INNOVATIVE SYSTEM SOLUTIONS FOR POWER QUALITY ENHANCEMENT

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INTRODUCTION

The privatization of utilities and 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. 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 discussed that address the question of power quality. This paper will also include a discussion on cost/benefit assessment of system solutions for improving the quality of power.

Power quality problems are caused by a wide range of phenomena. Many of these are natural causes, such as lightning. Other sources of power quality disturbance, for example the operation of power system equipment 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 comes 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 the 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.

PROBLEMS 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, e.g. 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 shown in Figure 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 may cause the load to drop out, while points above the curve can cause other equipment malfunctions, such as insulation problems, overvoltage trip or overexcitation. The CBEMA curve is a standard design target for all sensitive equipment intended to be operated off the power grid.

IEEE Standards Coordinating Committee 22 (Power Quality) and other international committees recommend that the following technical terms be used to describe main power quality disturbances shown in Figure 2.

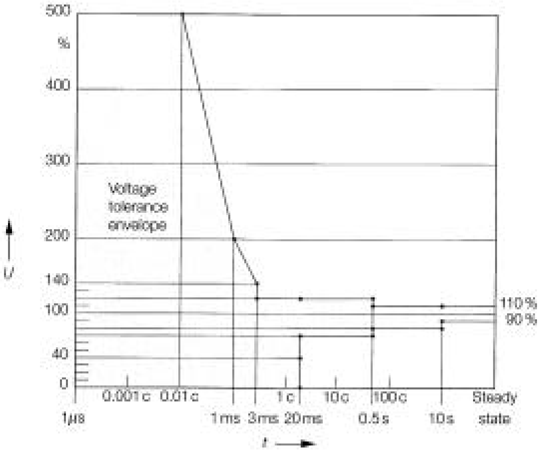


Figure 1: The CBEMA curve indicates the magnitude and duration of voltage tolerances for all types of equipment.

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.

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.

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.

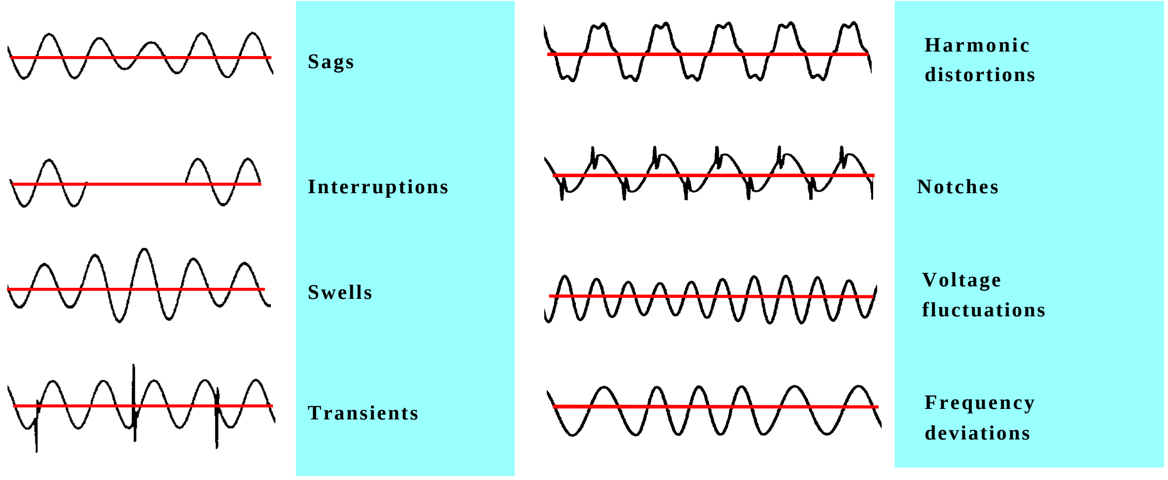


Figure 2 : Most significant waveform distortions associated with poor power quality

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.

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 ranges 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 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 are often applied when rapid response is essential for suppressing or counteracting the disturbances, while conventional devices (eg, power factor correction capacitors) 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 necessary to know the different sensitive load requirements. Consideration must also be given to the potential interaction between mitigation devices, connected loads and the power system [2].

Mitigation devices	**Sags**	**Interruptions**	**Swells**	**Transients**	**Over-voltage**	**Under-voltage**	**Harmonics**	**Notches**	**Voltage fluctuations**
SA				✓					
BESS	✓	✓	✓	✓	✓	✓			✓
DSTATCOM				✓	✓	✓			✓
DSC						✓			✓
DUPS	✓	✓	✓	✓	✓	✓			✓
DVR	✓		✓	✓					✓
PFC					✓	✓	✓		
SMES	✓	✓	✓	✓	✓	✓			✓
SETC	✓		✓		✓	✓			
SSTS/MTS	✓	✓	✓						
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
DUPS = Dynamic uninterruptible power supply
DVR = Dynamic voltage restorer
MTS = Mechanical transfer switch
PFC = Power factor controller
SA = Surge arrester
SMES = Superconducting magnetic energy 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

Table 1: Power quality problems and available mitigation devices

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.

Industry Segment	Industrial process
Continuous process	Paper, fiber and textile factories Plastics extruding or molding plants
Precision machining	Automobile parts manufacturing Large pump forging factories
High-technology products and research	Semiconductor manufacturing Large 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

Table 2: Customers with sensitive or critical process

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 Figure 3 , the DVR can respond within sub-cycles to a fault on the utility side, in effect shielding the customer from the fault.

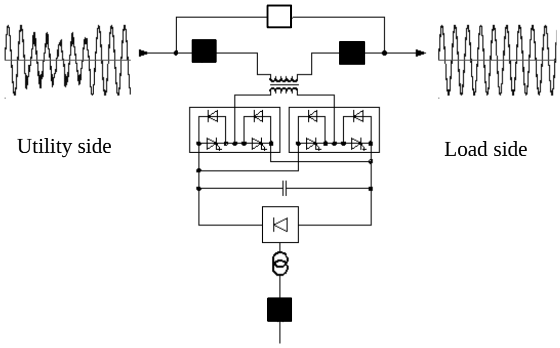


Figure 3 : Mitigation of voltage sags with the DVR

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 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) switching 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 Figure 4 .

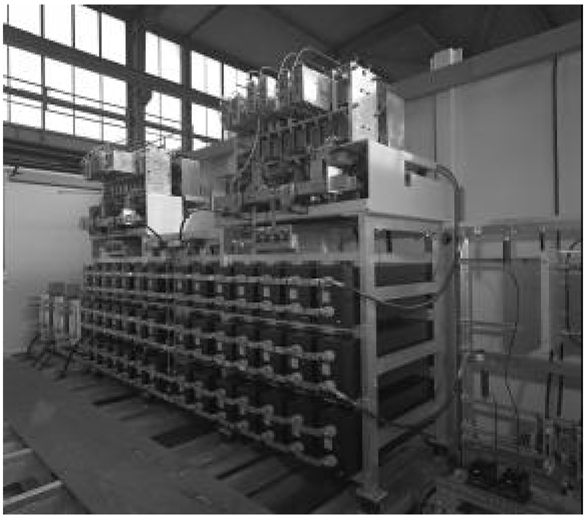


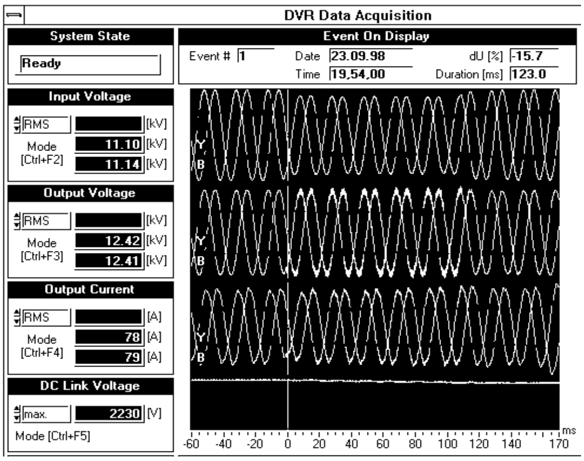
Figure 4: State-of-the-art IGCT-based voltage source converters of a DVR mounted on capacitor banks

A medium voltage container-based DVR installation for a 4-MVA load shown in Figure 5 provides further flexibility by facilitating relocation and therefore maximum utilization of the investment.

Actual field experience of the DVR verifies the system design and performance. Figure 6 shows measurements of a compensated 15% voltage sag on all three phases. The top set of traces show the incoming supply voltages. The second set shows the voltages of the protected load.

The third set shows the load currents and the final set shows the DC-link voltage. The fast and accurate response confirms that the DVR performs beyond expectations and that this is a cost effective device for industries suffering from sags in their supply voltage.

Figure 5: Container-based DVR guaranteeing a reliable supply and enhanced power quality for a 4-MVA semiconductor manufacturing plant



System State: Ready

Event # 1 Date 23.09.98 dU [%] -15.7
Time 19,54,00 Duration [ms] 123.0

Input Voltage: RMS [kV]; Mode [Ctrl+F2]: 11.10 [kV], 11.14 [kV]

Output Voltage: RMS [kV]; Mode [Ctrl+F3]: 12.42 [kV], 12.41 [kV]

Output Current: RMS [A]; Mode [Ctrl+F4]: 78 [A], 79 [A]

DC Link Voltage: max. 2230 [V]; Mode [Ctrl+F5]

Figure 6 : Actual measurements of a three phase 15% voltage sag compensation

Flicker compensation and energy supply with DSTATCOM

The DSTATCOM is a shunt-connected device based on pulse-width modulated (PWM) voltage source converters. Accordingly, 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 Figure 7 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 Figure 8 . It can be seen that the variations in voltage are effectively attenuated when a DSTATCOM is installed.

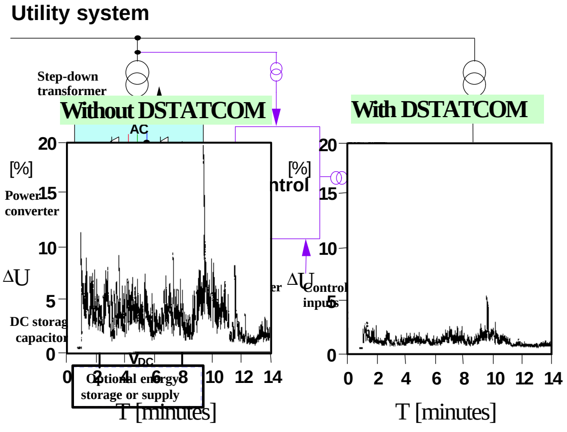


Figure 8: Flicker (voltage variations) associated with arc furnace operation

Figure 7: Arc furnace load compensation by means of a distribution static synchronous compensator (DSTATCOM)

A DSTATCOM coupled with a Solid-State Circuit-Breaker (SSCB) and an energy storage system (eg, BESS), is also advantageous. If a SSCB is installed between the incoming supply and the critical load bus, and a DSTATCOM equipped with an energy storage system such as a 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. Such a device is also referred to as a Dynamic Uninterruptible Power Supply (DUPS).

Transfer switch for mitigating supply interruptions

The Solid-State Transfer Switch (SSTS) or newly developed integrated Mechanical Transfer Switch (MTS) systems are designed to replace conventional mechanical autotransfer 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. These new solutions can also provide companies with a cost-effective alternative to an in-house uninterruptible power supply system.

A typical application for a solid-state transfer switch in a utility-provided power quality solution is shown in Figure 9. A sensitive consumer is fed via a radial line by the utility. 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 transfer switch system will immediately transfer the sensitive load to the secondary supply.

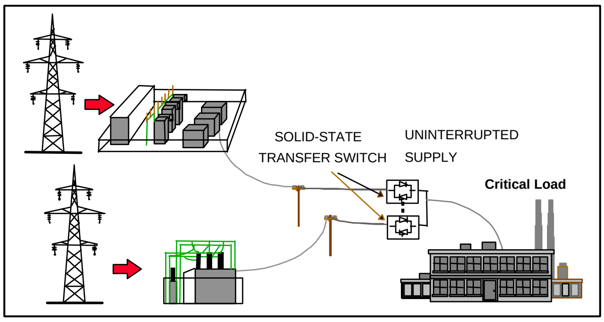


Figure 9: Mitigation of momentary, temporary and sustained supply interruptions by a solid-state transfer switch (SSTS)

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 transfer switches to be effective, the distribution system in which it is to be installed has to meet certain requirements:

- 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 Figure 10 show the load side voltages before, during and after the load has been transferred from the primary load feeder to the secondary feeder. Transfer of the load from the faulted feeder to the secondary feeder occurs within milliseconds and with no adverse effect on the load.

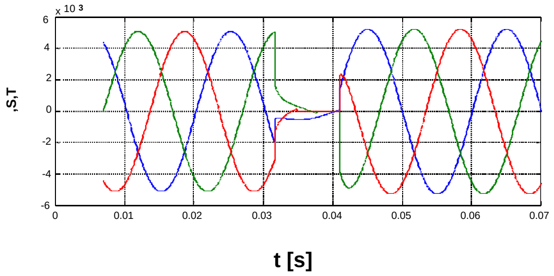


Figure 10**:** Load side voltages when switching from the primary to the secondary feeders in the event of a system fault.

If the transfer time for the load is less critical, ca. 25-30 ms, the integrated MTS solution presents a low cost alternative to the SSTS. The use of an intelligent control unit, modern sensors, vacuum breakers and recently developed fast magnetic actuators integrated typically into 2 normal sized MV switchbays, allows the system to achieve its transfer performance economically with no losses and minimal maintenance.

Reactive power compensation and switching transient reduction with the integrated power factor controller

Reactive power compensation for power factor correction in industrial plants is a prerequisite for achieving process efficiency and avoiding penalty charges due to poor power factor. The conventional equipment used to-date consist of shunt capacitors switched in or out depending on the reactive power requirements. Such operation induces fast switching transient into the power system that can cause disruption to processes (data loss) and damage to equipment (e.g. circuit boards) in particular in the present electronic age. Conventional power factor correction equipment therefore provides both a solution as well as a source of power quality disturbance to the consumer.

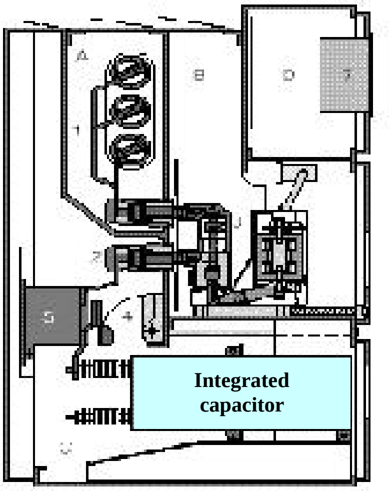


Figure 11: PFC with magnetic vacuum breaker and integrated capacitor power of 1.5 MVAr

The recently developed Power Factor Controller (PFC) as shown in Figure 11 addresses the deficiencies of the conventional equipment as well as providing an innovative integrated solution. The system includes typically of one or more breaker switched capacitor banks along with an intelligent control unit housed in MV switchbays. The circuit breakers, using magnetic actuators, are capable of carrying out a controlled and synchronized switching operation significantly reducing any switching transients. Furthermore, by using measured and target power factors and the capacitor information, the control unit determines if one or more capacitor banks need to be switched ON or OFF to bring the actual power factor as close as possible to the targeted power factor setting thus offering a more precise power factor compensation over traditional means.

BENEFIT/COST ASSESSMENT OF SYSTEM SOLUTIONS FOR ENHANCING POWER QUALITY.

In any business oriented environment, the level of added benefit in relation to the cost of the improvement must be weighed before any capital investment can be made. This holds true also for enhancing the quality of the supply particularly in the competitive electricity industry. Application of power quality indices plays a major role in assessing the cost versus benefit of alternative power quality solutions [5]. The difficulty is that application of this concept is still fairly new and available data within the utilities world-wide for the different types of disturbances is still an exception rather than the rule.

Voltage sag in power system results, for the majority of industrial customers, in outages and is taken as an example to demonstrate the procedure for benefit/cost assessment. The procedure has already been applied in a US based utility for comparison of alternative power quality solutions. The power quality index to be applied for this example is the System Average RMS Frequency Index (SARFI). This index specifies the expected number of aggregate events where the minimum voltage goes below some threshold value.

Power quality improvements that can be obtained with various mitigation methods are evaluated using SARFI calculations that address the voltage sags affecting customer operation. In order to evaluate the savings that different technologies can bring, the costs of the power quality variations need to be ascertained. This requires extensive voltage disturbance monitoring, and understanding of the equipment sensitivity to different types of power quality variations. A simplified approach based on typical equipment sensitivity to different types of rms variations can be used for economic evaluation, focusing mainly on the frequencies of several voltage sags levels. Weighting factors are generated using the cost of a momentary equipment interruption as the reference. Generally, a momentary interruption will cause a disruption to any sensitive load or process that is not specifically protected with some type of energy storage technology. After the weighting factors are applied to an event, the costs of the event can be expressed in per unit of the cost of a momentary interruption. The weighted events are then summed, and the total cost of all events expressed as the number of equivalent momentary interruptions.

Using this approach, the benefit of a power quality improvement technology can be estimated as the expected reduction in costs associated with voltage sags and interruptions at the facility. This value is then compared with the costs of the technology to determine the most cost effective recommendations.

Table 3 shows the decision making benefit/cost ratios to compare the different alternatives considered. A number of assumptions are made for these comparisons:

- The costs of a momentary interruption at the customer is assumed to be USD100,000 to illustrate the procedure. This varies for different customers .
- A protected load is assumed to be 4 MVA.
- The amortization period for the initial costs of each alternative is assumed to be 5 years with an interest rate of 10 %.
- Annual operating costs for each alternative are estimated . These annual operating costs include losses associated with the power conditioning technology, maintenance, cost of space, spare parts, etc.

The costs given for the different mitigation alternatives are for a particular installation with customer specific performance requirements and are used basically to illustrate the benefit/cost procedure necessary to make a good investment decision.

SSTS alternative assumes the availability of a secondary independent feeder. If this is not available, the cost of a new feeder must then be added and as such the DVR alternative will in most cases be the more cost-effective solution.

Technology	Expected savings (USD)	Cost of solutions (USD/kVA)	Total solution cost (USD)	Annual operating costs (% of total costs)	Total annual cost (USD)	Benefit/Cost Ratio
SSTS	220,000	60	240,000	5%	74,400	2.96
DVR	410,000	300	1,200,000	5%	372,000	1.10
UPS	540,000	800	2,400,000	25%	1,224,000	0.44
SMES	515,000	800	2,400,000	15%	984,000	0.52

Table 3. Economic comparison of voltage sags mitigation alternatives

CONCLUSION

With the trend towards deregulation and competition in the electric supply industry, benefits as well as values to customers are of increasing importance to decisions taken by utilities on power system investments. The deterioration of power quality levels as a result of deregulation, proliferation of more sensitive loads, and the increase in processes based on power electronics have in recent years been attracting growing concerns on power quality issues. 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 being drafted and adopted which describe levels which are acceptable for different types of disturbances in the electrical supply and ensure that these requirements are met.

This paper presented above addresses these power quality issues by providing:

- An overview of the power quality problems commonly affecting customer's processes
- Possible mitigation solutions
- Example applications of mitigation devices
- And last but not least, a procedure for benefit/cost comparison of alternative mitigation solutions.

Statistics show that the disturbances causing the most frequent process outages, and hence substantial economic losses, are mainly sags and interruptions. Hence much effort has been directed to provide solutions to mitigate these disturbances. The availability of different power electronic and mechanical based mitigation devices as well as customized solutions provides a range of equipment that satisfies user requirements both technically and economically.

Newly developed power electronics devices such as the IGCTs are now employed in power quality solutions that unite the benefits of Gate Turn-Off (GTO) thyristors with the strengths of Insulated Gate Bipolar Transistors (IGBT). These devices ensures high converter reliability, efficiency and inherent safety even under worst-case conditions.

Advances in innovative mechanical based solutions are also proving to be a cost-effective alternatives to solid-state equipment when performance requirements are less stringent. Integration of previously distinct components into an engineered package not only cut costs but also improves reliability through the reduction of interface problems and allowing the facility to be completely factory tested.

With the various power quality solutions available, the obvious question for a consumer or utility facing a particular power quality problem is which equipment provides the optimal solution. A procedure has been presented in this paper to answer this and an example has been provided to demonstrate its application.

For consumers, power quality issues will become an increasingly important factor in driving the global economy. For the electrical supply industry competing for customers, quality of power delivered will be one of the distinguishing factor for ensuring customer loyalty. To address the needs of energy consumers trying to improve productivity through reduction of power quality related process stoppages and energy suppliers trying to maximize operating profits whilst keeping customers satisfied with supply quality, innovative technology provides the key to cost-effective power quality enhancement solutions.

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