# Evaluation of the Urenco PQ Flywheel Energy Storage System for Enhancing the Ride-Through Performance of an Adjustable-Speed Drive

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# ABSTRACT

Power electronic technologies have revolutionized the process industry. However, power quality problems, such as voltage sags and momentary interruptions, threaten the continuity of automated processes that are endowed with power electronics. Adjustable-speed drives, programmable logic controllers, and microprocessor-based controls enable wonderful efficiency but are particularly susceptible to electrical disturbances. This report discusses the application of a promising energy-storage technology that enables sensitive power electronic technologies to ride through voltage sags and momentary interruptions. EPRI tested a 100-kW flywheel energy-storage system (FESS) applied to an adjustable-speed drive to determine its ability to hold up the drive during voltage interruptions. The FESS was connected to a three-phase, 460-V, 200-HP AC drive. During sustained and repeated voltage interruptions, the FESS was able to maintain the drive's DC-link voltage for about 90 seconds. Compared to conventional energy storage, such as batteries, capacitors, or low-speed flywheels, a FESS offers a wide operating temperature range, high cycling capability, guaranteed energy content, long design life, no maintenance, and low losses. However, because its power supply requires AC power, it is susceptible to the same voltage sags and interruptions that it is designed to mitigate. Therefore, a small UPS or other power-conditioning device would be required to protect its internal power supply. Also, because the flywheel can come to rest and be restarted a limited number of times, the life-expectancy of the pin bearing could be a concern if the FESS were to shutdown frequently.

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# 1

# BACKGROUND

In today's competitive markets, companies worldwide are searching for ways to increase their competitive advantage. Increasing productivity, while increasing or maintaining product quality is one way to accomplish this goal. To meet demand, industrial and commercial companies have begun investing in power electronic technologies. Power supplies, adjustable-speed drives, high-power semiconductors, and microprocessors are some of the most significant electronics and power electronics technologies that have revolutionized production of many industrial and consumer products.

Power quality and system compatibility are major concerns for electric utilities and their customers, particularly for their largest customers' industrial and commercial facilities. Power quality is a relative term to describe the state of electric power and can have different meanings depending on one's perspective. Utilities and equipment manufacturers often have different perspectives, but there is a common denominator for both – the effect on the end-user.

Voltage sags and interruptions are the most common electromagnetic phenomena affecting electric power systems. Today, most electronics-based equipment is affected in some way by power supply variations, in particular, voltage sags and interruptions. A multitude of problems can occur when sags impact electronic equipment – computers crash, production lines stop, and lights go out – all of which can spell disaster. Industrial and commercial facilities are usually hardest hit. Many companies produce materials with low profit margins. As a result, repeated trips can translate into significant monetary losses which can often lead to friction between the customer and the utility.

Utilities want to maintain customer loyalty and satisfaction. Therefore, responding to the needs of their customers becomes increasingly important for their future in a deregulated environment. As profit margins fall and competition increases, utilities will find themselves more and more in the business of resolving problems related to electrical disturbances and system compatibility issues.

In the many industries that require the continuous operation of process equipment, any interruption of power can wreck a company's bottom line. Idle time and lost production plus scrapping partially finished products, cleaning up, and re-starting the process are unexpected, unwelcome, but perhaps preventable expenses.

Over the years, ASD manufacturers have reduced the susceptibility of their products to voltage variations through design enhancements, including software strategies that permit ASDs to perform sophisticated "flying restart" and "kinetic buffering" motor-control techniques without creating "hard-trip" situations. These improved performance features give ASDs the ability to survive momentary interruptions and resume operation when line voltage returns.

However, some processes require precise speed and torque regulation at all times to maintain first-quality product. Even with sophisticated ride-through strategies for ASDs, deviations in system speed and motor torque will occur during momentary interruptions. In addition, no ASD of any size has the energy-storage capacity to enable it to operate at rated output torque for more than a few milliseconds during a voltage interruption. Therefore, energy-storage ride-through technologies must be applied to support ASDs in those systems with more stringent speed and torque-regulation requirements.

A number of energy-storage technologies are being used, adapted, and developed for use in power quality applications, which include superconducting magnetic energy storage (SMES), batteries, supercapacitors, written-pole M-G sets, fuel cells, and flywheel energy storage systems (FESSs). The Electric Power Research Institute (EPRI) has responded to the needs of its member utilities by taking the initiative to sponsor research into Power Quality and Power Quality applications of energy-storage technologies for enhancing the undervoltage protection of process equipment. Laboratory testing of emerging technologies and technical reports, such as this one, convey the latest information about the latest technologies and how they may be applied to improve customer satisfaction, increase customer retention, create added-value services, increase opportunities for building a market share and create a competitive advantage, and improve overall electric power supply reliability. This EPRI technical progress report highlights the integration and testing of a high-speed FESS with a voltage-source inverter AC drive. The purpose of the project was to demonstrate the feasibility of such an integration and to document the performance characteristics of a commercially available FESS.

EPRI purchased a 100-kW FESS system from Urenco (Capenhurst) Limited of Chesire, England. The FESS was installed at the EPRI PEAC laboratory in Knoxville, TN by Urenco engineers in August 2000. Figure 1-1 is a photograph of the FESS system as the device is currently installed at the EPRI PEAC laboratory.

(a) (b)

**Figure 1-1**
**Urenco PQ Flywheel Energy Storage System (FESS) at the EPRI PEAC Laboratory**

Figure 1-1a shows the electronics cabinet, the control power transformer, and the refrigeration and vacuum units. Figure 1-1b shows the actual flywheel unit installed in the EPRI PEAC DR Park.

# 2

# THE PRINCIPLES OF OPERATION

The Urenco flywheel has a rotor that is manufactured from a composite carbon and glass fiber material. Permanent magnet powder (neodymium iron boron, or NdFeB) is wound into the composite material on the center bore of the rotor. The rotor is magnetized with two distinct patterns. At one end, the rotor is magnetized circumferentially to create the poles for one-half of a magnetic bearing. The rest of the rotor is magnetized axially to create poles for the permanent magnet AC machine (motor/generator).

A steel shaft down the center of the flywheel supports the other half of the magnetic bearing and stator of the AC machine. The stator is comprised of conventional three-phase wye-(star-) connected windings with specific design efforts to minimize losses in the machine through hysteresis, eddy-current, and stator resistance. A maintenance-free, high-speed, low-loss oil pin bearing supports the mass of the flywheel. To eliminate rotor windage losses, the flywheel operates in a vacuum. All of the flywheel's mechanical components are housed inside a steel containment enclosure. Figure 2-1 shows a mechanical diagram of the Urenco PQ FESS.

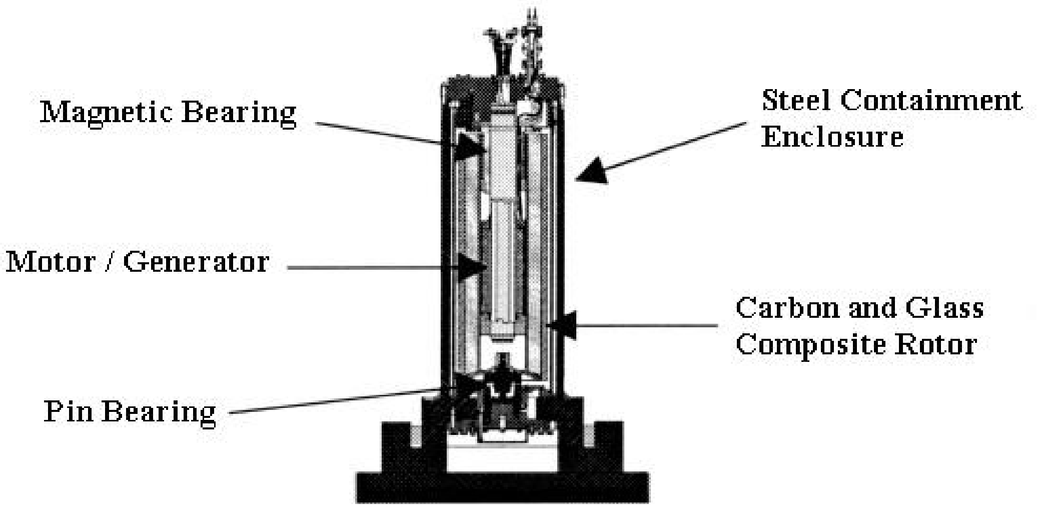

**Figure 2-1**
**Mechanical Diagram of the Urenco PQ FESS**

Electrically, the Urenco PQ FESS has a separate enclosure that houses the electronics. The microprocessor and its supporting electronics control and operate the flywheel. Figure 2-2 shows an electrical diagram of the Urenco PQ FESS.

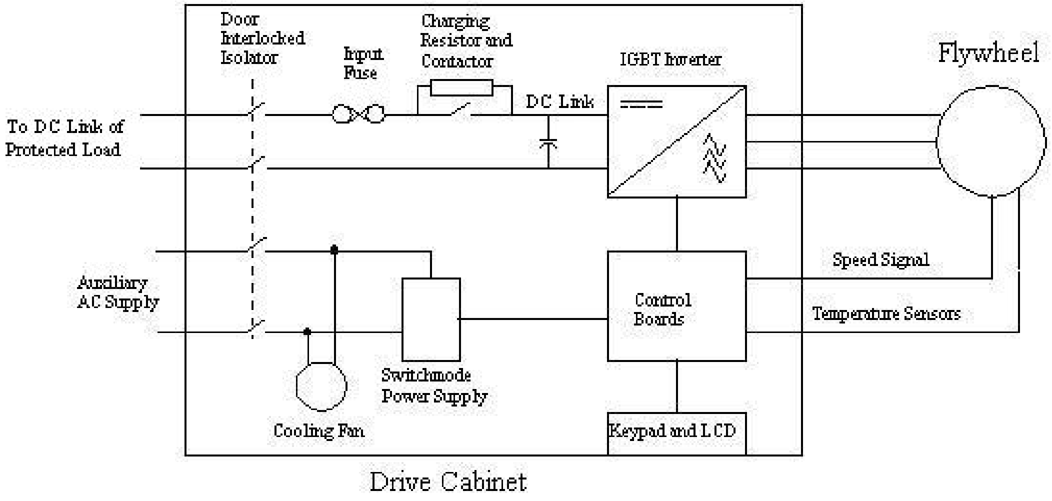

**Figure 2-2**
**Electrical Diagram of the Urenco PQ FESS**

The flywheel's DC link is paralleled with the DC link of the protected load. During standby operation, the flywheel coasts. When the flywheel speed decreases to approximately 98% of nominal, the inverter is used to return the speed to the nominal 36,000 rpm through motoring action. During acceleration the flywheel draws power from the utility power supply through the DC link of the protected load. When the flywheel speed reaches 36,000 rpm, the inverter shuts off and the flywheel coasts. This cycle repeats continuously during standby operation.

During ride-through, the flywheel effectively maintains the protected load's DC link at the DC voltage setpoint required to maintain operation of the protected load. When the protected load's DC bus falls to the DC voltage setpoint, the flywheel controls adjust the inverter frequency to regenerate power from the rotating energy stored in the flywheel's rotor to the DC link of the protected load. The flywheel will continue this operation as long as the protected load's DC link is below the low-voltage setpoint or until the flywheel can no longer supply sufficient energy to regulate the DC link voltage. Equation 2-1 describes the relationship between the speed, the mass moment of inertia, and the energy stored in the flywheel rotor.

$$E = \frac{1}{2} J\omega^2 \tag{2-1}$$

where $E$ is the energy stored in the flywheel rotor, $J$ is the mass moment of inertia of the flywheel rotor, and $\omega$ is the rotational speed of the flywheel.

At the end of the ride-through period when the protected load's DC link voltage has recovered, the flywheel begins to reaccelerate. The flywheel again draws power from the utility power supply through the DC link of the protected load. Once the flywheel reaches nominal operating speed, it re-enters the standby phase of operation. According to Urenco, the minimum reacceleration time from a complete discharge is 30 seconds. The Urenco 100-kW PQ FESS ratings are listed in Tables 2-1 and 2-2.

**Table 2-1**
**Urenco 100-kW PQ FESS Ratings**

| Characteristic | Rating |
|---|---|
| *Output Power* | 100 kW |
| *Output Voltage* | Application specific constant value between 600 and 750 Vdc. |
| *Discharging Time at Maximum Power* | 30 seconds |
| *Steady-State Losses* | Approximately 1.2 kW |
| *Charging/Discharging Efficiency* | > 90% for one operation |
| *Operating Speed* | 36,000 rpm |
| *Temperature Range* | -20°C to +40°C |
| *Design Life* | Minimum 20 years |
| *Number of Full Discharges* | Minimum 10 million |
| *Maintenance* | None for rotating parts |

**Table 2-2**
**Urenco 100-kW PQ FESS Power Delivery Ratings**

| **Duration** (minutes) | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 |
|---|---|---|---|---|---|---|---|
| **Rating** (kW) | 100 | 88 | 80 | 74 | 66 | 59 | 50 |

# 3

# PERFORMANCE CHARACTERIZATION OF THE URENCO PQ FESS

## Momentary Interruption Test

To evaluate the performance of the flywheel, the Urenco PQ FESS was connected to the DC link of a three-phase, 460-V, 200-hp TECO-Westinghouse AC drive. A 100-hp AC induction motor was electrically coupled to the AC drive and mechanically coupled to a 600-hp eddy-current brake dynamometer.

A test scenario was designed to determine how long the flywheel could maintain the drive's DC link at a specified voltage level during an input power interruption. First, the flywheel's DC link ride-through detection level required tuning. When operating the 100-hp AC motor at full load under nominal voltage (480V), the drive's DC link voltage was 630 Vdc. Based on this value, the flywheel's DC link ride-through detection level was set to 615 Vdc. This value would theoretically cause the flywheel to regulate the drive's DC link voltage at 615 Vdc by supplying energy to the AC drive during a power interruption to keep the drive from tripping.

After setting the flywheel's DC link ride-through detection level, the testing was ready to begin. The AC drive output frequency was set to 60 Hz. The dynamometer load torque was increased until full-load current (117 A) was drawn by the motor. At this point, the AC drive's output power measurement was recorded (84.2 kW).

An oscilloscope was used to monitor three test parameters: the AC drive's output frequency, the AC drive's DC link voltage, and the DC current from the flywheel's DC link to the AC drive's DC link. The AC breaker that fed power to the AC drive was shut off and the oscilloscope was used to record the test parameters. The results are shown in Figure 3-1.

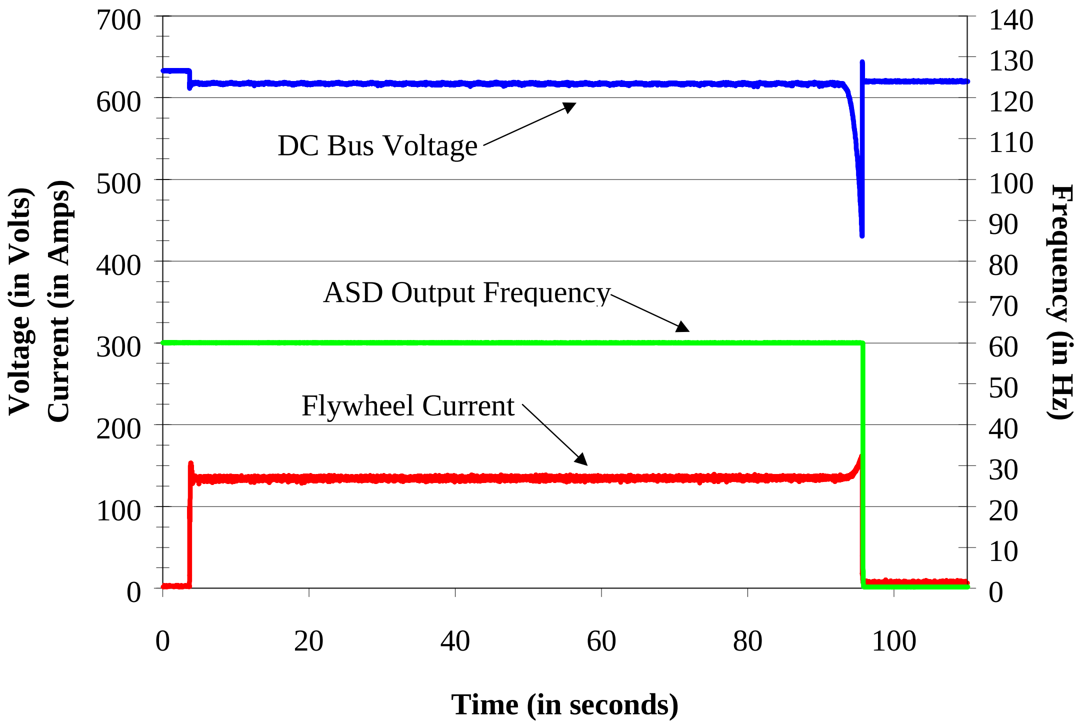

**Figure 3-1**
**Power Interruption Test Results**

The test results show that the flywheel was able to maintain the drive's DC link voltage at 615 Vdc for approximately 90 seconds. During the ride-through period, the DC current from the flywheel to the drive's DC link was approximately 135 A. After 90 seconds, the flywheel was no longer able to maintain the drive's DC link at 615 Vdc, which eventually led to the drive tripping on DC bus undervoltage at 95.5 seconds into the test.

At the initiation of the power interruption, the flywheel was operating at approximately 35,760 rpm (99.3% of nominal). At the end of the ride-through period, the flywheel was operating at 22,200 rpm (61.7% of nominal). When the AC breaker feeding the AC drive was switched back on, the flywheel immediately entered a "Run-Up" mode and the flywheel accelerated back to nominal speed. At that point, the flywheel entered the standby mode once again.

## Repeated Power Interruption Cycle Test

A second test scenario was designed to determine the effects of repeated interruptions on the flywheel's performance. Again the AC drive output frequency was set to 60 Hz. The dynamometer load torque was increased until full-load current was drawn by the motor.

An oscilloscope was used to monitor the AC drive's output frequency, the AC drive's DC link voltage, and the DC current from the flywheel's DC link to the AC drive's DC link. The AC breaker that fed power to the AC drive was turned off and on at regular intervals. First, the breaker was turned off for 20 seconds, then turned back on for 10 seconds. The off-on cycle was repeated until the flywheel was no longer able to sustain the DC link voltage of the drive. The results are shown in Figure 3-2.

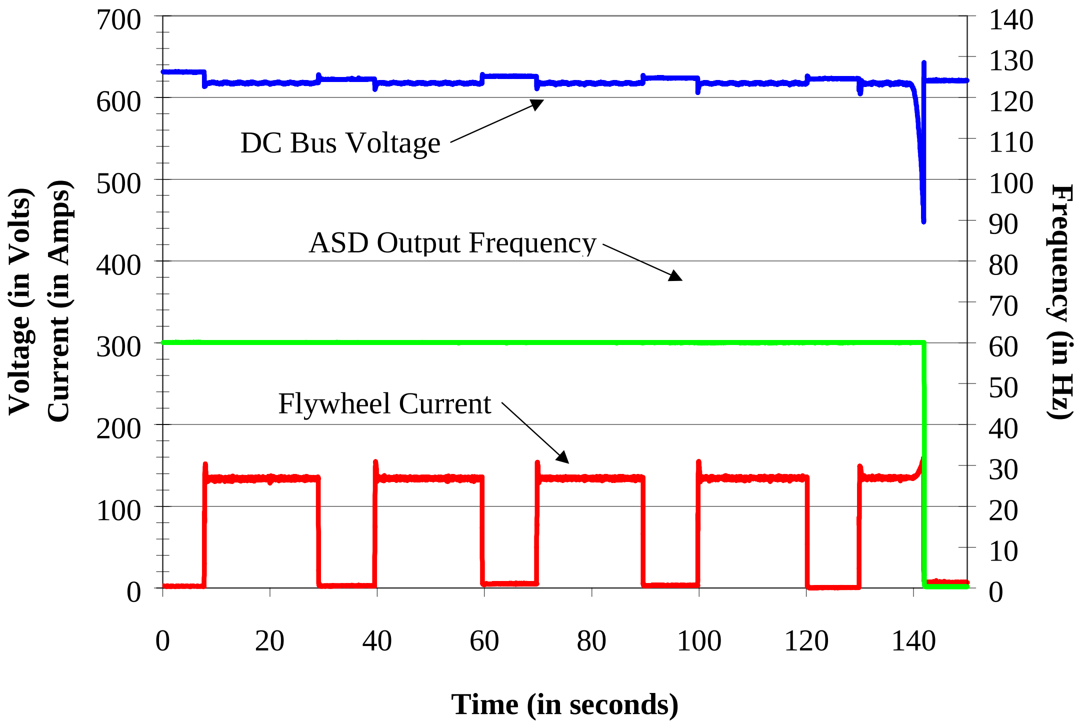

**Figure 3-2**
**Repeated Power Interruption Cycle Test Results**

Total discharge time was 90 seconds. Again, the test results show that the flywheel was able to maintain the drive's DC link voltage at 615 Vdc for a total ride-through time of approximately 90 seconds. Again during the ride-through period, the DC current from the flywheel's DC link to the drive's DC link was approximately 135 A. After 90 seconds, the flywheel was no longer able to maintain the drive's DC link at 615 Vdc, which eventually led to the drive tripping on DC bus undervoltage at 134 seconds into the test.

At the initiation of the power interruption, the flywheel was operating at approximately 35,880 rpm (99.7% of nominal). At the end of the ride-through period, the flywheel was operating at 22,200 rpm (61.7% of nominal). When the AC breaker feeding the AC drive was switched back on permanently, the flywheel immediately entered a "Run-Up" mode and the flywheel accelerated back to nominal speed. At that point, the flywheel entered the standby mode once again.

## Flywheel Energy Storage Systems for Power Applications

A number of companies are throwing their hats in the ring and are currently developing and marketing FESSs for power quality (PQ) applications. Caterpillar, Active Power, Piller, Beacon, Trinity, Powerware, and Urenco are examples. The flywheel-based power conditioning systems provide the power necessary to support electrical loads during voltage sags and momentary interruptions. The low-maintenance, high-reliability, and long life expectancy of FESSs make them an attractive alternative to battery and capacitor-based UPSs and DVRs. At the present time, some companies are marketing batteryless UPS systems with flywheels serving as the energy source during operation. A flywheel-based UPS system with an integrated standby generator provides uninterruptible power during prolonged, sustained interruptions. The flywheel provides energy to bridge the gap between the initial loss power and the start-up of the standby generator. Additional testing should be considered to analyze the feasibility and effectiveness of integrating the Urenco PQ flywheel with an existing DVR, UPS, or other custom power product that uses standard electrolytic capacitors or batteries as the energy storage element.

Other FESS applications include:

- Traction power supplies for railway systems.
- Cyclic or pulsed power applications such as lasers, lifts, rolling mills, and linear motors. By utilizing the energy in the flywheel, the peak power demand from the grid is reduced and the capital cost of increasing electrical infrastructure capacity is avoided. Disturbances to nearby loads and the power system are reduced as well.
- Common DC Bus AC Drive Systems can be supported with one flywheel. Applications where multiple AC drives are connected to a common DC bus will benefit through significant reduction in the cost of power conditioning. In most cases, one power conditioning device for multiple drives will cost significantly less than one device for each AC drive.

# 4

# CONCLUSION

Based on the test results, the Urenco PQ FESS was able to sustain the DC link voltage of an AC drive during a sustained interruption and repeated momentary interruptions. In fact, the FESS was able to deliver approximately 7.5 MJ of energy to the drive (84 kW for 90 seconds) during the tests, which agrees with the ratings defined by Urenco (*see Table 2*). The test results show that the Urenco FESS is capable of providing the necessary energy and DC link support for an AC drive application to enhance ride-through performance and protection.

According to Urenco, a PQ FESS with a capability of 200-kW for 44 seconds is possible with the same rotor construction as the 100-kW machine tested at the EPRI PEAC laboratory. Increased magnetic power loading in the rotor and increased ratings for the power electronics and AC machine windings to accommodate the increased power levels are the only major changes that are required.

High-speed FESSs offer a number of benefits when compared to conventional energy storage such as batteries, capacitors, or low-speed flywheels:

- *Wide operating temperature range.* Because the flywheel is essentially a mechanical device it is relatively insensitive to temperature fluctuations, operating between –20° C and +40° C. Batteries suffer a large reduction in storage capacity at low temperatures and a reduction in life expectancy at elevated temperatures. The life expectancy of electrolytic capacitors is also greatly reduced at elevated temperatures.
- *High cycling capability.* The flywheel is not affected by deep repeated discharges and is able to perform several million cycles. Almost all other forms of energy storage have limited cyclic capabilities.
- *Guaranteed energy content.* Because the flywheel relies on kinetic energy, knowing the speed of the rotor means that the amount of energy available is known. The speed is continuously monitored.
- *Long design life.* There are no flywheel parts that deteriorate with age. Therefore, a useful life of 20 years can be expected. Batteries and capacitors both deteriorate with age.
- *No maintenance.* The flywheel bearing systems and rotating parts require no maintenance. The design is based on gas centrifuge technology, some of which have been operating for 20 years with no maintenance. Low-speed steel flywheels need regular maintenance, as there is high stress placed on their bearings. This is particularly true where attempts have been made to run steel flywheels at moderately high speeds.
- *Low losses.* Efficient bearing systems and operation in vacuum conditions result in very low mechanical losses. Generator losses can be minimized for specific applications. Low-speed flywheels are subject to higher losses due to conventional bearing systems.

However, there are a few shortcomings of the Urenco PQ flywheel that should be addressed or considered before applying the device in the field for critical ride-through applications.

- The Urenco PQ FESS requires an AC power source for the vacuum and refrigeration systems and for the internal power supply of the microprocessor, controls, and inverter sections of the FESS. Although the vacuum and refrigeration systems are not a specific concern, the internal power supply is vulnerable to the same voltage sags and interruptions as the protected equipment. With the current configuration, a small UPS or other power conditioning device would be required to protect the internal power supply of the Urenco FESS. AC drive manufacturers have addressed a similar issue with the internal power supplies in their drives. Most AC drive manufacturers are taking advantage of the drive's internal DC link. They use switch-mode power supplies connected directly to the DC link instead of linear power supplies connected to the AC power supply. One of the main benefits of this design enhancement comes from the fact that the DC link capacitors provide significantly more energy storage capacity than the traditional linear power supplies used for the same application. The effect is a much longer ride-through time for the drive's power supply during voltage sags and momentary interruptions.
- The life expectancy of the pin bearing could be a concern if the FESS were to shutdown frequently. According to Urenco, the flywheel can come to rest and be restarted a limited number of times. Therefore, the flywheel would require some type of regular supervision. Should the flywheel experience a fault condition, the flywheel will coast until it is reset and restarted by a human operator. Because the rotational losses are very low, the flywheel will take approximately eight hours to come to rest. As long as the flywheel is restarted before it completely stops, there will be no degradation in the performance or life expectancy of the pin bearing. Thus, the flywheel requires a regular status check. A paging system or alarm could be used to alert the operator when the flywheel experiences a fault and shuts down.

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