Flywheel Energy Storage: an alternative to batteries in UPS Systems

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Introduction

A 2001 study by the Electric Power Research Institute found that electric power problems annually cost U.S. industry between $119 and $188 billion in estimated lost data, material and productivity. According to industry sources, US businesses spent billions annually on power quality and reliability products in an attempt to reduce such losses. It is reported that by 2003 Europe had caught up.

Conventional power quality systems have been constructed from an array of devices, including flywheels and batteries for short-term power disturbances, standby diesel generators for longer-term outages, and some form of control electronics to bridge the transfer from mains to generator. A short-term (seconds to minutes) energy storage device with control electronics is referred to as an uninterruptible power supply, or UPS.

Flywheels with 3-5 seconds of stored energy have been used in so-called 'diesel-UPS' (with an integrated diesel engine as an alternative prime mover) for over thirty-five years – typically spinning at 4,500 1/min. However specialist 'battery-free' technology UPS companies have now introduced a wide range of kinetic-energy storage (1,500-50,000 1/min) into the traditional UPS market as an alternative to battery storage. The speed of rotation dictates the sophistication and complexity of the rotor construction and mechanical bearing arrangements whilst typical stored energy levels are 10-15 seconds at full-load.

Autonomy

Depending upon the clients' critical power requirements it is interesting to note that often 10-15 seconds of autonomy is sufficient to meet the load demands without resorting to genset power at all. This is certainly true of industrial processes where a combination of unreliable grid power (due to weather or power infrastructure problems) and high-speed inspection, packaging and labelling processes occurs at the same time. Due to the fact that the vast majority of power quality events have a duration of only a few seconds[1], some power users have the opportunity to improve the quality of their power, all except long-term outage situations, with minimal space and cost outlay. Batch or process manufacturing sites with a history of short-term power glitches or sags (which have remained unprotected due to the high costs or space requirements of traditional energy storage) are ideal applications for high-power flywheel systems. Eastern Europe and North Africa are two prime examples of where 'glitch protection' is valued.

However, in other circumstances, the end user of critical power has a strong desire to eliminate the requirement for electrochemical batteries due to environmental restrictions, maintenance concerns or limited space. If the power quality configuration includes a standby engine/generator for long-term protection, a flywheel energy storage system is well suited for providing the 'bridging' power until the start and synchronization of the genset.

For 'commercial IT' UPS applications (Banking, Finance etc) the business demands require on-site power generation to cover all instances of grid power failure – no matter how short or long and so the question can arise *'why have 20 minutes of battery capacity when my generators start as soon as the mains fails?'*

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[1] In EMEA 97% of all power disturbances last less than 3 seconds

But is 10-15 seconds enough? In diesel-rotary UPS (DRUPS) it is common to have the diesel engine able to start and accept 100% load within 3-4 seconds – although these engines have to be particularly set-up for that duty, are highly stressed and consume a lot of maintenance resource in the process. With 10-15 seconds available a single genset (with no paralleling control) will be able to take over the load well before 10 seconds has elapsed in a rather relaxed fashion and standard machines can be used.

Batteries

The most common battery autonomy is specified in the range 10-15 minutes which raises the obvious question when gensets are applied: *'What are you going to do in 15 minutes that you can't do in 15 seconds?'* Some clients have tried to consider a 'one-minute' battery but the chemical reaction within a lead-acid recombination cell favours several hours of low-rate discharge, rather than a few seconds of high-rate duty, and the resultant battery takes up the same space as a 5-minute example. For lead-acid technology a practical minimum autonomy is 5 minutes.

So what is 'wrong' with batteries?

The answer can be *'nothing'* if they are selected, installed and maintained correctly - and then replaced before failure and in a timely fashion. Unfortunately not all batteries are so pampered and their failure mechanism is not conducive to running a high-availability power system. The basic problem comes down to that of reliability and predictability and the typical lead-acid batteries that provide ride-through power for UPS are commonly viewed as the most unreliable and most costly element of conventional power quality and reliability solutions. The worlds largest UPS OEM's freely admit that battery failure is the largest single cause of critical power system failure – along with human error.

Depending upon the basic design of gas-recombination valve regulated lead-acid that is used (stemming from either automotive or telecom technologies) and depending upon the build-quality of the battery the user can expect his battery to last from as little as 3 years to as long as 9 years at >80% capacity. Unfortunately the time for the capacity to fall from above 80% capacity to the critical capacity of 80% can be as short as three months – inside the normal planned maintenance period. For flooded cells with high lead content plates with the possibility of re-watering the service-life can be much longer – but at the penalty of initial cost, space, weight and maintenance work. There also has to be an effective lead-recycling system in place.

To achieve the most reliable battery installation it can be shown that the specification should include:

- A thick-plate telecom style cell suitable for a relatively low discharge (as opposed to high-rate thin-plate automotive cells suited for engine-cranking duty) with a Design Life of 10-12 years
- Autonomy rated for end-of-life not 'day-one', e.g. 80% capacity = rated capacity at ten years. This usually results in a 20-25% over-sizing of the battery.
- Specify 20°C ambient rather than 25°C – noting that the cells can offer higher Watts/cell at the higher temperature but with a shorter life (that might not be mentioned)
- Multi-string (not single) with at least three strings in parallel for semi-redundancy and at most five strings in parallel to avoid unequal charging across the strings

- If possible a fully-redundant string or, at least, ask for the autonomy to be stated in the quotation with one string out of service (if only three-strings this is often very short)
- Avoid 18V and 24V monoblocks with only two terminal posts accessible since the value of monitoring is problematical

To get the maximum life out of a battery requires a few simple conditions – conditions that point to the advantages that a flywheel system has over a lead-acid battery installation:

- Keep the battery room temperature at a steady 20-23° by means of air-conditioning. For every 10°K above 20°C the design life of a battery will be halved, e.g. a ten-year Design Life product will be reduced to a 2.5-year specification when run in 40°C ambient. This involves both cooling plant and its associated running cost
- Apply temperature compensated battery charging
- Provide regular maintenance and a load-bank testing regime to ensure capacity. A cell-based battery monitoring system is essential to record trends and identify failing cells/blocks.
- Provide redundancy (in batteries or in strings) to allow concurrent maintenance without load shutdown or increased risk.
- Replace the battery in its entirety before the capacity falls below 80%.

In addition to the cost of its replacement there is also the cost of the accommodation footprint.

Flywheels

The flywheel acts as a 'mechanical battery' and comprises a shaft mounted mass rotating in (or carrying) a motor-generator winding – converting electrical energy into kinetic energy as it accelerates (charges when speeding up) and then, when a discharge of energy is required, reverses the flow of energy and slows down as it gives up its stored energy in the form of electrical power. Some of the available flywheels operate at variable frequency AC and incorporate highly sophisticated power conversion electronics therefore the technology should not be considered 'old fashioned' or simple. It is worth noting that the high speed variants have more power electronic components than a double-conversion UPS.

The stored energy (E) is related to the inertia of the flywheel derived from its mass (m) and the square of its rotational speed (v), the formula being,

$$E = \frac{1}{2} * m * v$$

Combinations of the two variables provide many options to the designer but each has its basic limitation:

- Increasing the speed gives the highest return but imposes demands upon the rotor material used, the containment and the technology of the support bearings
- Increasing the mass is the technically simpler choice but has limitations on rotor material, bearing speed and penalties of size and weight

As a direct consequence of these choices the industry has divided into five broad technological segments:

Speed Class	Normal	Low	Medium	High	Ultra
Typical l/min	1,500	<3,600	<8,000	<36,000	<50,000
Rotor Material	Iron/Steel	Special forged steel	Special forged steel	Turbine quality steel	Carbon-Fibre composite
Bearings	Ball/Roller	+ Magnetic relief	+ Magnetic relief	Full Active Magnetic	Full Active Magnetic
Bearing Service Life	100,000h	70,000h	22,000h	Unlimited_	Unlimited[2]
Containment	Open	Helium	Vacuum	Vacuum	High Vacuum
Noise, dB(A)@1m	90	74	75	66	45
Power Electronics	No	Yes	Yes	Yes	Yes
Air-conditioning[3]	No	Yes	Yes	Yes	No[4]
Example proponent	KST	Piller	Active Power	Vycon	Pentadyne
Typical MJ/wheel	7.2	16.5	3.4	2.35	1.9
kW-seconds	640kW-11.3s	1100kW-15s	225kW-15.1s	220kW-10.7s	190kW-10s
Standing losses	1.3%	1.1%	0.9%	0.9%	0.25%
Footprint[5]	1.6 MJ/m_	5.8 MJ/m_	3.4 MJ/m_	3.2 MJ/m_	3.6 MJ/m_
Weight, kg/MJ	736	455	507	320	210

The balance between technological simplicity and complexity is less than clear, with the exception of the standby losses. For example, medium speed flywheels (8,000 l/min) comprise a steel disc spinning in a partial vacuum and utilise magnetic support (via the motor field coils) to minimise the load on the bearings. Some of the advantages of limiting the speed include the avoidance of exotic material technology for the flywheel rotor and the possibility to have 'emergency' bearings that (in the event of a magnetic bearing failure) actually can support the rotor without self-destruction. The downside is the relatively short service life of 30 months (22,000h).

Relative Reliability

We should consider the matter of Reliability[6] (and following on from that, Availability) in two separate parts:

- Kinetic-energy storage (in general) compared to battery storage technology
- The relative reliability of the various types of kinetic-energy storage machines

The theoretical calculation of MTBF is a valid tool when the results are used for comparison rather than absolute values. Clearly the input data has to be on an 'equivalent' basis.

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[2] With a separate UPS supply to the magnetic-bearing axis controllers. An active-bearing failure leads to total rotor failure

[3] For the cleanliness of the power electronics, not ambient temperature control

[4] Oil cooled electronics

[5] Kinetic storage element Including control cabinet

[6] By calculating the MTBF (Mean Time Between Failure) and MDT (Mean Down Time)

Reliability of kinetic energy storage Vs batteries

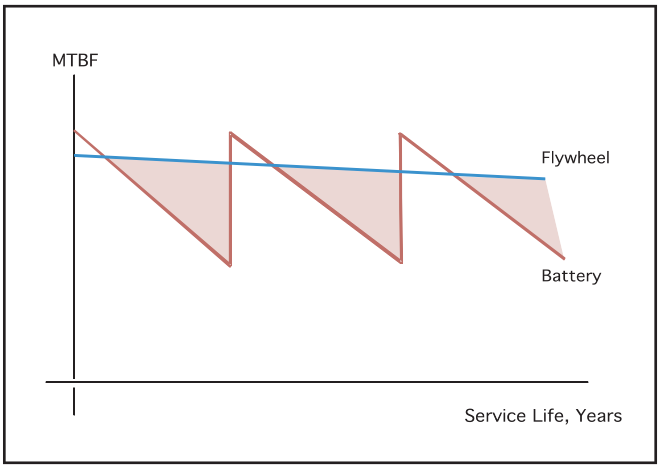
The difficulty in comparing the MTBF between a flywheel system (and all its associated parts) and a high-voltage UPS battery is that the battery itself is made up of one or more string(s) of cells or monoblocks in series – where the strings can be in semi or fully-redundant configuration. Added to that the battery technology can be lead-acid or NiCad, recombination or planté, valve-regulated or flooded. However the most difficult part is that the cells (regardless of type) start to corrode internally as soon as they are manufactured and steadily decline in capacity towards the critical 80% 'end-of-life' level whether they are discharged into a load or not. A VRLA battery can achieve up to 2,000 full-depth discharges before it no longer can hold a charge – but in UPS terms that is far higher than would ever be required. An urban UK UPS installation may see no more than the equivalent of one full discharge per year. Then there is the matter of the ambient temperature, with every 10°K above 20°C halving the Design Life.

With all this mind it is not surprising that the calculated MTBF for a 400VDC UPS battery can vary from as little as 14,000h for a single string low-cost 5-Year VRLA to 770,000h for a multi-string Planté installation. However, in terms of good practice, it would be fair to take for our comparison compare a multi-string 10-Year VRLA with an MTBF of around 140,000h (16 years). The full set of results can be found in Appendix 1 at the end of this paper.

However as soon as the 10-Year battery is installed and put on float-charge the clock starts the countdown. If we consider that at around 8 years (at 20°C ambient) it will soon reach the end of its useful capacity[7] and half of the MTBF will have elapsed then the 'running' MTBF will look like a saw-tooth graph with each replacement bringing the MTBF back up to the starting value.

On the other hand the kinetic storage machine (of any type) will have a much more gradual decline, regardless of actual starting value. The graph, right, illustrates the difference with the higher risk area in red.

The predictability of kinetic-energy storage avoids the 'on-demand' capacity failures typical of batteries since, unlike batteries, you can precisely predict the stored energy at any time.



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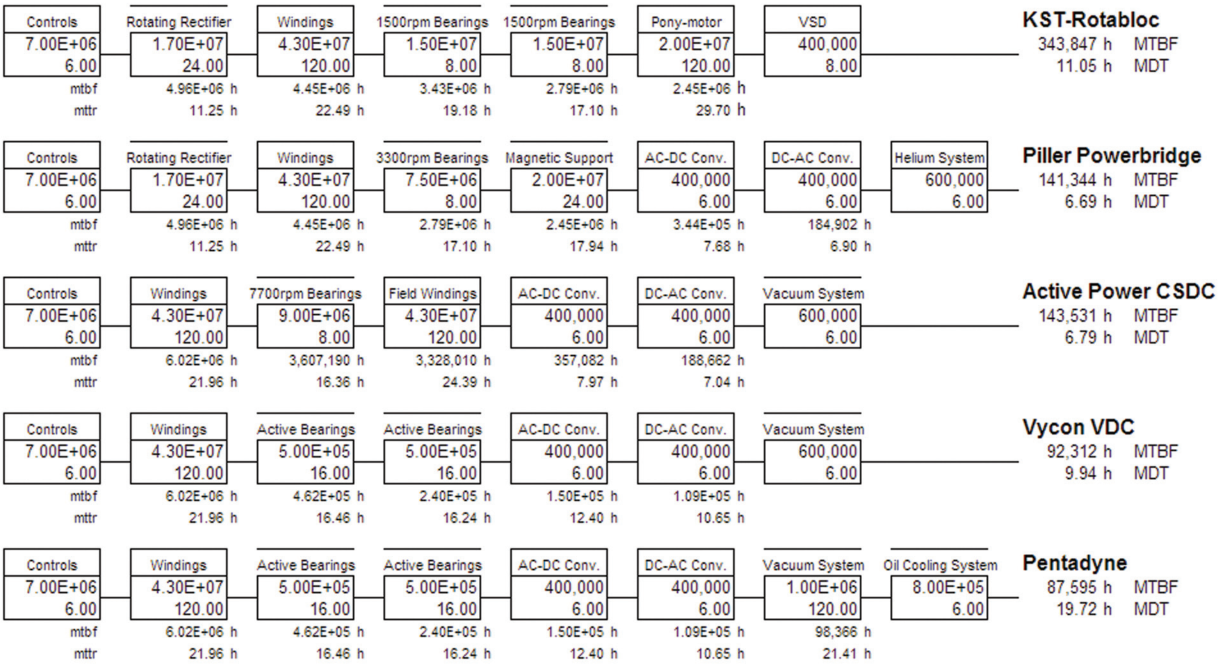
[7] And that, according to MTBF theory, 60% of the population will already have failed

Reliability of KST-Rotabloc Vs other topologies

When all of the technical features and components are taken into account the Reliability Block Diagrams reflect the simple conclusion that simplicity leads to reliability. The full set of RBDs are shown below:

Reliability Block Diagrams for comparison of Kinetic Energy Storage systems



All calculation techniques in accordance with BS5760 Part 9:1992

It is also interesting to note the comparison with battery storage (and in particular the multi-string VRLA 10-Year battery example) that we considered in the previous section. The relative Reliability results and associated Availability figures are then as follows:

Energy Storage	Relative Reliability	Availaility
KST-Rotabloc	100%	99.9968%
Active Power CSDC	41.70%	99.9953%
Piller Powerbridge	41.10%	99.9953%
10-Year VRLA Multi-String	40.70%	99.9829%
Vycon VDC	26.80%	99.9892%
Pentadyne	25.50%	99.9775%
5-Year VRLA Single-String	4.10%	99.8289%

It is suggested that the KST machine, through its simplicity and enhanced reliability, is the preferred technological solution for supporting critical UPS loads.

Summary of the KST-Rotabloc advantages:

KST kinetic-energy technology provides the following benefits over batteries:

- Service life not affected by ambient temperature
- Unlimited charge-discharge cycles
- Very short recharge time (a few minutes Vs many hours)
- Does not require air-conditioning, as there are no power electronics
- Space saving, from 25% for VRLA (for a 5-minute 5-tier rack) to 75% for a flooded cell installation (although batteries do have a far higher stored energy capacity, albeit not generally needed)
- 20+ years service life
- Higher inherent reliability and availability, through low component count, transparency of the state-of-charge and built-in monitor
- Less than half the comparable routine maintenance costs
- No battery replacement disruption and cost every 4-7 years

All of these features (together with the 96% overall efficiency of the associated KST UPS) lead to a Total Cost of Ownership showing that after 3-5 years (battery type and cost dependent) the flywheel UPS saves the client a considerable amount of running costs. Even over 10 years the overall cost of a flywheel UPS can be shown to be a fraction of a static UPS with batteries although the initial cost is higher.
In addition to the superior performance Vs batteries the KST kinetic-energy technology provides the following benefits over traditional integrated diesel-UPS:

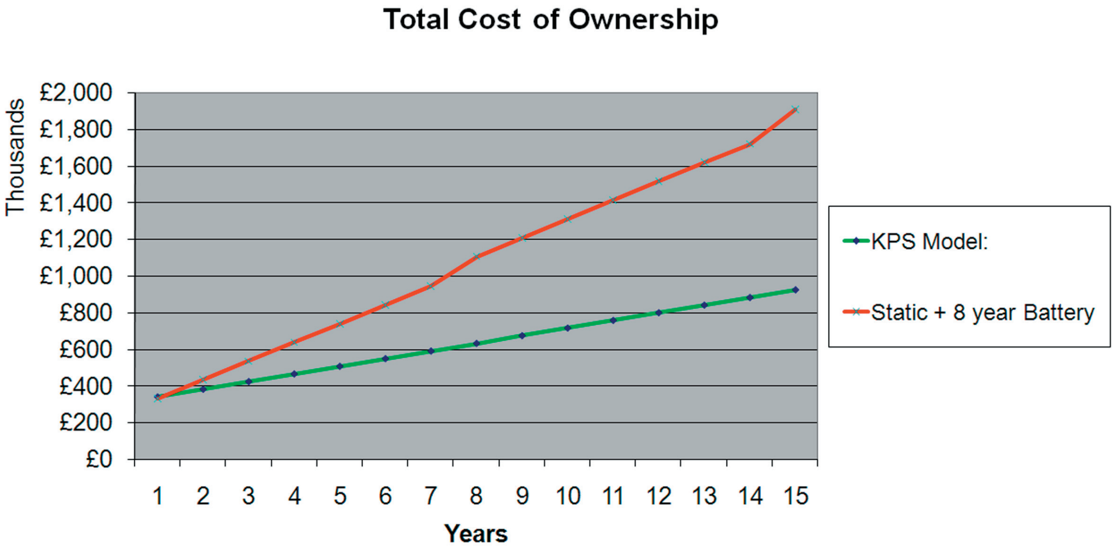
- Separate UPS and short-break load capacity
- UPS function without diesel engine, diesel function without UPS
- Smaller system building blocks with flexible space and N+1 redundancy options
- Hold-off of the engine starting cycle for at least one second, minimising starts
- Very low starting stress on the engine resulting in very low maintenance costs

Total Cost of Ownership

Compared with a static UPS (complete with associated VRLA batteries and gensets) the KST-Rotabloc KPS system will generally have a 10-15% higher Capital Cost but considerably lower running costs due to:

- Higher electrical efficiency of at least 3%
- No need for air-conditioning plant and the associated energy consumption
- Less than 50% of the annual maintenance costs
- No battery replacement cycles every 7 years
- No power-capacitor replacement cycles every 5 years

Each case can be calculated and demonstrated in detail but the graph below shows a specific example:



It is noteworthy that in this 1200kW example the energy savings alone (£45k/year at £0.09/kWh) closes any initial cost gap before the second year of service starts. At the same time, if this were a UK site, the savings in power station emissions would be 243,000kg of CO2 per year. That is the equivalent of around 150 cars with average annual mileage.

Conclusion: The 'perfect' UPS for the low carbon Green-Age?

The two basic KST UPS building-blocks are rated for 400kVA/320kW and 800kVA/640kW for 12 seconds and can be combined for N+1 configuration up to 3,200kVA with an associated N+1 standby generator system. For larger systems Medium Voltage solutions are available to 10MVA and beyond. The combination of line-interactive UPS topology, the KST rotary machine and kinetic-energy storage module leads to a UPS system that is worthy of the 'Green' title:

- 96% efficiency (>3% better than traditional large static UPS systems)
- Rated for leading Displacement Power Factor loads, 0.8lag-0.9lead for constant kW output power and therefore 'blade-ready' without adjustment
- 0.99 input power factor regardless of load power factor, therefore no PFC required in the building
- Very low input THCD regardless of load, hence no filters (active or passive) required
- High reliability and high availability with 'no-stop' service visits
- Very low incidence of diesel-engine starting compared to DRUPS due to the advantage of having a 1-2s hold-off time upon mains failure
- Compact and space saving

In addition there is one aspect of the efficiency profile that is paramount for the most critical Tier IV loads: Dual-corded computer loads requires two independent power systems. This results in the situation that most dual-bus systems will be running continuously at less than 45% load (90% of rated load, shared between two systems). In most IGBT based static UPS systems the operating efficiency falls below 90% at 40% load whilst the KST system remains above 93% - resulting in high energy savings.

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