Innovative system solutions for power quality enhancement

The privatization of utilities and the deregulation of the electrical energy market have introduced a new level of competition to the energy supply business. At the same time, the increasing use of electronics in everyday appliances and apparatus, plus a proliferation of highly sensitive end-user devices, are starting to draw the attention of consumers and energy suppliers alike to the issue of power quality. Solid-state transfer switches as an alternative to in-house uninterruptible power supplies, distribution static synchronous compensators for reducing flicker produced by arc furnaces, and dynamic voltage restorers that avoid production losses caused by voltage sags, are among the innovative solutions addressing the question of power quality.

Power quality problems are caused by a wide range of phenomena. About two thirds of these are natural phenomena, such as lightning. Other sources of power quality disturbance, for example the operation of power system equipment (eg, capacitor switching) may be found in industry, or within the power system itself, where faults may cause a voltage sag at the consumer end.

IEC (1000-2-2/4) and CENELEC (EN50160) standards define power quality as the physical characteristics of the electrical supply provided under normal operating conditions that do not disrupt or disturb the customer's processes. UNIPEDE also includes the supply availability as part of this definition. Power consumers with sensitive or critical loads need a constant network supply voltage with a sinusoidal waveform at nominal frequency and magnitude. A power quality problem therefore exists if any voltage, current or frequency deviation results in maloperation or failure of a customer's equipment.

The growing concern about power quality stems from:

- Consumers becoming increasingly aware of the power quality issues and being better informed about the consequences of interruptions, sags, switching transients, etc. Motivated by deregulation, they are challenging the energy suppliers to improve the quality of power delivered.
- The proliferation of load equipment with microprocessor-based controls and power electronic devices which are sensitive to many types of power quality disturbances.
- Emphasis on increasing overall process productivity, which has led to the installation of high-efficiency equipment, such as adjustable speed drives and power factor correction equipment. This in turn has resulted in an increase in harmonics injected into the power system, causing concern about their impact on the system.

A low-quality power supply may cause disruption of a customer's process, leading to a loss of revenues. It is therefore in the interest of customers to ensure that the process downtime caused by poor power quality is minimized. Conversely, a customer's process may affect the supply quality, and it is in the interest of the utility that this effect be minimized. To improve power quality, a partnership that brings together the customer, utility and equipment manufacturer is clearly needed.

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Problem areas in power quality

Power quality problems are evident in many commercial, industrial, residential and utility networks. As mentioned above, natural phenomena, such as lightning, are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply, eg when capacitors are switched, also contribute substantially to power quality disturbances. The most significant and critical power quality problems are, however, voltage sags or complete interruptions of the energy supply [1].

The CBEMA curve published by Technical Committee 3 (TC3) of the Information Technology Industry Council, formerly known as the Computer & Business Equipment Manufacturers Association 1, indicates the magnitude and duration of undesired events and is widely used by industry to measure the performance of all types of equipment and power systems. Points below the envelope will cause the load to drop out, while points above the curve can cause other equipment malfunctions, such as insulation failures, overvoltage trip or overexcitation. The CBEMA curve is a standard design target for all sensitive equipment intended to be operated on the power grid.

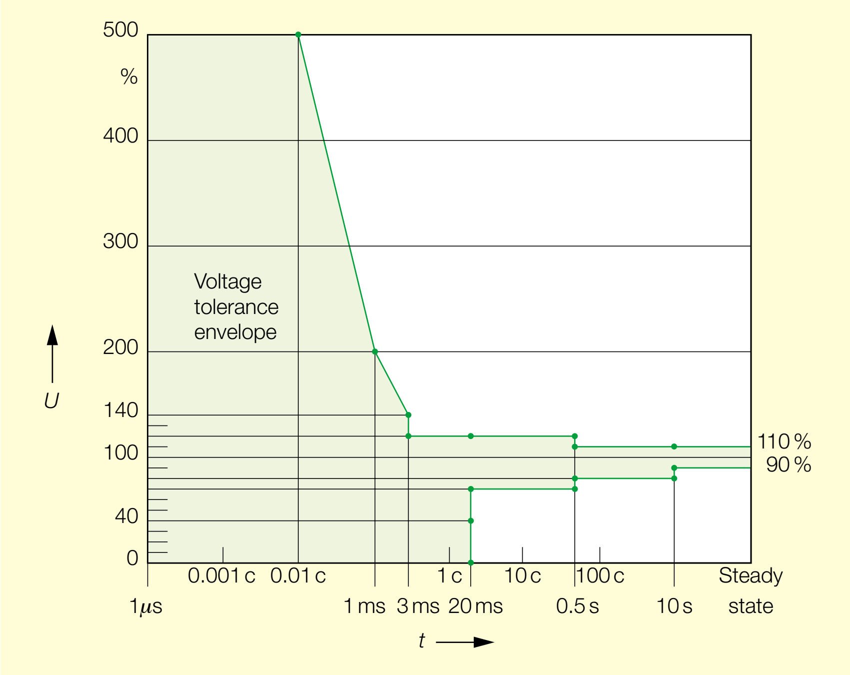
IEEE Standards Coordinating Committee 22 (Power Quality) as well as other international committees recommend that the following technical terms be used to describe main power quality disturbances **2**:

Sags

A decrease in rms voltage or current at power frequency for durations of 0.5 cycles to 1 minute. A voltage sag to 10 % means that the line voltage is reduced to 10 % of the nominal value. Typical values are 0.1 to 0.9 pu.

Interruptions

The complete loss of voltage (below 0.1 pu) on one or more phase conductors for a certain period of time. Momentary interruptions are defined as lasting between 0.5 cycles and 3 s, temporary interruptions have a time span between 3 s and 60 s, and sustained interruptions last for a period longer than 60 s.



The CBEMA curve indicates the magnitude and duration of voltage tolerances for all types of equipment. It is used widely in industry for performance measurements. **1**

U Voltage

t Time in cycles (c) and seconds (s)

Swells

A temporary increase in rms voltage or current of more than 10 % of the nominal value at power system frequency which lasts from 0.5 cycles to 1 minute. Typical rms values are 1.1 to 1.8 pu.

Transients

These pertain to or designate a phenomena or quantity varying between two consecutive steady states during a time interval which is short compared with the time scale of interest. A transient can be a unidirectional impulse of either polarity, or a damped oscillatory wave with the first peak occurring in either polarity.

Overvoltage

When used to describe a specific type of long-duration variation, this refers to a voltage having a value greater than the nominal voltage for a period of time greater than 1 minute. Typical values are 1.1 to 1.2 pu.

Undervoltage

Refers to a voltage having a value less than the nominal voltage for a period of time greater than one minute. Typical values are 0.8 to 0.9 pu.

The most significant waveform distortions associated with poor power quality **2**

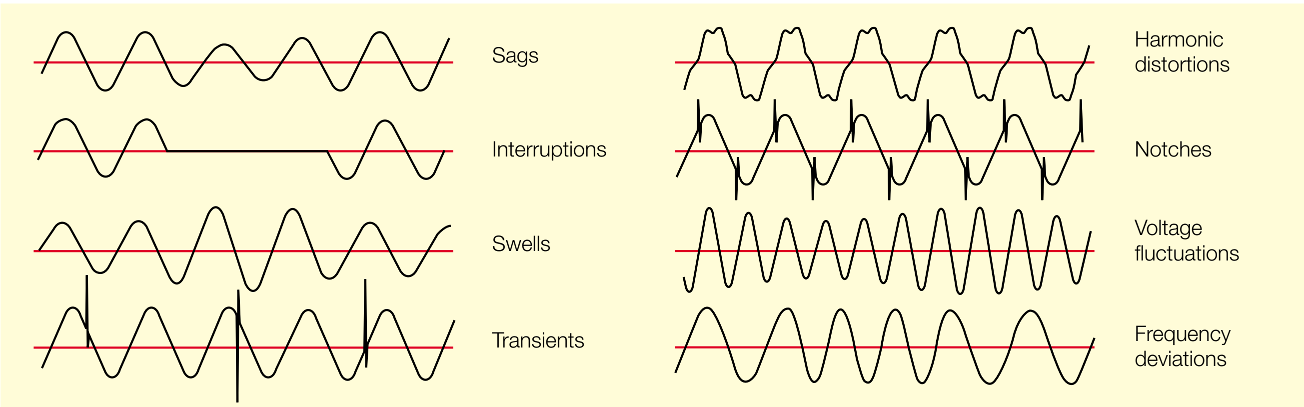


Table 1:
Power quality problems and available mitigation devices

Mitigation devices	*Sags*	*Interruptions*	*Swells*	*Transients*	*Overvoltage*	*Undervoltage*	*Harmonics*	*Notches*	*Voltage fluctuations*
SA				✓					
BESS	✓	✓	✓	✓	✓	✓			✓
DSTATCOM				✓	✓	✓			✓
DSC						✓			✓
DVR	✓		✓	✓			✓		✓
PFCC					✓	✓			
SMES	✓	✓	✓	✓	✓	✓			✓
SETC	✓		✓		✓	✓			
SSTS	✓	✓	✓						
SSCB		✓							
SVC	✓		✓		✓	✓			✓
TSC				✓		✓			
UPS	✓	✓	✓		✓	✓			
APF(TF)				✓			✓	✓	

APF(TF) = Active power filter or tuned filter
BESS = Battery energy storage system
DSTATCOM = Distribution static synchronous compensator
DSC = Distribution series capacitor
DVR = Dynamic voltage restorer
PFCC = Power factor correction capacitor
SA = Surge arrester
SMES = Superconducting magnetic energy storage system
SETC = Static electronic tap changer
SSTS = Solid-state transfer switch
SSCB = Solid-state circuit-breaker
SVC = Static var compensator
TSC = Thyristor switched capacitor
UPS = Uninterruptible power supply

Harmonics

Sinusoidal voltages or currents having frequencies that are multiples of the fundamental power frequency. Distorted waveforms can be decomposed into a sum of the fundamental frequency wave and the harmonics caused by nonlinear characteristics of power system devices and loads.

Table 2:
Customers with sensitive or critical processes

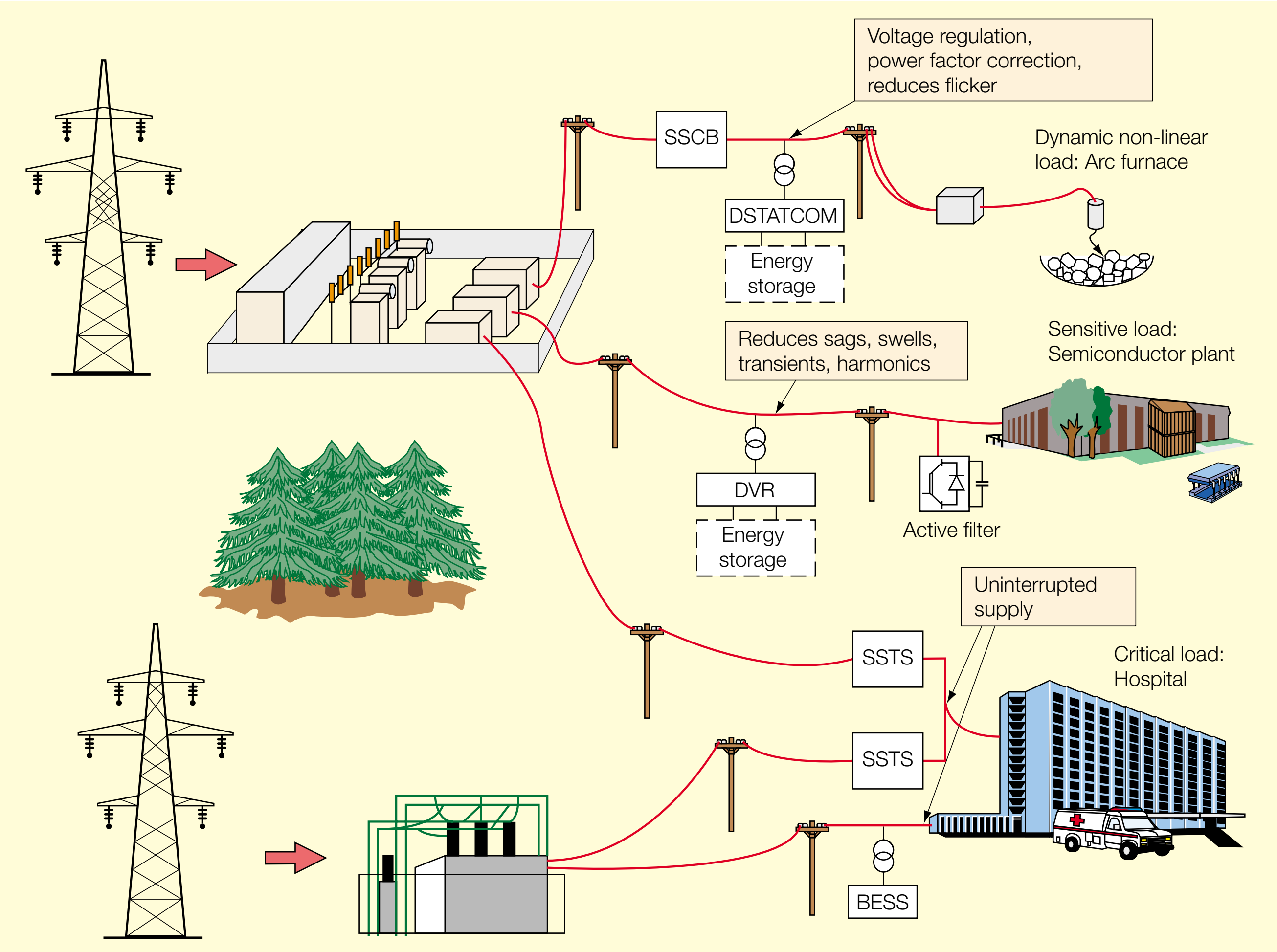
Industry segment	*Industrial process*
Continuous process	Paper, fiber and textile factories Plastics extruding or moulding plants
Precision machining	Automobile parts manufacturing Large pump forging factories
High-technology products and research	Semiconductor manufacturing Particle physics research centers
Information technology	Data processing centers Banks Telecommunications Broadcasting
Safety and security related	Hazardous process Chemical processing Hospitals and health care facilities Military installations Power plant auxiliaries Large transmission substations

Interharmonics

Voltages and currents having frequencies that are not integer multiples of the fundamental power frequency. Interharmonics are mainly caused by static frequency converters, cycloconverters, induction motors and arcing devices, and can have the effect of inducing visual flicker on display units. Power line carrier signals are also considered as interharmonics.

Notches

Periodic voltage disturbances lasting less than 0.5 cycles. Notching is caused mainly by power electronics devices when the current is commutated from one phase to another during the momentary short circuit between the two participating phases. Frequency components associated with notching can therefore be very high, and measuring with harmonic analysis equipment may be difficult.



Innovative ABB power quality mitigation devices **3**

BESS *Battery Energy Storage System*
DSTATCOM *Distribution Static Synchronous Compensator*
SSTS *Solid-State Transfer Switch*
DVR *Dynamic Voltage Restorer*
SSCB *Solid-State Circuit-Breaker*

Voltage fluctuations

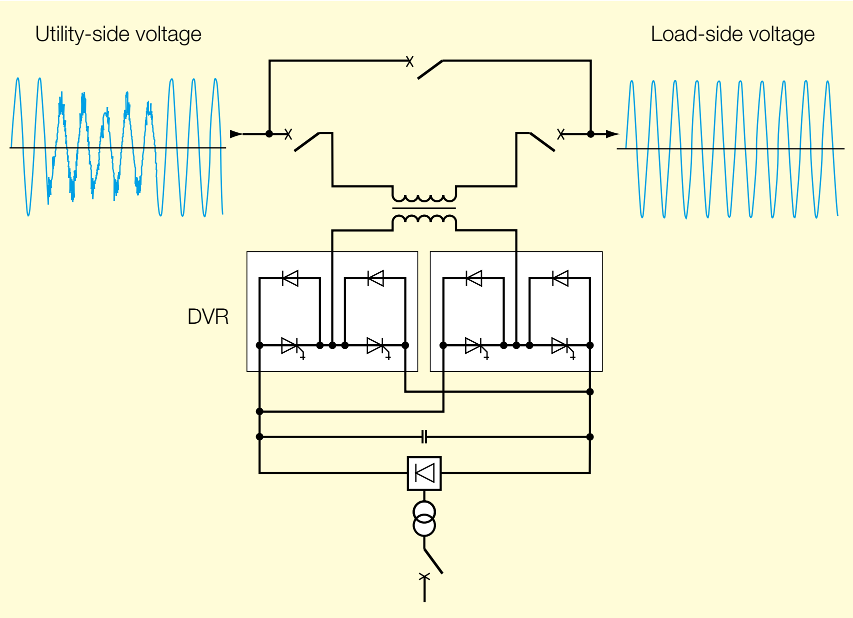
Voltage fluctuations are systematic variations in the envelope or a series of random voltage changes with a magnitude which does not normally exceed the voltage range of 0.9 to 1.1 pu. Such voltage variations are often referred to as flicker. The term flicker is derived from the visible impact of voltage fluctuations on lamps. Among the most common causes of voltage flicker in transmission and distribution systems are arc furnaces.

Innovative and conventional technologies for the mitigation of power quality problems

There are two general approaches to the mitigation of power quality problems. One, termed load conditioning, is to ensure that the process equipment is less sensitive to disturbances, allowing it to ride through the disturbances. The other is to install a line conditioning device that suppresses or counteracts the disturbances.

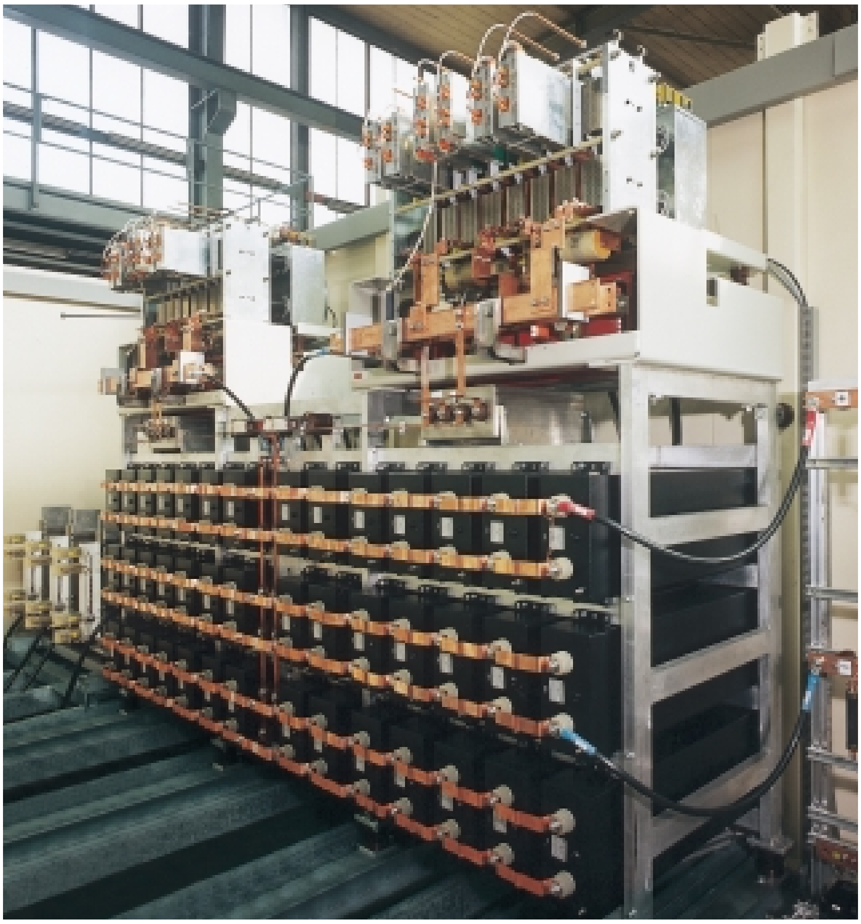
Commercially available mitigation devices tend to protect against a group of power quality disturbances. Mitigation devices vary in size and can be installed at all voltage levels of a power system (HV, MV and LV). The mitigation device and point of connection is chosen according to its economic feasibility and the reliability that is required. Innovative solutions employing power electronics **3** are often applied when rapid response is essential for suppressing or counteracting the disturbances, while conventional devices (eg, switched capacitor banks) are well suited for steady-state voltage regulation. An overview of the power quality problem areas and their possible solutions is given in *Table 1*.

For simple load applications, selection of the proper mitigation device is fairly straightforward. However, in large systems with many loads all aspects of the power system must be considered carefully. Also, when dealing with large systems it is



Mitigation of voltage sags with the Dynamic Voltage Restorer (DVR) **4**

State-of-the-art IGCT-based voltage source converters of a DVR mounted on capacitor banks **5**



necessary to know the different sensitive load requirements. Furthermore, consideration must be given to the potential interaction between mitigation devices, connected loads and the power system [2].

Application and examples of power quality devices

Poor power quality can cause unscheduled shutdown of industrial processes or equipment failure, resulting in substantial costs for customers. The industries affected are many and varied. A list of some of the industrial segments and related processes that are prone to power quality disturbances is given in *Table 2*.

Voltage sag mitigation with a dynamic voltage restorer

Semiconductor manufacturing plants have sensitive equipment that can be shut down or may be disturbed by momentary sags of the supply voltage due to faults on the utility side. To ensure that the production process is not interrupted during sags, a power quality device, such as the Dynamic Voltage Restorer (DVR), can be installed to mitigate this problem [3]. As shown in **4**, the DVR can respond within sub-cycles to a fault on the utility side, in effect shielding the customer from the fault.

To be able to mitigate voltage sag, the DVR must be capable of rapid control response and feature both an energy source and transformer for coupling the boosting voltages that provide the compensation.

The key components of the DVR **4** are:

- Switchgear
- Booster transformer
- Harmonic filter
- Two IGCT voltage source converters
- DC charging unit
- Control and protection system
- Energy source, eg a storage capacitor bank

As long as the power supply conditions remain normal the DVR operates in low-loss standby mode, with the converter side of the booster transformer shorted. Since no voltage source converter (VSC) modulation takes place, the DVR produces only conduction losses. Use of Integrated Gate Commutated Thyristor (IGCT) technology minimizes these losses [4].

When a voltage sag (or swell) occurs on the line side, the DVR responds by injecting three single-phase AC voltages in series with the incoming three-phase network voltages, compensating for the difference between faulted and prefault voltages. Each phase of the injected voltages can be controlled independently (ie, their magnitude and angle). Active and reactive powers required for generating these voltages are supplied by two pulse-width modulated (PWM) voltage source converters fed from a DC link as shown in 5.

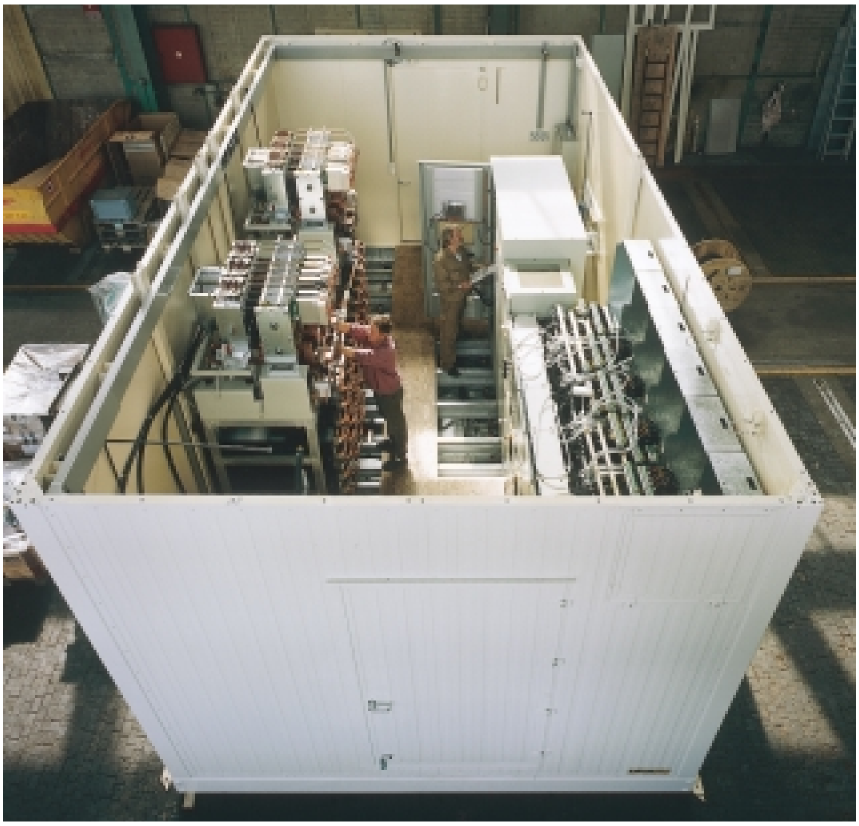
A medium-voltage, container-based DVR installation for a 4-MVA load 6 provides further flexibility by facilitating relocation and therefore maximum utilization of the investment.

To ensure that the DVR is capable of meeting the specified requirements, its dynamic performance and the control system functions must be verified using a real-time analogue simulator. The control system is a replica of the one to be used in the customer's installation.

The voltages on the network and load sides for a simulated 38 % voltage sag are shown in 7. The sag occurs at the instant the voltage peaks on one phase. The fault is cleared by the system protection after three cycles, with the supply voltages recovering to prefault levels. The DVR then returns to its standby operating mode. The load-side voltages remain at prefault levels for the duration of the fault, highlighting the rapid control response of the DVR. Good agreement between the calculated voltage values and the assessment carried out with a hardware-based model provide further verification of the system's design and performance.

Flicker compensation and energy supply with DSTATCOM

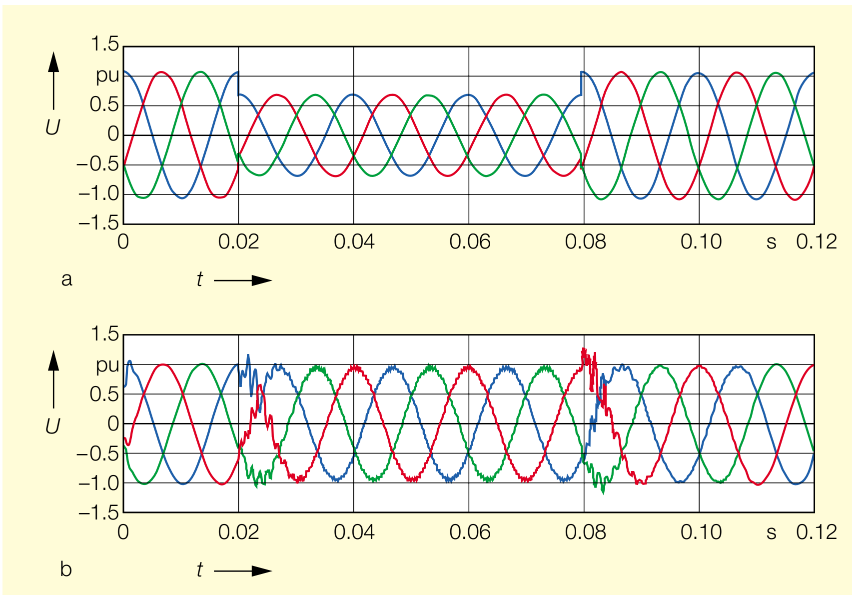
The DSTATCOM is a shunt-connected device based on pulse-width modulated (PWM) voltage source converters. Accord-

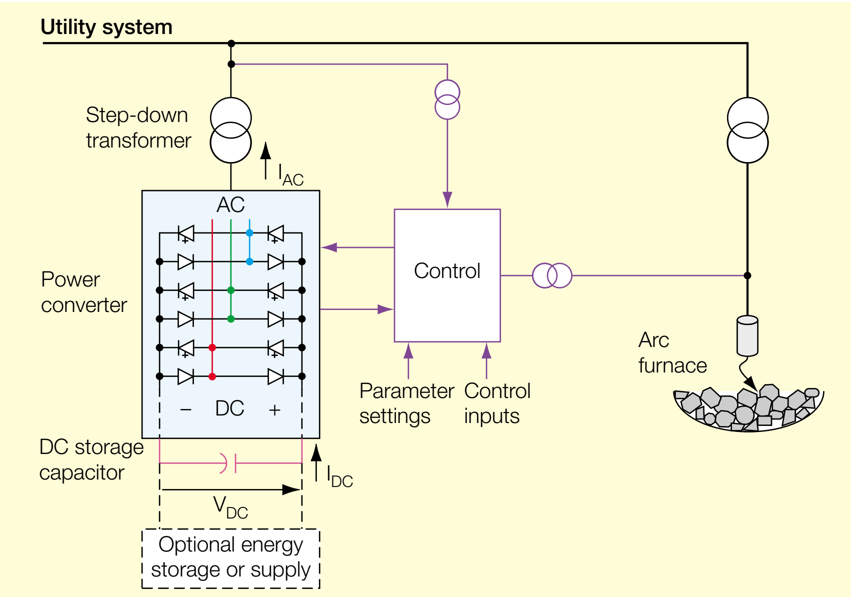


Container-based DVR guaranteeing a reliable supply and enhanced power quality for a 4-MVA semiconductor manufacturing plant 6

Calculated per-unit voltages on the network (a) and load side (b) during a three-phase voltage sag, with the DVR in operation 7

U *Input (a) and output (b) voltage of DVR*
t *Time*





Arc furnace load compensation by means of a distribution static synchronous compensator (DSTATCOM) **8**

ingly, it replaces conventional voltage and reactive power control elements. It can improve the voltage profile along feeders, reduce losses and is also capable of compensating for real power fluctuations on account of the presence of an energy storage system connected to the DC side.

Under normal power supply conditions, the DSTATCOM operates as a reactive power source or in low-loss standby mode. When voltage fluctuations occur, the DSTATCOM responds by injecting currents with the proper phase angle and magnitude.

The non-linear nature of arc furnace loads has a substantial influence on the quality of the power supply. Power fluctuations due to arc furnace operation cause unwanted, visible voltage flicker effects. The DSTATCOM solution shown in **8** can be applied to restore power quality in such situations. A DSTATCOM is able to meet the demanding flicker attenuation requirements with a response of an order of magnitude faster than with more conventional devices. Furthermore, the DSTATCOM does not contribute to resonant interaction in the AC system.

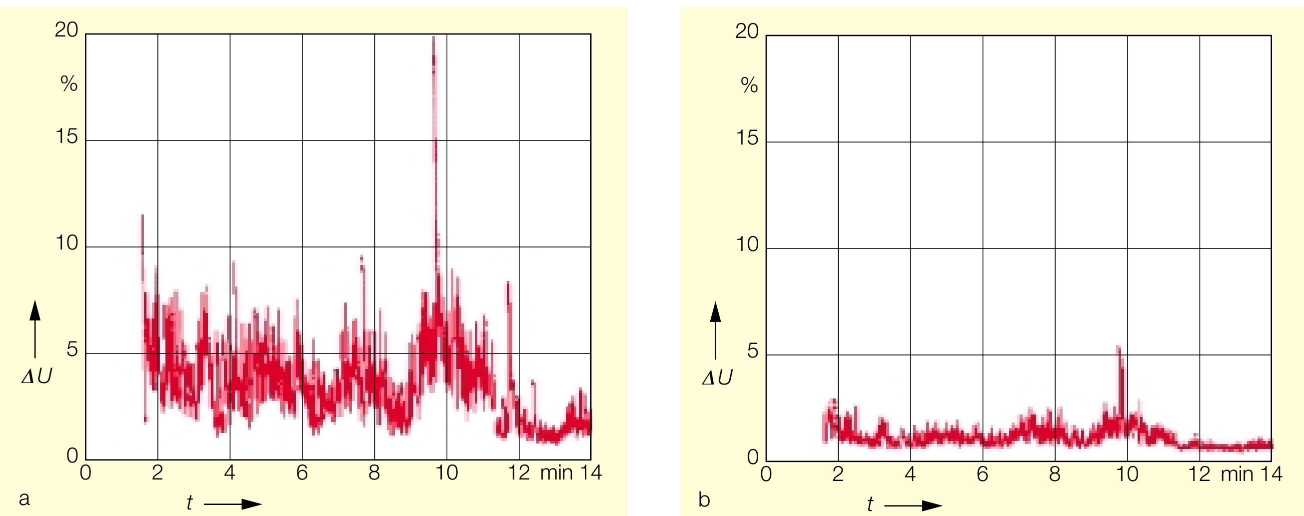
Flicker recordings of an arc furnace load that show the effect of using a DSTATCOM are given in **9**. It can be seen that the variations in voltage are effectively attenuated when a DSTATCOM is installed.

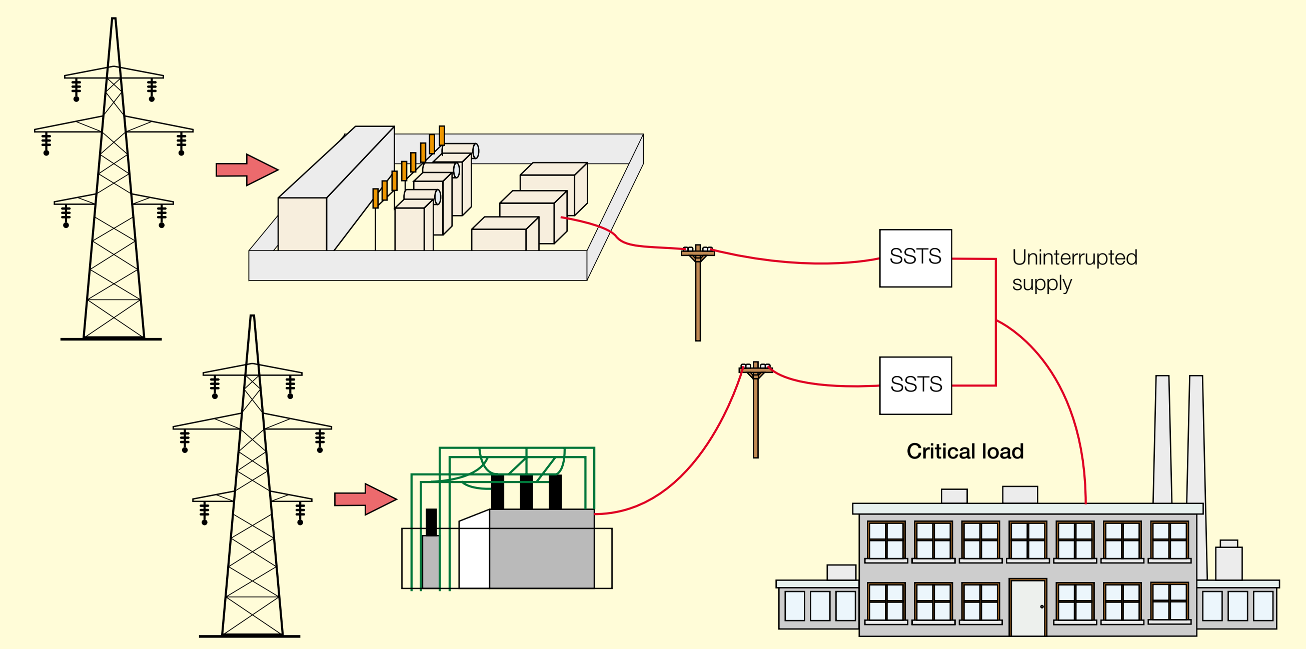
A DSTATCOM coupled with a Solid-State Circuit-Breaker (SSCB) and an energy storage system (eg, BESS), is also advantageous. If an SSCB is installed between the incoming supply and the critical load bus, and a DSTATCOM equipped with an energy storage system such as BESS is operated in parallel on the load bus, full support can be provided during temporary supply interruptions. The SSCB immediately isolates the critical load from the fault and the DSTATCOM supports the load with energy from the storage system.

Flicker (voltage variations) associated with arc furnace operation **9**

a *Without mitigation device*
b *With DSTATCOM*

ΔU *Voltage variation*
t *Time*





Mitigation of momentary, temporary and sustained supply interruptions by a solid-state transfer switch (SSTS) **10**

Solid-state transfer switch for mitigation of supply interruptions

The Solid-State Transfer Switch (SSTS) is designed to replace the mechanical auto-transfer equipment currently used to switch major industrial and commercial facilities from one feeder to another – a process that typically takes 0.5 to several seconds. An SSTS can also provide companies with a cost-effective alternative to an inhouse uninterruptible power supply system.

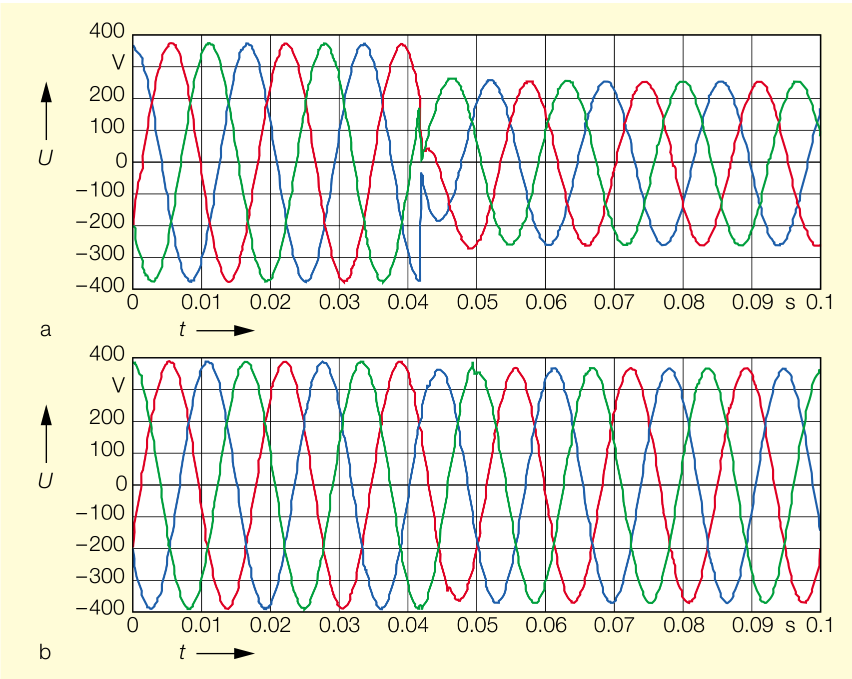
A typical application for an SSTS in a utility-provided power quality solution is shown in **10**. A sensitive consumer is fed via a radial line by a utility operating an isolated medium-voltage network. In the event of disturbances in the supply network an attempt is made to clear the fault through auto-reclosure. However, the brief interruption of supply power would be sufficient to trip the consumer's equipment, resulting in production downtime. A secondary independent feeder with sufficient capacity is available in parallel with the primary line. If auto-reclosure is initiated in the medium-voltage network, the SSTS will immediately transfer the sensitive load to the secondary supply.

During normal operation, the switch connected to the primary feeder is kept closed and the switch on the secondary feeder is kept open. If a disturbance such as a voltage sag, short-circuit or outage occurs on the primary line, the load is transferred to the secondary feeder within milliseconds.

In order for the SSTS to be effective, the distribution system in which it is to be installed has to meet certain requirements:

Primary (a) and load feeder (b) voltages in the case of a system fault **11**

U *Voltage*　　*t* *Time*



- Two feeders from different substations
- Spare distribution capacity in the back-up feeder
- Spare distribution capacity in the substation
- Reliable transmission with good power quality

Curves obtained from computer simulation of the SSTS 11 show the voltages of the primary load feeder and the load bus during a three-phase fault. Transfer of the load from the faulted feeder to the secondary feeder occurs immediately and with no adverse effect on the load.

Metal oxide surge arresters for transient overvoltage protection

Protection against transient overvoltages due to lightning strikes or switching of equipment plays an important role in improving the quality of the power supply.

Modern metal oxide surge arresters 12 reduce the transient overvoltages to under 1.5 per unit of the rated system voltage. They are therefore ideal for transient overvoltage limitation in transmission and distribution systems, and make an important contribution to power quality enhancement for both the high and the low voltage ranges [5].

Innovative system solutions – the key to cost-effective power quality enhancement

High power quality requires the physical characteristics of the electrical supply under normal operating conditions to neither disrupt nor disturb the customers' processes. Increasingly, national and international standards are adopted which describe levels which are acceptable for different types of disturbances in the electrical supply.

Statistics show that the disturbances causing the most frequent process outages, and hence substantial economic losses, are sags and interruptions. Concern about power quality is being driven by the deterioration of power quality levels as a result of deregulation, more sensitive loads, and the increase in processes based on power electronics.

POLIM® medium-voltage surge arresters for transient overvoltage protection 12

IGCTs have been chosen for the voltage source converters used in the ABB power quality solutions described. These newly developed power electronics devices unite the benefits of Gate Turn-Off (GTO) thyristors with the strengths of the Insulated Gate Bipolar Transistor (IGBT). The IGCT has the advantage of low losses when conducting like a thyristor and the excellent switching capabilities of an IGBT. IGCT-based converters are available for a wide range of powers from 0.5 MW to 100 MW with series-connected devices. In addition, IGCTs ensure:

- High converter reliability due to the use of a small number of field-proven components (MTBF ≥ 20 years).
- High converter efficiency in steady state operation. The total converter losses are only a very small fraction of the equipment rating.
- Inherent safety: even under worst-case conditions IGCTs will not open, but short the circuit, and are able to conduct currents far in excess of expected fault levels.

Power quality issues will become an increasingly important factor in the global economy. ABB High Voltage Technologies is well placed to provide power quality mitigation system solutions that address these issues cost-effectively through the use of innovative technologies.

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