technical update

Technology Assessment and Application Guide for Series Voltage Restorer (SVR)

Power Quality Mitigative Solutions

Problems Associated With Power Quality Disturbances

Sustained interruptions, which can cause significant process shutdowns, are not the only events that cause problems for electric power customers. The momentary breaker and re-closer operations before lockout can be just as detrimental to sensitive end-use equipment as the actual lockout itself. For example, semiconductor-manufacturing plants can be especially vulnerable to momentary interruptions. The total time required to produce a semiconductor chip may be as long as 30 days, with numerous critical processes involved. The chip can be ruined at any time during this process if a voltage sag or momentary interruption causes a sensitive machine to trip or causes an abnormal operation. Other industries that are sensitive to voltage sags and momentary interruptions include plastics, rubber, paper, textiles, glass, automobile, and steel manufacturing plants.

Some of the most common sensitive components are the contactors and relays that control the machinery. Contactors can drop out within 5 to 20 milliseconds after the start of voltage sags as low as 75% of nominal voltage. Often these contactors can be responsible for shutting down the entire process. These events can be complicated, time-consuming, and expensive to the electric power customer.

Series Voltage Restorer

This technical update documents the operation, features, applications and some of the application issues of a series voltage restorer (SVR), a three-phase power electronics inverter-based device designed to mitigate the effects of voltage sags. The Series Voltage Restorer is suitable for energy consumers with voltage sensitive equipment, such as in the semiconductor, printing, steel works, food processing, and pharmaceutical industries. The key features of SVR as specified by the manufacturer are as follows:

- Protects the load from voltage sags down to 50% of nominal (single-phase) and 62% of nominal (three-phase)

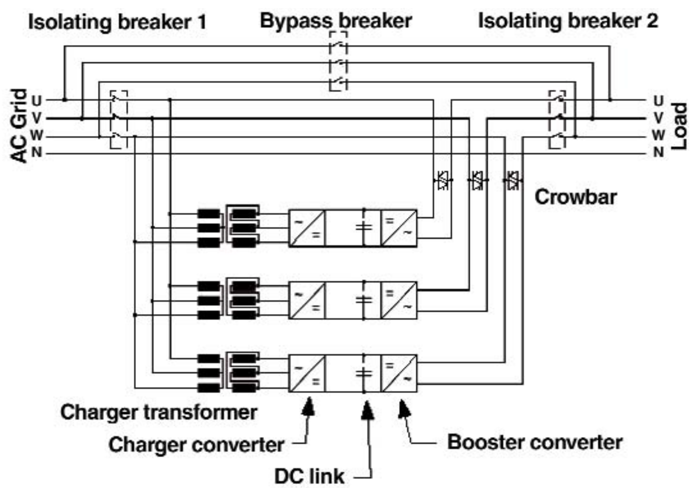

Figure 1. Schematic of the SVR

- Low voltage (400V to 600V) and high current (500A to 2500A) application
- Has quick response to voltage disturbance, typically 1 ms
- Stable operation, insensitive to rapid load changes
- It has optional power factor correction and continuous voltage regulation features

Operation of the Series Voltage Restorer (SVR)

The SVR is a fast acting device that is designed to protect critical loads from short duration voltage disturbances in the grid. It functions as a voltage source between the utility supply and the load. A simplified block diagram representation of the operation of the series voltage restorer is shown in Figure 1.

The line voltages of the utility tribution system are continuously monitored by the SVR control system. The charger transformer keeps the DC link completely charged so that the SVR can supply the missing voltage during the voltage disturbances.

In the case where a voltage disturbance is detected by the SVR control system, the crowbar is turned OFF. The active charging unit supplies the compensating voltage individually to each phase so that the line voltage can be restored. The active charging unit uses the remaining energy from the distributed supply system to charge the capacitor bank, which is acting as a dynamic buffer for the booster converter. The time taken for the total response of the SVR to the voltage disturbance is typically less than a quarter cycle, on the order of few milli-seconds.

The SVR has a programmable preset voltage level, which can be modified by the user to fit his needs. For example if the user has very sensitive loads that require the line voltage to be 95% or more of the nominal voltage, then the user can set the voltage level in the SVR to 95%. Then the SVR will protect the load when the line voltage drops below 95% of the nominal.

By engaging the two isolation breakers and the bypass breaker, the SVR can be effectively bypassed and the load will then be directly connected to the utility. The isolation breakers and bypass breaker are used during SVR maintenance to bypass the unit.

Figure 2 shows the actual voltage sag correction by the SVR. When the input line voltage sagged down to 80% of the nominal voltage, the SVR control detected it and compensated with the missing voltage.

The SVR uses basic blocks called PEBB, which stands for 'Power Electronic Building Blocks.' This is shown in Figure 3. The PEBB can be configured in many different ways to achieve the desired results. The charger converter and the booster converter of the SVR are made up of PEBB units.

The SVR also has two optional modes of operation based upon the customer's requirements. The two modes of operations

- Continuous voltage regulation (CVR)
- Power factor correction

In the continuous voltage regulation mode, the SVR continuously monitors the line voltage and regulates the output voltage to within ± 5%, within its operating limits. The typical response time for the SVR in this mode is 3ms.

In the power factor correction mode, the SVR compensates for the load power factor by injecting the reactive power up to 20% of the nominal rated power capacity.

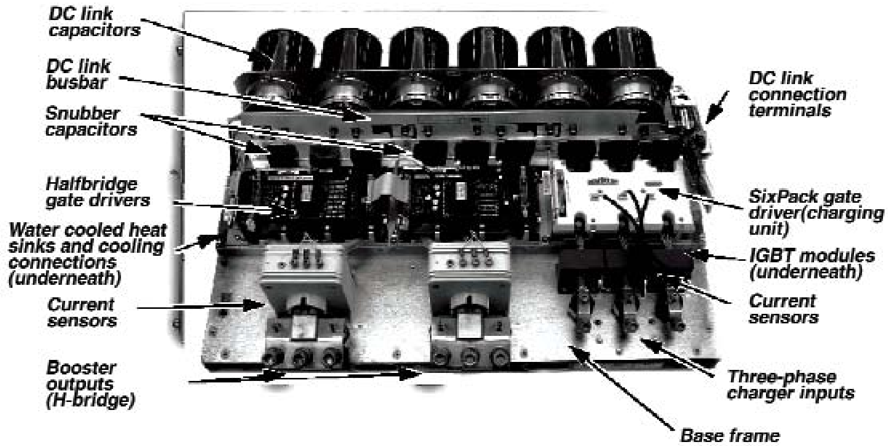

Figure 3. Power Electronic Building Block used in the SVR

Types of SVR

The SVR is a modular product family covering a nominal current range of 500 to 2500 A (at 400–600 VAC). The core components are the same for all sizes. Each type consists of up to four cabinets:

- One supply cabinet on the left hand side
- One or three power cabinets on the right hand side

This is illustrated in Figure 4.

Power Cabinet(s): The power cabinets are located to the right of the supply cabinet. The power cabinets contain:

- Charger input filter
- Charger input current measurement
- Charging transformer (One per power cabinet)
- Power Electronic Building Blocks (PEBB) including DC-link capacitors. Up to five PEBB modules are placed in each power cabinet.
- Booster output filter
- Cooling fan.

Supply Cabinet: The supply cabinet is located on the left hand side of the device and contains:

- Power cable connections
- Bypass and isolation breakers
- Crowbar (Fast acting anti-parallel thyristors)
- Grounding isolator
- Control equipment
- User Interface, process panel and emergency bypass button
- Cooling fan
- Auxiliary voltage supply and back-up batteries.

SVR Cooling

Water Cooling

The SVR is equipped with a water-cooling circuit for the main power components. Auxiliary air-cooling, by means of two fans inside the cabinets, is used for cooling the control equipment and other components. Figure 5 shows the actual water-cooling system used by the SVR. The power required for the cooling system is provided by the SVR output.

Air Cooling

The SVR is equipped with forced air-cooling. The air intakes are located in the cabinet front doors. They are equipped with filter mats to minimize air pollution in the converter. From the door intakes, the air flows through the cabinets and is then routed to the exhausts located on top of the cabinets. The exhausts contain one fan each. They are covered to protect the equipment inside. The filter mats can be replaced from outside while the SVR is in operation. Figure 6 shows the air inlets and the air outlets which provide the air circulation in the SVR.

SVR Characterization Tests

The following section covers the tests conducted on a 1.25MVA, 400V, SVR (Series Voltage Restorer) unit. Characterization tests highlight most of the common, and in some cases the extreme, conditions that may occur in typical manufacturing plants such as semi-conductor fabrication, glass manufacturing, and plastics manufacturing. The characterization tests bring out the ability of the device to handle extreme conditions in a plant. Additionally, the characterization tests provide information that may help the customer to evaluate the suitability of this device in a particular facility. The following sections provide a brief description about the tests, procedures, and the results.

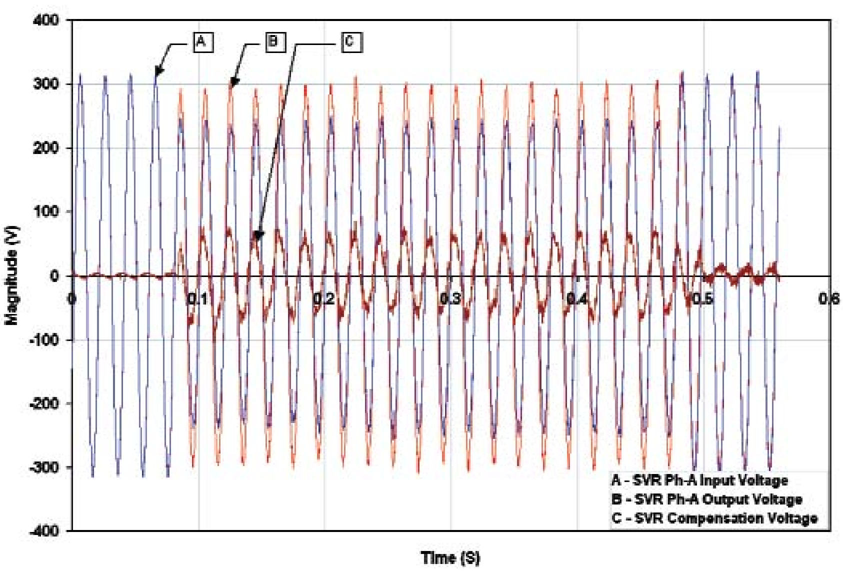

Figure 2. SVR voltage sag compensation

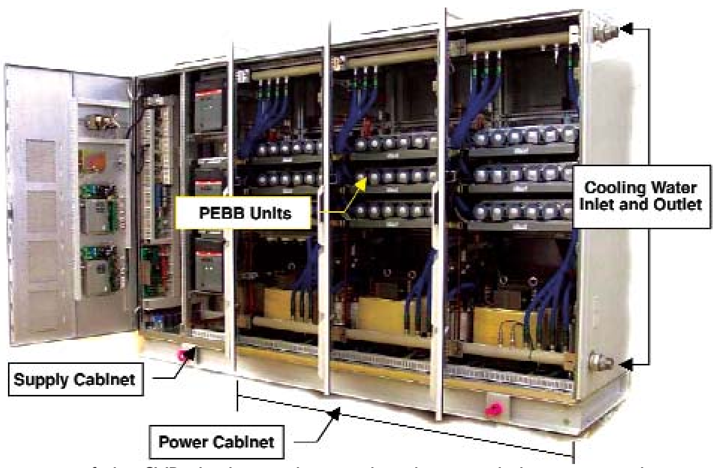

Figure 4. Front view of the SVR displaying the supply cabinet and the power cabinets

Figure 5. Water-cooling system used by the SVR

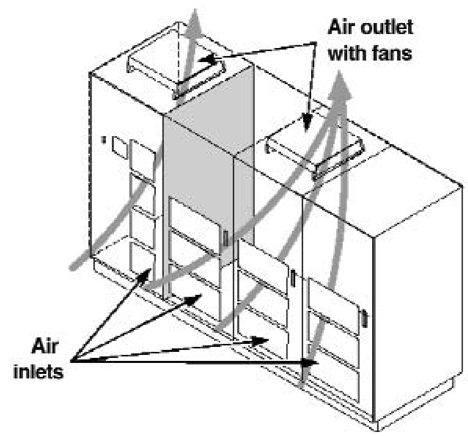

Figure 6. Forced air-cooling in the SVR

Some of the main characterization tests are:

- Voltage sag and swell tests
- Steady state over voltage and under voltage test
- Input source voltage unbalance test
- Post sag current inrush test

A 200 A portable sag generator was used to conduct the tests. Because of the limitation of the availability of a sag generator with the current rating of the SVR, all the tests were conducted only at partial load conditions. The following sections provide a brief description about the tests, procedures, and the results.

Test Description

Objectives

The objectives of the characterization tests are:

1. To characterize the performance of the SVR by conducting various rigorous tests such as voltage sag tests, swell tests, voltage unbalance test, and steady state under and over voltage tests.
2. To verify that the SVR meets the specifications set forth by the manufacturer
3. To test the control strategy used for the SVR
4. To uncover any application issues that will be important to the end user

Procedure

The test setup of the characterization tests conducted on the SVR is shown in Figure 7. The 380-V, 50 Hz utility feeder bus provides the input to the 200A portable sag generator. The output of the portable sag generator provides the input to the SVR. The output of the SVR then supplies the resistive load. The three phase SVR does not require a neutral, therefore if the load needs a neutral then the neutral conductor from the load is tied to the utility neutral. However, the SVR requires a neutral conductor just for the control system to determine the instrument references.

The portable sag generator has an inbuilt data acquisition system that is capable of measuring and recording the input and output voltage waveforms. However, precision instruments were also used to accurately capture the input and output waveforms of the SVR.

Test Setup and Results

The results of the performance characterization tests along with their significance are described in this section. All the tests were conducted at partial load conditions due to the high current capacity of the device under test (SVR). The test

- Momentary variation tests: Voltage sag and swell tests and response time
- Steady-state variation tests: Under voltage and over voltage tests
- Source voltage unbalance test
- Input current inrush tests

Momentary Variation Tests

Voltage Sag and Swell Tests

Momentary reductions in line voltage lasting several cycles or longer may occur during power system faults and when large loads are switched on. Voltage sags are one of the most common and most costly power quality issues in manufacturing environments. When voltage sags are severe enough to interrupt a manufacturing process, the common results are downtime, product waste, and a lengthy cleanup. A momentary increase in line voltage lasting several cycles can cause certain electronic equipment to respond by shutting down. Voltage swells can occur during power system faults or on secondary circuits in ungrounded systems. It is also possible for power lines to cross momentarily, causing a voltage swell.

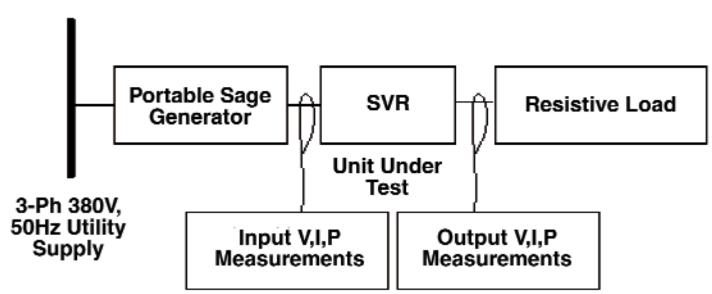

Figure 7. SVR characterization tests setup

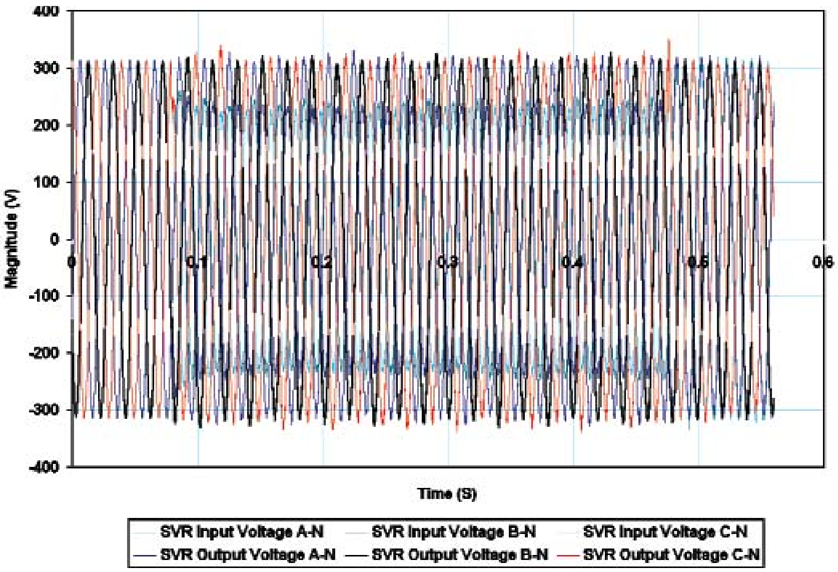

Figure 8. Input and output voltage waveforms of the SVR corresponding to a 3-phase balanced voltage sag down to 80% of the nominal voltage

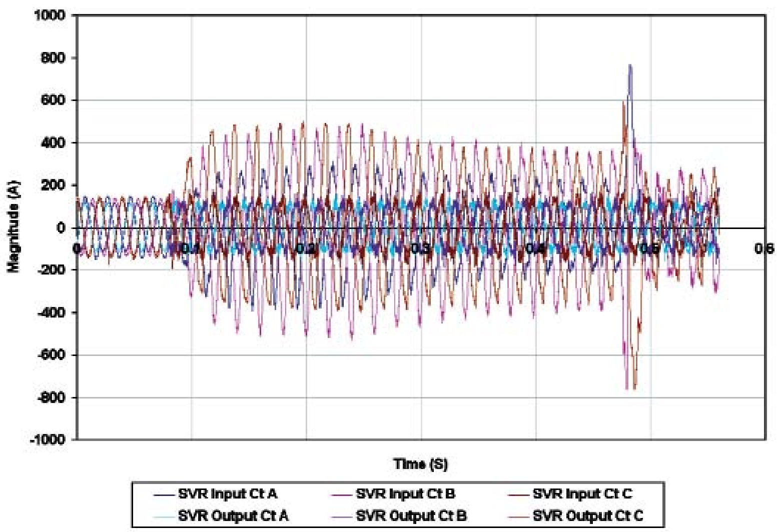

Figure 9. Input and output current waveforms of the SVR corresponding to 3-phase balanced voltage sag down to 80% of the nominal voltage

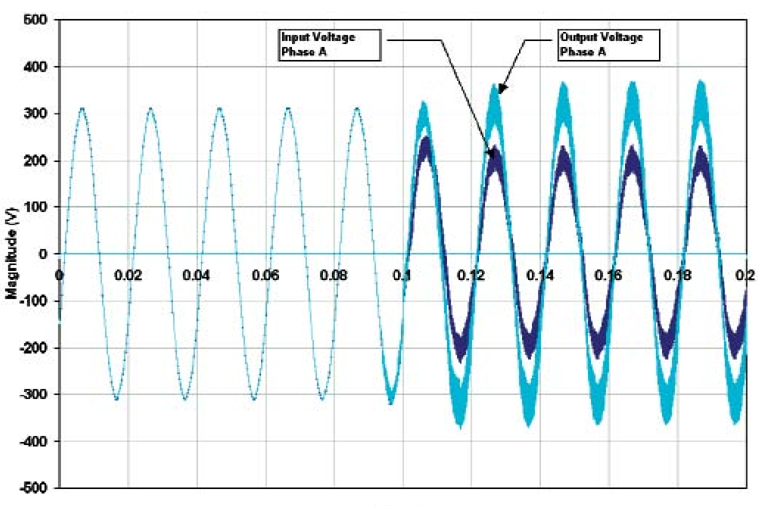

Figure 10. SVR voltage waveforms captured by an oscilloscope showing the switching noise during voltage sag correction

The SVR continuously monitors the input voltage on the three phases. Once the sag is detected the control circuit supplies the compensation voltage to all three phases separately. The sag is then corrected within a few milliseconds and the output voltage is restored to normal. Figure 8 shows the input and output voltage waveforms corresponding to a 3-phase balanced sag down to 80% of the nominal voltage. Figure 9 shows the input and output current waveforms corresponding to a 3-phase balanced sag down to 80% of the nominal voltage. However, one thing that has to be noted during the sag/swell correction is the high-frequency switching noise as shown in Figure 10. The switching noise during the voltage sag compensation may cause problems to the load, depending upon the sensitivity of the load.

When the SVR was tested for voltage swell correction, it didn't correct the voltage swells. However, since voltage swells are less common than the voltage sags and the loads are typically less vulnerable to voltage swells, the lack of correction may not pose a threat to the loads. The capability for swell correction will be available for future orders. Figure 11 shows the reaction of the SVR to the voltage swells. It can be clearly seen that the voltage swells are passed to the load without correction. Figure 12 shows the corresponding input and output current waveforms.

Response Time

Response time of the SVR is the time taken by the SVR controls to sense the onset of the voltage sag in the input voltage and to begin the injection of the correction voltage such that the output voltage of the SVR is within the specified voltage regulation. This is an important issue for standby-type power conditioners that have some transfer time because some sensitive loads can trip before the transfer is complete (less than one cycle). The response time of the SVR was found to be less than a quarter of a cycle. This can be seen from Figure 13, which shows the phase C response against the nominal phase C voltage if there was no voltage sag.

Steady State Variation Tests

Steady State Undervoltage and Overvoltage Tests

The objective of this test is to find out if the SVR can sustain the load if the utility supply has undervoltage or overvoltage for longer durations. Often the undervoltage and overvoltage may be in the range of ±10% of the nominal voltage. The SVR was able to mitigate the undervoltage and provide the load with corrected voltage. The option for overvoltage compensation is not yet available. Figure 14 shows a portion of the input voltage and current waveforms of the SVR corresponding to the steady state under voltage.

Source Voltage Unbalance Test Results

Voltage unbalance is characterized by the unequal magnitudes of the three phase voltages. ANSI C84.1 indicates an acceptable steady-state level of 3%. Unbalance that exceeds 3% can be problematic for three-phase motors, causing an increase in unbalanced current, which leads to overheating. Unbalanced voltages may typically be caused by the removal of individual capacitor banks for service or failure of a single-phase voltage regulator. Additionally, facilities can contribute to the unbalanced condition by unevenly distributing loads across phases. During the unbalance testing, the SVR was supplied with a 10% source voltage unbalance above and below the nominal voltage on phases A, B, and C to nominal. the SVR corrected the source voltage unbalance and the measured test results are given below:

- Baseline Unbalance = 1.4%
- Input Voltage Unbalance = 10%
  Phase A = 90%,
  Phase B = 100%,
  Phase C=100% of Nominal Voltage)
- Output Voltage Unbalance = 2.6%

Inrush Current Tests

Starting of a large motor load or energizing a transformer may cause inrush currents. There is another type of inrush current called the post-sag inrush current. If a power quality mitigation device is using a capacitor, either as an energy storage element or as a dc-link capacitor, the device experiences a high post-sag inrush current immediately after the sag event. This is due to the charging of the capacitors after the sag event due to the fact that the capacitors have been discharged., Figure 15 shows the magnitude of the inrush current on a short 20-cycle sag event down to 80% of the nominal voltage at light loaded conditions. The peak magnitude of the inrush current is as high as 7 times the normal current peak value. The magnitude of the inrush current depends on the depth of the voltage sag, duration of the sag and the loading of the SVR. It should also be noted that the inrush lasts only for half a cycle or less. The circuit breakers should be chosen such that they don't trip for this transient inrush condition. Inrush current can cause a voltage drop in the system and is a very critical parameter to consider when choosing a power conditioner.

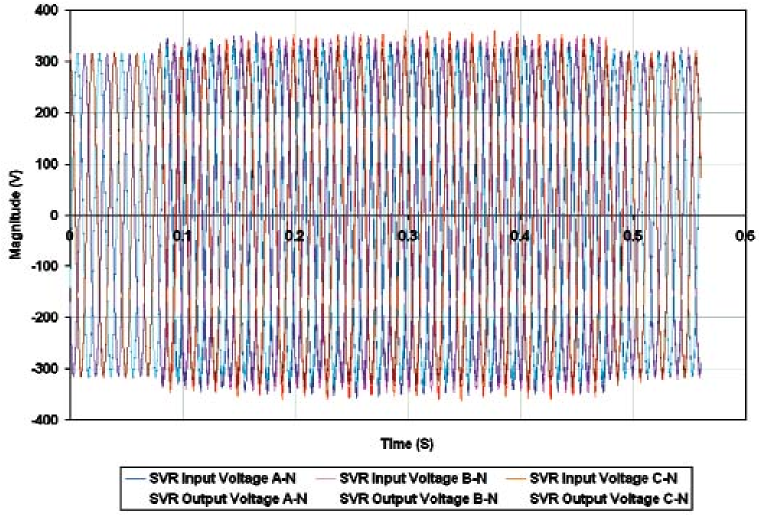

Figure 11. Input and output voltage waveforms of the SVR corresponding to 3-phase balanced voltage swells of 110% of the nominal voltage

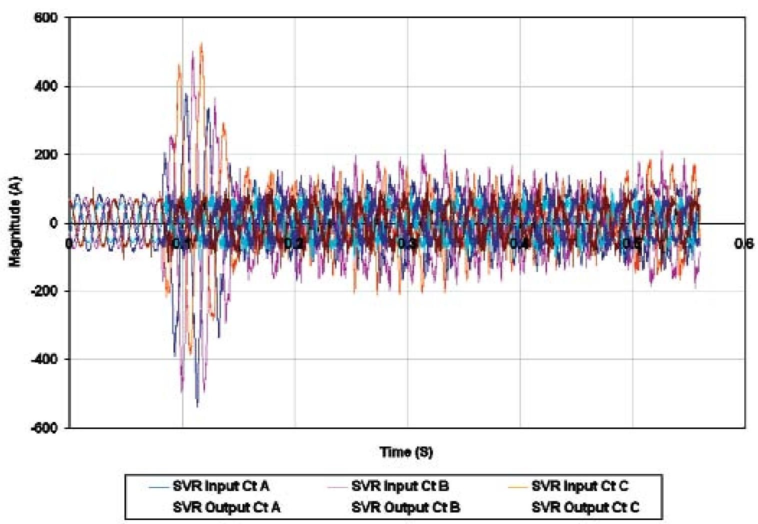

Figure 12. Input and output current waveforms of the SVR corresponding to 3-phase balanced voltage swells of 110% of the nominal voltage

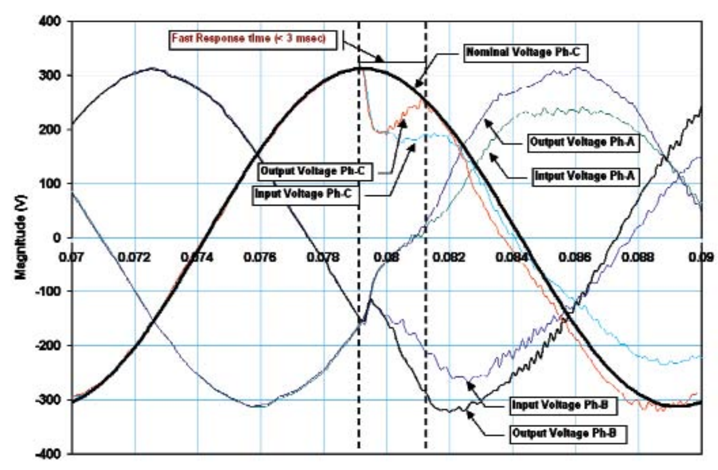

Figure 13. Response time of SVR

Knowledge of Equipment Versus Cost of Solution

Momentary voltage variations are the most common power quality problems that affect industrial customers. There are various causes for voltage sags, which include temporary loss of supply, short circuits, load switching, and power swings. Because of these voltage variations, there are many problems encountered by industries, such as:

- Dropout of contactors
- Tripping of variable-speed drives
- Dropout of PLCs
- Abnormal operation of protective relays

Any of these events can cause an unplanned shutdown of a process. In most cases, the prevention of the process shutdown or the dropout of contactors due to minor voltage variations may save industries significant amounts of money. This can be achieved by the use of ride-through devices, which protect the sensitive loads against momentary voltage fluctuations. The simplest approach to providing sag protection is to provide utility-level solutions; but the relative cost of such solutions can be on the order of millions of dollars. Protection can be achieved for much less inside the plant at the control level, but this requires more knowledge of the process and the equipment. Smaller, less expensive power conditioners can be applied if the process is well understood. Studies of process equipment can lead to a situation in which an SVR would be a viable option.

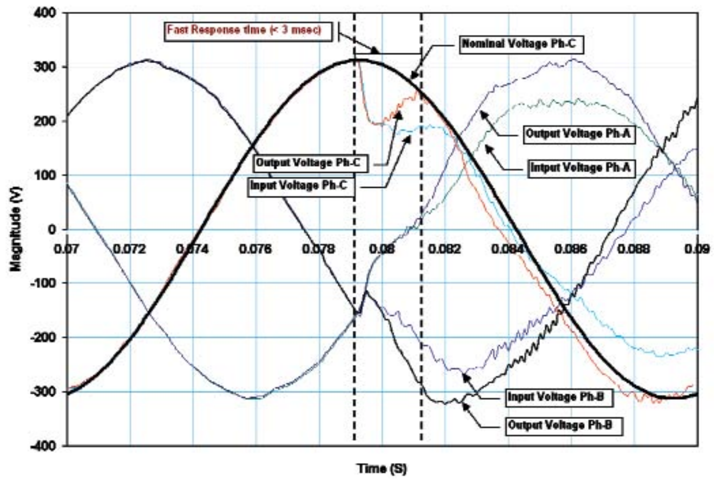

Figure 14. Input and output voltage waveforms of SVR corresponding to steady state undervoltage conditions

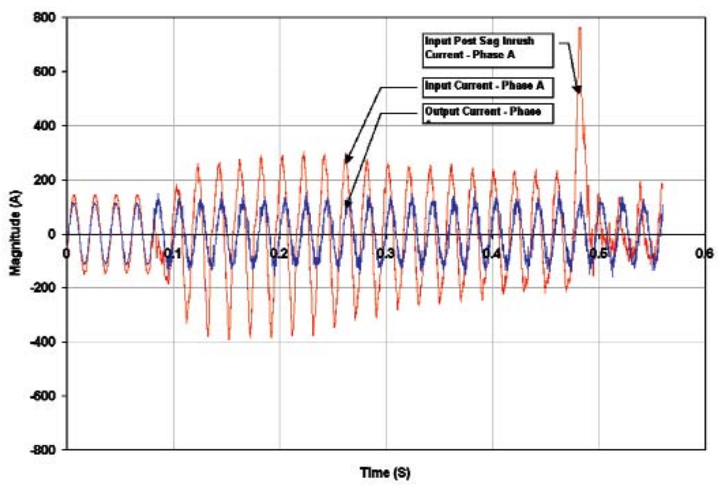

Figure 15. SVR post sag inrush current on phase A

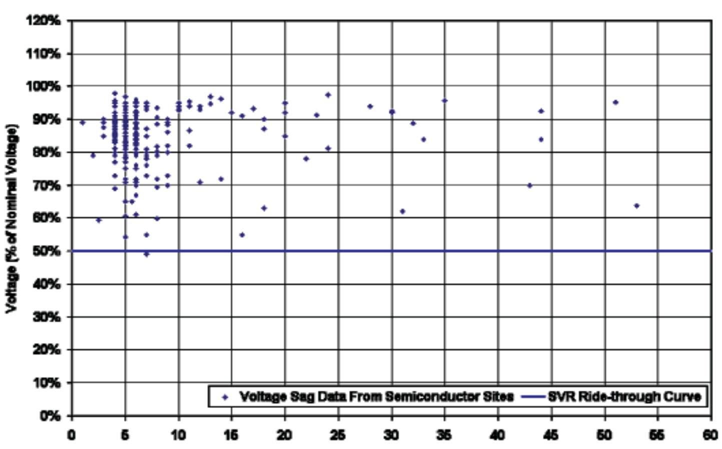

Figure 16. SVR ride through curve for single-phase voltage sags against actual semiconductor voltage sag data

Typical SVR Application

The SVR provides the optimum solution for the protection of sensitive manufacturing processes during partial and short duration voltage sags (e.g., caused by remote faults). Since the majority of disturbances cause only partial loss of power and not complete outages, the SVR is able to compensate up to 90 % of all faults in the electric grid. The SVR covers a power range up to 2500 A at 400–600 V and is used in 50 and 60 Hz supply systems. Figure 16 shows the voltage sag events (single and three phase) in a typical semiconductor plant and the ride-through curve of the SVR (single-phase). It can be seen that majority of the voltage sags lie within the time duration of 0 to 10 cycle and voltage magnitude of 70% to 95% of the nominal voltage. the SVR would be a good choice for any manufacturing plants that have similar voltage sag characteristics as shown here.

As an option, the SVR is capable of continuous voltage regulation and power factor correction.

The SVR is applied in a wide range of industries with complex continuous processes where even a short disturbance may result in several hours of production loss—the time needed to restart the process and to regain stable processing conditions. the SVR can be used both in different types of industries because of its versatility and some of them are mentioned below:

- Semiconductor fabrication plants
- Printing industry
- Textile and fiber spinning industries

- Glass and plastics production plants
- Pharmaceutical industries

Application Issues

The sections below describe some of the application issues found during the testing of the SVR. These application issues can be very useful to the customers who are evaluating the SVR for their industrial needs. In some cases, there may be other devices that are better suited to the application, based on performance characteristics and customer needs. The following are some of the key application issues associated with this device.

Wye-Connected Loads

The load side of the SVR provides the three phase voltages at the terminals U2, V2 and W2 as shown in Figure 17. At the bottom right side inside the supply cabinet the neutral terminal is placed to which the system neutral can be connected. The SVR does not provide a neutral on the load side, but requires a neutral connection on the source side for instrument reference. During the voltage sag correction, the SVR corrects the phase to neutral voltage. If the load is wye-connected load with a neutral connection, then the neutral can be carried through the SVR to the load.

EMI Noise Issues

There is a significant level of radiated and conducted noise that emanates from the SVR. The noise frequency is typically 10kHz and 15kHz corresponding to switching frequency of the power electronic devices inside the SVR. Please refer to Figure 10 to see the input and output voltage waveforms with noise. The noise appears in the waveforms only during the SVR correction process. The effect of this EMI noise on the load should be studied before purchasing the unit. However, using notch filters at the input and output side can reduce the effect of the noise on the load.

Diagnosis Software

the SVR is equipped with diagnosing software to determine fault conditions. The software is called DIAS, which stands for 'Diagnosis Information Analysis Software.' A feature of this software allows the user to communicate to the inbuilt computer through telephone lines. A transient recorder is also built inside the SVR and is capable of recording up to 16 channels. These 16 channels are fixed with certain monitoring parameters such as input voltage, current, temperature, etc. The data can be downloaded and used for diagnoses. The customer can also be set-up to receive emails regarding the SVR performance.

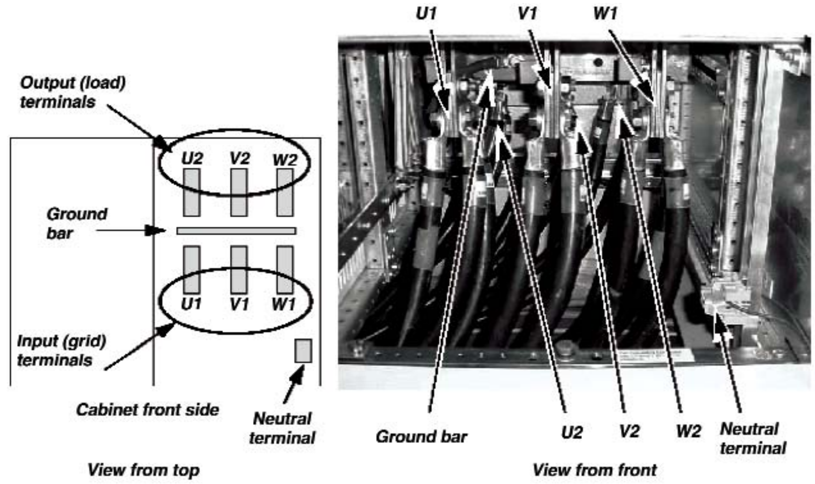

Figure 17. Input and output wire connection in the SVR

Installation and Maintenance Issues

The SVR comes with the default option of bottom access to the input and output connector cables. However the customer can specify to have the top-level access to cables based on the plant requirement.

The SVR has to be installed inside the facility. But because of the significant weight of the unit, about 4800 lbs for 500A unit to 11900 lbs for 2500A unit, the customer may opt to install the unit outside the facility. In that case, an enclosure has to be provided for the SVR.

The power electronic system used in the SVR is water-cooled. A separate water-cooling system is provided with the SVR main unit. Refer to Figure 5 to view the water-cooling system. If the customer chooses to install the SVR inside the facility the water-cooling system can be installed inside or outside the facility. No separate feeder is required for the water-cooling system. It gets power from the auxiliary power unit from the SVR. The cooling system motor pump requires approximately 4 amps during regular operation and 8amps during startup.

The SVR needs little maintenance once installed. However, if maintenance is needed then the bypass switches can be engaged (refer to Figure 1) to isolate the SVR from the load. Commissioning and service can be performed without disturbing the load downstream of the SVR with the help of the bypass and the isolation switches.

The typical time taken for commissioning a SVR unit is anywhere between 3 days to a week. During the commissioning time the customer may expect a down-time or interruption to the load for an hour or two.

Overloading Issues

CVR or continuous voltage regulation of the SVR is optional. If the customer chooses to have that option then there is one limitation that should be remembered. The thermal limit on the charging transformers will limit the time of continuous voltage regulation. If the thermal limits are reached then the SVR will automatically switch to bypass.

Circuit Breaker Issues

The bypass switch in the SVR can withstand up to 20 times the rated currents. Typically they can handle currents up to 65kAmp. In case of emergency or system failure in the SVR, the crowbar and bypass take the SVR out of circuit. The overcurrent protection in the SVR will trip the unit if the current limits are exceeded.

Comparison With Similar Power Conditioners

The comparison in Table 1 shows how the performance characteristics of the SVR compare with those of other three-phase power quality mitigation devices. Each has its specific advantages and disadvantages, and their use is application-specific. In order to properly specify the SVR, the user must study the process and acquire some knowledge of the equipment to be protected.

Summary

the SVR is a three-phase power quality mitigation device. It has many optional features like continuous voltage regulation, power factor correction etc., to enhance the capabilities of the SVR. The target industries for the SVR application are semiconductor fabrication plants, textile industries, crystal growth centers, plastic industries and pharmaceutical industries. The SVR is best suited for providing system-level protection to low voltage, high current processes and applications. It is available in the power range of 500A to 2500A at 400V to 600V. The SVR is suitable for both 50Hz and 60Hz operations. Though it cannot protect the critical loads from sustained interruptions with input voltage down to 0% of the nominal voltage, it can offer excellent sag protection to the loads with input voltages down to 50% of the nominal voltage. It can effectively handle sags without the help of any energy-storage devices. It has a fast response time to voltage sags, in the order of few milli seconds, so that the load will be protected from the voltage disturbances.

The results of the performance tests on the SVR conducted by EPRI Solutions were found to match the specifications provided by the manufacturer (ABB). The customer should however, pay close attention to the application issues listed in this document and should make sure that the issues do not affect his system before purchasing the SVR. Overall, the SVR would be a good choice for customers that are looking for a low-maintenance, no energy storage, three-phase power quality mitigation device to protect their system and processes from voltage fluctuations.

Table 1. Comparisons of Various Three-Phase Power Quality Mitigation Devices

Technology	Ride-Through (Sec)	Protection Voltage (% of nominal)	Active Voltage Regulation	Active Harmonic Compensation
Series Voltage Restorer	30	62% (3-ϕ) 50% (1-ϕ)	±2%during sags continuous voltage regulation is optional	Optional
Active voltage conditioner (AVC)	30	50% (3-ϕ) 25% (1-ϕ)	±1% up to 10% continuous 3-ϕ correction ± 2.5% at 30% 3-ϕ correction	No
CAT UPS/Caterpillar active power	15	0%	Yes	Yes
Flywheel UPS/Piller	12	0%	± 1% steady state with symmetrical load Regulation ± 5% dynamic for 50% load change	Harmonic attenuation >99% (input-to output and output-to-input)
Flywheel UPS/Hitec (with diesel engine)	2 (minimum)	0%	1% at steady state 5–10% at dynamic state	Max 4% (harmonic distortion with linear load)
Flywheel UPS/Precise Power (Written-Pole MG set)	12	0%	±5% of nominal voltage	NA
DySC/Soft Switching Inc	0.25	50%	+5% to -10% of nominal	NA

For More Information

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The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, CA, and Charlotte, NC, was established in 1973 as an independent, non-profit center for public interest energy and environmental research. EPRI brings together member organizations, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of power generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents over 10% of EPRI's total R&D program.

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