FLYWHEEL ENERGY MATRIX SYSTEMS – TODAY'S TECHNOLOGY, TOMORROW'S ENERGY STORAGE SOLUTION

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INTRODUCTION

Through third party testing, field trials and commercially deployed units, flywheel energy storage manufacturers have demonstrated that discrete flywheel energy storage modules are a viable energy storage option, which is technically suited for reliable and cost-effective use in various applications. Proven power quality compensation applications range from low-power telecommunication equipment support (low-kW for hours) to high-power industrial equipment support (hundreds of kW for seconds). Using today's technology at a discrete energy storage level, the author presents a conceptual system design to achieve MW output levels - not only for seconds, but even tens of minutes. The purpose is to validate the technical feasibility of combining the best features of high-speed flywheel energy storage with proven developments in high-power electronics for energy storage and delivery.

Two system-level matrix configuration options are discussed and presented as a complete flywheel energy storage system (FESS):

- Deployable, portable equipment – a system-modular approach, where an array of flywheels and power conversion electronics are packaged in a standard-size shipping container.
- Indoor installations - where strings of flywheels compose a matrix, which is installed in a building along with the Power Conversion System (PCS).

At a building block level, the technical discussion includes a component description of the flywheel and its motor/generator drive, electrical ratings, mechanical ratings and more. At a system level, an overview of component interconnection is provided, including links to the PCS. Further, proposed system footprint and weights are illustrated for both system configuration options.

This technical proposal also includes a range of innovative ways in which this energy storage solution could be used in electric supply systems. It breaks down some of the paradigms of what the new generation of flywheels can and can't do. Flywheels should not be viewed as replacements for batteries; flywheels and batteries are complementary technologies. In hybrid solutions each energy storage technology can contribute to performance according to its own relative strength. Flywheels, for example, can extend the life of a BESS by mitigating the cyclic content. Some of the technical characteristics that distinguish high-speed flywheels are:

- High Energy Storage Density - allows for a most efficient use of equipment space and weight
- Capable of Tens of Thousands of Cycles – optimum solution for highly cyclic applications
- Capable of Fast Recharges - as much as 1:1 discharge/charge rate
- Highly Efficient Operation - vacuum enclosure, magnetic bearings contribute at achieving low loss
- Predictable Operation – flywheel speed (RPM) is a direct indication of available stored energy
- Reliable Operation - IGBT drive electronics and proven mechanical design
- Performance Not Affected by Temperature Variations - within a prescribed wide range
- Very Low Maintenance - only auxiliary equipment requires annual maintenance
- No Need to Oversize Energy Storage Equipment - energy storage capacity does not decay with age
- Sustainable Green Technology - no costs associated with hazardous chemical transport, installation and disposal
- Competitive Life Cycle Cost

An article in the journal Physica C compares energy densities for some storage methods[1]. As shown in figure 1, the energy density in a composite-rim flywheel is much higher than that of other storage methods, due to the high strength and low density of carbon fiber composites. This chart should be considered as providing only an indication of how energy storage densities compare.

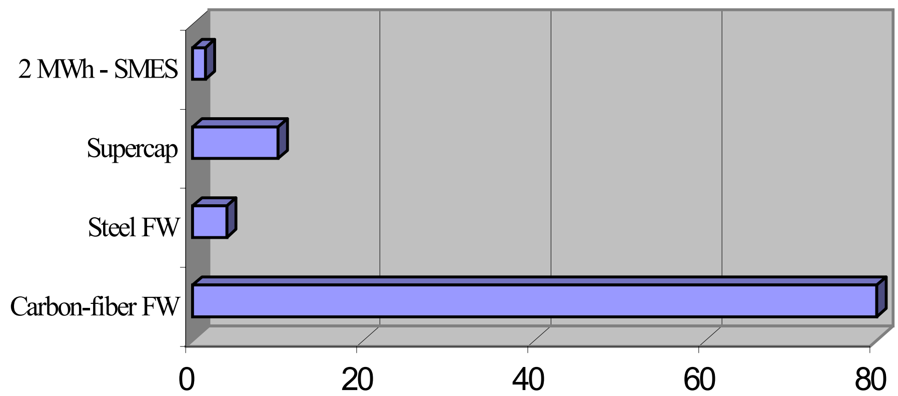


Figure 1. Stored Energy Density [Wh/kg] for Various Technologies[1]

BASIC BUILDING BLOCKS

The proposed flywheel energy matrix system is composed of two principal building blocks. The energy storage module (ESM) and the energy conversion module (ECM). Figure 2 shows their approximate size.

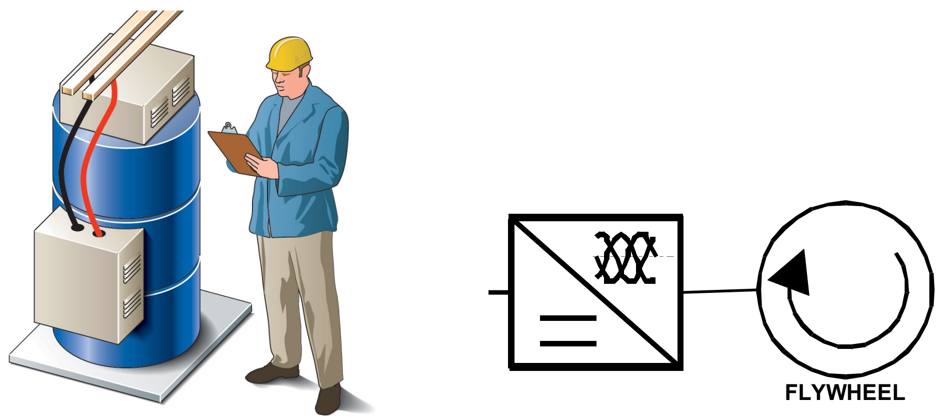


Figure 2. ECM and ESM Physical Appearance and Representative Electrical Symbols

Energy Storage Module

The energy storage module (ESM) is a kinetic-energy-based storage device that contains a flywheel rotor assembly and a motor / generator. This assembly is designed to operate at high speeds (>10,000 RPM) to achieve highest energy storage density [Wh/kg]. For high-energy storage capacity, a technical and cost-benefit analysis shows the optimum design is a high-strength, carbon/glass fiber composite rim. The motor / generator rotor is mounted on a shaft which is integral to the flywheel. An active lift magnet system supports the shaft axially. Two active magnetic bearing systems provide support at the ends of the shaft for frictionless and maintenance-free operation. The flywheel rotor assembly rotates in a low-pressure environment to reduce drag loss. The main interface between the ESM and ECM is the three-phase motor-generator connector. A section view of the flywheel and its components is shown in Figure 3. The ESM design consists of the following major components:

- Rotor assembly - a multi-component design consisting of a composite flywheel, metal hub and shaft, motor rotor, and interfaces for active lift and magnetic bearing systems.
- Motor / generator - 4-pole, permanent magnet design.
- Active lift and magnetic bearing system - commercially available lift and bearing system from leading producer of active magnetic bearing systems.
- Vacuum system - a sealed, self-contained, maintenance free, patented system to maintain low pressure for the service life of the unit.
- Vacuum housing - a steel, fully-welded, pressure vessel designed to maintain low pressure. It is the structural support for the flywheel rotor assembly and bearing system. No rubber or metal seals are used at assembly interfaces to avoid gas permeation, and to reduce cost.

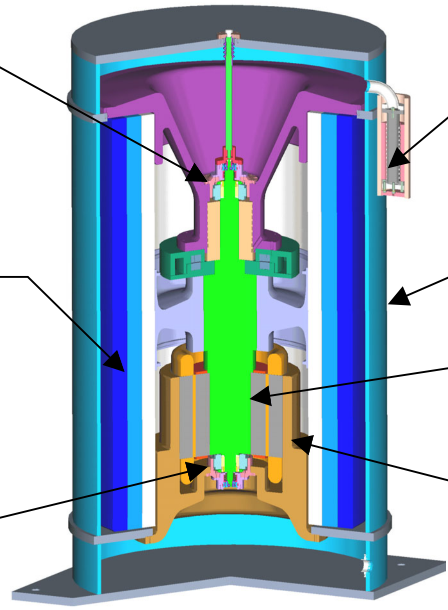


Figure 3. High-Energy, High-Speed Flywheel Assembly

Energy Conversion Module

The ECM includes a standard commercial bi-directional inverter and variable-speed motor drive. It contains IGBT power electronics controlled by a DSP/FPGA-based, high-speed digital controller. The ECM operates each individual flywheel in charge, discharge, or float modes. The ECM also manages all flywheel sensors and hosts the remote monitoring system available to the central control. This remote monitoring system allows the central controller to check system status and to assure readiness when called upon to change modes of operation. The flywheel's available energy is easily determined by knowing its speed. Once the speed is known, the available energy can be determined within 0.5%.

RATINGS, SIZE and WEIGHTS

ESM+ECM Pair

Electrical energy is available as a DC voltage source from the two output/input terminals of each pair of ECM married to a ESM. Each pair has the following size, weight and rating characteristics:

Electrical (DC Interface)
Output power: 250 kW max. continuous power
Output energy: 25 kWh @ 100 kW
Input/output voltage: 800 VDC
Standby loss: < 2% of rated power
Cyclic life: 50,000
Design life: 10 years
Response time: Instantaneous

Physical
Flywheel: 60 in H x 36 in diameter
Electronics module: 36 in H x 24 in W x 18 in D
Weight (flywheel): 3,000 lbs
Weight (electronics): 150 lbs

Environmental
Temperature range: -40 to +50 deg. C
Humidity: Up to 95% (non-condensing)
Earthquake: IBC zone 4 compliant
Installation: Above ground, on concrete pad or trailer frame

Flywheel energy matrix systems are sized based on a particular application. Energy storage capacity does not decay with aging; thus, it is not necessary to over size this parameter during the planning and design stage. Fundamentally, each ESM-ECM pair is capable of supplying/absorbing 25 kWh (90 MJ) of energy. Figure 4 shows the approximate hold-up time as a function of power [kW] for the discharge operation. Table 1 lays-out the number of ESM-ECM pairs required to support various loads for different periods of time.

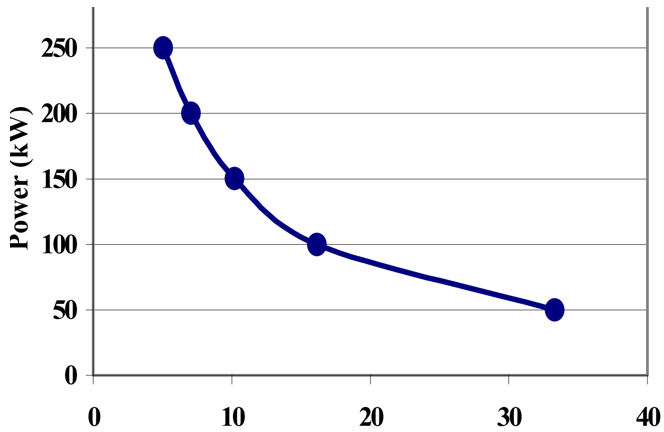


Figure 4. ESM+ECM Delivered Power [Minutes]

Table 1. Approx FESS Support Time at Various Loads

Support Time	5 Min	10 Min	30 Min
# of ESM+ECM	Total Load [MW]		
1	0.25	0.15	0.05
2	0.5	0.3	0.1
4	1	0.6	0.2
8	2	1.2	0.4
10	**2.5**	**1.5**	**0.5**
30	7.5	4.5	1.5
50	12.5	7.5	2.5
54	**13.5**	**8.1**	**2.7**
100	25	15	5

Deployable, Modular Matrix

As one option, we propose a system-modular approach where an array of ESM and ECM pairs are packaged in a standard-size shipping container for ease of shipping and installation. This mobile container would interface with a user's PCS at one pair of DC input/output terminals. Figure 5, shows a container enclosing ten ESM-ECM pairs.

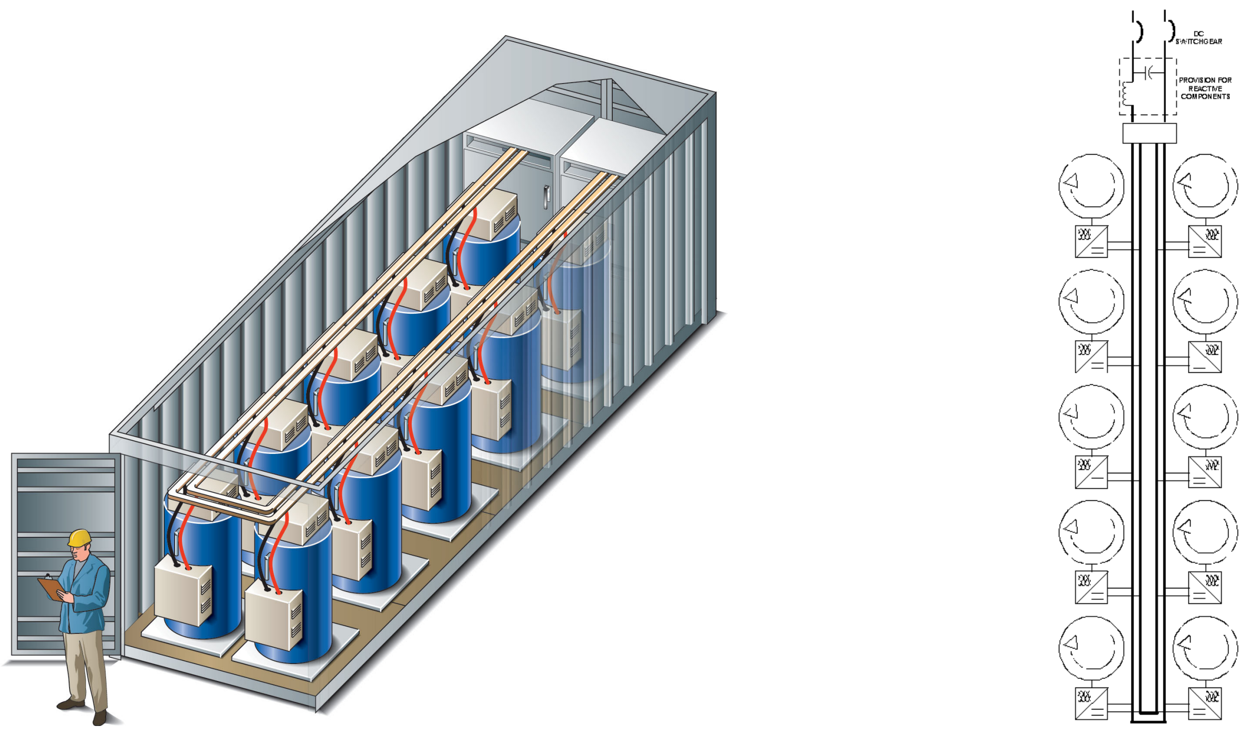


Figure 5. Modular Shipping Container and Electrical Schematic

As a module, each container offers the following size, weight and rating characteristics:

<u>Electrical (DC Interface)</u>
Output power: 2.5 MW max. continuous power
Output energy: 250 kWh @ 1.0 MW
Input/output voltage: 800 VDC
Standby loss: < 2% of rated power
Cyclic life: 50,000
Design life: 10 years
Response time: Instantaneous

<u>Physical</u>
Size: 30 L x 8 W x 8.5 H [ft]
Weight: 70,000 [lbs]

Building Enclosed Matrix

Strings of flywheels compose the matrix, which are installed in a building along with the PCS. Each string of flywheels is attached to a DC bus that has the same elements found in a modular trailer architecture: DC switchgear and reactive components (capacitors/inductors). The flexibility afforded by the modularity of each ESM+ECM building block allows for the customization of an optimum configuration given performance, size, weight and cost targets.

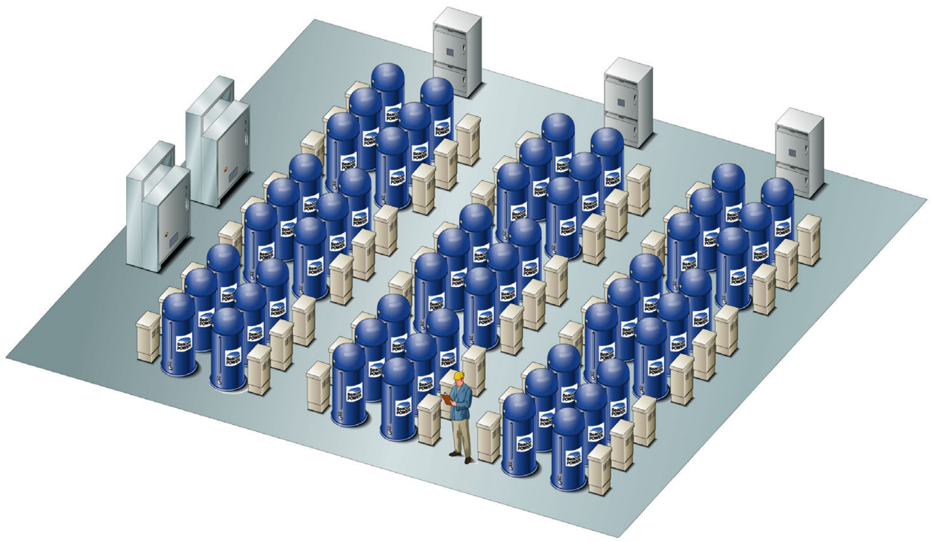


Figure 6. Building Enclosed FW Matrix

For example, the energy storage components in figure 6 have the following total size, weight and rating characteristics:

Electrical (DC Interface)
Output power: 13.5 MW max. continuous power
Output energy: 1.35 MWh @ 13.5 MW

Physical
Size: 60 [ft] L x 42 [ft] W = 2520 [ft^2]
Weight: 180,000 [lbs]

The DC output of each string is linked to a PCS module for DC/AC conversion. The AC terminals of the PCS are connected to step-up transformer(s) for interfacing with the end-user's three-phase AC bus at a kV level.

BASIC OPERATION

Regardless of size, the output of a FESS will be in the form of a pair of DC terminals. Typically, the end-user's bus interface is a three-phase AC bus. Thus, a PCS is required between these to convert DC to AC. In cases where the AC interface is at a kV voltage range, the PCS will include a voltage step-up transformer. The PCS interfaces with the AC bus in either of two ways: in line with each phase (series connection), or bridging across the phases (shunt connection).

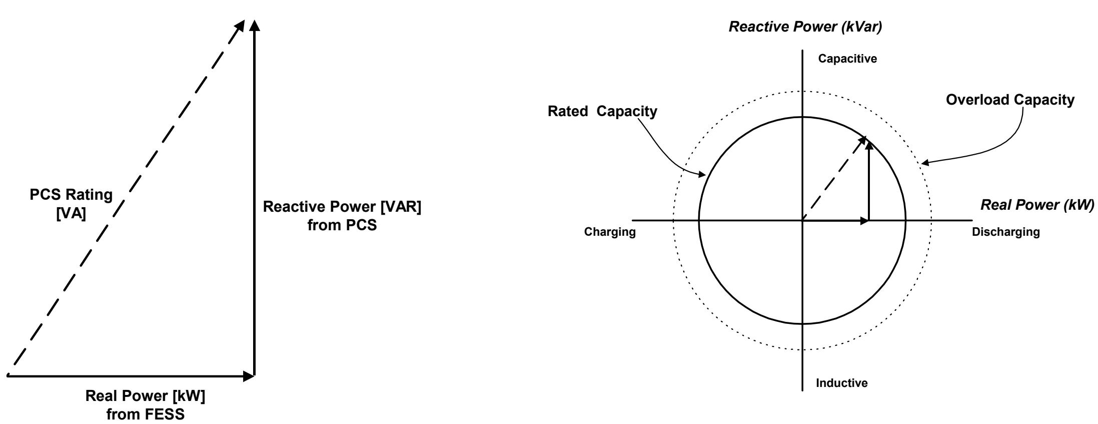


Figure 7. Real/Reactive Power Vectors and Vector Space[2]

The FESS and PCS compliment each other by contributing with different complex-power components. The FESS supplies or absorbs real power [W]. Conversely, the PCS injects or absorbs reactive power [VAR]. Although the FESS circuitry does play a role in reactive power and the PCS in real power; these magnitudes are relatively small. Depending on the interface configuration at the AC bus, the FESS+PCS combination can effectively operate in all four quadrants of the real/reactive power space[2] illustrated in figure 7. The sum of both, the real and reactive components, is bounded by the complex power capacity of the PCS, and measured in volt-amperes [VA]. In other words, the FESS+PCS combination will allow operation at any point inside the circle limited only by the kVA rating of the energy conversion system.

APPLICATIONS AT DISTRIBUTION VOLTAGE LEVEL

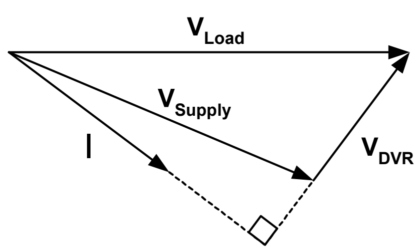
At distribution voltages between 4.16 to 69 kV, power quality is being addressed by incorporating “Custom Power” devices into the three-phase bus. The term “Custom Power Device” is used to describe power quality compensation systems designed to mitigate or eliminate common disturbances at a distribution voltage level. Common power quality issues at this voltage level include: voltage sag, voltage interruption, voltage surge, voltage imbalance, voltage flicker and harmonic distortion. A FESS offers great advantages to three commonly used devices: Dynamic Voltage Restorer (DVR), the Distribution STATCOM (DSTATCOM), and a distribution voltage level UPS which incorporates solid-state switches into a DSTATCOM configuration to allow for UPS operation supported by energy storage.

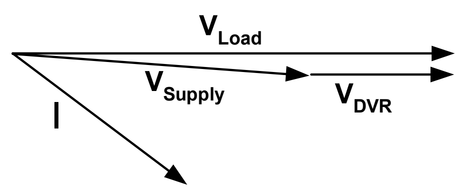
Table 2. Suggested Applications at Distribution Voltage Levels

	Discharge Time [minutes]	Energy Capacity [kWh]	Custom Power Device	Number of FESS Modular Trailers [based on kWh reqrd]
Peak Shaving	5 - 20	1000 – 3000	DSTATCOM	4 - 12
Power Quality	1/60 – 1	10 – 2000	DVR, DSTATCOM, D-UPS	1/10- 20

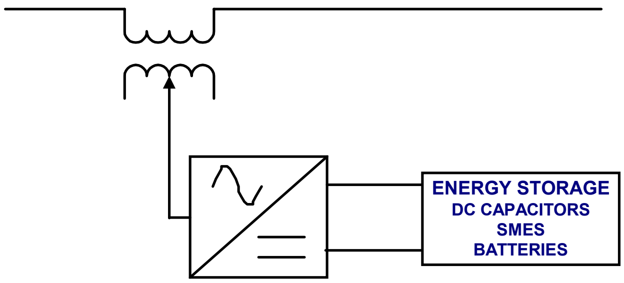
Dynamic Voltage Restorer (DVR)

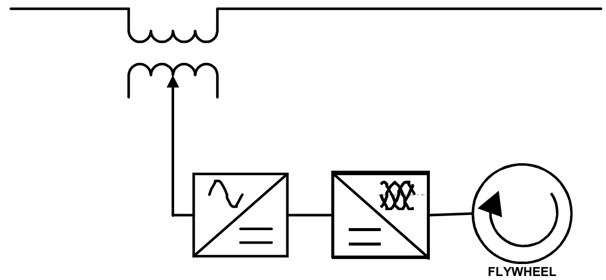
The main function of a DVR is to reduce or eliminate voltage sags or surges in the power flow path leading to a sensitive load. The DVR interfaces in series with each of three phases at a distribution bus, typically through three single-phase transformers. A voltage source converter (VSC) is used to inject voltages at the terminals of these transformers. The basic operating principle is that the converter adjusts the magnitude and angle of the injected voltages in relation to the currents flowing in the bus. The net effect is an additive or subtractive voltage applied to the sagging or surging supply bus voltage. Various approaches have been employed to avoid using significant energy storage. One relies on reactive power components where the intervention of the DVR is limited to supplying a voltage at a 90 degree phase angle with the current flowing in the circuit. As shown in figure 8a, this approach is limited by the size of the reactive components required to compensate for deeper sags[3]. Other topologies allow for drawing active power from the healthy phases and injecting it into the phase not affected by the disturbance. This approach limits the efficacy of the DVR to correct for disturbances involving only one or two phases at most. In many applications, energy storage supplying active (real) power is required. Figures 9a illustrates a topology commonly used. It employs DC capacitors, SMES or batteries as sources of real power. While conventional DC capacitors are an excellent stiff voltage source, the voltage compensation time is limited by their relatively low energy storage capacity. SMES has a similar limitation, in addition to the fact that the magnet/coil arrangement is a better match with a current source converter (CSC). Moreover, chemical battery life may be severely affected by the high-cyclic demand of many applications. We submit that a viable solution is to store and obtain real power from a FESS as depicted in figure 9b. Here, the flywheel’s inverter interface offers a stiff voltage source supported by stored kinetic energy for deeper and longer duration sags. As a result, voltage restoration will effectively be sustained as shown in figure 8b.





Voltage Restoration[3]: Figure 8a. With Reactive Power Only **Figure 8b. With Active & Reactive Power**

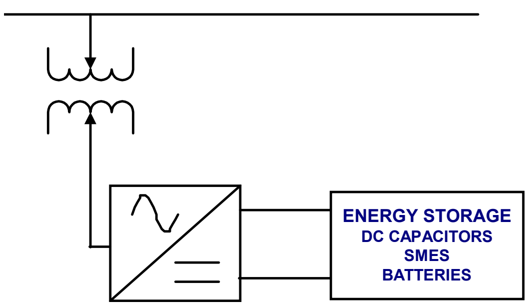


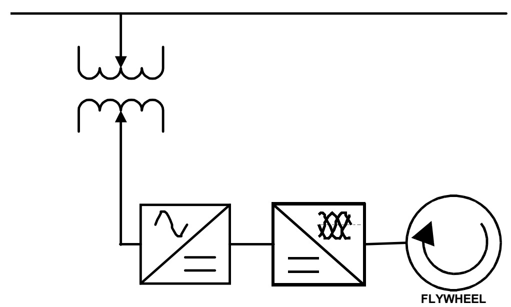


DVR Supported by: Figure 9a. Conventional Storage **Figure 9b. Flywheel Energy Storage**

Distribution Static Compensator (DSTATCOM)

Figure 10a shows the most basic configuration of the DSTATCOM topology as it interfaces with the distribution bus. Conversely to the DVR, the DSTATCOM's terminals bridge the individual phases with one another. In other words, it is shunt-connected to the bus via a tie reactance. A voltage source converter (VSC) is used to inject current through the windings of this reactance. The basic operating principle is that the VSC controls the amplitude and phase angle of the voltage source, with respect to the line terminal voltage, resulting in a controlled current flow through the tie reactance between DSTATCOM and the distribution lines. Consequently, the DSTATCOM controls the terminal voltage at the distribution bus interface. Depending on the sophistication of the electronics, the net effect is instantaneous voltage regulation, power factor correction and harmonics mitigation[6]. Likewise, we propose that an optimum solution is to store and obtain real power from a FESS through a topology illustrated in figure 10b. The flywheel's inverter interface offers a stiff voltage source supported by stored kinetic energy for deeper and longer duration disturbances requiring a real power source.

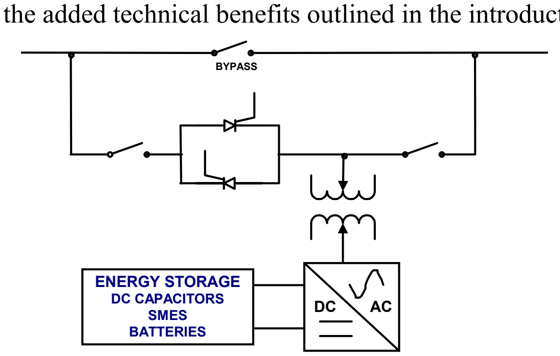


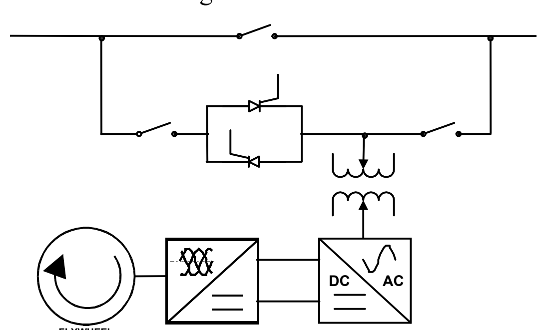


DSTATCOM Supported by: Figure 10a. Conventional Storage **Figure 10b. Flywheel Energy Storage**

Uninterruptible Power Supply based on DSTATCOM

To achieve uninterruptible power operation, DSTATCOM and the sensitive load are disconnected from the source[6]. Figure 11a shows an actual configuration, which is commercially available today at distribution voltage levels[7]. The UPS function is triggered at the sensing of a voltage disturbance beyond a pre-programmed limit. The controls signal the static switch to open, and within ¼ of a cycle the static switch isolates the sensitive load and the stored energy supply from the main supply. Energy flows freely from storage to sensitive load. Our view is that a FESS would provide tens of minutes of backup power with the added technical benefits outlined in the introduction of this document. See figure 11b.





D-UPS Supported by Figure 11a. Conventional Storage **Figure 11b. Flywheel Energy Storage**

Moreover, a FESS can also contribute uniquely to UPS' installed on the secondary side of the step-down distribution transformer. For years now, manufacturers have deployed flywheel based UPS' for interfacing at a three-phase, 480 V bus. Most, if not all, offer back-up support for only a few seconds. We propose the use of the trailer-based flywheel matrix to support, for example, a 500 kW load for up to 30 minutes or a 1 MW load for approximately 15 minutes. To illustrate the point, figure 12 shows a proven design now being used at 480 V buses in conjunction with high-speed flywheels. There are two reasons for the absence of a transformer at the three-phase bus interface: no need to step-up the voltage to a distribution kV level, and the implementation of a unique design involving a fourth independent-pair of IGBTs to accommodate seamless interfacing with 4-wire systems. From a technical standpoint, this system has offered power quality compensation that includes load harmonic compensation, load power factor compensation, flicker reduction, load unbalance correction, power sags and swells mitigation, and support for ride-through events. A matrix of high-speed flywheels offers a unique solution for ride-through events by providing instantaneous real power for longer duration.

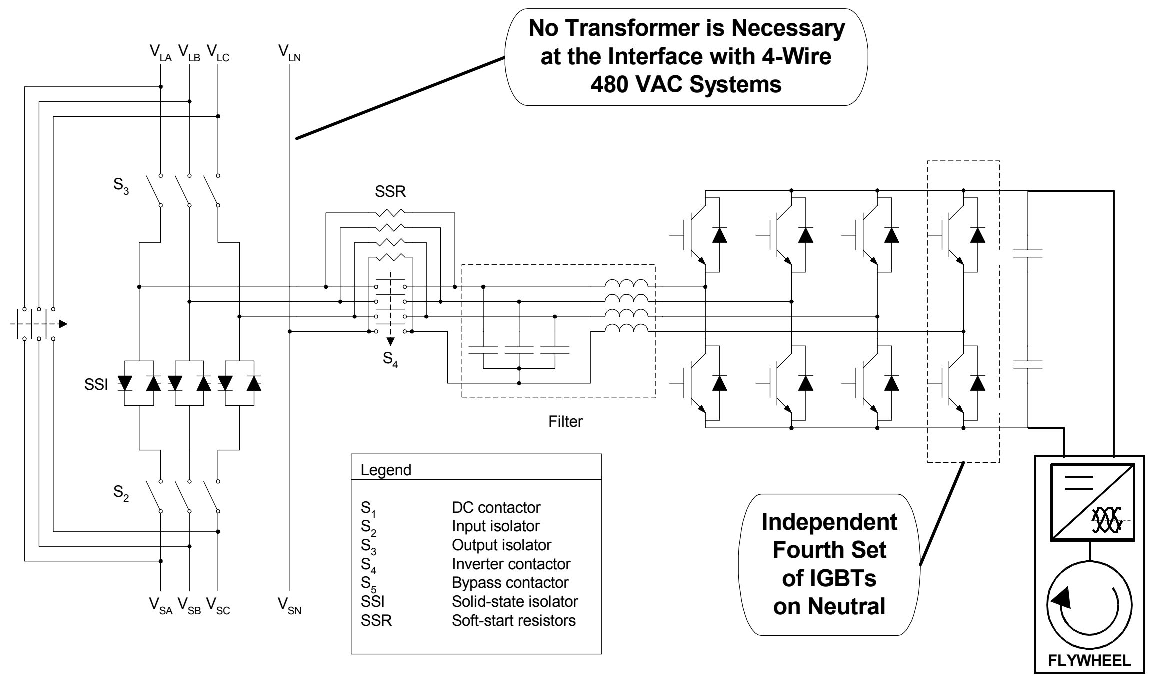


Figure 12. Flywheel Supported Power Quality Compensator at 480 Volts

APPLICATIONS AT TRANSMISSION VOLTAGE LEVEL

FACTS Devices

The FESS has great potential for effectively supporting Flexible Alternating Current Transmission System (FACTS) devices; in particular, those devices employing power converters. Traditionally, a voltage source converter in combination with a capacitor (dc storage element) is used to supply real power into a transmission line. A more contemporary approach is to use super-conducting magnetic energy storage (SMES). Both of these storage methods have limited storage capability that bound the functionality of the FACTS device to supply real power for only a few seconds. The DC output of a flywheel's motor/generator drive qualifies as an adequate alternative to these two storage technologies since it also offers a stiff voltage source. Additionally, the DC output is backed-up by the kinetic energy storage of a FESS that would enable the FACTS device to provide real-power support for tens of minutes.

There are two possibilities for a FACTS device converter topology[3]: a voltage source converter (VSC) or a current source converter (CSC). The voltage source converter needs a stiff voltage; whereas the CSC requires a stiff direct current source [3]. There is an intrinsic compatibility between a VSC and flywheel energy storage because a FESS DC output behaves as a capacitor. Depending on the interface between the VSC and the transmission line, a FESS supported FACTS device can effectively operate in all four quadrants of the real/reactive power space illustrated in figure 7; for tens of minutes. The FESS in particular, would supply or absorb real power for damping system frequency deviations in isolated electrical networks – see horizontal component in figure 7. The FACTS device, as a power conversion system (PCS), would help regulate system voltage by injecting or absorbing reactive power – see vertical component in figure 7.

Moreover, the FESS-FACTS combination would allow operation at any point inside the circle bounded only by the kVA rating of the energy conversion system. The expected result is an outstanding system performance due to their complementary functions. Studies have shown that “the FACTS/ESS (energy storage system) combination exhibits increased flexibility over the traditional FACTS with improved damping capabilities due to the additional degree of control freedom provided by energy storage systems”[4]. Figure 14 graphically illustrates this premise. We submit that, among various choices of energy storage, FESS offer an optimum solution to complement the role to FACTS and custom power devices.

Table 3. Suggested Applications at Transmission Voltage Levels

	Discharge Time[min]	Storage Capacity [kWh]	FACTS Device	# of FESS Trailers [based on kWh reqrd]
		TRANSMISSION		
Peak Shaving	5 - 30	>5000	STATCOM	>20
Power Quality	1/60 – 5/60	>20	STATCOM, SSSC, UPFC	> 1/10
		UTILITY POWER FLOW MANAGEMENT		
Area Control	1/6 – 1.7	>100	STATCOM, UPFC	>½
Frequency Control	1/6 – 1.7	>100	STATCOM, UPFC	>½
Fast Spinning Reserve	5 - 30	>10,000	STATCOM	>40

The three most widely used FACTS devices typically employ voltage source converters[3]:

- The static synchronous compensator (STATCOM) creates a shunt voltage source, of the desired magnitude and polarity, across the three-phase lines. This is the same fundamental arrangement as the DSTATCOM, as shown in Figure 10b, however at a transmission voltage level. The net effect is current injection into the bus for voltage control.
- The static synchronous series compensator (SSSC) acts as an additive or subtractive voltage source, of the desired magnitude, in series with each three-phase line. The basic topology as the DVR in figure 9b. The net effect is real and reactive power flow control.
- The unified power flow controller (UPFC) is a combination of the former two topologies. It circulates energy between series and shunt connected sources, as shown in Figure 13.

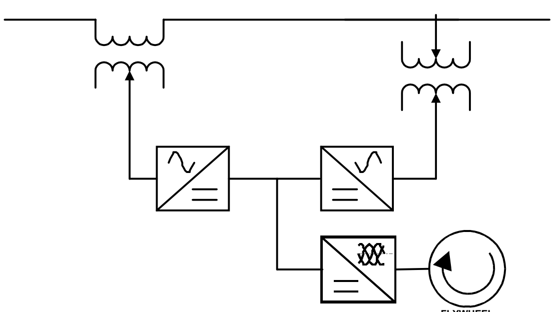


Figure 13. Unified Power Flow Controller (UPFC)

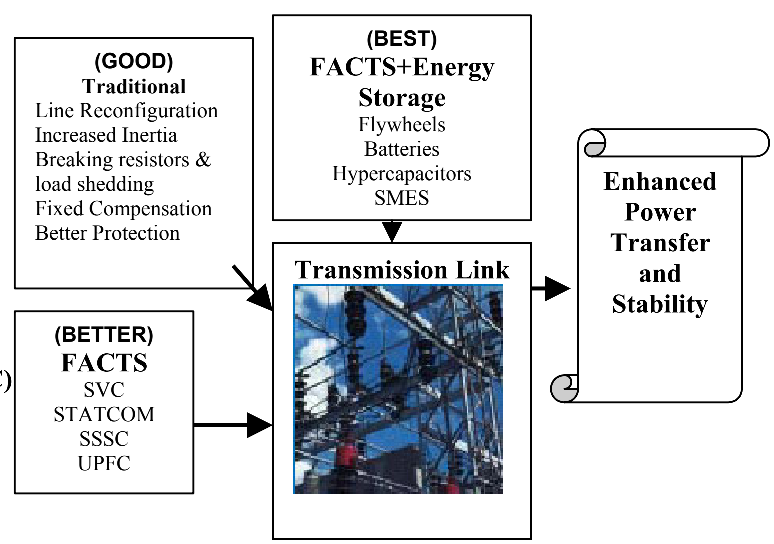


Figure 14. The Ultimate Solution: FACTS+ESS [4]

Hybrid Energy Storage Systems

According to an EPRI PQNA power quality study, FESS installed in parallel with lead-acid battery storage systems isolate the chemical batteries from 96% of all power events at an "average" location in the United States[5]. Flywheel manufacturers have gathered and produced data on how a FESS can add years to the life of UPS batteries and increase the overall reliability of UPS systems in high-power industrial equipment applications (hundreds of kW for seconds); as well as low-power telecommunication equipment applications (low-kW for hours). Simplifying, these configurations involve connecting the FESS' and the battery's DC interfaces together, and setting the FESS' charge/discharge thresholds to accommodate various DC bus voltage settings so that it will always be above the open circuit voltage of the chemical battery stack[5].

We propose a similar approach to achieve an optimum solution for various applications listed throughout this document; especially, in highly cyclic applications where there is a large number of "shallow" discharges and a smaller number of deep discharges. In such a scenario, the FESS would supply instantaneous power during more frequent discharge/charge cycles; leaving the deeper less frequent discharge/charge cycles to the chemical batteries.

Summary

At a discrete level, flywheel energy storage modules offer unique performance characteristics suitable for many applications. It is technically feasible to combine the best features of high-speed flywheel energy storage with proven developments in high-power electronics. Two system-level matrix configurations are technically achievable: a deployable, portable matrix configuration which is an array of flywheels and power conversion electronics packaged in a standard-size shipping container, and a building enclosed indoor flywheel-matrix installation where higher energy output and storage can be achieved as a whole.

There is a wide range of applications for the proposed FESS configurations at distribution as well as transmission voltage levels. All would benefit from the outstanding performance that discrete FESS modules offer. Finally, flywheels and batteries are complementary technologies. In hybrid solutions each energy storage technology can contribute to performance according to its own relative strength. For example, flywheels can extend the life of a BESS by reducing the cyclic content.

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