POWER QUALITY EVALUATION OF 480-V, 2-MVA UPS SYSTEM

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ABSTRACT
A mobile 480-V, 2-MVA UPS System utilizing battery energy storage was installed at S&C Electric Company's Polymer Products Fabrication Building in Chicago, Illinois in May 1999 to provide uninterrupted power to the building for up to 15 seconds in the event of a voltage sag or momentary interruption in the local utility supply. Similar units can be applied at medium voltage through the application of a step-up transformer to provide momentary power disturbance ride through of up to 30 seconds for loads up to 15 MVA at system voltages ranging from 4.16 kV to 34.5 kV.

A power quality evaluation of the installation was performed over a six-month period from July 1999 to early January 2000. This paper describes the details and results of this power quality evaluation, which involved two phases. Phase I involved the collection and review of power disturbance data and the effects on process equipment, while Phase II involved power quality monitoring of utility source and building load voltages and currents over a period of six months.

Review of power disturbance data and equipment power-disturbance ride-through characteristics during Phase I of the project indicated that the polymer fabrication process in the building is affected by the tripping of motors driving hydraulic pumps for the thermalset molding machines. The tripping of these motors may have resulted in direct production losses in 1998 of approximately $468,000. The monitoring conducted during Phase II of the project showed that the PureWave UPS operated as intended during 12 utility voltage sag events to protect the building's load against momentary power disturbances. In addition, the unit operated successfully during many staged interruptions involving opening of a source-side circuit breaker.

1. INTRODUCTION
A Mobile PQ2000 Power Protection System, developed by the former Omnion Power Engineering Corporation and funded by the US Department of Energy through Sandia National Laboratories, was installed at S&C Electric Company's Ridge Boulevard Complex in Chicago, Illinois in May 1999. The unit, now known as the PureWave™ UPS System, was installed to provide uninterrupted electrical service to S&C's Polymer Products Fabrication Building, which is home to a continuous three-shift fabrication operation. It was designed to supply up to 2 MVA of uninterrupted power for up to 15 seconds at 480 volts in the event of a voltage sag or interruption in the local utility supply.

The basic UPS System consists of a main system container with up to eight power modules and system control computer, a power-electronic switch (PES) with its associated bypass and isolation switchgear, and an isolation transformer. See Figure 1. Each power module includes its own power conversion system, including inverter bridge, batteries, and battery charger.

The installation of the mobile UPS System at S&C was accomplished in about three days. Conduit for the connecting cables was prepared prior to arrival of the unit. From the time of arrival of the unit, three electricians completed installation of the conduit to the cable interface box on the trailer, modified the
The UPS System is now being introduced commercially by S&C Electric Company. The US Department of Energy's involvement in the commercialization of the unit through Sandia National Laboratories led to the initiation of a power quality evaluation of the UPS System and the installation at S&C. The first phase of the power quality evaluation involved data collection and review of power disturbance data to determine the effects thereof on process equipment in the Polymer Products Fabrication Building. The review included determination of power-disturbance sensitivity levels of process equipment, and the economic benefit provided by the UPS System. The second phase of the power quality evaluation involved continuous monitoring of 480-V bus voltages on the source and load sides of the UPS System through two Dranetz/BMI PQNode 7100 disturbance analyzers over a six-month period.

2. COLLECTION AND REVIEW OF POWER DISTURBANCE DATA AND THE EFFECTS ON PROCESS EQUIPMENT

2.1. Electrical system
The building's medium-voltage system is supplied from the Rosehill Substation of the local utility, ComEd, via two 12-kV feeders. The Rosehill Substation has two 12-kV ring buses, each of which are
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supplied via two 50-MVA 138 kV/12 kV transformers. The two buses are tied together via a normally-open bus-tie circuit breaker, which may be closed at times depending on loading conditions. Each ring bus supplies 18 distribution feeders, which supply mostly residential, institutional, and commercial loads in the area. Feeders are mostly underground, with some sections of overhead, mainly in residential distribution areas.

The two 12-kV feeders supply the building through a common-bus preferred-alternate scheme. In the event of an interruption or outage on the preferred feeder, the conventional source-transfer equipment is set to transfer the building and other connected loads to the alternate feeder in approximately 2.5 seconds. Contactors in voltage-sensitive equipment, as well as adjustable-frequency drives could still be affected under such a transfer scheme, resulting in tripping of equipment due to the relatively slow speed of transfer. Furthermore, in the event of momentary sags due to faults in the utility system, the conventional source-transfer scheme will not even attempt to transfer due to the fact that the initiation of transfer is intentionally delayed for coordination purposes.

The building's utilization voltage is derived from a 12 kV/480/277 V delta/wye-grounded transformer supplied from a feeder in the medium-voltage switchgear. The mobile UPS System is connected to the secondary side of this transformer and to the 480-V bus via the bus tie circuit breaker. The 3000-Ampere, 480-V bus supplies 8 feeders which supply different Motor Control Centers (MCCs) and distribution panel boards.

2.2. Process equipment affected during power disturbances

The fabrication process in the Polymer Products Fabrication Building involves the manufacturing of polymer-based (Cypoxy®) insulators, and voltage and current sensors used in many of S&C's products. The process basically involves the carefully controlled mixing, heating, molding, and curing of a two-part liquid epoxy resin system. The two parts commonly known as materials A (resin) and B (hardener) contain large amounts of “powder-like” fillers to enhance the mechanical properties of the part. The filler-added A and B materials are dynamically and statically mixed before transfer into the molding machine. The mixed material is then transferred through a hose before it enters a hot mold. As the mixed material heats up in the mold it will thin out slightly just before turning solid. The mold clamping machinery maintains the mold at a preset pressure (around 1,700 psi) and temperature and also provides for addition of inserts (mechanical hardware) to the polymer product. The molding process takes about 17 minutes. When the part is fully cured, it will be removed from the mold and post-cured in a large batch-oven to complete the chemical reaction.

Process equipment affected by momentary power disturbances includes mainly the hydraulic system used for thermalset molding, movement of platens, and retention of clamping. The hydraulic system is powered by a 480 V, 20 hp motor driving a rotary-vane hydraulic pump. Pump maximum output pressure is about 3,480 psi, while an accumulator is used to maintain system pressure around 2,700 psi. Once started, the electrical motor is controlled by an Allen-Bradley MicroLogix 1000 programmable logic controller (PLC) through a 24 V DC relay. The 120 V AC motor starter contactor is supplied through a 460 V/120 VAC, 750 VA transformer. If a voltage sag of sufficient depth and duration or momentary interruption occurs during the molding process, the 120 V AC motor contactor would drop out, resulting in the motor and hydraulic pump shutting down. This, in turn, will result in a drop in the hydraulic system pressure, which will initiate a low-pressure switch to open and interrupt the molding process. All parts in the mold would have to be scrapped. Another cause of the power disturbances could be the shutting down of the PLC, which could also interrupt the molding process. Since the PLC can cause the motor starter contactor to drop out, it could also be the cause of motor tripping if it is more susceptible to power disturbances than the contactor.
Two 10-hp adjustable-frequency drives (AFDs) used in the dispersing equipment could also be affected by momentary power disturbances, but the shutting down of these drives for brief periods will not affect the fabrication process. Two 100-hp AFDs and two 50-hp AFDs used for supply, return, and cooling tower fans in the air-conditioning system of the building can also be affected by momentary power disturbances.

Specific power-disturbance ride-through characteristics of the AC motor starter contactor for the 480 V, 20-hp motor driving the hydraulic pump was not available. However, ride-through characteristics of low-voltage AC contactors are described in the Power Quality Testing Network’s Brief No. 10[1]. This report describes the ride-through performance of three 480-V open-type NEMA contactors, rated 5 hp, 10 hp, and 50 hp based on tests performed. All contactors were equipped with 120 V AC coils. With the coil voltage reduced to 0 V, the contactors were able to keep their motor supply contacts closed for 3.5 to 7 cycles. These ride-through durations were obtained when the onset of the sag occurred at zero voltage. Since the current through the coil lags the voltage by 90 degrees, the current would be at peak during this instant, resulting in maximum magnetic flux. The 10-hp contactor could only remain closed for a half cycle when the onset of the sag occurred at peak voltage. At peak voltage the current through the coil and corresponding flux are near zero, reducing the time the contacts can be held closed.

The two 10-hp AFDs used in the dispersing equipment, as well as the two 100-hp AFDs and two 50-hp AFDs used in the air-conditioning system of the building have a specified power-loss ride-through of 15 milliseconds (i.e., almost 1 cycle) at full load. Since the ride-through capability is a function of the connected load, longer ride-through can be expected at reduced loads. These AFDs are all Allen-Bradley type 1336 PLUS drives. The Allen-Bradley MicroLogix 1000 PLC has a specified input voltage in the range 85 to 264 V AC. Thus, assuming nominal input voltage of 120 V, the PLC will not be affected at sag levels above 71% of nominal voltage. The PLC power supply is typically designed to shut the DC output voltage to the processor (and I/O modules) off when the AC input voltage falls below the minimum rated voltage for 1 cycle. Thus, the PLC is expected to shut down within about 1 cycle of the rms value of the input voltage falling below 85 V AC. This level of susceptibility to voltage sags and interruptions could result in the PLC being more sensitive to power disturbances than the 120 V AC contactor.

2.3. Economic impact of power disturbances

There are 12 molding machines in the Polymer Products Fabrication Building. The cost of individual parts in the mold ranges from about $500 to about $1,000. Each mold can hold up to four parts. Thus, the cost of production loss in the event of a power disturbance during the molding process averages around $3,000 per molding machine (i.e., 4 parts times average cost of $750 per part). In 1998, a total of 13 power-disturbance events affecting production were recorded (the building was only commissioned in 1997). Using these 13 events as a representative number of power disturbances per year, the direct cost of lost production is approximately $39,000 per molding machine per year. If all 12 molding machines are affected during each of the 13 power disturbances, the potential direct cost of lost production could be as high as $468,000 per year. Since it is unlikely that all 12 molding machines would be in the molding process during each of the power disturbances, the actual direct cost of lost production would likely be less than $234,000 per year. Disruption of the fabrication process due to power disturbances could also potentially severely impact the production schedules of other S&C products containing Cypoxy-molded components as subassemblies. Approximately 70 percent of all S&C products contain Cypoxy-molded components. Shortages of polymer products due to power disturbances can result in delays in delivery of S&C products and subsequent payments. These shortages can also result in cancellation of product orders.

and affect bidding on potential new orders with tight delivery schedules. When taking these considerations into account, the potential financial impact of polymer product shortages could easily exceed the direct cost of lost production due to power disturbances.

3. **POWER QUALITY MONITORING**

Two Dranetz/BMI PQNode 7100 disturbance analyzers were installed during July 1999 for continuous monitoring of 480-V phase-to-neutral voltages on the source side of the UPS System and the 480-V bus on the load side of the UPS System. Refer to Figure 1. On August 14, 1999 a circuit breaker was installed between the supply transformer secondary and the input to the UPS System to simulate source-side interruptions. The circuit breaker controls were equipped with a timer circuit to automatically reclose the circuit breaker approximately 6 seconds after interruption. After installation of the source-side demonstration circuit breaker, the source-side disturbance analyzer connections were moved to the load side of the circuit breaker. Disturbance analyzers were configured to record voltage and current waveforms in the event of a voltage sag (phase-to-neutral rms value less than 90% of nominal voltage) or voltage swell (phase-to-neutral rms value more than 110% of nominal voltage). In order to trigger both source- and load-side disturbance analyzers when power disturbances occur, the analyzers were configured to capture waveforms in the event of a waveshape disturbance: these disturbances are triggered when voltage waveform values, compared in a small “window” on a cycle-by-cycle basis, exceed a preset value. Even though the UPS System was expected to compensate for the momentary power disturbances, it takes at least 208 microseconds for the controls to detect and respond to such disturbances. Thus, parameters to trigger waveshape disturbances were set such that the actual voltage waveforms could be recorded on both disturbance analyzers during momentary power disturbances.

3.1. **Voltage sags**

A total of 12 voltage sag disturbances that were due to events on the serving utility’s electrical system were recorded on the source-side disturbance analyzer over the six-month monitoring period. Actual recorded phase voltage waveforms during one such disturbance are shown in Figures 2(a) through 2(c). Note that there is a difference of a few seconds between the time stamps for the same event on the source- and load-side disturbance analyzers due to a drift in clocks between the two units. During this event the source-side phase-to-neutral voltages sagged to 83.5% of nominal voltage for approximately 0.18 seconds (i.e., almost 11 cycles). The load-side voltage waveforms clearly illustrate the compensating action of the UPS System in restoring the normal phase voltages.

Figure 2(a): Source-side phase-to-neutral voltages at the start of the voltage sag recorded on November 15, 1999.
The magnitude and duration of the 12 recorded voltage sags, based on the phase voltage with the lowest voltage magnitude during the sag, are summarized in Figure 3. Also shown are the undervoltage portions of the CBEMA and revised CBEMA (ITIC) curves, which indicate the sensitivity levels of single-phase computer and data processing equipment to voltage sags. The UPS System operated as intended during each of these voltage sag disturbances, except for two disturbances during which the rms value of the voltage sagged to only 89% of nominal voltage. This most likely occurred because the rms voltage value was barely less than the 90% value required for triggering the controls of the UPS System.

Based on the equipment voltage sag sensitivity levels indicated by the CBEMA and revised CBEMA (ITIC) curves, only 1 of the 12 voltage sags recorded over the six-month period may have resulted in equipment tripping if the UPS System was not installed. (Note that the section below each curve represents the magnitude and duration of voltage sags that may affect equipment). However, since the
specific magnitude-duration sensitivity levels of the hydraulic pump’s AC contactor and the PLC in the hydraulic system are not known, process disruptions may have occurred on at least one more occasion (due to the voltage sag of 72% in magnitude and 0.05-second or 3-cycle duration).

![Magnitude and duration of source-side voltage sags measured over the six-month monitoring period.](image)

**Figure 3**: Magnitude and duration of source-side voltage sags measured over the six-month monitoring period.

### 3.2. Interruptions

No actual interruptions involving the opening of the utility’s feeder circuit breakers occurred during the monitoring period. However, the 480-V source-side circuit breaker installed during August 1999 was used to stage source-side interruptions in order to demonstrate the operation of the UPS System (refer to discussion in section 3). A total of 25 such staged interruptions of approximately 6-second duration were recorded during a three-month period. The UPS System successfully compensated for the missing source voltage during each of the 25 staged interruptions. Figures 4(a) through 4(d) show the source- and load-side phase-to-neutral voltages during one such staged interruption.
Figure 4(a): Source-side phase-to-neutral voltages at the start of the interruption recorded on the source-side disturbance analyzer on August 19, 1999.

Figure 4(b): Load-side phase-to-neutral voltages at the start of the interruption recorded on the load-side disturbance analyzer on August 19, 1999. Note the compensating action of the UPS System evidenced by the overshoot in the A- and C-phase voltages.
Figure 4(c): Source-side phase-to-neutral voltages at the end of the interruption recorded on the source-side disturbance analyzer on August 19, 1999.

Figure 4(d): Load-side phase-to-neutral voltages at the end of the interruption recorded on the load-side disturbance analyzer on August 19, 1999. Note that there is very little change in the load-voltage waveforms as the UPS System reconnects the source.

4. CONCLUSIONS

Momentary power disturbances can cause disruption in the Polymer Products Fabrication Building at S&C through the tripping of AC motor contactors and PLCs associated with the hydraulic system used in the thermalset molding machines. The estimated economic benefit of the UPS System in this installation is on the order of $234,000 to $468,000 per year when considering the cost of direct production losses only, and can be significantly more if parts availability and associated considerations are taken into account. The UPS System demonstrated that it could be effectively applied to provide emergency power for momentary power disturbances, including voltage sags and interruptions, at this facility.