The Issue Is Reliability……
Introducing the High Speed Clean Energy Storage Flywheel

Socomec Sicon UPS in collaboration with Pentadyne

Background: A flywheel system is essentially a dynamic battery that stores energy mechanically in the form of kinetic energy by spinning a mass about an axis. Electrical input spins the flywheel rotor and keeps it spinning 24/7 until called upon to release the stored energy through a generator, such as a reluctance motor generator. The amount of energy available and its duration is governed by the flywheel mass and speed.

The kinetic energy generated by a flywheel is proportional to its mass and the square of its revolution speed:

$KE \sim M(rpm)^2$

Where KE = kinetic energy
M = mass of the rotating object and
rpm = revolutions per minute of the rotating object.

Until recently, commercially available flywheels relied on mass as a source of energy: doubling the mass doubles the energy. Using a large mass, however, limits maximum RPM. Limiting rpm hampers energy density.

Socomec Sicon UPS has launched the VSS+ Flywheel in Europe/Middle East and Asia thank to the collaboration with Pentadyne Power Corporation, a Los Angeles based company that broke the mold a couple years ago by perfecting a high-speed flywheel. Instead of utilizing the mass as a primary source of energy it takes advantage of rotational speed. The higher the speed, the smaller the mass needed for any given energy output. And while doubling mass doubles stored energy, doubling speed *quadruples* stored energy.

Power Quality vs. Power Reliability: Poor utility power quality is a well known issue; however, the real key is Power Reliability – the ability to sustain the sine wave when an incoming utility anomaly/disturbance occurs. Common battery-based uninterruptible power systems (UPS systems), attached to the DC bus, provide seamless ride-through power until utility power is restored or a standby engine assumes the load within a few seconds. A typical double-conversion UPS uses a string of batteries connected to the DC bus between the rectifier and the inverter. In most cases, less than 10 seconds are needed to bridge the gap between utility failure (collapse of the AC bus) and genset start. The major obstacle is that batteries are prone to unpredictability. One dead cell in a battery string can render all batteries ineffective.

Battery manufacturers state that battery life can be maintained as advertised for at least four years if*, and only if,* they are kept at a constant 25°C (requires air conditioning) and experience no excessive cycling, i.e., *not used.*

The major reasons batteries fail (as cited by their manufacturers) are attributable to the following factors; heat or cold, poor maintenance, corrosion, loose connectors and ripple current. But the primary source of battery failure is quite simply their usage. Every time the battery is used in a short discharge activity or “cycling,” it experiences the “coup de fouet” or “whiplash” effect, rendering it significantly less capable of operating properly when most needed. Interestingly and factually, each of the factors above can be addressed - including the last one – use. By utilizing a flywheel in parallel with the battery, the flywheel can greatly reduce the "cycling" of the battery and by proper integration can virtually eliminate the debilitating "whiplash" effect.

According to EPRI (Electrical Power Research Institute), a well respected organization formed originally to assist utilities, 98% of all utility power anomalies/disturbances last less than 10 seconds; about 80% last less than 2 seconds. Based on this, the flywheel with its superior reliability is an excellent substitute for batteries when used without a standby engine generator set for industrial applications where extended outages can be tolerated. For power quality applications where continuous power is critical, the flywheel system paired with a UPS and genset is the ideal solution.

Alternatively, the flywheel could operate in parallel with the batteries to "harden" them or increase their longevity. This alternative configuration allows the flywheel to absorb all short-term anomalies/disturbances before it affected the batteries. This can easily be accommodated by setting the flywheel DC bus voltage regulation set-point above the battery discharge voltage.

Utility Power Reliability is Getting Worse: National and local utility studies are signaling that electric grid reliability is in decline and that costly power outages will become more frequent. The increased use of microprocessors in a large variety of power and control equipment, processes and manufacturing equipment increase sensitivity to common electric grid power fluctuations. One or two disruption of industrial processes, for example, due to a utility outage or disturbance can cost as much as a UPS deployed to protect that process. In the case of the healthcare industry and in telecom functionality, the issue can be life-threatening. Providing a very reliable flywheel system for integration into a UPS package has been a major priority and the issue of finding a very reliable battery substitute has finally been resolved.

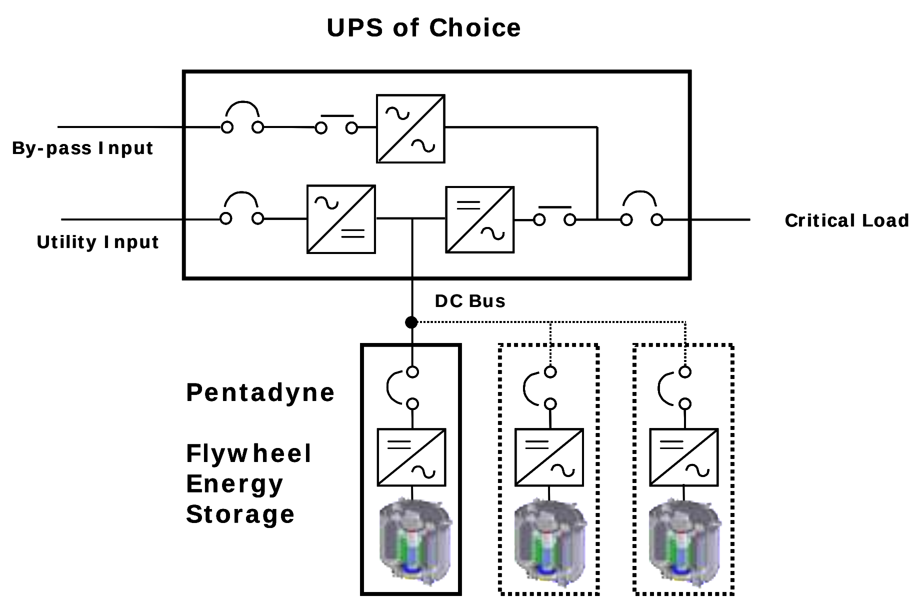

FIG 1. - SINGLE LINE UPS/FLYWHEEL

Integrating the Socomec Sicon UPS VSS+dc flywheel product with a double conversion UPS is made easy by connecting to the UPS DC bus between the rectifier and inverter. Almost all UPS systems have batteries, and those batteries are attached to the UPS DC bus. The batteries are normally kept at float or in a ready/charged state. An incoming AC grid anomaly or disturbance will affect the DC bus causing it to collapse. When the bus drops below the battery discharge voltage, the batteries discharge DC output into the DC bus, powering the UPS inverter to make AC power that supplies the load. This change over is instantaneous and transparent to the load. The impact to the batteries, however, is far from transparent. Each time they output power, the functionality, reliability and life of the battery is compromised.

Fortunately, a flywheel power storage system can mitigate this effect, vastly extending the life and reliability of a battery array, and vastly reducing the cost of its operation and maintenance. The VSS+dc flywheel system integrates with a wide range of double conversion UPS systems available on the market today. As shown in Figure 1, a flywheel can be connected as the first line of defense. The Socomec Sicon UPS VSS+dc spins in a vacuum at more than 50,000 rpm, able to instantaneously respond to a collapsing DC bus. When the bus deteriorates below the pre-set voltage level, the flywheel's synchronous reluctance electric motor generator maintains power to the DC bus. The response time of the VSS is less than 0.5 ms and initial transient voltage drop is less than 5% of nominal voltage. While the output of the flywheel motor/generator is AC, its integral bi-directional converter delivers DC to the bus. Like battery-based UPS systems, the DC then moves through the inverter to become AC for the load. Unlike battery-equipped UPS systems, this discharge cycle has no appreciable effect on the life of the VSS+dc.

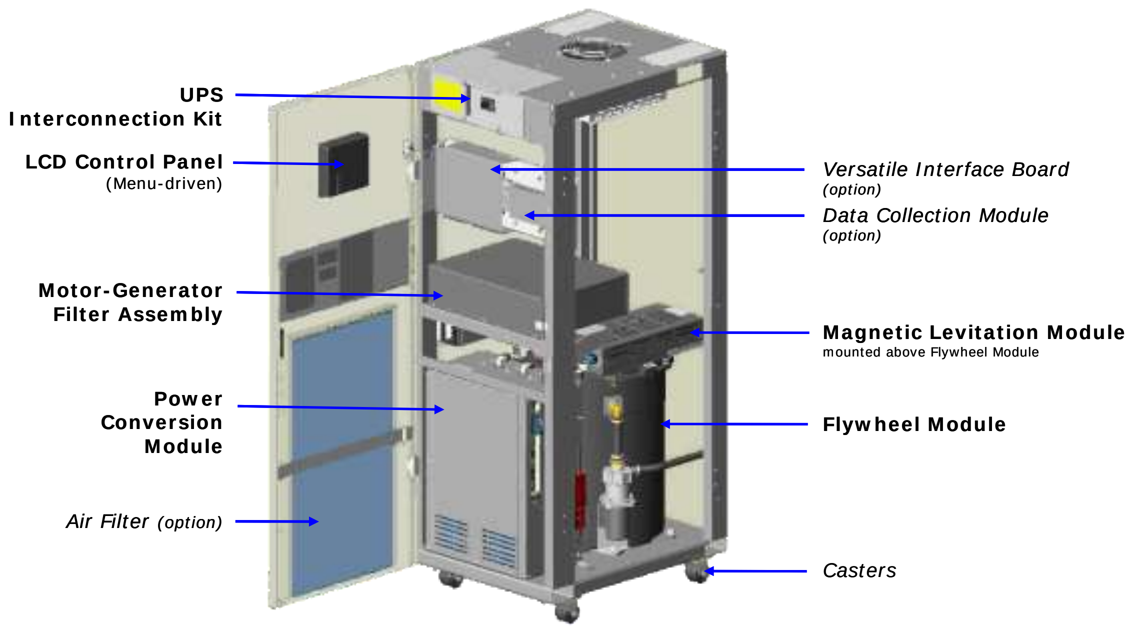

FIG. 2 - CABINET OUTLINE DRAWING

The Socomec Sicon UPS VSS+dc is a self-contained "plug-&-play" system in a cabinet similar to that used to hold batteries. Within the cabinet are four major modules: the Main Control Module, Magnetic Levitation Module, Power Conversion Module and the Flywheel Module, containing the flywheel that is hermetically sealed inside of a canister (not shown is the human/machine interface touch screen panel).

Main Control Module– This module contains the controls that operate the Magnetic Levitation Module and provides overall control of the flywheel system as well as its synchronous reluctant motor generator. This module is powered from the internal DC bus which receives its power from the UPS DC bus or the flywheel's synchronous reluctance motor generator.

Power Conversion Module (PCM) – This module contains a bi-directional power conversion system capable of sourcing or sinking power to and from the stator. When called upon for duty, it converts variable frequency, variable voltage from the stator to deliver constant voltage DC output to the UPS DC bus. When performing its rapid recharge, the PCM converts DC voltage from the UPS DC bus into variable frequency and variable voltage power to bring the synchronous reluctance rotor back up to speed.

The Magnetic Levitation Module -This module provides control of the active magnetic levitation subsystem that fully levitates the flywheel-rotor assembly: the one moving part of the Socomec Sicon UPS VSS+dc. This enables the flywheel to rotate without any physical contact, eliminating the drag inherent with bearings and achieving high reliability with zero maintenance.

Cooling fans are located at the top of the cabinet. The cabinet is compact and will fit through all normal size doors. Measuring only 63 cm wide, 83 cm deep and 180 cm high (25 x 33 x 71 in) and weighing 590 kg, the Socomec Sicon UPS flywheel's footprint is barely more than 0.5 square meters Installation requires simply rolling the unit into place via its premounted casters, then bolting it to the floor via two parallel rails attached to the cabinet frame. This prevents rotation being transferred to the casters. No pad or any special leveling is needed. The VSS+dc may be installed on concrete floors, raised floors and wooden floors.

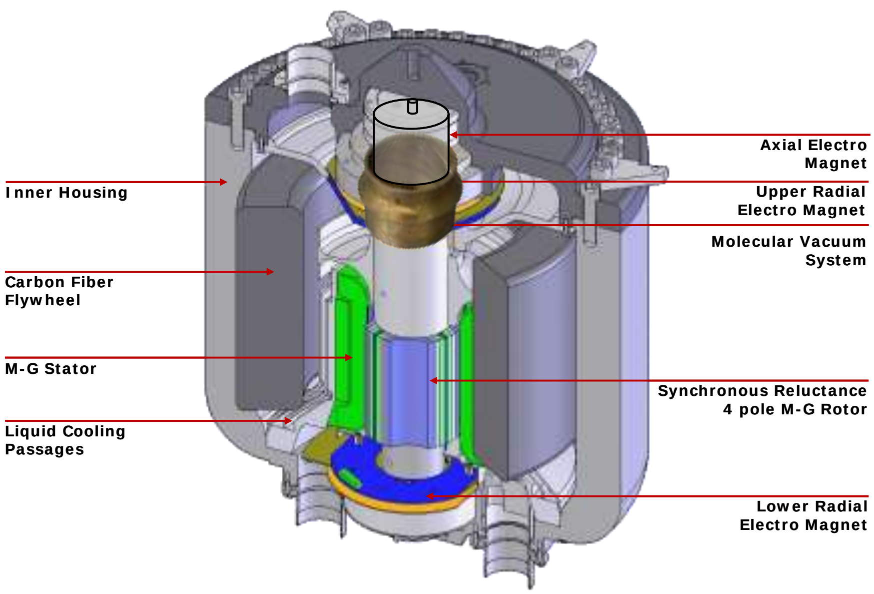

FIG. 3 - FLYWHEEL MODULE

The flywheel itself is relatively small, housed inside a canister about 60 centimeters high and 46 centimeters in diameter. This relatively small size is accomplished by spinning the magnetically levitated flywheel in a vacuum at up to 54,000 rpm (heavy steel flywheel systems operate at about 8,000 rpm). The flywheel encounters near zero aerodynamic drag inside the vacuum-sealed primary housing. Upon starting, the 52-pound flywheel/rotor shaft is immediately levitated by the upper electromagnets. The other four electromagnets (two at the top and two at the bottom) maintain precise shaft centering and perpendicularity.

Designed for safe and dependable operation: The flywheel is made of about 4.5 miles of epoxy-wetted, carbon-fiber string tightly wound, compressed and dried. Unlike a large metal flywheel weighing hundreds of pounds, the Socomec Sicon UPS flywheel will not fragment. In a rare case of the flywheel separation, it will simply unravel into strings and dust if rotated more than 33% in excess of its 54,000 rpm normal operating speed.

The flywheel is contained within two housings: an inner housing that contains the rotating group in a vacuum, and an outer housing – both made of steel. The inner housing is designed to handle the pressure load and to contain all the flywheel elements in the event of a rotating group failure. The cavity between the two housings is filled with a viscous fluid that acts as a coolant during normal operation and as a hydrodynamic buffer if the flywheel were to fail within the inner housing. The inner housing is attached to the outer housing via a break-away flange and the fluid will pick up the rotation of a failed flywheel inside the inner housing. The inner housing will rotate briefly within the cooling fluid that now acts as a hydraulic break to halt the rotation. This repeatedly, tested containment system allows the energy from a failed flywheel to be dissipated safely within a few seconds, ensuring that no significant torque is transferred to the cabinet. Safety is paramount in the design of the VSS+dc.

Electricity is generated via the synchronous reluctance 4 pole motor generator (MG). The rotor is the central shaft shown in Figure 3. The stator is partially obscured at the bottom of the shaft attached to the housing. There are 4 nodes at the bottom of the shaft that has metal strips (alternating magnetic and non-magnetic) laminated into the nodes. When energized, the MG immediately provides electricity to the bi-directional converter. Energizing the MG is similar to that of a typical “squirrel cage” motor.

In order to maintain a pristine, frictionless vacuum, the Socomec Sicon UPS VSS+dc has a molecular drag pump integrated into the upper portion of the shaft. The rotating shaft acts as the pump rotor. The pump contains helical grooves to allow escaping water vapor *molecules* (not droplets) to be pumped into the upper of two chambers. The upper chamber is at low pressure, the lower chamber is at extremely low pressure (high vacuum). As molecules are pumped into the upper absorbers, the absorbers collect and store the molecules to maintain low pressure in the lower chamber. The total system will outgas molecules to the magnitude of 5 grams throughout the system life – about 20 years. The absorbers are designed to assimilate more than 5 grams through this lifecycle, and can be dried and revived without removing the hermetic seal.

The operational rpm range of the VSS+dc is 54,000 – 25,000 rpm. This range provides 190 kW for 13 seconds. Below 25,000 rpm the VSS+dc disconnects from the UPS DC bus. Upon commissioning, the system takes less than 15 minutes to spin up to full speed when connected to most UPS systems. After discharge, the system generally returns to full charge within 2-3 minutes. In the UPS application, the UPS only provides a small amount of “charging” power and the VSS+dc makes the most of this power. The VSS+dc is designed so that it can absorb power at the same rate it discharges power. When full charging power returns, the VSS+dc can fully recharge in less than 30 seconds. The flywheel is considered “symmetrical” in that it can accept charging power at the same rate as it can discharge power.

Standby operation of the system requires only 300 watts, about $1/10^{th}$ that consumed by slow, heavy flywheel systems on the market. While the VSS+dc can pay for itself by the time of the first battery string replacement, its significantly greater energy efficiency alone can more than pay for the system over its operational life. More energy efficiency is achieved since it requires none of the air conditioning needed by UPS batteries. Its operational range is from -20°C to 50°C.

Maintenance needs of the Socomec Sicon UPS system are surprisingly low. The flywheel is designed to operate for more than 50,000 hours (six years, non-stop) before a recommended replacement of filter capacitors. Even after 15-20 years, if all systems are reading normal, there is no need to break the factory-sealed vacuum. There are no bearings to replace and nothing to lubricate. The integrated molecular drag pump never needs service or replacement. The power electronics require no adjustment at any time. There is a coolant pump that may need to be checked from time to time and coolant added as required.

The flywheel system follows the basic principals of physics and has a rather flat efficiency curve down to about 50% power. With 2700 kW-sec. of delivered energy at rated power of 190 kW (i.e. 190 kW for 13 seconds), the power vs. supply duration curve shows that at half load (95 kW) ride-though duration more than doubles to nearly 30 seconds.

FLYWHEEL VERSUS BATTERIES

Weaning users away from their love-hate relationship with batteries is no easy task. Batteries are a known commodity, have been around for many years and experienced users are usually aware of their significant shortcomings. Yet some are still reluctant to step into a more reliable solution simply because they've learned to work around some of the inherent flaws and limitations of batteries. Some end-users even refuse to test a battery string, since doing so negatively impacts performance and reliability when called upon to do real-world duty. Yet the gamble is taken and batteries continue to be installed, along with requirements that include;

1. Frequent and costly maintenance
2. Air conditioning, which introduces its own failure profile and expense
3. Expensive monitoring
4. Large footprint for high power requirements
5. Massive weight that limits placement flexibility
6. Slow recharge
7. Frequent replacement
8. Second string redundancy as insurance
9. Employee safety and OSHA requirements for toxic chemicals and explosive gases
10. Disposal issues
11. Separate battery room requirements
12. An overarching "cross-your-fingers" approach to power reliability

Replacement with a flywheel reverses the negative impact of each of the above;

1. Infrequent, low-cost maintenance
2. No temperature control or ventilation requirements
3. Built-in monitoring
4. Minimal footprint/high power density
5. Low weight enables siting flexibility anywhere in the building
6. Rapid and symmetrical recharge functionality
7. Flywheel module not replaced for at least 20 years

8. Redundancy due to poor reliability is not applicable
9. No hazmats or dangerous emissions
10. Nothing to dispose of
11. No separate room required
12. A reliable strategy for power reliability

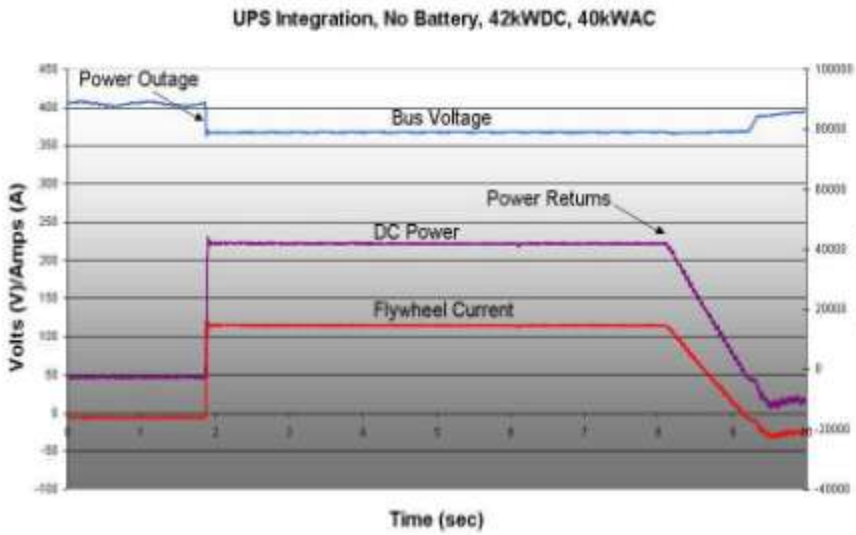

FIG. 4 - UPS INTEGRATION NO BATTERY

The primary market for the Socomec Sicon UPS VSS+dc flywheel is the same as where batteries are currently utilized. They can even be deployed as a battery-free UPS solution to provide seamless ride-through to emergency generation hand-off. Figure 4 shows a scope trace made from a UPS integrated with a flywheel and no batteries. Based upon this trace it is clear that the flywheel adapts itself to the UPS quite well and provides the required ride-through time in a similar fashion to batteries. At the moment of power outage (upper left), the flywheel responds instantly and holds the preset DC bus voltage steady until power is restored either from the utility or from the standby generator. The load is unaffected and operations continue with the action taken being utterly transparent to the load. The flywheel will spin down and release 6 to 10 seconds of kinetic energy then spin itself up and be ready for the next outage. In this instance, however, there are 10 to 14 seconds of energy still remaining in the flywheel. As such, the flywheel will cover one or more brief outages as long as they are within the remaining available time parameters. Between each discharge, the flywheel will immediately resume its rapid recharging.

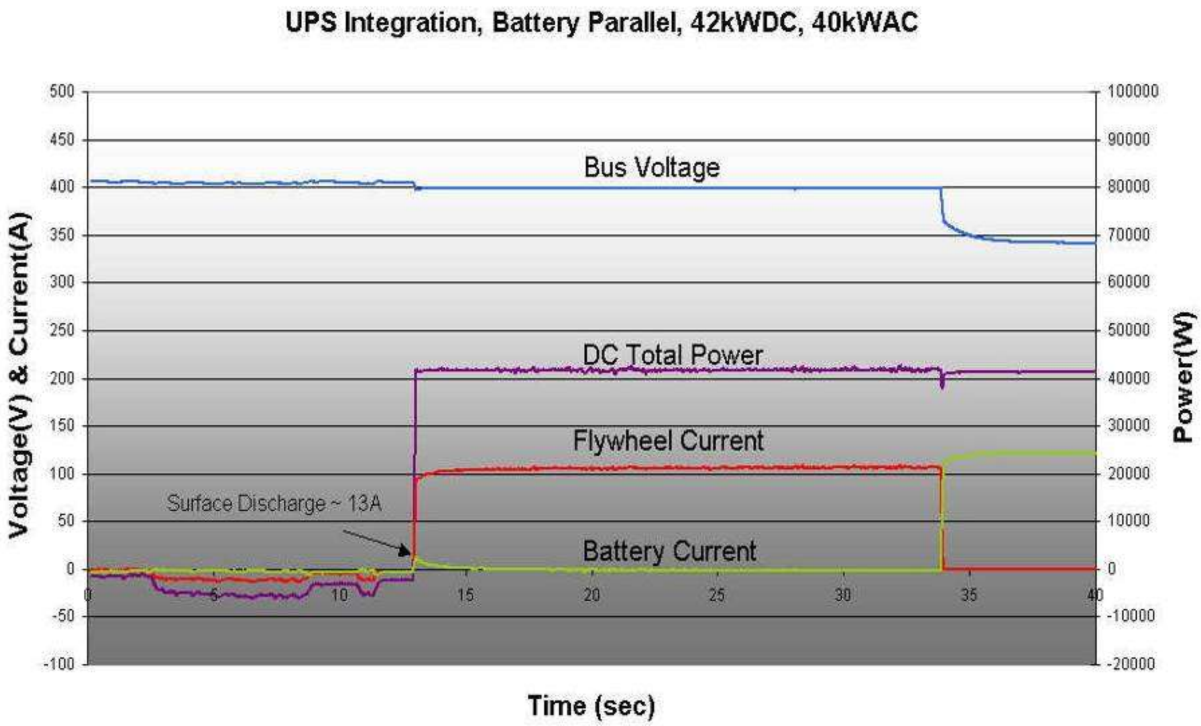

FIG. 5 - UPS INTEGRATION BATTERY IN PARALLEL

Figure 5 shows the Socomec Sicon UPS VSS+dc response when paralleled with a UPS (no standby generator). The flywheel responds based on the preset voltage (above the battery discharge voltage), and holds the bus voltage through the entire spin down to its cutoff speed, 25,000 rpm. In this instance the outage event is transparent to the batteries until the VSS+dc has exhausted its energy supply and the bus voltage drops to the battery discharge level. This will occur in about 13 seconds at the VSS+dc rated power of 190 kW (longer at lower output), as the flywheel spins down. As the flywheel is coming to the end of its energy release, the batteries come up and a “soft hand off” occurs as the batteries take over. This saves the batteries from an abrupt discharge and eliminates the damaging battery coup de fouet/whiplash effect.

The flywheel thus lengthens battery life (battery hardening) by preventing battery usage, assuming incoming power is restored before the flywheel releases all of its energy. The batteries remain at float level (stay fresh) below the preset flywheel DC voltage. The flywheel can handle a variety of DC anomalies or disturbances within its 20 second parameter to extend battery life. The exact amount of battery life extension is dependent upon the batteries themselves as they are all different. Battery life is a function of the chemical performance of the battery, which by its nature is unpredictable and hard to control.

Operating the flywheel in parallel with batteries delivers an excellent N+*x* configuration that maximizes battery longevity and reliability by using the whiplash-proof flywheel to ride through all short term outages without drawing upon the batteries. When that occurs and a standby generator set is present, some users may decide that the batteries can be disposed of completely and be replaced by the flywheel.

LIFE CYCLE COSTS

While a flywheel is slightly more expensive than batteries, it recovers its cost rapidly and soon becomes an ongoing source of power security and cost-containment. The power consumption to run a VSS+dc 190KW flywheel, 24 hours a day on a 7/24 basis is about 300 watts. Battery float charging for a 190kW system is nearly 10 times that. The first scheduled VSS+dc flywheel maintenance is 6 years or 52,560 hours and 20 years for the Flywheel Module itself. During the 20 year period there is minimal maintenance. However, during that same period the battery string would need to be replaced at least 5 times based upon an optimistic life expectancy of 4 years. In addition to periodic battery string replacement, other battery ownership costs include air conditioning costs, frequent maintenance with individual battery replacements, battery disposal, battery space costs – footprint required, OSHA compliance costs, and the most costly of all – downtime.

Paralleling flywheel units is done with two purposes in mind: redundancy or higher load. At 190kW the Socomec Sicon UPS flywheel is targeted at the high volume UPS market: 80 KVA – 200 KVA. The bulk of 3 phase UPS systems are sold in this 80 KVA – 200 KVA range. Market demand below 120 kW would come from users who have a lighter critical load but desire longer ride through.

Paralleling UPS systems is common for redundancy or load. However, because they have AC outputs via their rectifiers (AC to DC) and inverters (DC back to AC load) synchronization is necessary because of the modulated current. The AC outputs are synchronized using specialized gear. This is an extra electronic component that requires additional space and cost. Since the flywheel is a DC output system, the need for synchronization gear is eliminated. The flywheels can be easily connected to each other and to the UPS with no communication between them. This is a far simpler and less costly installation compared to synchronization cabinetry required for AC equipment.

When paralleled, each flywheel will load share for capacity or for redundancy i.e. continuing to carry the load if a flywheel in the array, for some reason, drops out). The VSS+dc flywheel systems are paralleled without the need for a master controller. Any number of units can be added in a paralleled fashion and with appropriate operating control setup, each will supply its required share of the load. This paralleling capability allows Socomec Sicon UPS to provide ride through for larger loads, even utility sub-station loads of 3 to 5 MW. The total space occupied for a 1.7 MW/2000 kVA VSS+dc array would be only 4.2 square meters. This is a reduction of at least 50% when compared to the familiar wet cell or even VRLA (Valve Regulated Lead Acid) batteries required for a 1 MVA UPS system.

The Socomec Sicon UPS VSS+dc high speed flywheel represents a breakthrough, innovative and highly reliable technology which is:

- Designed for high volume low cost production
- Highly rated safety containment
- High reliability (5 year warranty)
- Low maintenance - 20 year Flywheel Module maintenance cycle
- High impact resistance
- Free of bearings, via magnetic levitation
- Carbon fiber flywheel operating between 54,000 – 25,000 rpm
- Hermetically sealed vacuum with internal vacuum pump

- High power rating of 190kw
- Ride through of 13 seconds at rated power
- Electrical power via a synchronous reluctance motor/generator
- Easily paralleled for redundancy or for load
- Small and compact
- Plug-&-play integration with all popular double conversion UPS models
- High power density, each module needing less than 0.5 sqm floor space
- Multi market application – UPS, VSD, DG, Vehicular
- No emissions and hazmat-free, a “Green Machine”

FIG. 8 - SOCOMEC SICON UPS FLYWHEEL CABINET