Industrial Applications of Flywheels

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ABSTRACT

This article examines the technical and economic factors behind the application of a flywheel system to an industrial application to alleviate the damaging and costly effects of electrical sags and momentary power interruptions. The article examines an industrial customer who was losing production through sag and momentary power outage events. In a single event, the affected customer was out of action for 11 hours following a sag in the electrical power that tripped four extrusion lines. Previously, industry had considered that it is uneconomical to provide continuous power ride-through for adjustable speed drive equipment in the extruder application. Now industry has a new tool that can be employed to add security to the process through the use of kinetic energy stored in a flywheel. It is very clear from the results of this demonstration project that there are many industrial applications that would gain from this form of low-speed flywheel energy storage system.

INTRODUCTION

There are many industrial customers who suffer the damaging and costly effects of electrical sags and momentary interruptions. As the demand for more exacting quality standards draws more sophisticated control apparatus onto the shop floor, industry becomes more vulnerable to power quality events. A large degree of success in protection against sags can be obtained using conventional mitigation devices. However, in large industrial processes, there may be a series of linked applications that require full power to maintain production. One of these applications is the common extruder application. A small deviation in electrical supply conditions may create flaws in the extruded product. For years, industry has considered that it is uneconomical to provide continuous power ride-through for adjustable speed drive equipment in the extruder application. Economics of energy storage were hindered first by the cost of the power electronics, second by the lack of reliability, and third by the environmental impact and space requirements of the chemical storage batteries used to provide the energy for the load. Used to mitigate power quality events, batteries have very short life cycles, as little as one-fifth the warranted life of the battery. Now industry has a new tool that can be employed to add security to the process through the use of kinetic energy stored in a flywheel. Flywheels are not new. What is new is the availability of power electronics to permit the stored energy to be converted to fixed frequency and voltage supply during a discharge event. The combination of modem power electronics and a low speed (<14,000 rpm) flywheel can provide for the multiple short discharge periods required by a power quality event without loss of warranted life or reliability.

Duke Power identified a customer who was losing production through sag and momentary outage events. In fact, the affected customer was disabled for 11 hours following a sag that tripped all four extrusion lines. Remedial action included sending all available employees to the shop floor to work sequentially on each of the four extruder lines. Once one extruder was running the next was worked on. This was a painstaking process because each line produced multiple separate filaments of plastic that had to be threaded by hand through the machine. The candidate process line selected for the energy storage project had 64 such separate filaments.

The cost of a power quality event at the extruder reached far beyond the direct production loss to include the cost of scrap material, the indirect labor cost, and the potential purchase of competitors' material. The plastic strip extruded in this plant was being continuously used as the woven backing of carpet. This particular extruder application had come under careful scrutiny by the manufacturing engineers of the connected customer. Power quality mitigating devices such as uninterruptible power supplies (UPSs), ferroresonant transformers, surge arresters and contactor coil-hardening devices had already been fitted, but this only made it more clear that an energy-storage solution was required to enable the process line to ride through sag and momentary outage events successfully.

SYSTEM DEFINITION

Duke Energy and the Electric Power Research Institute (EPRI) completed an in-depth study of the candidate extruder line. The result was the process diagram shown in Figure 1, which illustrates the complexity of the complete extruder system. To keep the plastic strip intact, each of the motor systems shown in the process diagram potentially needed protection from supply sags or interruptions.

What was very clear from the study was that the electrical supply to the system was provided from two different utility transformers. This highlighted the need to make some reconnection of the loads to achieve full protection from a single electrical supply backed up with energy storage. What was not known was how much of the process would ride through a sag without the need for energy storage. The answer to this question would require the components of the production line to be tested with a sag generator, a device that is designed to introduce various sag depth and duration characteristics to components of the load. These tests required planning with the connected customer because the process line components were required to be individually tested over the period of 2 days.

PROJECT METHODOLOGY

Introduction

The project used the following stages to obtain improved power quality through the use of ride-through flywheel energy storage equipment:

- Characterization of process equipment requirements
- Selection and testing of the process ride-through equipment
- Review of the low speed flywheel energy storage features
- Official testing
- Sag testing
- Energy storage equipment integration
- Installation
- Start up
- Critical examination of the weak links in the process
- Specification language to ensure good coordination and performance.

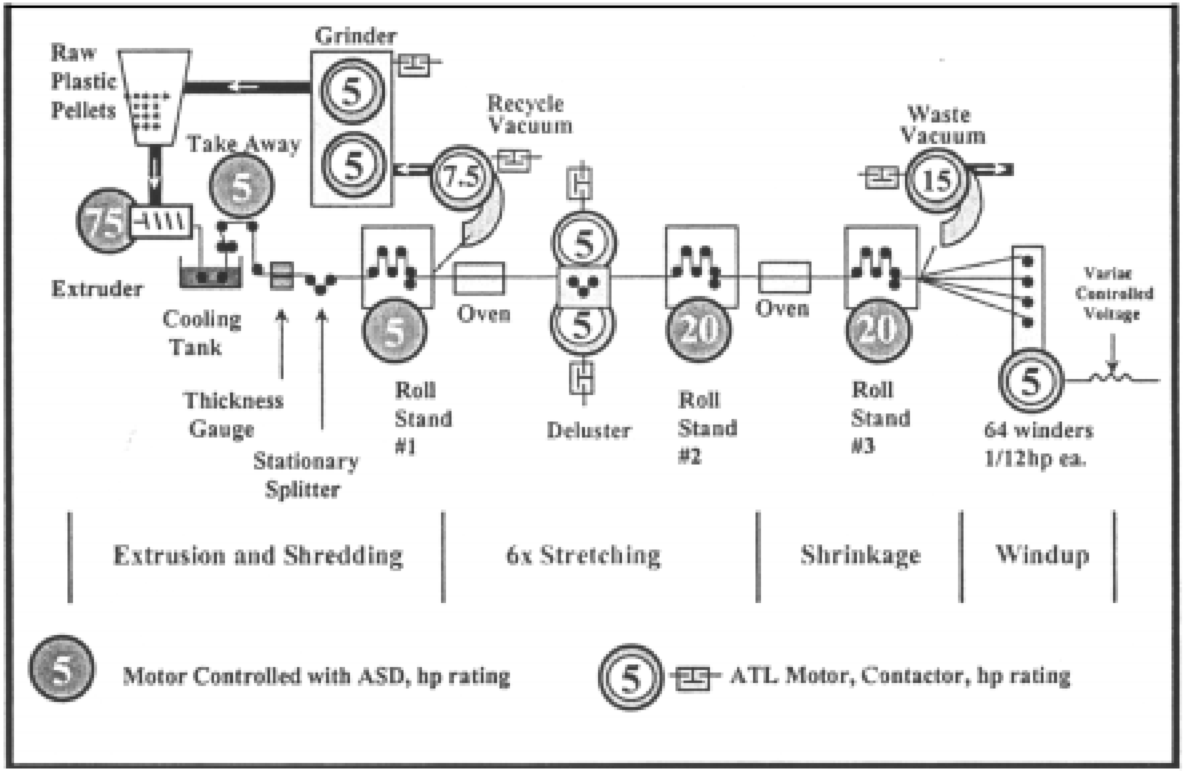


Figure 1. Extruder Process Diagram

Characterization of the Requirements of Process Equipment

To characterize equipment that can ride through an electrical supply disturbance and maintain the necessary process quality, it is necessary to quantify both the supply disturbances likely at the site and the response of the process to the event. Process sensitivity to supply voltage varies widely between applications. The requirement of the ride-through project is to keep the process within the limits of process parameters that provide acceptable product quality. For the extrusion process, it is necessary to keep all the sections of the process line running at the demanded speed, unchanged during the supply disturbance. Any disturbance on the motor speed will significantly affect the extruder manifold pressure and compromise quality. Success of the ride-through project depended on obtaining a practical definition of process requirements.

Characterization of the electrical supply is the most important preparatory step to improve power quality immunity. For the extruder process, the most significant requirement was the continuous availability of power. A voltage transient brings with it a power transient and potential disruption of the process conditions. Rotating machinery with more inertial energy will, when subjected to a power transient, take longer to slow down than elements with less inertia.

This can result in plastic strip breakage or serious product quality problems. The exact system response to the supply transient is made more complicated by the involvement of contactors, alternating current (AC) relays, programmable load controllers (PLCs) and other auxiliary devices that may individually or collectively cause the process to shut down. Sags, the most common event at the Shaw Industries plant, produce a predominance of power quality events lasting 5 to 25 cycles. Momentary interruptions are also experienced, but less often. This was confirmed by the results of a 12-month monitoring period. It was also noted that during a power quality event, power may be reapplied briefly several times during breaker operations. All the events recorded lasted less than 3 seconds. However, Duke Energy confirmed that longer momentary interruption events did occur, but only very rarely.

A critical analysis of the application was first completed to be sure that the provision of energy storage would solve the site problem. For this project, energy storage is clearly needed to keep the extruder screw turning and maintain extruder manifold pressure. Thus, flaws in the plastic strips, a major causes of "wrap rounds," will be avoided. Once this conclusion had been reached, the next step was to quantify the energy and power level required and draw up a potential list of solutions that could be employed to provide the process ride-through energy and reach the project goals. The most expeditious method of gathering practical information for this project was to organize a visit to the site and examine the process and proposed solutions in detail with the plant manager and operators. For this project, the meeting was held at the proposed site. The goals of the meeting were to establish the absolute requirements for the extruder system to operate during the electrical system disturbance. This involved confirmation that energy storage was required, definition of the range of speed and torque variation that can be tolerated by the process before a plastic strip break occurs, and establishment of the worst-case scenario for the AC power supply at the process line. This determined the period over which the energy would be required to be delivered to the load.

From the information on the electrical faults, it was determined that the minimum time the load needed to be maintained was 3 seconds. This was based on the typical momentary interruption experienced at Shaw Industries. For the project to calculate the power level required from energy storage, the assumption was made that the process line was called upon to operate at constant speed during the whole electrical disturbance. The power requirements of the process line had been measured at 83 kW. On this basis the minimum energy required from the storage equipment is equal to 83 kW x 3 seconds = 249 kJ.

Resulting from the site meeting a number of actions were determined, each aimed at documenting the extruder application precisely. Duke Energy continued to monitor the power at the drive cabinet and summarize data on the range of power supply conditions for use by the project team. Duke Energy also worked with Shaw Industries to establish an accurate and current single line drawing for the electrical apparatus. This included transformer, cables, power quality mitigation devices and all power distribution components. Shaw Industries identified all the electrical supplies connected to the process line that required electrical ride-through support. They checked the records of the installation to identify the mechanisms used by the existing system to confirm that the AC was healthy.

Any one of these mechanisms may potentially defeat the object of the proposed energy storage system by shutting the process down without extracting the available energy from the equipment.

Selection of the Process Ride-Through Equipment

A review of the available energy storage devices revealed that there were a limited number of options. Cost-effective solutions used either flywheels or capacitors. Flywheels store energy in the rotational motion of the mass of steel or composite glass-fiber rotor. Capacitors store energy as electrical charge manifest as voltage between their terminals. It is worth noting for the future that a new group of solutions is becoming available that harnesses the power available in two good phases to provide power for the third and faulted phase. This group of solutions, although very cost effective for the common single-phase fault, would become expensive in this three-phase situation. They could only be employed in this application with the addition of three energy storage devices, one for each phase to be mitigated. The device selected for this project was the low-speed flywheel with AC system connections, arranged as shown in Figure 2. This solution had all the special features to make it particularly suited to the extruder application at Shaw Industries.

Review of the Low-Speed Flywheel Energy Storage Features

- Energy storage capacity in modules of 3000 kJ are available
- Charge/discharge voltage of 480AC ideally suited the combination of 460 Volt-AC adjustable-speed drives and process equipment
- Single conversion configuration for maximum efficiency
- No toxic chemicals
- 500,000 energy discharge cycles are available before inspection
- No regular maintenance, except for air filter replacement
- Small footprint
- Easy to isolate. There are only AC connections
- Easy to integrate. It is completely self-contained with internal bypass
- Quick recharge is achieved in 2 hours total
- An electronic monitor is provided for recording discharge events.

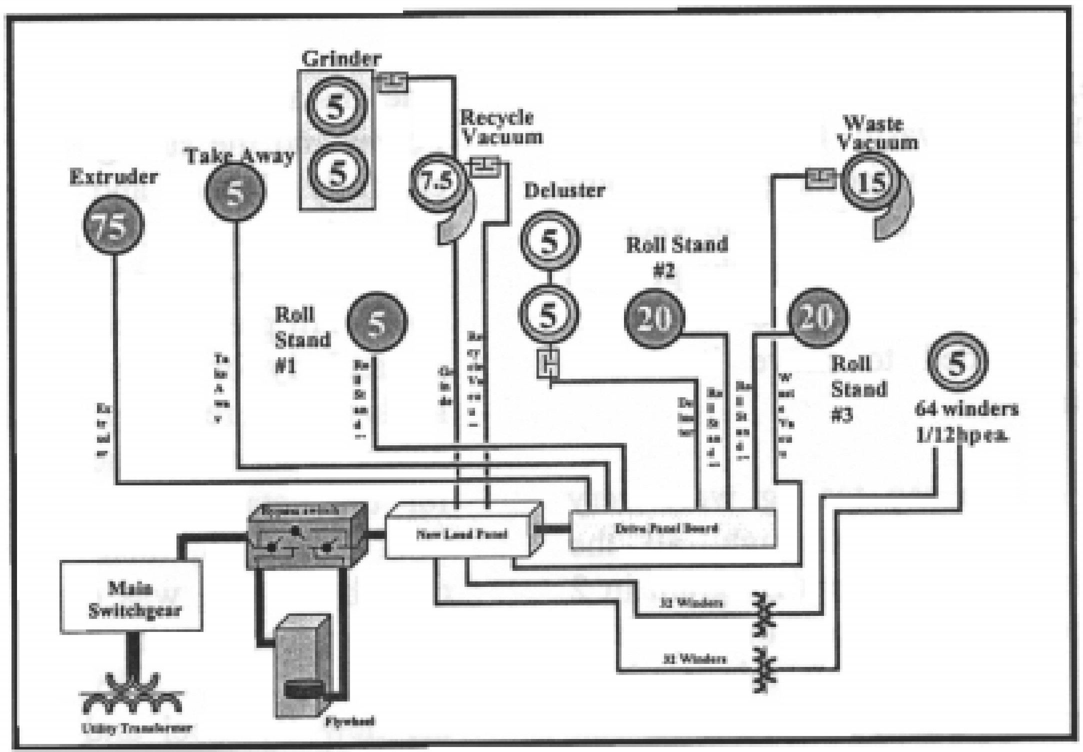


Figure 2. Flywheel Energy Storage System

Official Testing

The manufacturer of the flywheel system arranged for the new system to be tested under the most rigorous of load conditions. A full rated load of a 250-kW, nonlinear six-pulse rectifier with capacitive filter characteristics was used. Under this onerous load, the voltage distortion was raised to 10%. It was understood that the manufacturer would continue to develop the algorithm that controlled the voltage waveform so that an optimal version would be available before field installation at Shaw Industries.

Sag Testing

Sag testing was scheduled for a plant shutdown during the 1998 Thanksgiving holiday. The results of the testing were very helpful in determining the loads to be supported by the flywheel system. Results confirmed that the connected customer's plant engineer had used power quality mitigating devices to very good effect. Tests confirmed that all roll-stands, takeaway motor, and extruder needed to be on the flywheel output. The 64 winders also needed support because any change in speed caused the winder to cut the plastic strip and stop operating. The recycle and waste vacuum motors did not electrically need to be supported, but because the recycle vacuum was located above the process line, it seemed prudent to minimize the possibility of waste falling into the production line by supporting that motor with the flywheel. Because the waste vacuum was the only remaining motor of the process line not wired from the main power source, it was also decided to move it to the flywheel source.

The results of the sag testing were very clear. To achieve ride-through, all the motors shown on the process diagram in Figure 2 needed to be powered from the flywheel system. To achieve this result, a new load panel was proposed to handle all extruder loads. This avoided the possibility of maintaining voltage on other unspecified parts of the manufacturing plant, which may have introduced new coordination problems.

Energy Storage Equipment Integration

Once the load had been fully investigated and the mitigating device selected, the next stage in the process was to make sure that there was complete coordination between the existing system and the new mitigating device. The first stage was to check the configuration of the supply system. In this case, the supply was connected as a 480 volt ungrounded wye. The selected mitigating device, a CAT 250 kVA UPS flywheel, required a neutral connection. This neutral was pulled from the utility transformer to the customer's incoming switchgear. Luckily, for this installation, the distances were short. The flywheel system had been manufactured and already contained an internal bypass switch and isolators. However, to make sure that the equipment could be safely removed from the process line during normal production, a parallel set of external bypass switches were installed in a floor-mounted cabinet.

Installation

The installation of the flywheel by Duke Power and the storage system supplier was carefully planned and coordinated with the connected customer. As much preparation as possible was made before the plant shut down. All possible conduit runs were made, particularly for the long runs associated with loads that were being reconnected from one power panel to another (see Figures 3 and 4 for the detailed connection changes). The CAT 250 UPS, measuring 4-ft wide by 3-ft deep by 6-ft tall, was easily positioned. The most time consuming part of the installation was connecting the bypass cabling between the new flywheel and the bypass cabinet. For future installations, modifications are required to facilitate the bypass cabinet installation. Once the bypass was in place, each load was carefully connected to the new distribution panel.

Start Up

The flywheel arrived on site with protective support pieces in place of bearings. Once the bearings had been inserted, air from within the flywheel enclosure was drawn out by vacuum pump, reducing the pressure in the flywheel enclosure to minimize flywheel system loses. The start-up was momentarily delayed by a faulty safety relay, after which the flywheel was run up to its normal storage speed, close to 7700 rpm. Each section of the extruder line was connected to the feeder, backed up by the energy storage system. After all the loads were connected, but before plastic extrusion was passed down the line, the incoming breaker for the process was opened. Under these conditions, the process line electrical demand was 80 kVA. The process line ran for up to 40 seconds with the supply breaker open. This test was repeated using multiple short intervals with the breaker open and equally good ride-through times were obtained. The extruded product was then threaded, and the test repeated. The process line demand increased to 85 kVA when raw material was being processed. The process line operated smoothly during the time the

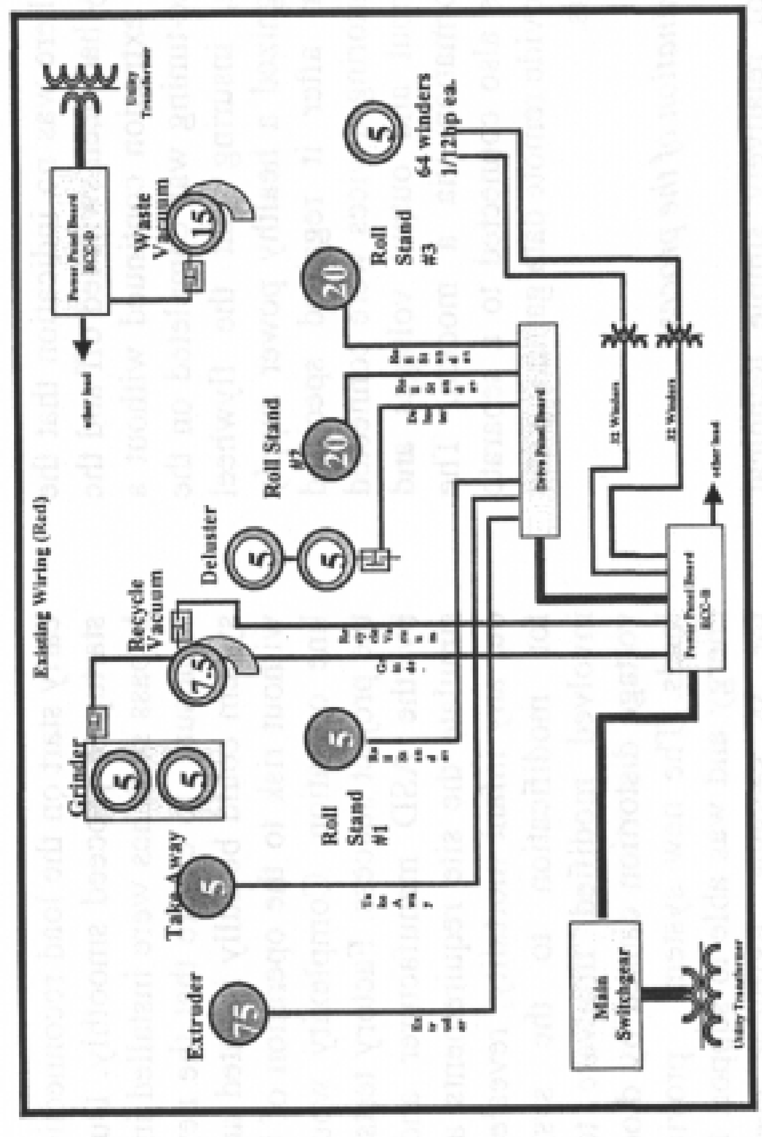


Figure 3. Original Power Distribution

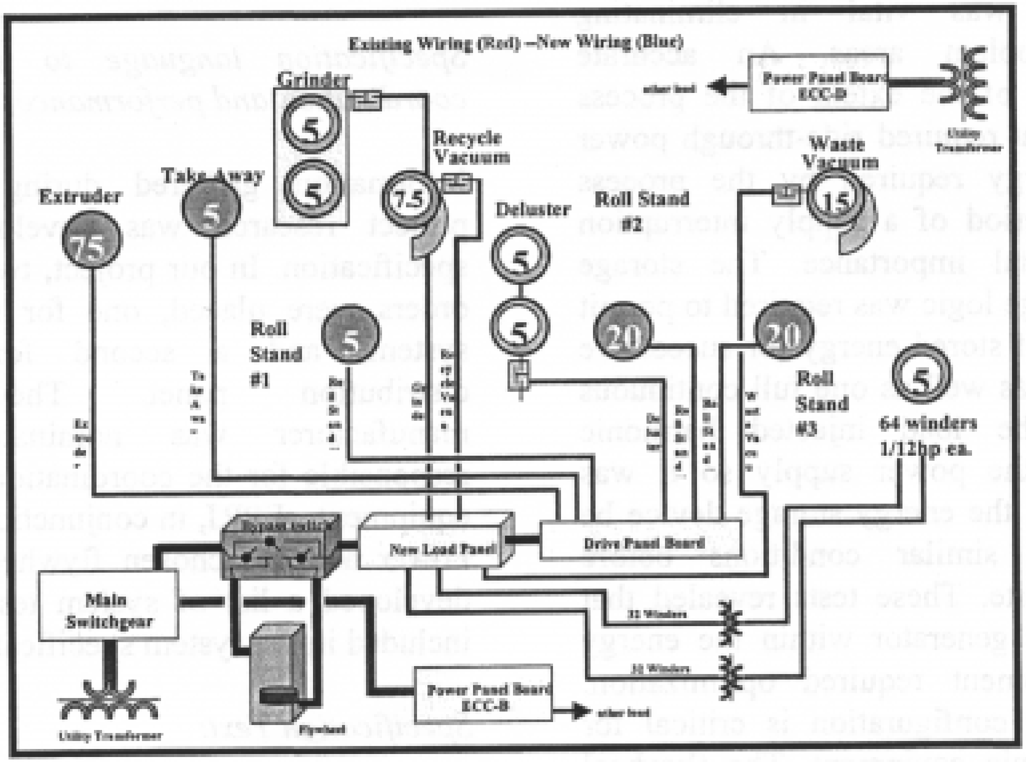


Figure 4. Modified Power Distribution

input breaker was open. There was no indication that the power supply had been switched off and the high quality extrusion continued without a change. Fine-tuning was completed on the new system, ensuring that the flywheel system recognized a healthy power supply voltage soon after it regained specified levels. Monitoring devices were connected to collect input and output voltages and provide information via a modem. The flywheel was also connected to a separate modem to provide remote data gathering and fault diagnosis.

Critical Examination of the Process

A number of relatively simple technical issues could have derailed this demonstration project if precautionary steps had not been taken during the course of the project. The development of equipment specification was vital in eliminating potential problem areas. An accurate determination of the extent of the process equipment that required ride-through power and the energy required by the process during the period of a supply interruption was of pivotal importance. The storage device recharge logic was required to permit the delivery of stored energy for successive short periods, as well as one full continuous discharge. The load injected harmonic current into the power supply so it was important that the energy storage device be tested under similar conditions before shipment to site. These tests revealed that the waveform generator within the energy storage equipment required optimization. Power supply configuration is critical for power electronic equipment. The flywheel system, as configured for this project, required a neutral connection. This was provided inexpensively on this project.

Electric delivery originally provided through two distribution panels required careful planning the provision of a new panel and an early start on the load reconnection to allow start-up to proceed smoothly. Duplicate AC bypass switches were installed in a separate enclosure to ensure that the new flywheel system could be fully isolated and serviced without risk to the operation of the process line. Complexity would hamper the project success. Factory tests developed by the ASD manufacturer and EPRI to simulate the site requirements and to iron out any infant mortality, revealed the need for modification to the system. This involved modified firmware to improve voltage distortion caused by diode rectifier loads. The new system provided excess energy and was able to support the process for 38 seconds. Extruder system loads consume power at a relatively constant rate; however, the energy storage system will provide proportionally longer ride-through periods with reduced load.

Specification Language to Ensure Good Coordination and Performance

Information gathered during the initial project research was developed into a specification. In this project, two equipment orders were placed: one for the flywheel system, and a second for the new distribution panel. The flywheel manufacturer was selected to be responsible for the coordination of the new equipment. EPRI, in conjunction with Duke Power and the chosen flywheel supplier, developed a list of system tests that were included in the system specification.

Specification Text

The flywheel energy storage system shall provide 250 kW for 12.5 seconds, and proportionally more ride-through time with lower than 250 kW loads.

- The flywheel energy storage system shall be designed to provide all available stored energy in one continuous discharge period at 250 kW or in multiple short periods that sum to 12.5 seconds.
- The process line rated at 80 kVA shall ride through a three-phase momentary outage lasting 38 seconds.
- The storage system shall commence recharge upon the AC input return to ±10 % of nominal.
- Complete recharge from the discharged state shall be accomplished in less than 2 hours.
- The energy storage system shall maintain constant output frequency during each discharge event.
- The system shall include means of on-load bypass and isolation of the flywheel system.
- The energy storage system shall provide an event history, documenting the number of discharges, the duration of each event and the time of the occurrence.
- The energy storage system shall be free from toxic chemicals found in storage batteries.

PERFORMANCE AND RESULTS

The flywheel demonstrated a very fast response by reacting to the switching event of a power factor correction capacitor located at the local substation. Figures 5 and 6 show the flywheel input and output waveforms (the black waveform illustrates the load current). When the current waveform "flat-lines" in Figure 5, the flywheel is supporting the load.

Within days, the flywheel system caught a 17-cycle sag and protected the extruder process line. Figure 7 shows the input voltage waveforms for the 17-cycle sag that occurred on January 6, 2000. It is worth noting that the three other extruders in the same building were tripped by this sag event, causing hours of lost production. It is interesting too, that this duration of sag has been identified in EPRI studies as the most prevalent event on radial feeder systems.

This installation, at the time this article was written, uses only about one-third of the flywheel's rated capacity, so measurements of efficiency give lower than the nameplate information. This will change as the load is increased by the connection of another extruder line.

Regular maintenance of the equipment air filters is important. On one occasion, the filters became sufficiently blocked to cause the flywheel system to shut down on over-temperature. At this time, the modem was also put of action, the equipment fault was detected by the diligence of the Shaw Industries' operators. This whole situation has been corrected through regular filter replacement and new automatic radio modems that do not rely on telephone connections.

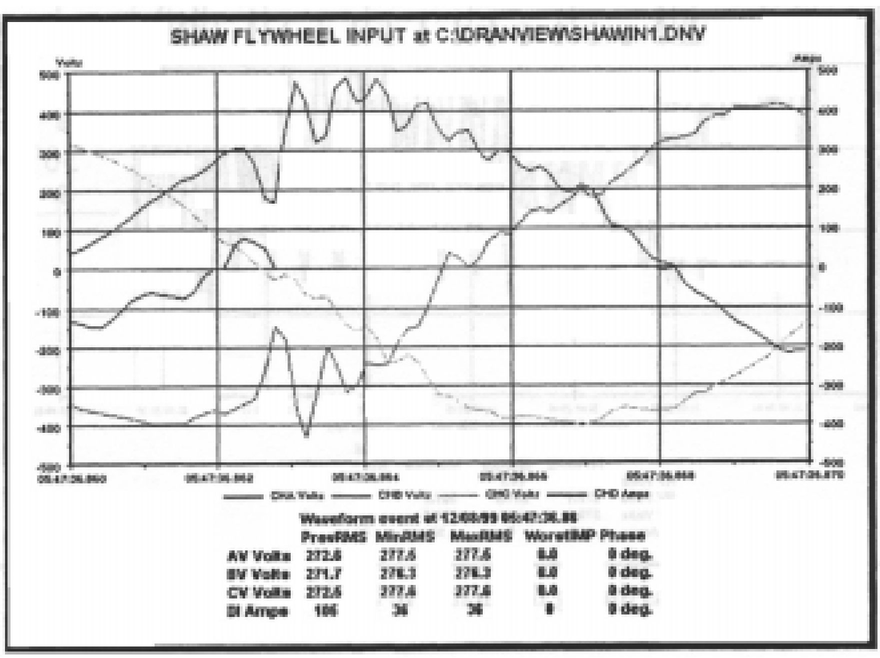
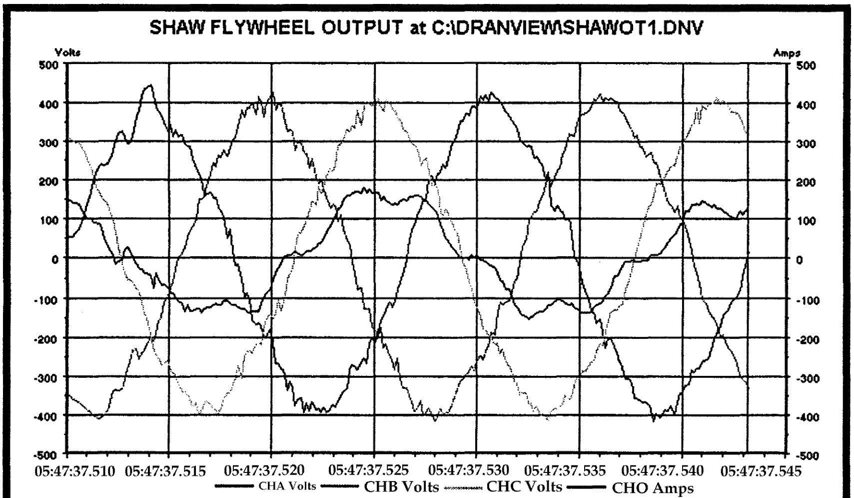


Figure 5. Capacitor Switching Response Flywheel System Input



Waveform event at 12/08/99 05:47:36/86

	PrevRMS	MinRMS	MaxRMS	WorstIMP	Phase
AV Volts	273.1	267.9	276.4	0.0	0 deg.
BV Volts	272.2	271.8	276.4	0.0	0 deg.
CV Volts	273.3	270.1	273.8	0.0	0 deg.
DI Amps	97	104	110	0	0 deg.

Figure 6. Capacitor Switching Response Flywheel System Output

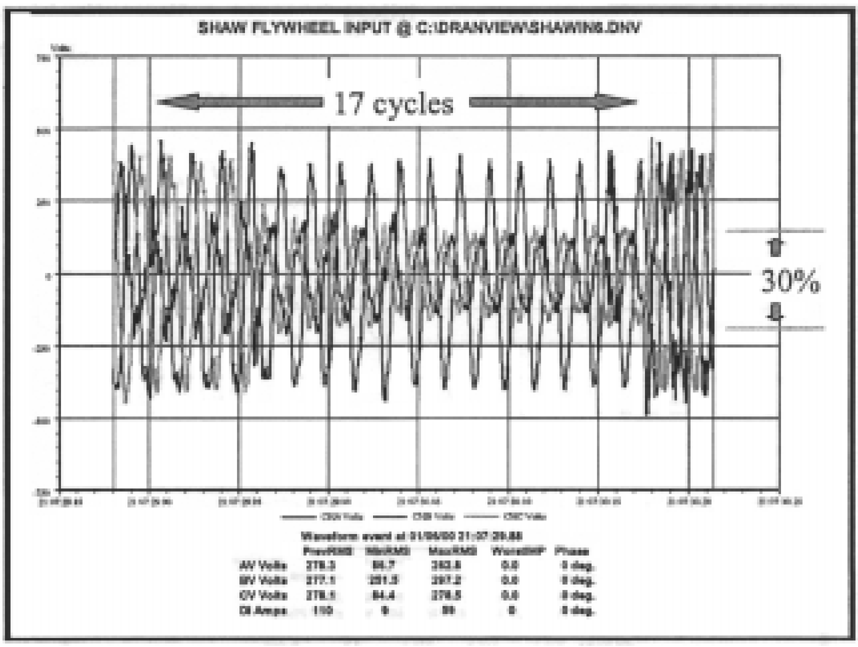


Figure 7. Input Voltage Conditions During the First Save by the Flywheel on January 6, 2000.

ECONOMIC ANALYSIS

Based on the electrical monitoring and customer records, extruder line #1 was stopped on average 30 times per year. The line was down on average 45 hours. This downtime represents $15,000 dollars of lost product that can be saved with a new energy storage device. Each time an outage occurs, the restart time is 1.5 hours and absorbs the labor of at least two operators. At the time of system trip, all the material on partially filled bobbins (<1/2 full) is scrapped. This represents on average 2 hours of production, because a full roll takes 4 hours to produce. With the process line down, the company would (potentially) need to purchase material from a competitor to ensure that production is maintained in the carpet backing weaving plant.

Plans are in place to improve the efficiency of extruder line #2 so it can be added to the flywheel. When this additional line is added, the savings will increase by $36,000 dollars, for a total of $51,000 annually.

CONCLUSIONS

The flywheel with AC output has been applied to a critical load and has performed well, protecting the load from sags and momentary power outages. Close to 40 seconds of ride-through is currently available to the extruder line. Part of this energy will be used on other extruder lines to give the customer increased value for its investment.

Work needs to continue on the harmonic content of the load voltage waveform. It is very clear from the results of this demonstration project that there are many industrial applications that would gain from this form of low-speed flywheel energy storage system with AC output.