, and power system stabilization. These advantages are similar to the ultra capacitors and also depend of the capacity and performance of the series-connected power electronic conversion system.

The two companies providing this type of system are ASC, IGC and BXT. ASC provides the only commercially available system as shown in figure 7. In this case the system only contains sufficient energy storage time to bridge between already available power sources such as independent utility feeds. Normally two seconds is not sufficient time to start an engine generator. The system is effective in bridging momentary low voltage conditions in the power supply such as sags or an instantaneous recloser operation.

The functions in this application are solid-state isolation from the faulted utility by an electronic



Power:	750 kVA,1.7 MVA
Discharge duration:	>2 seconds
Usable energy:	2.4 MJ
Input voltage:	400-600 V ac; 3-phase
Output voltage:	400-600 V ac; 3-phase
Response time:	< ½½ cycle
Recharge time:	< 2 minutes
System dimensions:	48 ft trailer

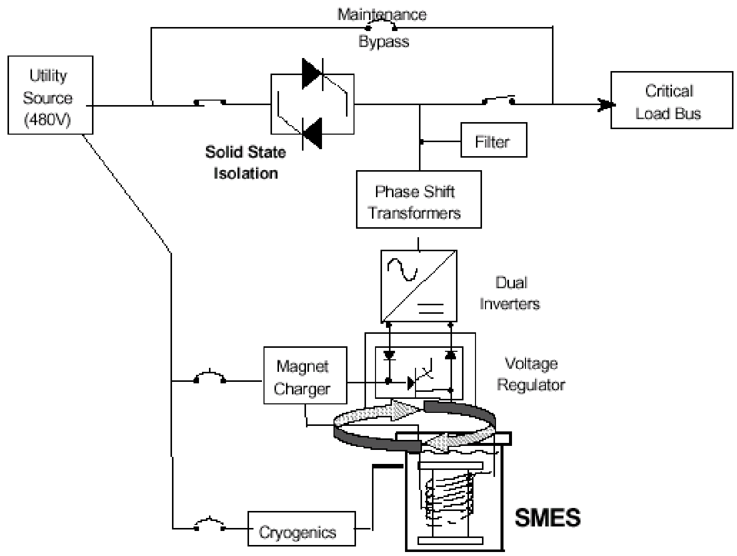


Figure 7. Trailer-based SMES System for AC Power Quality Applications (Courtesy of ASC)

interrupter. Magnetic energy storage is converted to dc current through a chopper-regulator; this device also serves as a magnetic charger to replenish the energy in the coil. A simple inverter is used to make AC and with phase shifting transformers and a filter the waveshape is smoothed. In the future other technologies like SMES and exotic batteries are expecting significant cost reduction and performance improvements. Therefore it is not really clear at this stage, which technologies will dominate in the future. It is interesting to note that the technologies that have higher power density tend to be more economical for short-duration, high-power applications than conventional lead-acid batteries, which provide moderate power density but lower cost for long duration applications.

Comparison of Bridging Technologies

For the purposes of this paper it is useful to compare primary types of bridging power systems according to the storage medium, the converter, and the system parameters. In the followings three tables these comparisons are made based on available technologies. Six available storage technologies for bridging application are lead-acid batteries, pulse- and traction-type ultra capacitors, low- and high-speed flywheels, and high-temperature SMES. Table 3 compares the energy storage parameters for these ac bridging systems.

Table 3. Comparison of Typical Energy Storage Parameters for Available AC Bridging Power Systems

Bridging System	Types	System Rating[1]	Run time	Energy MJoule	Cost $/kW [2]	Watts/kg @ 15 sec[3]	kJ/kg @ 15sec (x .28 = W-H)[3]
Lead Acid	Cranking	250 kW	30s	7.5	40-50	250-350	4-8
U-Caps	Traction	250 kW	10s	2.5	130	300	4
U-Caps	Pulse	250 kW	10s	2.5	150	500	8
LS Fly W	.9-3.6 kRPM	1340 kW	12s	16.1	250	200-250	3-3.5
HS Fly W	5-50 kRPM	250 kW	12s	3.0	100	200-250	2-2.5
Mag. Coil	SMES	600 kW	2	1.2	600	N/A	N/A

1. **Energy storage rating is ~ 10-25% higher than system rating to cover conversion losses.**
2. **Equipment first cost for energy storage element at rated time (life cycle cost not considered).**
3. **Weight used is for energy storage components of commercial product not theoretical.**

Bridging applications are often hybrid systems mixing technologies to improve performance, taking advantages of various strengths and compensating for weaknesses. For example, the idea is to use the relatively high-power, fast acting, but energy-limited storage system to compliment the slower starting, long-term high-energy from natural gas or diesel fueled systems. Together they provide effective bridging and protection of a critical load. The exception is the SMES, which typically does not store enough energy to bridge to a standby diesel. SMES is therefore most effective at bridging very short events such as momentary voltage sags of a few cycles or full time stabilization of system transients.

A hybrid system combining a 1 second SMES with a static-transfer switch and two active power sources might provide an effective bridge to a power outage.

By integrating fast acting electronic interfaces into these systems the moment-to-moment control of the local system voltage is allowed to occur. The presence of energy storage is essential to carry out the desired power conversion and bridging. Still, it is the performance of the power conversion component that provides for fast control and stabilization. Table 4 compares some of the key parameters of power conversion in eight different available bridging systems. It should be noted that there are numerous different system configurations and converter technology options. Additional work is needed to fully characterize and compare these systems.

Table 4. Comparison of Typical Conversion Technology Parameters for Available Bridging Power Systems

Bridging System Type	Power Converter Type[1]	Input/ AC Output Voltage	Output Regulate & Shape[2]	Conv. Eff.	Grid Isolation Method	Output Inter-Active[3]	Temp. Over-Load
Lead Acid	Inverter	400-570Vdc/480ac	PWM	95%	Static Switch	No	160%
U-Caps	Inverter	300-650Vdc/480ac	PWM	95%	Static Switch	No	200%
LS Fly W	Dc Gen/Invt	1800rpm/550Vdc	Dc Field	95%	Rectifier	No	N/A
LS Fly W	Induction Gen	1980rpm/480Vac	Ind. Gen.	96%	Series Choke	Yes	500%
LS Fly W	Induction M-G	1750rpm/480Vac	Sync W-P	84%	Mechanical	Yes	600%
HS Fly W	PM-Rect/Invt	H-F500Vac/480ac	PWM/filter	93%	SS & Choke	Yes	500%
HS Fly W	PM Gen/Rect.	400-800Vdc/800dc	Dc Field	94%	Rectifier	No	N/A
Mag. Coil	Dc to dc/Invt.	600Vdc/480ac	2x6P/filter	95%	Static Switch	Yes	230%

1. **All converters are connected in parallel with the load except the LS Flywheel, Induction M-G.**
2. **Output voltage regulation and wave shaping when the system is isolated from the grid.**
3. **Output voltage stabilization is active in all operating mode, on grid, in transition and on standby.**

The primary function of the converter is conversion of the stored energy to the form of useful electric power that will provide a bridge between external sources, e.g. dc to ac or variable speed mechanical energy to 3-phase, 60-Hz electric power. Also defining the different converter performances is output voltage regulation, wave shaping, and overload capacities. In order for the converter to serve the critical load a device to isolate grid disturbances is required, and by interacting with transients on the load bus the converter can help to stabilize local voltage. Other functions usually provided by the power converter, and not compared in table 4, are system control, synchronization and paralleling.

In table 5 the general system parameters are compared for typical bridging power systems. Some system parameters are well defined such as the overall kVA rating, method and time for recharging the storage element, standby losses, round-trip efficiency (source-side electric to electric), and the method or device for transferring between sources. Also the need for controlling temperature is shown as "temp. cond.", which indicates if the storage and or converter subsystems require environmental control as opposed to operating in the ambient environment.
There is another category of system parameters that are more subjective not as easily defined without a lot of field experience and special evaluations. These are reliability, availability, maintainability and durability, sometimes referred to as RAMD. Some well-defined measures have been developed for RAMD parameters such as reliability as "mean time between failure," maintainability or repairability as "mean time to repair" or availability as "(total time – downtime)/total time" given in % of total. However, it is often difficult to get the long-term field experience data needed establish the RAMD measures. Therefore only a subjective assessment of "maintenance level," based on general system characteristics, is given in table 5.

Table 5 Comparison of General System Parameters for Typical Available Bridging Power Systems

Bridging System	System Rating[1]	System $/kVA	Recharge Method	Charge Time (s)	R-T eff.	Stby Loss	Maint. Level[2]	Temp. Cond.[3]	Transfer Method[4]
Lead Acid	250 kVA	$ 345	Aux charger	3600	75%	1.5%	Med	Yes	T. Switch
U-Caps	125 kVA	$ 640	dc-dc covt.	30	98%	2.0%	Low	No	via Rectifier
LS Fly W	250 kW	$ 83	IM motor	240	93%	1.0%	Med	No	via Rectifier
LS Fly W	2200kVA	$ 341	W-R IM/ASD	120	96%	4.0%	Med	No	via Clutch
LS Fly W	35 kVA	$1,000	IM motor	60	84%	N/A	Med	No	Via M-G
HS Fly W	250 kVA	$ 335	PM motor	150	95%	2.0%	Low	No	T. Switch
HS Fly W	100 kW	$ 550	PM motor	40	92%	2.0%	Low	No	via Rectifier
Mag. Coil	750 kVA	$ 800	Sync inverter	90	97%	3.0%	Med	Yes	N/A

1. **Includes all the components constituting the overall system rating.**
2. **Subjective assessment based on components such as battery vs flywheel, air conditioning, and bearing types.**
3. **Temperature or environmental conditioning is used.**
4. **The device that allows connection to two power sources such as an automatic transfer switch, "T. switch."**

Conclusion

Short-term energy storage applications such as bridging power, voltage stabilization, and regulation have found a market in high-tech industries requiring continuous and high quality electric power. Chemical storage in the form of conventional lead-acid batteries used in UPS is dominant in this market. However, technologies that are based more on the principles of physics, including low-speed and high-speed flywheels, ultra capacitors, and magnetic-coil storage are beginning to compete for this important market. The clear advantage of the lead acid battery is first cost, while the physics-based technologies show higher round-trip efficiencies, respond faster, are less impacted by environment, and are expected to have a longer-life. There are many commercially available short-term bridging power products currently available that use various energy storage types described in this paper. The trend is expected to be toward storage technologies that can provide fast response interactive power control, with integrated power electronics, longer life and better environmental compatibility. In the future we can expect the short-term energy storage product market to support new and improved energy storage technologies that may eventually contributed to other storage applications.