Integrated Flywheel Uninterruptible Power Supply (UPS) Systems for Industrial Applications

White Paper 109

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Objective

This white paper will review the significant growth in industrial applications that have turned mission critical as a result of highly digitized processes from the paper mill to the water bottling plant. In an attempt to drive efficiencies, much of the manufacturing processes has turned digital and as a result are controlled by highly sophisticated computer equipment. As processes are computerized, the paper will discuss how an integrated flywheel based UPS system can effectively and predictably protect the mission critical computer loads that directly drive manufacturing output.

Digitizing Industrial Processes

Global competition is driving industrial users to reevaluate every aspect of factory efficiency. To this end, ever-increasing levels of automation are being employed, especially in the areas of process and machine control, communications and computerized optimization of material flow. In essence, electronics is invading the manufacturing floor in much the same way desktop computers proliferated in offices ten years ago. The average factory worker, like his or her office counterpart, is now armed with state-of-the-art computer technology in the never-ending quest for higher productivity, better quality and lower overhead costs. An array of automated equipment is now commonplace on the factory floor.

Figure 1: Robot working from a computer-aided design (CAD)/computer-aided manufacturing (CAM) program.

Both low horsepower motor-controllers and high-power adjustable-speed drives are being deployed to lower electrical energy bills and provide better control over processes. Programmable controllers have become commonplace due to their significant value in improving product quality through enhanced control, data collection and communications. Real-time production statistics are being used by an every-widening audience to affect decisions from the machine operator to the CEO.

Computerization in every aspect of the production cycle is being explored for its potential for improvement and to maintain the highest levels of availability through integrated control. However, most of these tools for enhancing competitiveness are vulnerable to the same power quality issues that have threatened more traditional computer applications, plus they are subjected to additional environmental factors. The factory environment presents significantly more hazards to electronics with wide temperature extremes, high airborne particulate density and more frequent voltage dips and sags – as compared to air conditioned computer room floors. Against this backdrop, expectations of total availability are increasing. Thus, the whole issue of power to the factory floor is being re-examined.

Industrial Processes Turning Mission Critical

It has long been recognized that some processes cannot tolerate a power disturbance without loss of a batch or run of material. Certain diffusion steps within the semiconductor industry are critical and an incorrect temperature or loss of a timer can render an entire production lot as very expensive scrap. Failures in certain serially integrated extrusion processes result not only in a lost batch of finished product, but also in serious machine damage. For example, machines can become choked with raw material if a heating function fails or if a motor controller trips off-line.

Today, factory management is concerned with global availability as well, and there is a growing trend toward providing multiple sources of electrical power to the entire operation. Electrical feeders from two or more substations may be used or power may be generated locally in the form of engine generators or cogeneration plants. In general, tolerance for lost production due to power problems is quickly approaching levels that exist within the information technology arena. Because of the criticality and the diversity of the loads used in the industrial sector and in conjunction with the need for an environmentally robust UPS, Active Power's CleanSource UPS with its integrated flywheel is used as a benchmark throughout this paper.

INDUSTRIAL POWER QUALITY AND RELIABILITY PROBLEMS

An Electric Power Research Institute (EPRI) study on recurring U.S. power problems revealed that greater than 90 percent of manufacturing facilities will experience sags of utility voltage greater than 20 percent from nominal. The study also states there will be in excess of 30 dips over 10 percent annually. These disturbances occur at the electrical input to the building and are a function of both natural events and random occurrences caused elsewhere in the power grid. Complete outages should also be considered which vary in frequency though out the world.

Even in the United States, with relatively stable power production, there is significant variation in the number of total outages by region:

- Areas with high Kuronic rates (lightning strikes) will experience more naturally caused power losses than areas with lower incidences of thunderstorms.

- Industries at the end of long feeder routes are at higher risk for outages than facilities that are closely coupled to electrical substations.

- Buildings in older parts of a city or suburb may experience higher failure rates due to equipment aging or poor maintenance.

In general, it is clear the electrical power infrastructure needed to support an operation that has requirements for "multiple nine's" of electric reliability is not generally available from the public utility today and will certainly degrade in the future as factors such as deregulation take effect. This power delivery reliability problem is universally recognized and is outlined in EPRI's "Roadmap Initiative." As part of the Power Delivery Infrastructure Challenge, EPRI states:

> *…the existing radial, electromechanically controlled grid needs to be transformed into an electronically controlled, smart electricity network in order to handle the escalating demands of competitive markets in terms of scale, transactional complexity and power quality. These reliability and power quality limitations already cost the U.S. economy more than $30 billion each year. The upgraded system is not a luxury, nor even an option for the future. Rather it is an imperative to build productivity and ensure global competitiveness in the $8 trillion plus U.S. economy. The bad news is this program has been established as a 50-year endeavor, which leaves American businesses with profound limitations due to the lack of power reliability.*

INDUSTRIAL EQUIPMENT LIMITATIONS

Over time, factories employing computerized machine operation and process control typically accumulate a wide variety of hardware from multiple manufacturers. Each general category of hardware has unique electrical power limitations, functions of both design and application. Many embedded and stand-alone PC and network servers have a recommended power immunity “design envelope” published by the Computer Business Manufacturers Association (CBEMA) – see Figure 2. This is a recommendation and not an absolute standard, although it does provide a useful tool for comparing protection capabilities. Other standard process control equipment such as Programmable Logic Controllers (PLCs) do not have a joint recommendation of power immunity and therefore each supplier’s recommendation may be different. For integrated controller/machine equipment, specific power immunity specifications must be obtained from each manufacturer, but as a point of reference, their characteristics could be overlayed on the

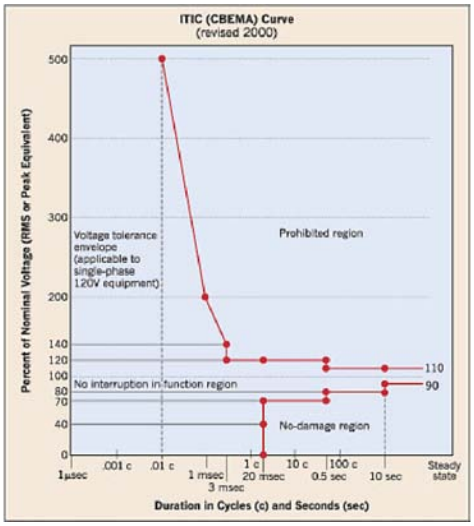

Figure 2: CBEMA Curve

CBEMA curve.

Motor controllers and adjustable speed drives have little power disturbance ride-through capability and tend to trip off-line anywhere from one half cycle to about three cycles of power anomaly. Many applications of these motor controllers are found in continuously running processes, such as paper mills where many are used on a single production line. Tripping of one adjustable speed drive (ASD) or non-sequential tripping of the total motor population will cause a huge increase in scrap and the need for significant human involvement to get the process back in operation.

In each of these examples, there have been historical attempts at solving the electrical problems with distributed or localized solutions, such as placing small UPS systems on the controls portion of numerically controlled machines or by placing energy storage devices on the DC bus of the motor controllers. Diesel generators are also employed, but typically they are used only after the plant has experienced an unexpected shutdown and are not well coordinated with the total power needs. The industrial market has not had a well designed, integrated solution that would provide total power protection for any type of equipment and, at the same time, keep the factory running through a total power loss.

THE INTEGRATED FLYWHEEL UPS

An integrated flywheel UPS system has been specifically designed for the harsh environment of the factory floor and incorporates total protection from transient over- voltages, dips and sags to total power outages with no time constraints. In order to understand the operational performance of the UPS system, the CBEMA curve and EPRI data will be used as references to power disturbances along with actions and performance of the new system in mitigating these power quality problems. Comparisons to the well known battery-based, double-conversion UPS will also be made.

Voltage Transients

A true line-interactive inverter was chosen for CleanSource UPS because it represents the best solution when the entire protection package is considered. In this system, the inverter is continuously operational and is constantly monitoring the quality of input power. Any transient over-voltage that occurs will be attenuated by two actions. First, there are high-energy transient-voltage surge suppressors (TVSS) and large line-isolating inductors on the input. There are redundant surge suppressors on the output of the inverter terminals. Both of these assemblies have been designed to meet the American National Standards Institute (ANSI) C-62.41 - 1991 standards for high-energy (6kv at 3ka), high exposure transients. In addition to these fast acting passive energy absorbers, some energy will also be harmlessly transferred to the DC capacitors through the inverter. Through the use of these transient reduction techniques, a stiff 6,000 volt peak on the input will be reduced to a harmless voltage deviation on the output. This level of transient protection is consistent with the typical double-conversion UPS.

Voltage Sags

The EPRI report on power disturbances points out a majority of power system problems are voltage sags of 10 to 30 percent below nominal and they extend from three to 30 cycles in duration. These are the kind of disturbances that cause adjustable speed drive (ASD) controlled processes to be momentarily interrupted or permanently tripped off-line. An integrated flywheel UPS system will sense the beginning of a voltage sag and immediately begin to take energy from the integrated flywheel to compensate. If we examine the worst case of a 30 cycle, 30 percent dip, followed by a controlled walk-in back to normal operation, this will represent an energy draw of less than 10 percent of the total stored energy. Recovery of the energy used following the 30 percent dip is very rapid, bringing the flywheel back to its full outage capability within 20 seconds. Unlike a lead-acid battery energy-storage used in conventional double-conversion UPS systems, the flywheel has no restrictions on the number of energy discharge cycles and has no significant wear-out mechanisms based on the number of discharges. The flywheel also has a much broader operating temperature range (0 to 40 degrees Celsius) than does the lead-acid battery. Installations on factory floors can be completed without the mandatory air-conditioning required to achieve the life and performance of batteries.

Voltage Surges

The inverter has output voltage sense ranges, which can be easily tailored for the customer's specific requirements through software. The range of acceptable voltage on the output of the UPS (chosen by the customer) will determine when the system takes energy from the flywheel or when it starts the engine-generator. There is a fast response range to take action for dips and there is a slower response range that can take alternate actions for sags and surges. For electrical power that temporarily exceeds these programmable ranges of acceptability, energy will either be seamlessly taken from the flywheel, on a temporary basis, or from the engine-generator for longer periods. The load voltage will always remain within the selected voltage range for any disturbance time from subcycle to continuous.

Power Loss

The flywheel will be used to supply short duration energy needs from single cycle to 14.5 seconds (at 100 percent load) or longer. For all outages in excess of the flywheel storage time, the diesel generator will be used as the preferred source. In order to achieve high reliability with the engine generator, a special redundant start-power function is added to the flywheel UPS system that uses energy from the flywheel for 24VDC starting power. Since the flywheel system is constantly monitored and controlled, the end user has instantaneous knowledge of the availability of the flywheel for starting purposes meaning there are no surprises at the absolute worst time. Military Handbook 217 reliability studies of this novel integrated start function reveal an integrated flywheel UPS system that has very similar mean time between failures (MTBFs) as legacy lead-acid battery based static double-conversion UPS, but without the maintenance, wear out and failure problems of batteries. It also has the novel characteristic that the protection time is not limited to 15 minutes as compared to legacy battery based systems, but is only limited by the diesel fuel supply. The system could therefore extend protection for natural disasters, which seem to occur on a regular basis.

Frequency Limitations and Efficiency

Line-interactive UPS technology is used in the integrated flywheel UPS in order to provide the customer with operating efficiencies (typically 98 percent) that are significantly higher than double-conversion UPS (92-94 percent), therefore lowering lifecycle costs significantly. However, there is no frequency isolation from input to output. This is not an issue while operating from the utility since the utility has to be extremely frequency stable in order to maintain a connected grid. Minor frequency deviations (> 0.1 percent) can cause the entire grid to begin to collapse if not addressed by the utility infrastructure. Greater frequency deviations typically come from free running engine generators or small cogeneration plants. Although their base frequency stability is quite good (acceptable with all known industrial, commercial and IT loads), large cycling loads can cause frequency swings, especially on improperly sized generators. The integrated flywheel UPS addresses this in two ways.

• First, the static inverter of the integrated flywheel UPS and the generator are sized to be completely compatible.

• Second, the UPS will sense any transient or in-rush current load change and with the use of flywheel energy prevent the transient from impacting the frequency presented to the load.

In effect, the UPS and flywheel act as a large filter between the engine and the load. When a load transient occurs which would result in a line frequency disturbance, the UPS will detect and intervene, providing a stable operating frequency to the load at a maximum tolerance of ± 1.0 Hz. This is the same tolerance a double-conversion UPS is typically set for in order to track an engine generator. Double-conversion UPS systems advertise a very stable run frequency (typically ± 0.1 Hz). However, they also track the frequency of a connected generator to ± 1.0 Hz. This is done in order to keep synchronization with the source so in case of UPS failure the load can be switched to the generator via the bypass and still be in phase with the generator. Thus, the integrated flywheel UPS system operates with the same frequency limits that a double-conversion UPS does and like the double-conversion, can be software configured for tighter requirements if an actual need is determined.

Fault Clearing Capability

Experience has shown industrial venues have many more internal branch breaker operations than either the commercial or IT arenas. This is mainly due to a higher opportunity for machine operator error and dynamic machine failures. To maximize availability of the entire enterprise, the UPS system must be able to provide circuit breaker or fuse fault-clearing energy without degrading the output power to the point where other critical loads are compromised. The integrated flywheel UPS has a more reliable chance of successfully clearing a branch breaker than does a double-conversion UPS system. The double-conversion system will typically sense a fault-based overload and immediately transfer to bypass to provide the maximum amount of fault-clearing current. The integrated flywheel UPS system is already connected to the utility and does not need to switch the load through a static switch. Thus, the probability of failure of the static switch must be considered in the evaluation of the double-conversion UPS fault-clearing action.

Output Voltage Total Harmonic Distortion (THD)

Under normal operation, the UPS output voltage distortion will be a reflection of the source voltage. Since manufacturing plants typically have a stiff, low-impedance power distribution connection that is sized for growth, sine-wave distortion is generally characterized by transient events such as dips, sags and surges. Under worst case continuous conditions, non-linear loads from uncorrected low power-factor motor controllers will typically cause a voltage distortion of five to eight percent. The isolating inductors of the line-interactive UPS will add a small amount to this level of distortion, but it should remain below 10 percent for most applications.

Input Current Distortion (THD)

Most double-conversion UPS systems use a six pulse rectifier on the input. This controlled rectifier has a characteristic input current distortion of 28-30 percent regardless of the non-linearity of the load. Even in the presence of a unity power factor load (all real power), the UPS will continue to pull 28-30 percent non-linear current. Because of this distortion, manufacturers of the double-conversion solution offer passive input filters that will reduce this distortion down to 10 percent. Unfortunately, these filters can cause system problems especially when the UPS is lightly loaded. They can circulate large reactive currents to an engine generator, especially if there is any question of instability between the UPS and the generator controls. They can also cause a “fast response” generator output voltage to go very high if the UPS load appears as capacitive impedance. The capacitors in the filter can also cause certain types of motors to “self-excite” and continue to run even after utility power has been lost – causing an out of control situation and safety risk.

The line-interactive inverter of the integrated flywheel UPS system works differently than the controlled rectifier and normally will pass the load current distortion through to the source. However, since the industry trend is rapidly moving toward power factor corrected loads, the usual distortion the integrated flywheel UPS system will place back on the utility will typically be less than the standard double-conversion UPS.

Lifecycle Costs

A major benefit of the integrated flywheel UPS system is its operating efficiency. Whereas most double-conversion UPS have efficiencies in the range of 92-94 percent, this system operates at 98 percent, which includes the necessary power to keep the flywheel rotating at its fully charged point. A simple examination of the operating costs of a UPS system protecting a 2,000 kilowatt load will reveal that at $0.10 per kilowatt hour and a six percentage point difference in efficiency will result in an annual savings of $105,120. This number does not factor savings of the reduced cooling requirement on a UPS loss 25 percent of that of a battery-based double conversion UPS system. If we add the replacement cost of a typical lead-acid battery as used with a conventional UPS system, they would have worn out from one to two times over a 10 year period. As a result, the total lifecycle cost savings easily make the integrated flywheel UPS system an excellent choice for the industrial market.

Environmentally Friendly Technology

The softer aspect of an integrated flywheel UPS system is the reduced carbon footprint, making it environmentally friendly in more than one way. The DC energy storage is derived from a spinning steel mass and not lead-acid like that of chemical batteries. When it comes to chemical battery replacements, a tremendous amount of energy goes into recycling the lead – as much as six to ten times the energy a single battery will ever put out in its useful life.

At an efficiency differential of as much as six percentage points, the integrated flywheel UPS system consumes only 25 percent of the power of a battery-based double conversion UPS, which equates into a reduction of 1.6 million pounds of CO_2 emissions on a 2,000 kilowatt load each year. This is the equivalent of powering 691 average U.S. households each year.

CONCLUSION

Computerization of the industrial market is changing the philosophy of manufacturing from batch processing to mission critical. In a mission critical environment, even a small power glitch can have significant implications on the output of a given industrial plant, whether that is a paper mill or water bottling company.

The integrated flywheel UPS system provides significant benefits in harsh environments like that of industrial plants. The fact the system can be placed virtually anywhere and in close proximity of the equipment it is protecting is very appealing. Since there are no chemical batteries, the need for strict temperature control is no longer there. At 98 percent efficiency, there are significant efficiency benefits to be gained that over time will pay for the investment itself and directly impact the environment with 75 percent lower CO_2 emissions than that of battery based double-conversion UPS systems.