

**CUSTOM POWER
STATE OF THE ART**

Working Group 14.31

August 2002



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CHAPTER 1 INTRODUCTION

1.1 Definition of Custom Power

Custom Power is a concept, based on the use of static controllers in the distribution system or in some instances, rotating machines, for the electric utilities to supply value-added power with the reliability and power quality requested by the customers.

The broadly used term Power Quality, includes consideration of all aspects of power supply that impact individual customers, including harmonics, inter-harmonics, voltage dips, overvoltages, range of steady state voltage and frequency variations, and phase unbalance, in addition to the above consideration of reliability. Further to the total outage time per year, assessment of reliability of the utility power supply should generally include the number and time period of voltage reductions (also known as dips) and interruptions. Figure 1.1.1 provides a simplified view of how power quality is characterized.

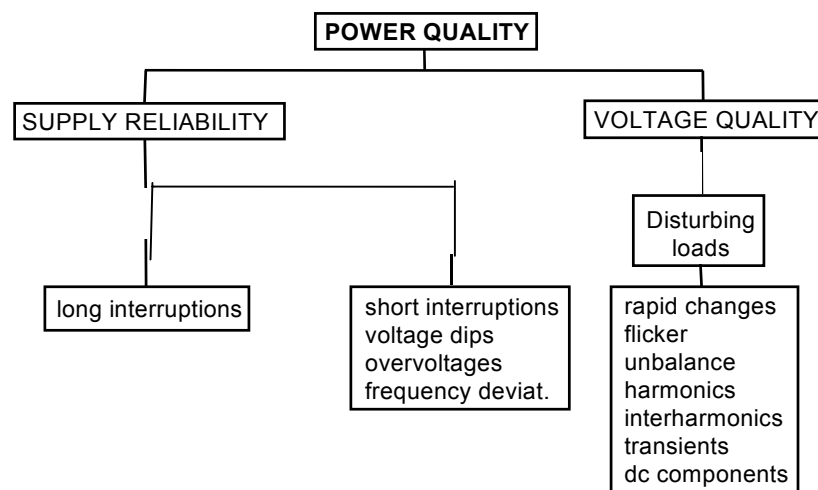


Figure 1.1.1: Simplified characterization of power quality

1.2 View of Needed Quality of Power Supply Including Reliability

In modern society, electricity is fundamental to economic activity and essential to the standard of living and quality of life. With the emergence of computers, modern communications and a high level of automation, reliable electric supply has become a basic necessity.

Historically, utilities, particularly in the industrialized countries, have evolved and responded to the customers' need of electric power supply. In the early days of electricity, lighting was the main load, and the customers were served from power plants via radial feeders. The introduction of electric motors led to rapid development of local power supply systems. Reliability then was

not such a big factor, and customers could wait for hours or even days before their electricity was restored. With increasing industrialization, the expectation of reliability, assessed in terms of the cumulative number of hours or days per year that power was not available, continued to increase. Then came the era of the interconnection of individual networks in order to take advantage of the diversity of loads and generation, lower cost hydro power resources, and also to provide a pool of backup reserves in order to improve reliability. With the large economic benefits of interconnections, utilities continued to add interconnections on a regional, national, and international basis. With long distances and large systems covering hundreds and even thousands of kilometers, the issues of stability emerged which were dealt with by the use of high speed circuit breakers, advanced generation controls, etc. in order to prevent large scale blackouts and collapse of the power system.

On the distribution side, widespread use of alternate feeders, automatic reclosers and improved maintenance practices has ensured high reliability of power supply at the customers' terminals.

Throughout this evolution, as new innovations have increased, many new uses of electricity and the reliability of utility systems has continued to improve, and customers have come to expect a highly reliable power supply with a cumulative outage time of only a few or a few tens of hours per year.

Nevertheless, it is significant to note that in the developed countries, the number of long term outages (exceeding a few tens of seconds) are very few, in the order of one or two per year. This results from having reliable transmission interconnections and good operation and maintenance practices. Also until recently, the number of short-term outages and voltage reduction was not an issue; the number of cumulative hours of interruptions per year has been the benchmark measure for reliability.

Those industries that have a lower tolerance level of interruptions have managed by mechanically switching over to a utility provided alternate feeder, in some cases to their own standby generator, and in a few cases when use of electricity involves critical services, both the alternate feeder and a standby generator. Where low levels (up to a few kilowatts) of un-interruptible supply is needed for critical controls, shunt or series connected Un-interruptible Power Supply (UPS) with batteries as the storage backup have served the purpose.

Over the last ten years or so, the customers' perception of reliability has been changing, and the pace of change has accelerated in recent years. The concept that an outage time of a few cumulative hours per year as being an extremely reliable supply is no longer valid for an increasing number of customers, industrial and commercial in particular. An event of a few cycles interruption, or even of voltage reduction to less than 90%, can cause big problems for industrial customers. With the age of automation, computers, process controls, drives and robotics, a new concept of reliability must be developed. The number of outages and voltage dips and their duration is much more important than the cumulative outage time per year. Hypothetically if one cumulative hour is made up of 2400 interruptions of a quarter of a second duration each, it would be a disaster for any automated industrial customer or even, say, 6 interruptions of 10 minutes duration each would create major losses to many automated industrial customers, as compared to one interruption of one hour.

The variety of disturbances that may affect a customer's equipment and productivity include:

- **Undervoltages:** Interruptions and voltage reductions may be of a few cycles to long term duration. Most of these would occur in the utility system on account of lightning faults on transmission and distribution lines, trees touching the wires, equipment failure, switching, low frequency dynamic swings of the transmission system, etc. However voltage dips may also be a consequence of large load changes affecting customer's own equipment or affecting other customer's equipment via the utility system.
- **Overvoltages:** Impulse, switching surge and temporary overvoltages affecting the insulation, would most likely result from lightening strikes and switching events on the distribution system, but at times these may be the consequence of the customers' own equipment. Temporary overvoltages lasting from several cycles to several seconds would largely result from large load changes, capacitor switching, transformer switching, dynamic stability swings etc. in the utility system.
- **Harmonics:** Harmonics would most likely be the consequence of high harmonics in the customer load, or the saturation of utilities' transformers caused by higher voltages during light loading conditions, and amplified by resonance in the utility system.
- **Flicker:** High system impedance along with frequently changing load can result in lighting flicker.
- **Voltage unbalances:** Voltage unbalances in a three-phase supply would occur mostly due to large unbalanced loads on a utility's distribution lines and long lines with unbalanced phase impedances.
- **Carrier Noise:** Many distribution lines are used as a communication carrier for load management and there is a strong trend towards use of wires for various communication needs of customers. Loads incorporating power electronics can generate noise that may interfere with an existing or future carrier communication.
- **DC Sources:** With multiple grounds in the system and customers, use of halfwave rectifiers and asymmetric loads can cause dc current to flow through the transformers, which in turn would result higher harmonics and additional loading of the transformers.

These disturbances, discussed in Chapter 2, are not altogether new, and utilities have by and large attended well to these problems. The need for the utilities to take a new look at the whole issue of power supply to their customers, arises from the fact that the customers' needs and the nature of loads are rapidly changing. The solution, on one hand, calls for a re-examining of the customers' obligations in terms of the nature of their loads, through mechanisms of standards and contracts. On the other hand, it also requires utilities to re-examine their basic supply system requirements in general, their perception of reliability, and in addition, provide value-added options to industrial and commercial customers relating to their specific needs.

In view of the degree of impact on the customers and importance in terms of the utilities' role, the concept of Custom Power emphasized the issue of reliability in terms of the interruptions and voltage reductions.

There are a number of reasons for the choice of the Custom Power concept for many large customers and industrial parks, and on a long term basis for most customers on a wide area basis. These reasons are:

- Providing reliable power, as well as ensuring reasonably low levels of harmonics and voltage unbalances, overvoltages, etc., as well as defining utility - customer interface has always been the business of the power supply and should remain so.
- Most of the voltage reductions and interruptions result from events that involve the utility system. Events that occur in the transmission system, such as lightning faults and switching, are felt over a wide area.
- In general, the total cost of the solutions that involve improvements in transmission and distribution systems, coupled with appropriate Custom Power equipment installed at the points of supply to the large customers, industrial parks and wide customer areas, would be much less than the cost of solutions put in place by the individual customers.
- At least from the point of view of reliability, migration to the Custom Power concept seems to be inevitable.

Above issues of the quality of power supply including reliability are discussed in Chapter 2.

It should be recognized that Custom Power is likely to involve additional investment by the utilities, customers or other intermediate entities. Also if the utilities' power supply is improved to meet the new challenges, this will not bring additional revenues under the traditional tariff mechanism. Therefore it is suggested that:

1. Custom Power could be pursued in terms of value-added services.
2. Regulations and standards for the basic services need to be revised. Current practices and standards are discussed in Chapter 3.
3. The responsibility of ensuring power quality needs to be shared among 3 parties. The parties are the manufacturers of electric equipment, the customers, and the utilities.

1.3 New Products Available

While it is not possible to draw hard lines of solutions suited for the utility side vs. those for the customer side, it would be reasonable to suggest that the Custom Power concept is for utility loads exceeding a few hundred kilowatts. While the sub-issues of harmonics, grounding, integrity of computer memory, etc. require due attention from the customer side, the utilities must attend to the underlying issues of reliability.

There are a variety of new products available as we move into the new era of value-added services including Custom Power. Clearly one available product of importance is equipment that monitors and measures different aspects of value-added power quality service, for the purposes of verification, settling disagreements, billing, etc.

Custom Power equipment that can be applied at distribution substations and/or customer entrances for power conditioning, basically consists of two categories:

1. ***Switching Equipment:*** including Circuit Breakers, Transfer Switches, and Fault Current Limiters. These are based on solid state switching and high speed sensing to change the system configuration rapidly and frequently as necessary.
2. ***Conditioning Equipment:*** including series, shunt and series/shunt combination equipment needed to condition the supply as necessary to meet the customers' requirements. Series conditioning basically involves adding variable voltage or impedance in series; examples include, Solid State Voltage Regulator and/or Tap Changer, Dynamic Voltage Restorer, Thyristor Controlled Series Capacitor, and Series Active Blocking Filter. Shunt conditioning basically involves injecting variable current or applying variable shunt impedance to the line; examples include, Static VAR Compensator, STATCOM, Shunt Active Filter and Voltage Limiter. Conditioning may involve just the reactive power, or active power or combination of active and reactive power. The delivery and absorption of active power requires storage equipment such as capacitors, batteries, superconducting magnet, or a rotating mass including flywheel and co-generation, etc. Just the absorption of active power involves energy dissipation equipment such as linear or non-linear resistors.

Conditioning Equipment can utilize in addition to thyristors and diodes, Gate Turn Off thyristors (GTO), Integrated Gate Commutated Thyristors (IGCT) or Insulated Gate Bipolar Transistors (IGBT).

These technologies are described in Chapter 4, with solution examples in Chapter 5 and vision for the future in Chapter 6.

CHAPTER 2

SUPPLY RELIABILITY AND VOLTAGE QUALITY

2.1 General

As described in Chapter 1, power quality consists of two components; the supply reliability and the quality of the voltage. The voltage quality can be described in terms of magnitude, flicker, frequency deviation, waveform distortion and asymmetry of the three phase voltages. The supply reliability is characterized by the number of service interruptions and voltage dips, and includes their duration and the total interruption time per year.

For the purposes of Custom Power, the definition of power interruption is the loss of supply for a period significant to a customer.

It should be noted that the term “reliability” has a very wide range of meaning and cannot be associated with a single specific definition. For our purposes, power system reliability assessment is divided into two basic aspects: system adequacy and system security. These two terms can be described as follows:

Adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer load demand and system operational constraints. These include the facilities necessary to generate sufficient energy and the associated transmission and distribution facilities required to transport the energy to the actual consumer load points. Adequacy is therefore associated with steady state conditions that do not include system disturbances.

Security relates to the ability of the system to respond to disturbance arising within that system. Security is therefore associated with the response of the system to whatever perturbations it is subjected to. These include the conditions associated with both local and widespread disturbances and the loss of major generation and transmission facilities.

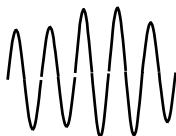
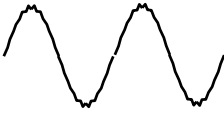
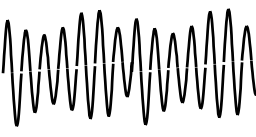
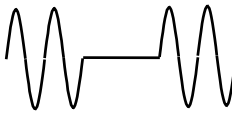
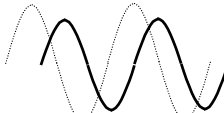
The term *reliability* in the utility context usually refers to the amount of time that customers are totally without power for an extended period of time (i.e. a sustained interruption). Among utilities, definition of what constitutes a sustained interruption varies in the range of 1 to 5 minutes. This is what many utilities refer to as an “outage.” Current power quality standards efforts are leaning toward calling any interruption of power for longer than 1 minute a “sustained interruption.” On the other hand there is a movement to extend the traditional reliability indices to include momentary interruptions as well.

Of course, many industrial customers have a different view of what constitutes reliability. For them, even short interruptions and voltage dips are issues of reliability because they disrupt their processes and require several hours to get back into production.

A voltage *quality* problem refers to any variation of voltage waveform resulting in misoperation or failure of customer equipment from disturbances such as; voltage dip, overvoltage, transients, harmonic distortion and electrical noise.

The disruptions of electric service that impact the voltage quality and supply reliability are described in the following paragraphs and summarized in Table 2.1.

Table 2.1. Voltage disturbances

Disturbance		Possible causes	Consequences
Voltage dip		■ Successfully cleared faults resulting from lightning, insulation failure, etc. ■ Start-up of large motors	■ Shutdown of certain equipment, particularly electronic devices.
Overvoltages		■ Fault in another phase ■ Lightning strike on network structure ■ Incorrect setting in substations (sustained overvoltages)	■ May harm equipment with inadequate design margins.
Harmonic distortion		■ Non-linear load ■ Resonance ■ Transformer Saturation	■ Voltage distortion, causing additional heating in motors. ■ Disturbed operation of electronic equipment.
Flicker or fluctuations		■ Start-up of large motors. ■ Electric arc furnaces. ■ Repetitive large loads (ie arc welding)	■ Weakening of components ■ Malfunctions
Transient overvoltages		■ Lightning strike ■ Switching event	■ Insulation failure. ■ Reduced lifetime of transformers, motors, etc.
Interruption		■ Close faults ■ False tripping ■ Load shedding	■ Shutdown of equipment.
Phase unbalance		■ Single phase loads.	■ Machine overheating

2.2 Physical Phenomenon

Most electrical equipment is fed from power plants through the transmission and distribution systems. The whole power system is important for providing quality electric service to the customers. However, between power plants and customers, it undergoes several influences or disturbances which may downgrade its quality.

These disturbances may result from:

- Atmospheric phenomena: lightning, storms, ice, etc.
- Faults in the power system: short-circuit in a substation, an overhead line, or an underground cable, etc.
- Power system swings.
- Faults in customers premises,
- Special loads in neighboring facilities: arc furnaces, welding machines, adjustable speed drives, etc.
- Loads inside the customer's own facilities: starting of large motors, working of relays, etc.

The rms value of the voltage varies throughout the day, due to changes in the loads that are supplied by the network. The electricity companies design and operate the network in such a way that the envelope of the variations remains within accepted limits.



Figure 2.2.1: Slow voltage variations

Normal equipment can withstand slow variations up to at least $\pm 10\%$ of the rated voltage without problem (Figure 2.2.1). The expression “voltage swell” is sometimes used to characterize a situation where the rms value of the voltage is above the normal range, whatever its cause and duration.

Several types of disturbances may be distinguished according to their nature, origin, effects and remedies.

2.3 Frequency Variations

So far as frequency variations are concerned, emergency operation one or two Hz below nominal frequency is possible. Power system swings can also go one or two Hz above nominal frequency. Some of the islanding schemes in the 60 Hz WSCC system are set to

activate separation at 58.2 Hz. Emergency operation for about one hour at close to 59 Hz went on for one hour during one of the major disturbances in the WSCC system. Thus, systems that need to operate at all costs should ride through large frequency swings. Also, faults and switching of reactive power banks cause large instantaneous phase shifts, which can upset the commutation in converters and causes other problems. These show up as very large frequency changes in most frequency transducers. Thus, when specifying any frequency range it is imperative to also define how sudden phase shifts are getting through the frequency transducers. That is, the impulse response for the measuring systems needs to be defined.

Generally speaking, frequency variations are not of great importance to the customers.

2.4 Undervoltage

In power quality terms, undervoltage can be expressed as voltage “dips” or “sags,” which are usually due to faults in the utility power system or within customer’s facilities. Only voltage reductions to less than 90% of nominal are considered as dips, since smaller magnitude variations fall in the voltage fluctuation category. Their duration may range from 10 ms to several seconds, depending on the location of the fault and on the functioning of the protection devices (faults are normally eliminated within 0.1 s to 0.2 s in HV, 0.2 s to a few seconds in MV). Short circuits are unavoidable in a power system because they are random events caused by atmospheric conditions, lightning, device failure or accidents etc.

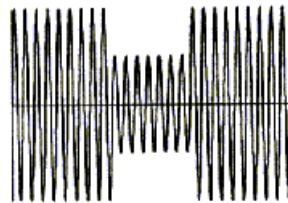


Figure 2.4.1: Voltage dip (sag)

Voltage dips may cause customer equipment to misoperate, when their magnitude and duration exceed some limits (depending on the sensitivity of the particular load). The consequences may be extremely costly.

The transient undervoltage of a duration less than one half cycle cannot be neglected since many specifications require $\frac{1}{4}$ -cycle response or less. There is no definition for how an undervoltage of a duration less than a half cycle is defined. There may be many ways of doing this, but the volt-second deviation from nominal may be the most meaningful. However, this would also show up if there were a sudden phase shift in the voltages. The problem extends to when there is a capacitor switching event with a high frequency damped oscillatory wave superimposed on the normal voltage. In some instances, this would be considered as a voltage dip followed by an overvoltage, which does not fall into convenient definitions for sags and swells. However, it could affect commutations in an adjustable speed drive and cause problems, so it is not a trivial problem.

2.5 Overvoltage

Largest transient overvoltages for customers - but fortunately the less frequent - are due to lightning. Their magnitude may reach several kV in overhead LV networks. Furthermore, such transients may propagate up to underground LV networks.

More frequent transient overvoltages are produced in customer premises, e.g. due to switching of LV appliances. Their energy content is less than for lightning induced overvoltages, but their magnitude may exceed 1 kV in LV networks. Also they can have very sharp (rise times near 1 ns, i.e. 10^{-9} s) and can therefore be dangerous for electronic circuits.

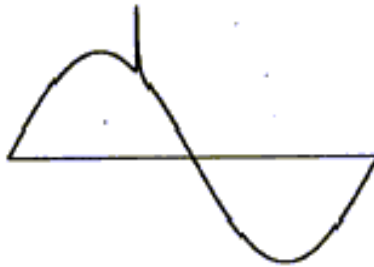


Figure 2.5.1: Transient overvoltage due to LV appliance switching

2.6 Periodic and Non-periodic Disturbances

Disturbances from different sources may be periodic or transient (or non-periodic) in nature. Notches due to power electronic converters or controllers are not transients in the classical sense. Waveforms of Figures 6 and 7 are repetitive and might be described, as a series of harmonics. However, it is the magnitude and steepness of the voltage changes that causes the trouble and they may be considered as repetitive transients.

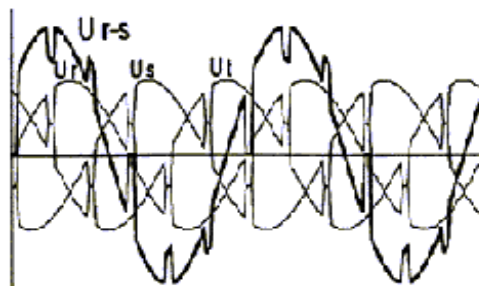


Figure 2.6.1: Notches due to a 3 phase rectifier

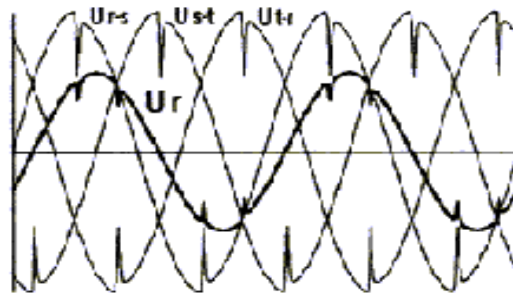


Figure 2.6.2: Notches due to a 3 phase controller

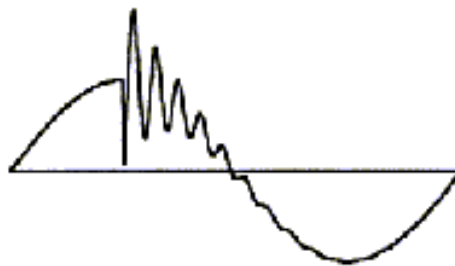


Figure 2.6.3: Damped oscillatory transient due to capacitor bank

Oscillatory transients that are non-periodic in nature, decay following some switching event such as from energizing of a capacitor bank as shown in Figure 2.6.3, or from magnetizing current inrush effects when a transformer is energized.

The sensitivity to non-periodic disturbances has risen significantly with the development of digital controls and power electronics. For example, direct capacitor bank energizing was very frequent in the past and did not cause trouble. However, nowadays, the great sensitivity of adjustable speed drives (ASDs) to such transients requires particular attention (synchronized switching, series reactors, etc.).

Oscillations, as components of voltage or current, cause sine wave distortion. The oscillations are mainly due to nonlinear loads such as electronic converters or controllers, arc furnaces, etc. Their magnitude may be amplified by resonance phenomena, such as when capacitor banks are installed without the needed attention.

High harmonic and distortion levels cause overheating of equipment, e.g. capacitors and rotating machines, and may disturb the working of electronic systems.

Components whose frequency is not just a multiple of the fundamental are less common but not rare. They are called interharmonics.

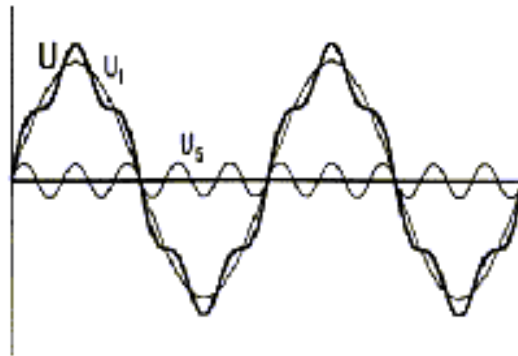


Figure 2.6.4: Distortion caused by single harmonic component ($h = 5$)

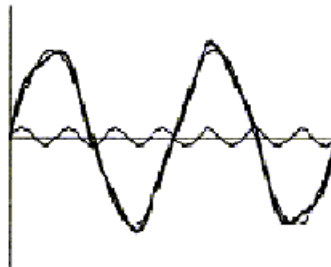


Figure 2.6.5: Distortion caused by single harmonic component ($h = 3.5$)

These components cause variations in peak value and zero crossing of the sine wave and are therefore more disturbing than plain harmonics, requiring more severe limitations (Figures 2.6.4 and 2.6.5).

2.7 Flicker (Voltage Fluctuations)

Rapid voltage changes, repetitive or stochastic, are caused by sudden power variations of loads such as welding machines, arc furnaces, etc.

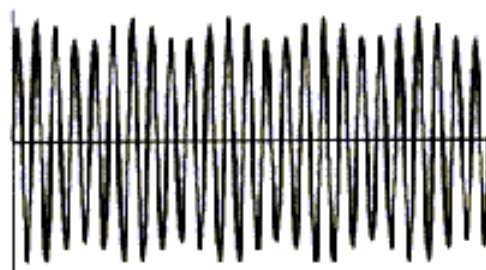


Figure 2.7.1: Voltage fluctuation

These voltage fluctuations may result in light flicker, possibly annoying for customers, even for voltage variations of only a few tenths of a percent. However, other appliances are normally not affected by those phenomena as long as the voltage variations remain smaller than some 10%.

2.8 Unbalance

Network asymmetries cause only small levels of voltage unbalance (generally not more than a few tenths of a percent). some single-phase loads (particularly single-phase railways substations) cause unbalanced currents and therefore significant unbalanced voltages.

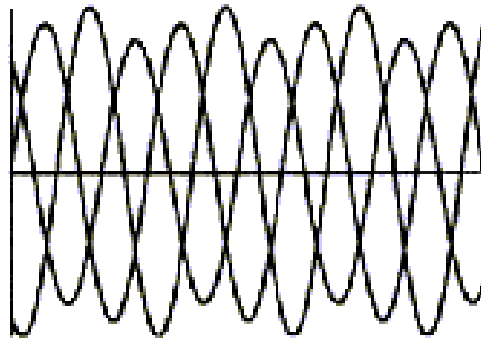


Figure 2.8.1: Voltage unbalance

The main problem with steady state unbalance is that it is causing overheating in three-phase rotating machines.

2.9 Ripple Control

Carrier signals applied to electric power distribution to enable control of up to several thousand electrical loads from a central point. Carrier signals can thus be used to smooth load curves by controlling the start-up of certain loads which can either store energy (e.g. water heaters) or whose operation can be delayed for a period without incurring any major disadvantages (e.g. air conditioners etc.). Carrier signals also enable remote management of different electricity rate options.

Carrier signals are injected into power networks at frequencies different from the fundamental frequency and its harmonics are, known as remote control frequencies. Typical remote control frequencies are between 160 to 1400 Hz.

On one hand customer equipment may interfere with the carrier signals. On the other hand, the carrier signals may cause misoperation of customer equipment.

There are two possible injection methods:

- Series injection using a generator connected in series with the network, via an injection transformer.
- Parallel injection using a generator connected in parallel with the network.

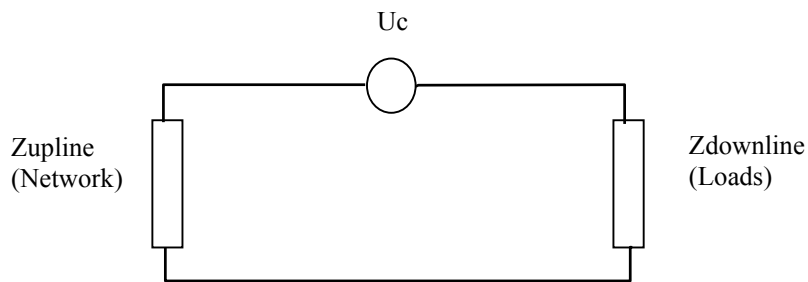


Figure 2.9.1 Series transmission

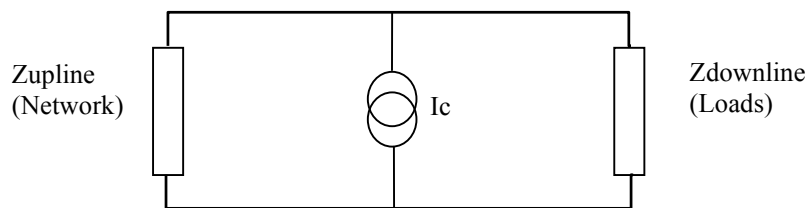


Figure 2.9.2 Parallel transmission

With series transmission, the ratio of the carrier signal at the terminals of the load is proportional to the impedance ratio:

$$\frac{|Z_{downline}|}{|Z_{downline} + Z_{upline}|}$$

In general, as the network impedance is actually considerably less than the impedance of the loads, the level of the carrier signal is sufficiently high to ensure effective reception by the electrical consumers.

However, in certain network configurations involving decentralized generation systems connected at medium voltage, the impedance downstream of the carrier signal generator is considerably weakened. The voltage level at the remote control frequency is thus too low to be received by the electrical consumers, which freezes load control or rate-band switching.

2.10 Customer Viewpoint

2.10.1 Impacts

With service interruptions or disturbances, customers will experience economic losses. Large commercial and industrial customers are increasingly effected by the reliability and quality of the power supplied by electric service providers. They use large magnitudes of energy that is increasingly applied on electrical and electronic equipment controlling processes to a very tight tolerance. Because the large customer can be very effective in expressing dissatisfaction with the quality of the electricity supply, it is advisable to take into account their requirements in the engineering design and operating alternatives for their electric service.

Residential customers on the other hand are numerous with many connected to one distribution feeder. Their interruption costs per customer are very small, usually in the range of zero to just a few dollars per disruption. On the average, the cost of service disruption to a residential customer is several orders of magnitude less than the interruption costs for industrial customers. An exception is where there are an increasing number of home-based business enterprises. It is wise to approach the design and operating alternatives for supply to large industrial and commercial customers and even residential customers on an individual basis.

Interruption costs to residential customers reflects as inconvenience and possible deterioration to food if the outage is long enough to cause thawing of refrigerated goods. In extreme weather conditions, loss of electricity supply can be life threatening. Hospitals, airports and other critical loads have emergency standby power and un-interruptable power supplies (UPS) to provide essential service.

For the large industrial and commercial customer, outage related costs are those costs resulting from the disruption which include the following [6]:

- Loss of business
- Labor costs to restart production.
- Labor costs to make up production.
- Material costs to restart production.
- Damage costs to materials.
- Damage costs to physical plant.
- Cost of reprocessing materials.
- Cost to operate back-up generation equipment.

It is possible that there are disruption related savings that reduce the total cost of the outage to the customer. These savings include:

- Cost of wages unpaid to workers during the outage.
- Cost of raw materials unused because of the outage.

- Cost of unused fuel.
- Scrap value of damaged materials.

It is very difficult to closely estimate service disruption costs to customers. However, they are real, and they must be taken into consideration in the design of Custom Power solutions.

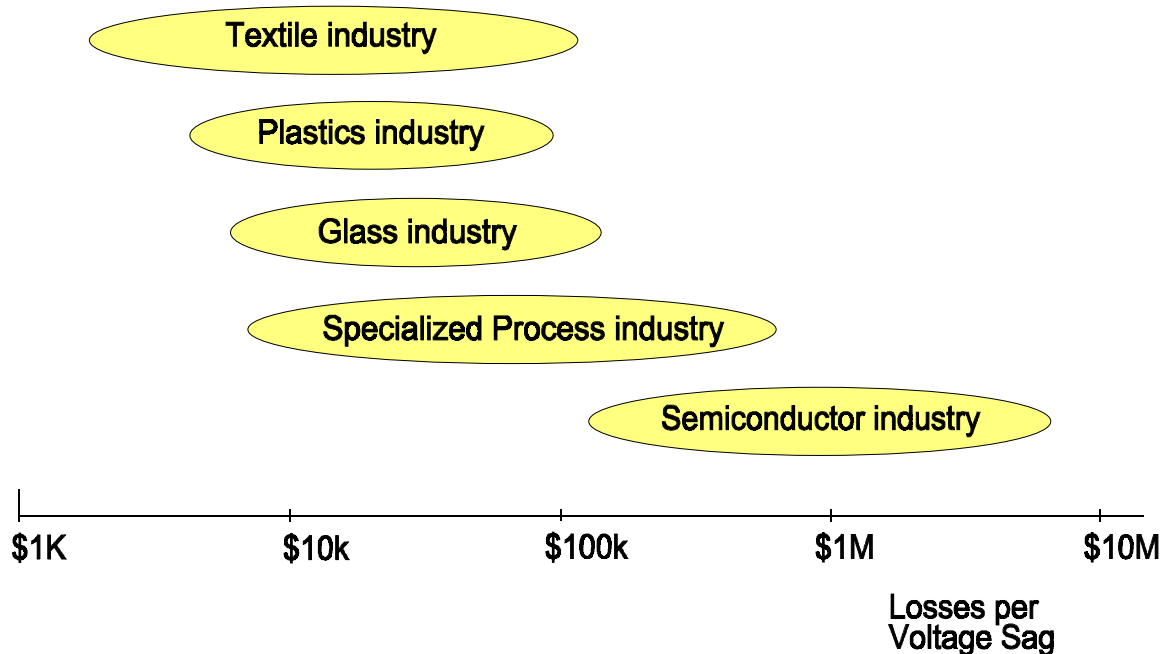


Figure 2.10.1: Cost of industrial losses per incidence of voltage dip.

Production equipment has differing sensitivity to power system disturbances. Some systems can recover from a short-term outage. This could be the case with an arc furnace for metals production because it takes time for the molten metal to freeze. However, if the controllers for such systems cannot recover and restart the process, the fact that the process can survive a relatively long duration outage is immaterial. Thus, it is difficult to generalize.

The reality is that some processes will be equipped with UPS systems because this is the only viable alternative. Others could use high-speed voltage restorers to deal with short term single or three-phase voltage dips. Some only need a slow speed transfer to an alternate supply (electromechanical switching is adequate). In most production facilities, a portion needs UPS systems, another segment could benefit from high-speed transfers and the rest may not need any backup for short-term interruptions. However, sometimes such simple systems as exhaust fans are critical because if they stop the factory must be evacuated.

In most facilities, the power distribution systems are not sufficiently segmented to allow for an optimum power backup solution. Rewiring the facility may be expensive so this may not be

an option. That is, each customer will have a different view on what the cost of a disturbance is and what solutions that would be acceptable.

Liability costs is a factor for the power users, too. Although emergency lights are typically required, it is still possible to have someone fall and injure them self when the lights go out. People stuck in elevators are another possible problem. Finally, there are the perception issues, too. If people expect a certain power system reliability and do not get it, they will complain. If there are options for the customers to go elsewhere for their power purchases, they will leave the entity with inadequate power system reliability and go to a competitor. This will probably be the major factor for the power system suppliers to deal with in the future.

2.10.2 Mitigation

Commercial customers may have large loads consisting of electronic equipment with switch mode power supplies. The harmonic distortion generated in a large office building for example, may be quite extensive causing unacceptable power quality. The customer in this case may apply custom power solutions including active filters, UPS and shunt dynamic voltage restorer. Any single phase non-linear loads which generate significant 3rd harmonic currents may result in a very large neutral current, perhaps even exceeding any one phase current.

The large industrial customer may require voltage support in the form of SVC, STATCOM, perhaps acting in combination with an active filter, and static transfer switch.

The residential customer may be willing to live with lower power quality than the industrial or commercial customer, because the economic impact is less. Most residential impacts are nuisance types, such as blinking clocks after voltage dips, which are resolved by competition between the manufacturers of clocks. Those that cause equipment damage, such as overvoltages, are mitigated via surge suppression devices for computers and expensive electronics in the home. In areas with poor voltage regulation, as in remote, developing areas, domestic on-line voltage regulators are applied.

2.11 Electrical Supplier's Viewpoint

2.11.1 Impact

The cost of poor power quality to utilities may include

- Poor customer relations
- Loss of customers to competition
- Loss of energy delivered
- Dealing with customer damage claims

As a result, customers expect utilities to work to improve power supply quality, and the utilities have an incentive to do so. The utility's ability to satisfy this demand obviously influences its image among its customers.

An important consequence of these impacts is a pressure on utilities to remedy selected portions of the system, at the expense of all customers. Further adding to the pressure on utilities is the reality, often unrecognized, of the extreme cost to implement a remedy on the utility system.

2.11.2 Mitigation

The solutions available to utilities to deal with problems of improving power quality consist mainly in network improvements:

- Network strengthening (new substation, dedicated outgoing feeder, new transformer).
- Network maintenance; an effective solution to problems of interruptions and voltage dips, but must be performed on a regular basis.
- Underground cables. This solution will be effective if applied on a general basis. However, underground cables have two consequences which must be considered; networks are lengthened as a result of having to bypass certain areas, and the impedance of underground networks is lower than that of overhead networks, which leads to enhanced propagation of voltage defects.
- Neutral point arrangement.
- Lightning arrestor for overvoltages
- Rearrangement of networks.
- Improve structure grounding and insulation to reduce fault incidence

These network solutions are related to the development strategy for networks, which also depend on environmental constraints.

In addition, customer vulnerability is highly dependent on their processes. For this reason, it may be more expedient due to much lower costs, to improve quality as close as possible to the sensitive point through the use of dedicated Custom Power equipment.

In terms of targeted quality enhancement approach, Custom Power solutions implemented as close as possible to the disturbed load represent an effective alternative to conventional and costly network strengthening solutions.

Table 2.2. Non-exhaustive list of customer equipment sensitive to disturbance

Equipment	Sensitive to:
Industrial processes (in particular those using PLCs)	Voltage dips, transients (network and cabling), radiated fields
Numerical command devices, computers, IT equipment	Voltage dips, transients (network and cabling), radiated fields
Electronic command devices in power converters, including adjustable speed drives	Voltage dips, transients, overvoltages
Switches and relays	Voltage dips
Power capacitors	Harmonics, transient voltages
Motors, including their controllers	Voltage dips
X-rays and radioscopy	Harmonics, transients, radiated fields, flicker
Telecommunications	Radiated fields, disturbances introduced on the communications link
Lighting	Voltage fluctuations

Table 2.3. Non-exhaustive list of disturbing equipment

Equipment	Disturbance Caused:
Static power converters (rectifiers, PWM converters, cycloconverters, etc.), including adjustable speed drives	Harmonics, interharmonics, voltage fluctuations
AC power controllers (motors, lighting)	Harmonics
Asynchronous motors, compressors, heat pumps	Transients (brief voltage dips) on start-up
Power controllers using half-wave rectifiers	Transformer saturation
Induction heaters	Radiated fields, harmonics
Electric arc furnaces	Transients, voltage fluctuations (inter)harmonics
Welding equipment	Transients, voltage fluctuations, imbalance
High frequency heaters	Radiated fields
Discharge lamps	Harmonics
Switch mode power supplies (TV, etc)	Harmonics
Coils, relays, switches, fuses	Transients (fast and overvoltage) on cut-out

CHAPTER 3 CURRENT PRACTICES AND STANDARDS

3.1 POWER QUALITY

3.1.1 Standardization, Basic Concepts

Current developments in the standardization procedure can only be understood if the basic concepts have been made clear. These concepts are key in estimating the objective aspects of the quality of supply and for the study on the connection of disturbing loads.

Compatibility levels. These are reference values (IEC publications 1000-2-1 [8] and 1000-2-2 [9]) used for the coordination of emission and immunity of equipment making up or being supplied by a network in order to ensure EMC throughout the whole system. These levels are considered to correspond to a 95% probability that the limit values are not exceeded in a whole system, taking account of the time and space distribution. This level of tolerance is built in because it is impossible for a utility to control all parts of his network at any moment. An assessment of the real levels of interference compared with the compatibility levels would have to be done on the whole network - hardly a realistic exercise. There is therefore no evaluation method defined in relation to the compatibility levels. It should be stressed that these are references rather than operational values.

Voltage characteristics. European standard EN 50160 [10-12] lists the main characteristics of the voltage at the customer supply points in low and medium voltage utility networks and under normal operating conditions. They represent virtually guaranteed limits (at least for certain parameters) covering all points of the network. These limits are equal to, or slightly higher than, the compatibility levels. The method for evaluating a real characteristic at a given point on the network (to be compared to the specified characteristic) is based on a solely time-related statistic. For example, for a harmonic voltage the measurement period is one week and 95% of the rms values over successive periods of 10 minutes should not exceed the specified limit.

Planning levels. These levels are used for planning when evaluating the impact on the network of all customer loads combined (see IEC publications 1000 3-6 [13] and 1000 3-7 [14]). The planning levels are specified by the utility for all voltage levels on the network and can be considered to be internal quality targets. They are usually equal to or less than the compatibility levels. Only indicative values can be given in international recommendations because the target levels differ in each case depending on the structure of the network and circumstances. The method used to estimate the real level (to be compared with the planning level) again uses a solely time-related statistic, as for voltage characteristics; but it seeks to characterize more accurately the disturbing capacity of the phenomenon and therefore generally returns higher values. Because these higher values are to be viewed against lower limits, it is clear that requirements are much more severe for the network. It is therefore the “planning levels” rather than the “voltage characteristics” that should be taken into account when considering future changes to the network or connection of disturbing loads.

Figures 3.1.1 and 3.1.2 illustrate the basic concepts described above highlighting the most significant relations between them.

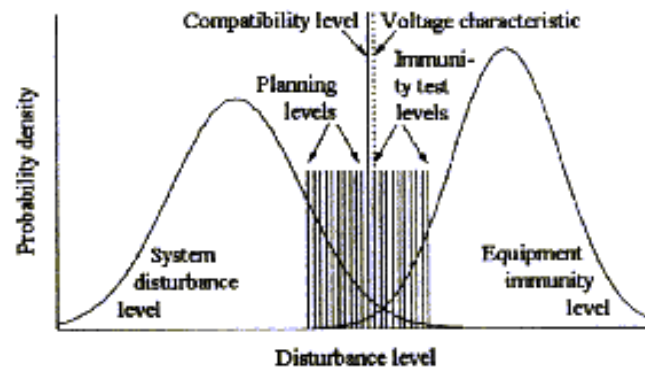


Figure 3.1.1: Illustration of basic voltage quality concepts with time/location statistics covering the whole system

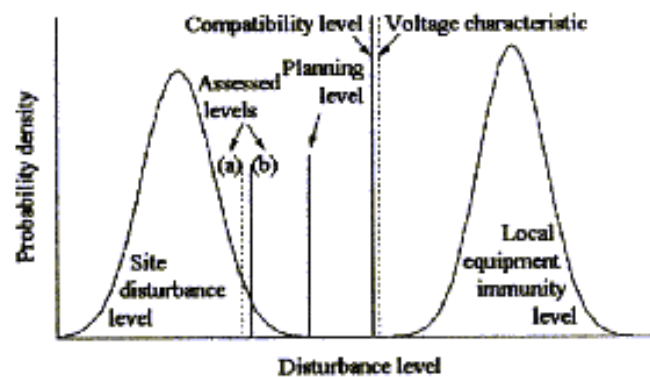


Figure 3.1.2: Illustration of basic voltage quality concepts with time statistics relevant to one site of the system Taking the system as a whole (Figure 3.1.1), interference is bound to arise at certain times and, consequently, the distributed levels of disturbance and immunity overlap. We have already seen that the voltage characteristics can be equal to or greater than the compatibility levels (and are given in European standard EN 50160) whereas the planning levels are normally equal to or less than the levels of compatibility (and are established by the network operator). The levels of immunity tests are specified in the relevant standards or are the subject of an agreement concluded between users and manufacturers.

At most locations in the supply network (Figure 3.1.2 is merely one illustrative example) there is little or no overlapping between the distributed degrees of interference and immunity. Effects are therefore minor and appliances will continue to operate satisfactorily.

3.1.2 Quality indices

According to current international standards and recommendations the parameters for voltage quality are: frequency, magnitude, rapid changes, dips, temporary or transient overvoltages, unbalance, harmonics, interharmonics, mains signaling and dc components.

From 3.1.1 we can deduce that the quality target for the network is the planning level for each of the parameters under consideration. As a rule this level should be chosen on a case-by-case basis by the utility and on the basis of the compatibility level. For further information on this point, provided by the IEC and Cenelec, see References [9, 10, 13, 14] and the summary given in Table 3.1.1:

Table 3.1.1: Parameters of the quality/reliability. Summary of data available within IEC (worldwide standard organization) and CENELEC (European standard organization)

TOPIC	Compatibility levels (IEC 1000-2-1)	Voltage characteristics (EN 30160)		Planning levels (indicative values) (IEC 1000-3-6, 1000-3-7)	
		LV	MV	MV	HV
Frequency	49 – 51 Hz	49.5 – 50.5 Hz (95% week), or 47 – 52 Hz (100% week)	49.5 – 50.5 Hz (95% week), or 47 – 52 Hz (100% week)		
Magnitude		$U_n \pm 10\%$ (95% week, 10min RMS)	$U_c \pm 10\%$ (95% week, 10min RMS)		
Rapid voltage changes	3% 8% infrequently Flicker: limit curve Pst = 1.0 Plt = 0.8	5% 10% infrequently Flicker: Plt = 1 (95% week)	4% 6% infrequently Flicker: Plt = 1 (95% week)	4% (0 = 1/h) 3% (1/hr = 10/h) 2% (10/hr = 100/h) 1.25% (100/h = 1000/h) Pst = 0.9 (99% week) Plt = 0.7 (99% week)	3% (0 = 1/h) 2.5% (1/hr = 10/h) 1.5% (10/hr = 100/h) 1% (100/h = 1000/h) Pst = 0.8 (99% week) Plt = 0.6 (99% week)
Temporary overvoltages phase/earth		<i>Indicative</i> 1.5 kV RMS	<i>Indicative</i> 1.7 U_c (systems with solidly or impedance earthed neutral 2.0 U_c (isolated or resonant earthed systems)		
Transient overvoltages phase/earth		Generally = 6 kV (occasionally higher)			
Voltage unbalance	$U_- = 2\%$	$U_- = 2\%$ (95% week, 10 min RMS) (3% in some areas)	$U_- = 2\%$ (95% week, 10 min RMS) (3% in some areas)		
Harmonic voltage	$U_5 = 6\%$ $U_7 = 5\%$ $U_{11} = 3.5\%$ $U_{13} = 3\%$ etc. and THD = 8%	$U_5 = 6\%$ $U_7 = 5\%$ $U_{11} = 3.5\%$ $U_{13} = 3\%$ etc. and THD = 8% (95% week, 10 min RMS; higher values possible if resonance exists)	$U_5 = 6\%$ $U_7 = 5\%$ $U_{11} = 3.5\%$ $U_{13} = 3\%$ etc. and THD = 8% (95% week, 10 min RMS; higher values possible if resonance exists)	$U_5 = 5\%$ $U_7 = 4\%$ $U_{11} = 3\%$ $U_{13} = 2.5\%$ etc. and THD = 6.5% (95% day, 3 sec RMS; max week, 10 min RMS) $U_h = 1.5 - 2.0\%$ limit (max week, 3 sec RMS)	$U_5 = 2\%$ $U_7 = 2\%$ $U_{11} = 1.5\%$ $U_{13} = 1.5\%$ etc. and THD = 3% (95% day, 3 sec RMS; max week, 10 min RMS) $U_h = 1.5 - 2.0\%$ limit (max week, 3 sec RMS)
Interharmonic voltage	0.2%	Under consideration	Under consideration	0.2%	0.2%
Mains signalling voltage	110-500 Hz: 3.5-6% 0.5-2.0 kHz: 2.5% 3-20 kHz: 2% 20-150 kHz: 0.3%	100-500 Hz: 9% 1-10 kHz: 5% (99% day, 3 sec mean)	100-500 Hz: 9% 1-10 kHz: 5% (99% day, 3 sec mean)		
Dc components	Under consideration				
Voltage dips	<i>Indicative:</i> Urban: 1 to 4/month Rural: much more	<i>Indicative:</i> Up to a few tens to up to one thousand	<i>Indicative:</i> Up to a few tens to up to several hundreds		

N.B. (1) For HV levels, see also [30].

(2) Cenelec EN 50160 gives the following definitions for U_n and U_c :

- nominal voltage of a system (U_n): the voltage by which a system is designated or identified and to which certain operating characteristics are referred;
- declared supply voltage (U_c): the declared supply voltage U_c is normally the nominal voltage U_n of the system; if by agreement between the supplier and the customer a voltage different from the nominal voltage is applied to the terminal, then this voltage is the declared supply voltage U_c .

3.2 SUPPLY RELIABILITY

3.2.1 UNIPEDE

The European Commission has proposed the following directive to be issued by the Parliament and the Council on the electricity market [15]:

- *The system operator shall draw up and publish an annual report on the quality of supply and the quality of service.*
- *The Commission shall establish the appropriate criteria for the content of the reports in order to ensure their compatibility at Community level.*

To check the contents of this annual report UNIPEDE to create the Disqual expert group whose last available draft report dates from May 1996 [16].

While accepting that the concept of supply and service quality can cover many areas, Disqual has so far concentrated on the availability of supply. The aim in fact is to characterize long interruptions (>3 min.); short interruptions are considered a problem of EMC and reference here is simply made to standard EN 50160 [10]. The following three indices are proposed:

- (a) *Interruption frequency: Number of interruptions on average per year per consumer (interruptions/year).*
- (b) *Supply unavailability: Number of minutes without supply on average per year per consumer (minutes/year).*
- (c) *Interruption duration: Average duration of consumer interruptions (minutes/interruption).*

N.B. The concept of supply unavailability is defined by the annual number of minutes during which time all consumption would be interrupted if the outages that occur sporadically in various places were generalized to cover the whole consumer base (same number of MW-min). Where interruptions due to the generation and transmission at voltages between 50 and 380 kV are concerned, for the monitoring period from 1982 to 1991, UNIPEDE established a ten-year international average of 20 minutes/year.

3.2.2 IEEE [17]

The traditional reliability indices for utility distribution systems are defined as follows:

SAIFI: System Average Interruption Frequency Index

$$\text{SAIFI} = \frac{(\text{No. customers interrupted})(\text{No. of interruptions})}{\text{Total No. of customers}}$$

SAIDI: System Average Interruption Duration Index

$$\text{SAIDI} = \frac{\Sigma(\text{No. customers affected})(\text{Duration of outage})}{\text{Total No. of customers}}$$

CAIFI: Customer Average Interruption Frequency Index

$$\text{CAIFI} = \frac{\text{Total No. customer interruptions}}{\text{No. customers affected}}$$

CAIDI: Customer Average Interruption Duration Index

$$\text{CAIDI} = \frac{\Sigma \text{ Customer interruption durations}}{\text{Total No. customer interruptions}}$$

ASAI: Average System Availability Index

$$\text{ASAI} = \frac{\text{Customer hours service availability}}{\text{Customer hours service demand}}$$

Where customer hours service demand = 8760 for an entire year.

Typical target values for these indices are:

Index	Target
SAIFI	1.0 h
SAIDI	1.0-1.5 h
CAIDI	1.0-1.5 h
ASAI	0.99983

3.3 CURRENT AND NEW PRACTICES

There were always special loads that caused problems at the network/consumer interface. The conventional approach taken by utilities consisted of:

- Informing the customer of the constraints (disturbance levels that should be tolerated by sensitive loads/emission levels that should not be exceeded by disturbing loads);
- and giving advice on any possible solution that can be installed - at the consumer's expense - in its facility.

The new technologies currently emerging suggest that another approach could be taken (Custom Power):

- In addition to the information already given in the conventional approach, the customer could be offered an active help to solve the problem (electricity product of a higher quality for sensitive loads/new ancillary services for disturbing loads);
- The customer could also be given the choice between different Customer Power solutions.

CHAPTER 4 CUSTOM POWER EQUIPMENT

4.1 Switchgear

As the amount of sensitive equipment such as computers, programmable logic controllers, and adjustable speed drives has increased, the reliability and quality of electric power received by the customer has become more important. Typically, industrial and commercial facilities with a dual service medium-voltage supply use electromechanical switchgear to automatically transfer service from one source to the other during an interruption or a disturbance. Electromechanical switches commonly take from 1 to 10 seconds, depending on the coordination with upstream devices, to make the transfer after interruption of the normal supply feeder. Many of the sensitive electronic devices are susceptible to distribution system disturbances, such as voltage sags and swells, for which mechanical transfer systems cannot transfer in time to prevent the interruption. Solid state switches based on thyristors or GTO thyristor technologies (including the IGCT and IGBT) are emerging for transfer switch, fault current limiter and breaker applications [18 through 26]. At the 600V level and below, the impact of power system disturbances have been reduced through the use of a Low Voltage Static Transfer Switch (LVSTS), which uses two low-voltage power electronic switches to take the place of the mechanical transfer gear. The use of medium-voltage power electronics for similar applications has evolved in the recent past. Where there is local generation or where a transfer between asynchronous sources is needed, solid state breakers may be useful. Such breakers must be able to interrupt current and therefore, gate turn-off thyristor devices or the equivalent have to be applied. It can also be beneficial to employ fault current limiters as a means of reducing fault currents and thereby, reduce the voltage sags on the unfaulted systems segments. Such systems in most instances also require turn-off devices although concepts have been introduced which do not require such devices.

4.1.1 Transfer Switch technologies

4.1.1.1 MVSTS Design and Operation

A single line diagram of the Medium Voltage Static Transfer Switch (MVSTS) system is shown in Figure 4.1.1. The MVSTS system consists of three main components:

- Sub-cycle Transfer Switches
- Mechanical Bypass Switches/Breakers
- Isolating Switches/Breakers

The sub-cycle transfer switch consists of two ac thyristor switches. Under normal conditions, the ac switches allow for fast transfer of power from one source to another. The mechanical bypass & isolation switches/breakers enable the MVSTS to be protected, bypassed and isolated for maintenance, testing, emergency overload, or as required by system operations.

Under normal conditions the customer load is fed through ac sub-cycle switch #1 as shown on Figure 4.1.1, by the primary source of power. The bypass switches are open and the preferred - alternate source switches/breakers are in the closed position.

The MVSTS protects the connected loads from experiencing problems due to voltage sags, swells, and momentary or sustained electrical power interruptions by transferring from one source to another in synchronism with the first. (Note that for voltage swells, the total sense and transfer time may take up to 8 milliseconds to allow for the sine wave to reach the zero crossing.) In any circumstance for which the MVSTS is “off-line”, the controller must provide a fail-safe return of control to the electromechanical switchgear in order to protect the load from sustained interruptions by initiating a bypass operation.

The MVSTS should inhibit transfer under the following conditions:

- Load side faults or overload conditions.
- Voltage of alternate source is outside programmed limits.
- Both sources are out of phase more than programmed limit.

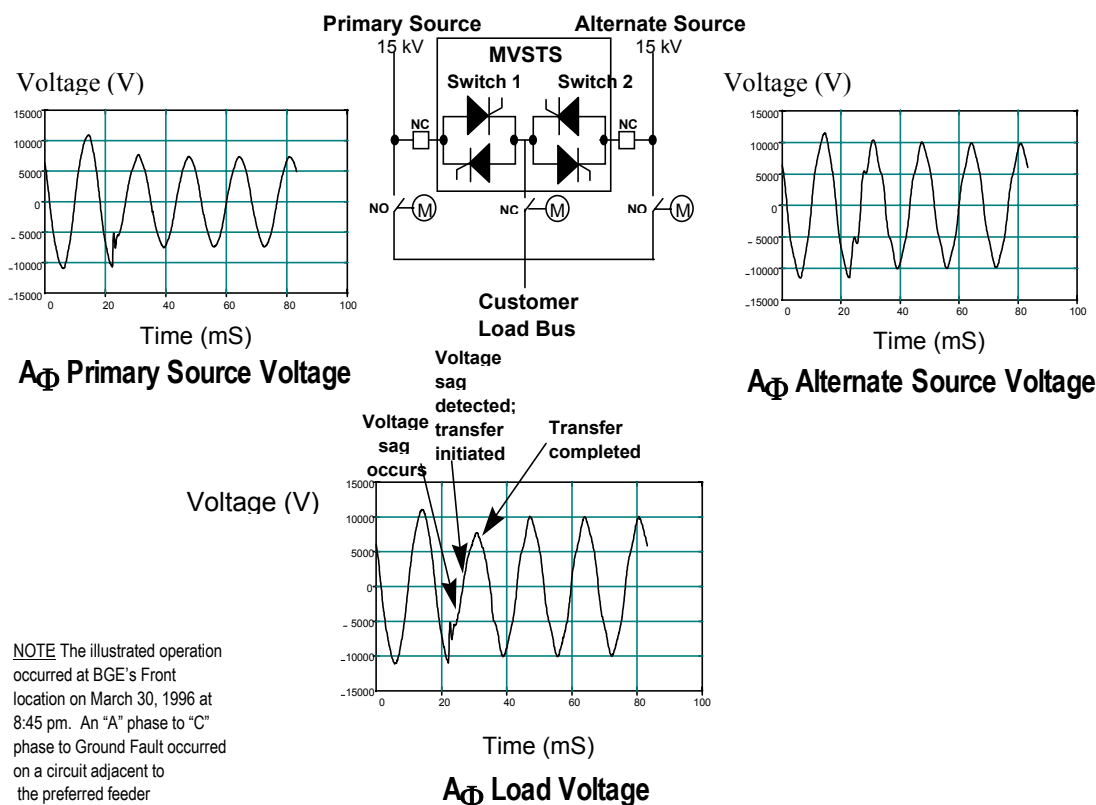


Figure 4.1.1. Single line diagram of the PowerDigm Medium Voltage Static Transfer Switch

Note that the thyristor switches do not have to interrupt power for a short circuit or ground fault on the load side of the switch. It only has to allow for the fault current to be conducted until the fault is cleared by means of fuses or breakers. After such a fault is cleared, the thyristors can be allowed time for a cool-down before the switch will have to be capable of performing a fast transfer again. This is different from the duty of a breaker, which has to clear the fault and withstand full voltage

including voltage transients after clearing of the fault. This does not allow the junction temperature of the thyristor devices to rise as much as can be tolerated for a transfer switch.

4.1.1.2 Actual Transfer Result - Voltage Sag

Under normal conditions, ac switch #1, as shown in Figure 4.1.1, is turned on and current flows from the primary source to the load. When a disturbance, such as the voltage sag shown in the figure is detected by the MVSTS the gates signals are removed from ac switch #1 and the gate of the ac switch #2 is then energized. Since ac switch #2 most of the time has a higher voltage potential, the thyristors of switch #1 will be forced to commutate off when switch number 2 is turned on.

The data shown in Figure 4.1.1 was collected at BG&E's Front Street facility during a voltage sag in March of 1996. An "A" phase to "C" phase to ground fault occurred on a circuit adjacent to the preferred feeder which resulted in approximately 60% voltage sag. The transfer took place within 4 ms after the event started, keeping the sensitive computer equipment within the office complex in service.

4.1.1.3 MVSTS Design & Electrical Ratings

The MVSTS is typically applied in a single switch, preferred-alternate, or split-bus configuration. It must be designed to meet the following electrical requirements:

- Rated voltage 5 kV to 38 kV rms phase-to-phase
- Continuous Current 200A to 1200 A rms
- Fault Current up to 18 kA symmetrical., offset to 45 kA crest for 15 cycle ride-through
- Impulse voltage withstand up to 150 kV crest (15 kV systems)

The design of a 15 kV MVSTS should meet the following requirements:

- Voltage rating of each switch: Each ac switch must be able to block 8.66 kV_{rms} (12.25 kV_{peak}) phase-to-neutral voltage under normal operation and up to 3 p.u. voltage under transients such as capacitor switching and be able to withstand a ringdown of motor load if load is interrupted by means of the switch.
- Power dissipation of thyristors (99.5% efficiency at full load): The conduction losses of the thyristors is relatively large compared to conventional load break switches and circuit. The heat generated by the thyristors must be removed.
- Surge current ratings of thyristors: The MVSTS should be designed to conduct a fault current of up to 18 kA symmetrical (45 kA crest) for 10 to 15 cycles to allow time for either upstream or downstream protection devices to operate.
- Impulse Voltage Rating of Sub-cycle Switch: The low-voltage control system must be isolated from the high voltage switch elements to withstand an impulse voltage of 110 kV for a 15 kV switch.
- Gate Drive System: Since the thyristors of the ac switch must conduct for the complete 180°, the thyristor gate drives need a source of continuous power, which is located at

ground potential -and must be insulated from the thyristor level to withstand a voltage impulse of 110 kV for a 15 kV switch.

- Load Transfer Performance: Each ac switch must be able to transfer motor loads as well as block transfer when there is a fault condition on the load side of the switch.

4.1.1.4 Transfer Switch Application Considerations.

The GTO type switch is obviously the only one that can reliably force a current zero. However, in transfer switch applications, a fast commutation from one source to another with lower ac voltage can be achieved only if two opposing thyristors are put into conduction since otherwise, a short circuit between the two sources (loop through) will be result. Thus, the sources have to be synchronous in order for a commutation to take place and load dynamics have to be taken into account when the transfer is initiated. Also, the coordination with protective devices between the switch and the loads has to be achieved. There are different ways of doing this. One way is to design the switch to ride through the short circuit current. This is the typical utility approach. Another would be to have the thyristors go into a current limiting mode or to use fuses for coordination between the thermal capability of the thyristors and the “downstream” overcurrent protections. All of these options are either available or are under development. There are obvious cost implications from these requirements. The newer switches, such as the one shown in Figure 4.1.2, have been designed to ride through the short circuit event.

Transfer switches are typically air-cooled. Figures 4.1.2 and 4.1.3 show two different designs. Most are built using air cooling systems with a highly directed flow. Some are built for once-through airflow. Such switches must be designed to operate even under polluted conditions including condensation mixed with dust and other pollutants. This will also put special requirements on gate drivers and other electronic components exposed to polluted air. Other switches are built with a two stage cooling system in which recirculation of air in a closed environment coupled with a secondary typically refrigerant-cooling loop is used. This type of system should eliminate pollution and condensation as factors determining the performance of the switches in the outdoor environment. Thus, there appears to be a trade-off between reliability of the switch under polluted conditions and reliability of the cooling system leading different designers to different solutions. There is to date very little experience with performance medium voltage power electronic systems in the outdoor environment. The operating experience from HVdc and SVC applications are not providing any guidance as to what approach to take because these types of systems are housed in buildings with suitable environmental conditioning.



Figure 4.1.2: One 3-Phase SPCO Built Medium Voltage Sub-Cycle Transfer Switch.

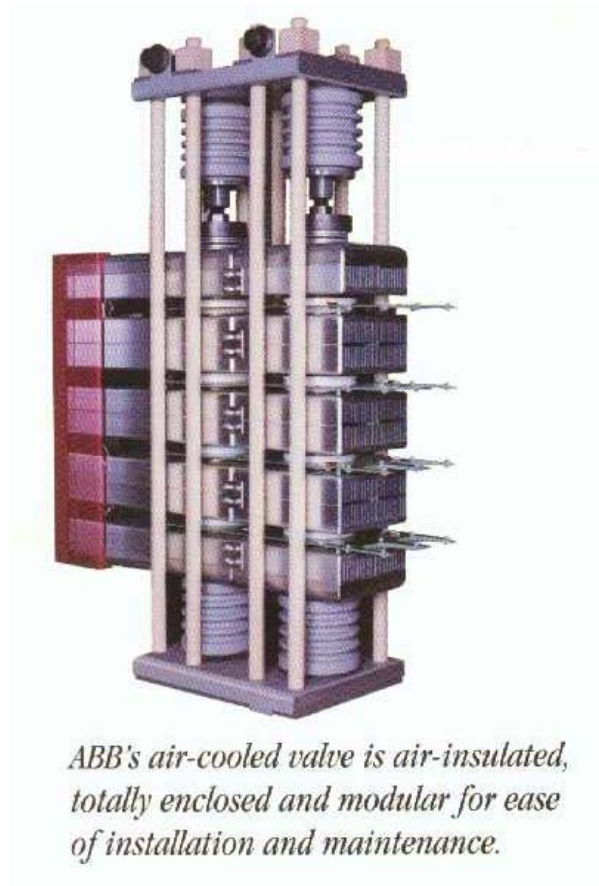


Figure 4.1.3: One ABB Built Transfer Switch Module.

4.1.2 Solid State Breakers (SSB)

Solid State Breakers are in contrast to transfer switches designed to interrupt the ac current. If the solid state devices used in the SSB are gate-turn off (GTO) thyristors then the current can be interrupted at any point on the wave. That is, it is not necessary to wait for a naturally occurring current zero for the interruption to take place. However, if the SSB interrupts the fault current prior to operation of fuses or protective relays on the load side of the SSB then the fault will not be disconnected and isolated in the way normally desired for fault isolation because fuses and relays take time to operate. In that case, the SSB may be combined with thyristor switches in a fault current limiter configuration, which enables both fast removal of large fault currents by means of the GTO part of the SSB and reduced voltage sag on the source side of the SSB as a result of the limited fault current which is let through to enable operation of conventional fuses and protective relays. The application of SSB will be explained below using a Siemens' (Westinghouse) developed SSB to illustrate one of the possible design approaches.

4.1.2.1 SSB Applications

The circuits in which SSBs are applied are similar to those where STS equipment is used but the function differs in that the STS does not interrupt fault currents. Four main applications for the SSB are described below:

- Two SSBs can be connected to form a STS. If two independent utility feeders are available to a facility, this application can provide a highly reliable source for a critical load. This arrangement is shown in Figure 4.1.4.

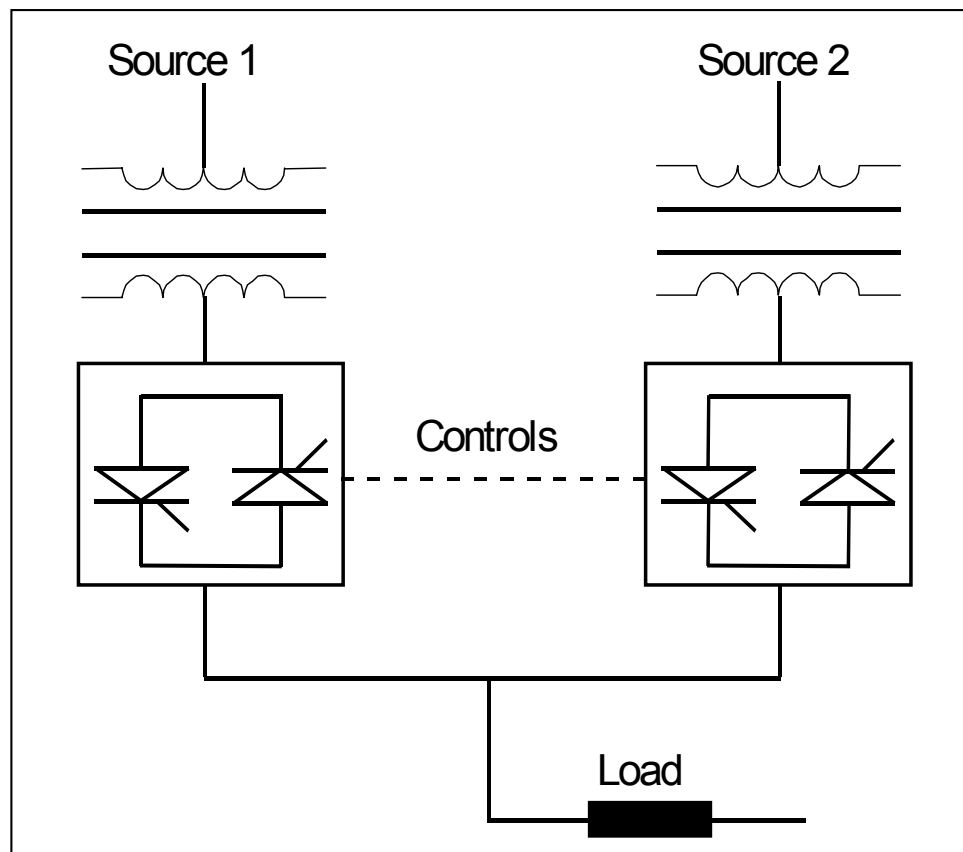


Figure 4.1.4 Two solid state breakers and control system form a Solid State Transfer Switch. Two independent sources improve reliability.

- The combination of a SSB with a DSTATCOM and energy storage (not shown in the figure) can act as a large-scale UPS system. This arrangement is presently limited by the cost of large-scale energy storage systems.
- When combined with a current limiting reactor or resistor, the SSB can rapidly insert the current limiting device into the distribution line to prevent excessive fault current from developing from sources of high short circuit capacity, e.g. multi-sourced distribution substations.

- The SSB can also be used as a bus tie breaker, shown in Figure 4.1.5.

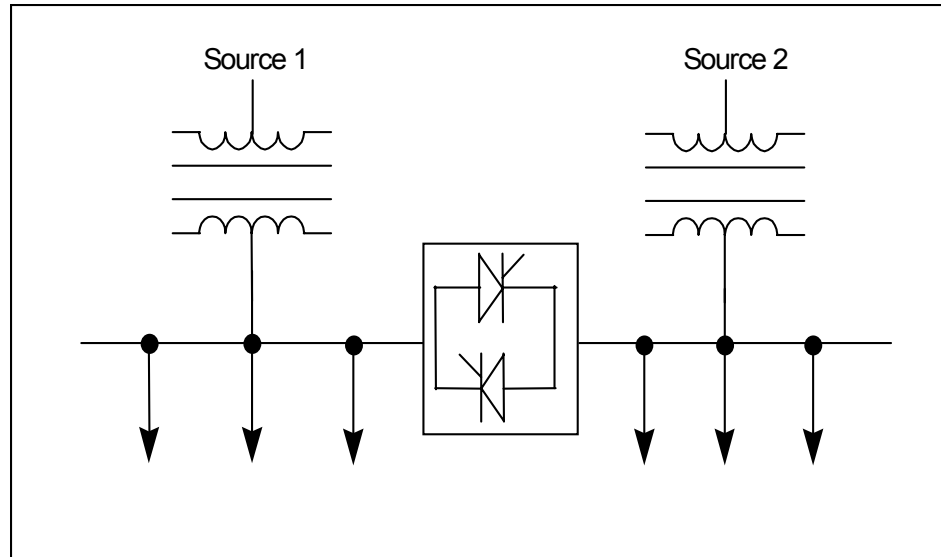


Figure 4.1.5: A Solid State Breaker configured as a bus tie breaker.

4.1.2.2 SSB Description

The Siemens (Westinghouse) built 15 kV class SSB is designed to conduct inrush and fault currents for several cycles and to disconnect faulty source-side feeders in less than 1/4 cycle. The capability of the SSB to provide this performance is dependent primarily on the rating and operating characteristics of the power semiconductor devices used for the AC switches making up the breaker. At the power levels associated with 15 kV and higher voltage class systems, commercially available Gate Turn-Off (GTO) and conventional thyristors can be used for the AC switch. The Siemens (Westinghouse) SSB consists of two parallel-connected circuit branches: a solid-state switch composed of GTOs and a second solid-state switch using thyristors in series with a current limiting reactor or resistor. The GTO switch is the main circuit breaker used to clear source-side faults. It is rated for the maximum normal line current, but not rated for fault currents. It is normally closed and conducts current uninhibited until the magnitude of the current reaches a pre-set level at which point it opens rapidly interrupting the current flow.

The GTOs are assembled in anti-parallel air-cooled modules. To achieve the required SSB voltage for application to the utility 13.8-kV primary distribution voltage up to six GTO modules are required in series which provides for a one-unit redundancy. The six series modules make up a complete GTO SSB pole. There is one pole for each phase.

The SSB can reduce distribution system problems that result in voltage sags, swells, and power outages. Siemens (Westinghouse) experience in SSB development and applications includes two units delivered in 1992 to the U.S. Army to provide "soft starting", current limiting, and instantaneous clearing on a 4160 V distribution feeder serving critical test facilities. In February

1995, a SSB (13.8 kV) and current limiter was placed in service at the Ridgefield substation on the Public Service Electric and Gas Co. (New Jersey) system and is shown in Figure 4.1.6.

4.1.2.3 Solid-State Circuit Breaker Specification based on Siemens (Westinghouse's) 15 kV Class SSB

1. Purpose:
 - a) Instantaneously interrupt the current in a 13.8 kV three phase, grounded neutral distribution line.
 - b) After the initial instantaneous current interruption, limit the fault current to a predetermined value to allow downstream coordination.



Figure 4.1.6: 13.8-kV, 600A GTO and 8-kA SCR SSB for Custom Power Applications (placed in service on PSE&G system 2/95)

2. Nominal Voltage Class:
13.8 kV
3. Nominal 3-Phase MVA Class:
1000 MVA
4. Rated Maximum Voltage:
15 kV RMS

5. Rated Continuous Current Ratings:
670 A RMS
6. Maximum Peak Current Interruption Level:
2,500 A Peak
(Note: The SSB interrupts instantaneously preventing the fault current from exceeding the maximum peak current interruption level.)
7. Fault Let-through Current Rating:
8,000 A RMS for 15 cycles followed by open for 15 cycles (repeated two more times)
8. Rated Interrupting Time:
30 microseconds (approx. 1/500 of a cycle) from conducting to non-conducting
9. Maximum Number of Fault Interruptions:
Unlimited
10. Rated Closing Time:
One cycle
11. Rated Closing Capability (Momentary):
8,000 A RMS for 30 cycles when operating in current limiting mode
2,500 A Peak for 3 successive interruptions when operating in the interrupting mode
12. Insulation Level:
95 kV Crest, rated impulse withstand test voltage (BIL)
36 kV RMS, rated low frequency withstand test voltage (Hi-Pot)
13. Losses:
Maximum of 40 kW at 670 A RMS continuous
14. Design Features:
 - a) 10% redundancy in the individual power electronic devices in each leg
 - b) Forced air cooled devices with a minimum of one redundant fan
 - c) Replacement of individual power electronic devices requires no more than 2 hours
15. Mechanical Assembly:
 - a) The SSB is supplied in an outdoor metal enclosure
 - b) This assembly is supplied with bushings for connection to the main power leads
 - c) The maximum size of the enclosure is:

Height	118 in.	(excluding the bushings)
Width	70 in.	
Length	70 in.	
Weight	5000 lbs.	
16. Control Power Requirements:
5 kVA maximum continuous, 1-phase, 120 V, 60 Hz

4.1.3 Fault Current Limiters (FCLs)

4.1.3.1 Solid-State Current Limiter Using GTO Thyristor

The principle and fundamental characteristics of a solid-state current limiter using GTO thyristor is that the short-circuit current activates an overcurrent detectors, so that the solid-state switch interrupts immediately, e.g. within 1 ms [25]. The short-circuit current is then commutated to the current limiting impedance. After the circuit breaker on the load side interrupts the fault, a load current flows to other loads through the impedance and the solid-state switch is then given a turn-on signal to let the load current flow through the GTO switch path again. For a line fault on the load side of the FCL, the fault current is not interrupted by any breaker opening and therefore continues to flow. In that case, a mechanical switch in series with the GTO switch is activated to isolate the fault within a few tenths on a second.

Because GTO thyristors are more limited in its current carrying capacity, some GTO based FCLs have a thyristor switch in parallel with the GTO switch to enable the limiter to carry sufficient current for the conventional protective devices to clear the faults. It is also possible to use thyristors in fault current limiting modes but with more complex circuits or the limiter will not be able to go into a limiting mode of operation until after the first current zero crossing. One FCL concept is shown in Figure 4.1.7. This will automatically limit the current to a preset level with no real time delay.

4.1.3.2 Thyristor Controlled Ground Fault Current Limiting System (TGCL)

A thyristor controlled ground fault current limiting system (TGCL) as shown in Figure 23 has been proposed [26] to prevent single-line ground fault current rises due to increased capacitance to ground. Basic components of the TGCL are a main ground fault current limiter, which rapidly adjusts the compensating reactor level, and the TGCL's controller. The main current limiter is a fast tap-changing system using thyristors. Control is ensured by an in-phase control method for zero-phase sequence voltage and current in order to determine the direction of ground faults and the compensating reactor level. The effects of the TGCL are as follows:

- Precise compensation for charging current of capacitance to ground
- Quick current limiting by solid-state switches
- No need to reduce grounding resistance for many pole transformers.

Simulations of the ground fault current, and the compensating current flowing through the compensating reactor have been run. For a simulated ground fault, the initial compensation level is 6.0 Arms. At 44 ms after the fault occurrence, a compensation level of 18.6 A is output. In response to tap changing on the solid-state switches, the compensating current is increased to 18.0 Arms. Consequently, the ground fault current drops from 23.7 Arms to 12.0 Arms. These results indicate that the TGCL can detect a ground fault, compute its compensation level, and control the solid-state switches within 50 ms after the fault occurrence. The fast control that can be realized shows the TGCL is a valuable protecting system for high ground fault current distribution systems.

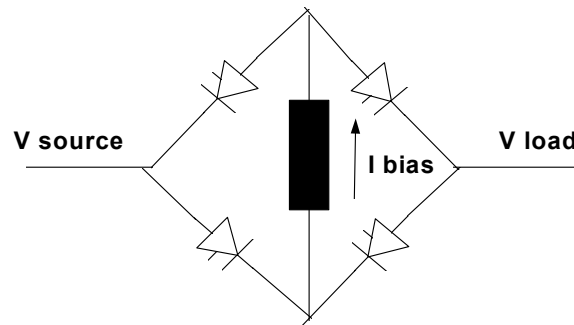


Figure 4.1.7: Fault Current Limiter Concept using a Reactor with an Injected DC Bias current

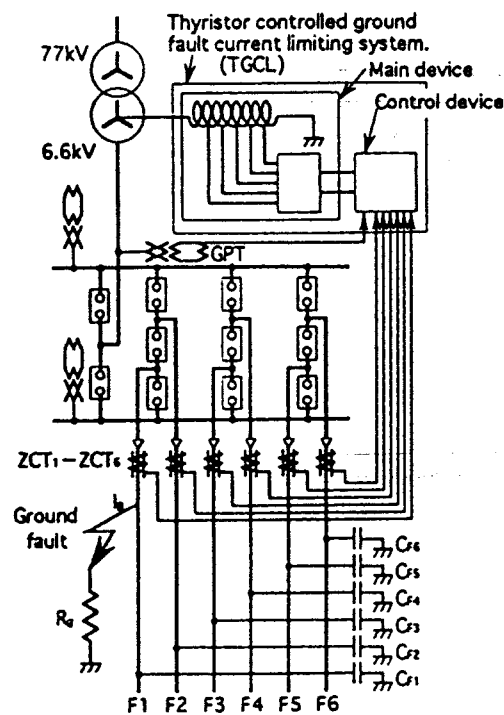


Figure 4.1.8: Thyristor Controlled Ground Fault Limiting System.

4.2 Shunt Conditioners

A variety of solutions have been employed over the years to correct or eliminate power quality disturbances. The most troublesome types of disturbances include voltage sags and surges, momentary interruptions, transients, and harmonic distortion. Each of these can wreak havoc with users' equipment and account for substantial monetary loss from subsequent equipment repairs and process disruptions.

The exact, and sometimes not so final solutions that are available depend on a customer's specific circumstances and the nature of the power quality problem. Minor power disturbances in commercial and even industrial buildings can be solved by making changes to the facility wiring and grounding schemes. In this way, sensitive loads can be isolated to minimize interference and interactions with other loads or circuits that are known to affect power quality. Shunt-connected passive and active equipment can be used individually or in combination to deal with customer installations that have more severe power quality problems. The following sections highlight some of the shunt connected options that are available to address power quality problems in a more robust and effective manner.

4.2.1 Static VAR Compensator

Static var compensators (SVCs) were developed in the late 1960s to provide fast reactive power (VAr) compensation for large, fluctuating industrial loads such as electric arc furnaces. These compensators used either thyristor-switched capacitors (TSCs) or a thyristor-controlled reactor (TCR), with permanently connected power factor correcting capacitors, which also provided some degree of harmonic filtering when combined with appropriate tuning reactors. In the late 1970s, the need for the dynamic compensation of electric power transmission systems had become increasingly evident to achieve better utilization of existing generation and transmission assets. SVC schemes, using TCRs in combination with TSCs and fixed capacitive filters on the secondary side of a coupling transformer, were devised and successfully applied for dynamic compensation to achieve voltage support, increased transient stability and improved damping. Figure 4.2.1 shows a typical arrangement. These SVCs relied on thyristor devices without gate turn-off capability for the control of the capacitor and reactor VAr sources.

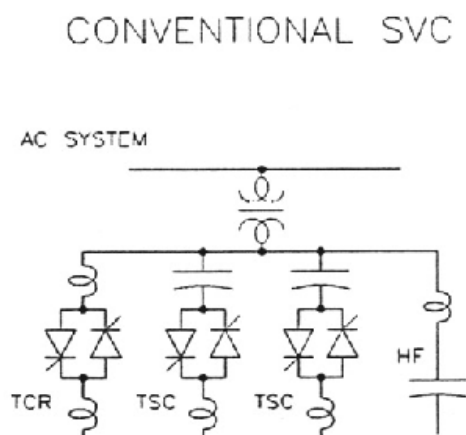


Figure 4.2.1: Typical SVC configuration

Functionally, the thyristor-controlled SVCs are essentially controllable reactive impedances. The thyristor valves control the current drawn by capacitor and reactor banks. This, in turn, influences the reactive power that is either generated or absorbed from the ac system. Consequently, the capacitor and reactor banks in an SVC are rated for the full reactive outputs that include the reactive power needed to cancel the output of the fixed capacitor banks. The thyristor valves must also be rated for the total controlled reactive output. Thus, an SVC requires fully rated capacitors and reactors to generate or absorb reactive power, and an electronic switching circuit (thyristor valves) for control that is rated for the sum of the maximum capacitive and inductive output. A complete SVC system involves a number of major components such as a transformer, capacitors, reactors, switchgear, and thyristor valves.

In the late 1960s, when the first static var compensators were developed, the solid-state power electronics represented the major share of the total equipment cost. By the mid 1980s, ongoing semiconductor device development yielded a factor of three increase in the voltage rating of power thyristors with a commensurate increase in their current handling capability by a factor of over four. Thus, the overall power handling capability of power thyristor devices has increased by a remarkable factor of at least twelve. This resulted in a drastic reduction in the number of thyristors required in an SVC of a given rating, with a corresponding decrease in the cost of the power electronic control. Today, the cost of the total power electronic control is less than 20 percent of the cost of a typical utility SVC installation.

While SVCs continue to find widespread usage for dynamic compensation of utility transmission systems, they have been successfully applied to industrial applications as well, especially in ac electric arc furnace applications. This demanding application is quite unique and presents a formidable threat to an ac system's power quality since the electric arc furnace generally presents an unbalanced load of poor power factor to the ac power system, and exhibits rapid and random variations in current. The large erratic reactive current swings cause corresponding voltage drops across the reactive impedance of the ac system resulting in a sometimes significant variation of the terminal voltage at the "critical bus" which is common to both the arc furnace and other utility customers.

The main concern over this voltage variation is the resulting variation in the light output levels of electric lamps that change in response to the ac power system voltage variations. This phenomenon is generally referred to as "flicker" and the human eye is rather sensitive to "flickering" lamps. To reduce the flicker, utilities usually require that the arc furnace load be complemented with an appropriately controlled reactive power generator so that the net reactive power variation in the ac system is reduced. The use of a VAR generator like an SVC also keeps the voltage variations to a minimum and the system power factor close to unity. This allows maximum utilization of the arc furnace and reduces costs associated with the steel making operation.

Traditionally, rotating synchronous condensers and constant or mechanically switched passive capacitor banks have been used to improve the power factor of electric arc furnace installations. However, constant or mechanically switched capacitor banks have been proven to be ineffective for flicker reduction. Although rotating synchronous condensers have met the requirement with more success, their wide application has been hindered by their inherent shortcoming in response

time, their inability to supply unbalanced VAr demand, their relatively high price, and their need for regular maintenance.

The role of the SVC and other reactive power generators is being challenged by the continual advances in power electronics technology. This impetus is allowing the realization of a new generation of static VAr generation equipment that has the potential to supplant entrenched equipment that has been customarily used to address power quality issues. This new equipment relies on the use of voltage source inverters to generate or absorb reactive power without the use of physical capacitors or reactors.

4.2.2 Static Synchronous Compensator (STATCOM)

Custom Power is a technology-based concept that provides utilities or industrial customers with the ability to offer a preferred power quality solution over wide areas in distribution-level power systems. Ideally, all Custom Power devices are able to react in real-time to the state of the distribution system to maintain the required level of power quality. A special class of Custom Power equipment that relies on power electronic-based concepts has been developed and is now commercially available to broaden the repertoire of solutions for customers plagued with poor power quality. This new breed of Custom Power equipment relies on the use of three-phase voltage source inverters that operate synchronously with the power system to perform specific functions that enhance distribution system power quality.

One such device is the Static Synchronous Compensator or STATCOM. It is a shunt-connected reactive power source that is coupled to the ac power system via a coupling reactance. The coupling reactance is typically derived from the leakage impedance of a standard distribution-class transformer although some manufacturers are experimenting with direct-connected or transformerless equipment that is tied to the line via fixed reactors. Figure 4.2.2 depicts the functional arrangement of a modern STATCOM. Its operation is much like that of a synchronous condenser but with a significantly faster response time.

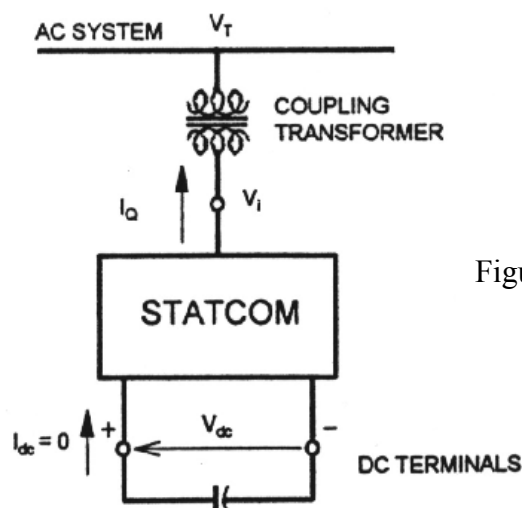


Figure 4.2.2: STATCOM functional arrangement

The STATCOM synthesizes output waveforms for insertion into the ac power system through high frequency switching action in its associated power electronic stages or dc-to-ac inverter. In its simplest form, the inverter is composed of six semiconductor switches that possess inherent gate turnoff capability. The inverter generates a set of three synchronous voltage waveforms at fundamental frequency by connecting its dc terminals sequentially to the three output terminals via the appropriate inverter switches. Since the inverter supplies only reactive output power, the real input power provided by the dc source (charged capacitor) is zero. The dc capacitor plays no direct part in the reactive power generation process. In other words, the inverter simply interconnects the three ac terminals in such a way that the reactive output currents can flow freely between them to effect a circulating power exchange among the phases of the ac system. The STATCOM has the unique ability to absorb or generate dynamic VARs well in excess of its steady-state rating. Thus it can effectively provide compensation during severe ac power system disturbances and yield superior benefits for the end user.

Its fast acting nature also enables the STATCOM to compensate for harmonic distortion in addition to providing accurate dynamic voltage regulation. It achieves this by synthesizing and injecting harmonic currents required by the load thus freeing the power distribution system to supply only fundamental current at near unity power factor. The reduction of harmonic load current flowing through the power system consequently reduces the voltage distortion within the power system as well. The ability of the STATCOM to provide harmonic compensation occurs automatically and transparently up to the bandwidth limitation of the equipment regardless of any changes in the harmonic profile of the offending loads within the ac system.

The STATCOM controls the reactive power exchange between itself and the ac system by varying the magnitude of the output voltages produced at its ac terminals with respect to the power system voltage. For example, if the amplitude of the output voltage is increased above that of the ac system voltage, current flows through the coupling reactance, and reactive (capacitive) power is generated for the ac system. Conversely, if the amplitude of the STATCOM's output is decreased below that of the ac system voltage, reactive current flows from the ac system to the STATCOM and the STATCOM absorbs reactive (inductive) power. If the output voltage is equal to the ac system voltage, the reactive power exchange is zero. Figure 4.2.3 shows a simplified depiction of the STATCOM power circuit and the voltage relationships corresponding to the generation or absorption of reactive power.

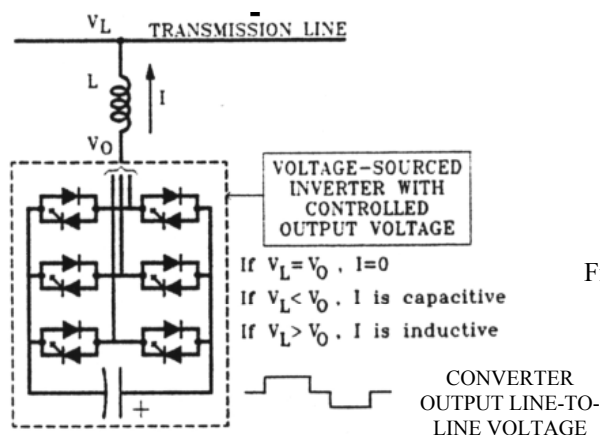


Figure 4.2.3: STATCOM basic power circuit and operational relationships

The STATCOM is capable of generating continuously variable inductive or capacitive shunt compensation at a level established by the maximum VA rating of the STATCOM's inverter. Unlike its conventional counterpart the SVC, the amount of compensation provided by the STATCOM varies linearly with the line voltage due to its unique voltage source inverter technology. Thus, it can continue to provide compensation and benefit even at low system voltage levels. For instance, the STATCOM is capable of supplying full capacitive current at any system voltage down to about 0.15 per unit. This ability to support the system voltage is superior to other techniques that rely on passive components, like switched capacitor banks or SVCs, whose compensating current falls in proportion to the impressed voltage.

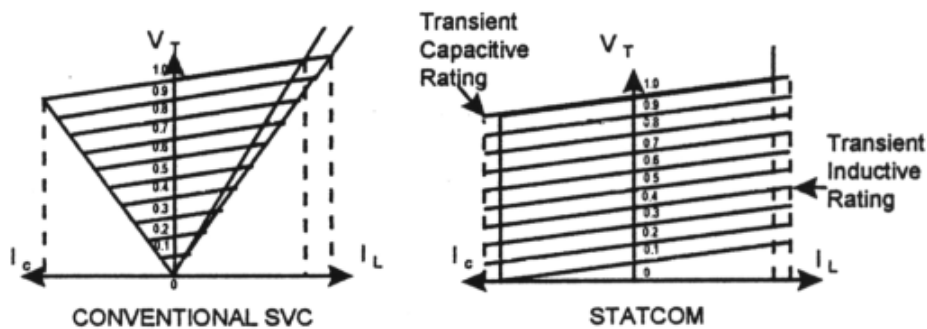


Figure 4.2.4: Operating characteristics of a SVC and STATCOM

The key technology that has made voltage source inverter-based compensating equipment like the STATCOM possible is the commercial availability of solid state switching devices at high power levels that exhibit inherent self-commutation or gate turn-off ability. Developments in gate turn-off (GTO) thyristor technology and insulated gate bipolar transistors (IGBT), in particular, allow suitable high power applications to be realized at a cost that makes them economically feasible for use at distribution power levels.

Two types of GTO thyristors are available. One is a symmetrical device with full reverse voltage blocking capability and the other is asymmetrical with no or very limited reverse voltage blocking capability. The latter is suitable for voltage source inverters where the devices are not exposed to reverse voltage stresses. Asymmetrical devices rated 4,000 to 6,000 volts with turn-off current ratings at 4,000 amperes are commercially available. Voltage ratings up to 9,000 volts and turn-off currents of 6,000 amperes for asymmetrical devices are emerging. The GTO product has been stretched for improved for applications in pulse width modulated converters for power applications. The so-called IGCT (integrated gate-commutated thyristor) also called GCT is supplied with special gate designs and is supplied with the special gate drivers. These devices exhibit fast turn-off and are capable of operating hard switched (without any snubber capacitors) although with some current derating.

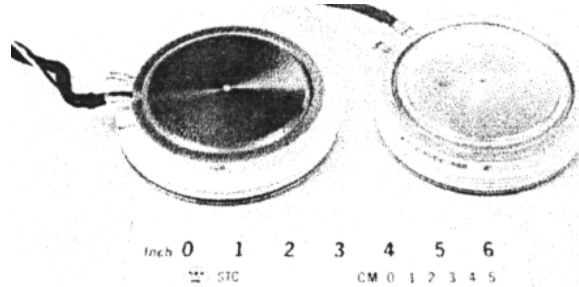


Figure 4.2.5: GTO devices rated for 4,500V and 4,000 A

The IGBT has reached 4,500 volts and 3,000 amperes repetitive peak forward current but sample devices with higher voltages are becoming available. The IGBT is modulated by means of the gate signal. The turn-on current rate of change can therefore be controlled, as can short circuit currents because the IGBT is a non-latching device. In fact, a latchup is a failure mode of the device. Some IGBT devices are available in double-sided cooled press pack versions, too. These are built specifically to be series connected for higher voltage valves. The IGBT has been the subject of major R&D investments. Faster switching speeds and lower forward voltage drop has been achieved. In view of the heavy R&D investments in IGBT technologies, this device type can be expected to have substantially improved performance in the future.

Also important to the realization of this new family of equipment like the STATCOM has been the companion advances made in control system implementation. A typical STATCOM features a fully digital control system using a mix of high-speed micro-controllers, digital signal processors (DSP), VLSI logic devices, fiber optic communication pathways, and advanced control techniques. These components enable the STATCOM's control system to constantly monitor the conditions on the distribution line and compare the measured data with reference quantities to produce the desired response from the equipment to mitigate power quality disturbances.

The STATCOM typically contains a common dc-side connection and can inherently accommodate an energy storage device if the Custom Power application requires real power transfer. A number of technologies are now at sufficient stages of maturity to be considered as viable additions for Custom Power applications. These include:

- Ultra-high energy density capacitors (e.g., capacitor double layer technology)
- Advanced batteries
- Flywheel energy storage
- Superconducting Magnetic Energy Storage (SMES)
- Fuel cells

All of the above can provide dc output and are hence capable of deriving their energy from the dc terminal of the inverter. However, to control the flow of energy between the energy storage and

the inverter, usually some form of dc-to-dc power flow controller is required to compensate for any voltage differences. This circuit manages both the rate of charge and discharge from the energy storage medium.

A complete uninterruptable power controller and compensation system can be configured by adding a sub-cycle, solid-state breaker (SSB) upstream of the STATCOM along with some form of energy storage. The STATCOM can then be used to provide full voltage support and harmonic compensation to a critical load during extreme unavailability of the power system.

In the event of a supply disturbance, the SSB isolates the line and the STATCOM supplies the entire load from its local energy storage. The amount of time that the critical load can be supported during this interval is determined by the amount of energy storage attached to the STATCOM. Typically this energy storage element is sized based on system studies or through an examination of historical event records. Energy can be exacted from the storage device through the STATCOM consistent with the VA rating of the STATCOM's inverter.

The high bandwidth and dynamic compensating ability of the STATCOM is aptly suited to perform flicker reduction in industrial ac electric arc furnace applications. Studies have shown that the STATCOM can be dramatically more effective for flicker reduction than conventional thyristor-controlled arc furnace compensators. Conventional SVCs are inherently limited in their ability to respond to the fluctuating arc furnace load. Once triggered, the thyristor valves must remain in conduction until natural commutation occurs at the next zero crossing of the current. Thus control (gating) information is determined and essentially locked into the SVC on a half cycle basis. This constrains the SVC from responding to changes in the load current that will occur in sub-cycle intervals due to the fast, random and very erratic nature of the arc. Another limitation of SVCs in being able to mitigate the effects of flicker, stems from the fact that they can only supply reactive power compensation and cannot supply any portion of the fluctuating instantaneous power drawn by the furnace.

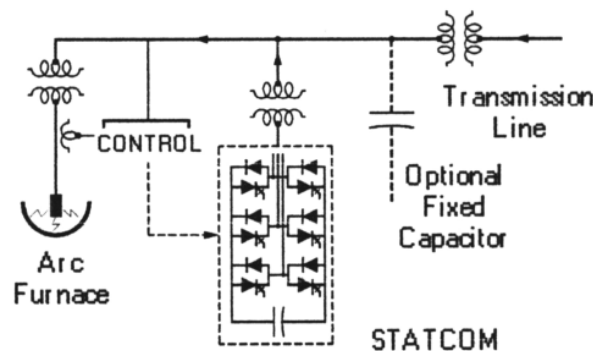


Figure 4.2.6: Using a STATCOM for flicker control

These are not the case with the newer technology exhibited in a STATCOM. The STATCOM can virtually force three-phase currents of arbitrary waveshape into the ac power bus on an relatively instantaneous basis. Therefore, it can supply the arc furnace with non-sinusoidal, unbalanced, randomly fluctuating currents and fundamental reactive power. The addition of energy storage at its dc terminals enables the STATCOM to also provide any fluctuating real power demanded by the arc furnace. Thus, the ac mains will be relieved of having to provide these components

eliminating flicker and dramatically improving the power quality. This type of comprehensive compensation of the arc furnace is unattainable using conventional technology like the SVC.

Studies have confirmed that a factor of 3 or so improvement in flicker attenuation over SVCs can be expected using the STATCOM technology. A full-scale demonstration of an 80 MVA STATCOM in this application has been undertaken by Siemens (formerly Westinghouse) that will serve to verify the unprecedented improvement in flicker compensating performance.

Fully-functional STATCOMs have been developed by a few equipment suppliers and are successfully operating in customer's facilities. Chapter 5 contains examples and case studies of recent customer experiences with the STATCOM equipment in Custom Power applications to improve power quality. In general, the STATCOM has been quite effective at achieving its intended objective of solving customers' problems in this area.

4.2.3 Shunt Active Filters

The concept of the active power filter, also referred to as active power line conditioning, was first proposed in the late 1960's and 1970's as a way to address power quality problems at the point of connection of end user equipment arising from waveform distortions in an ac power distribution system. The rapidly increasing proportion of nonlinear loads connected to the distribution circuits causes waveform distortion. Nonlinear loads draw square wave or pulse-like currents from the ac power system instead of the purely sinusoidal current that is characteristically drawn by conventional linear loads. The load current flows through the predominantly inductive source impedance of the electrical supply network and causes distortion of the ac load voltage in response to the deviation from the ideal sinusoidal shape of the load current. The voltage supply thus becomes distorted and tripping may result among various sensitive loads connected to the same bus. Other types of problems can also arise when equipment is connected to a distorted bus. Transformers, as an example, can suffer a significant increase in overall losses because of this distortion that can cause overheating and the consequential reduction in useful operating life.

The degree of current or voltage distortion can be expressed in terms of the relative magnitudes of harmonics in the waveforms. Total harmonic distortion (THD) is one of the accepted standards for measuring voltage or current distortion in the electric power industry. Furthermore, various standards have been developed by the many organizations that serve the industry to quantify the acceptable limits of harmonic distortion and also contain measurement techniques and methods to evaluate applications.

Another related problem occurs when the load current contains triplen harmonics (harmonics that are related to the fundamental ac power system frequency by a multiple of three (i.e., $3f$, $6f$, $9f$, etc. where f is the fundamental frequency of the power system)). The resulting currents flow in the neutral conductor of the power system and can grow to significant magnitudes if an appreciable amount of triplen harmonics are present. Often, the resulting neutral current can exceed the rated line current, which can be troublesome since the neutral conductor is typically sized to carry only a fraction of the normal line current. Overheating or even fires can result in a building whose electric service is designed for conventional electric loads. Clearly, this is an incentive for relieving the electric power network from supplying harmonic currents, which is one of the underlying operating objectives of an active power filter.

The actual embodiment of an active power filter usually takes two forms -- shunt type and series type -- although variations do occur whereby both shunt and series types are combined into a single unit. Another variant is the hybrid filter arrangement that combines a conventional passive harmonic filter with active power equipment. The active portion serves as a vernier to enhance the effectiveness of the passive filter by providing fast response and compensation for higher order harmonics that may otherwise escape the passive element. The active power equipment can be fractionally rated since the bulk of the filtering occurs in the passive components.

The primary purpose a shunt-connected active power filter is to supply any harmonic current demanded by a nonlinear load in order to free the ac power system to furnish only fundamental current. The shunt active power filter thus serves as a controllable current generator as opposed to a controllable voltage generator as is the case of the series active power filter. The shunt active filter can compensate the load harmonic current without affecting the flow of fundamental load current. The harmonic current generated by the filter circulates between the active filter and the load. The resulting current from the ac power system consists only of the fundamental component of the load current, and is therefore sinusoidal. In an ideal situation, all of the compensating harmonic currents are furnished perfectly by the shunt active filter. The voltage at the load terminals therefore becomes sinusoidal and distortion free. In addition, the shunt active filter also has the ability to compensate for harmonics that may be present in the source current as well by virtue of its shunt connection with the ac power system and load. Normally, however, shunt active filters are used to compensate *only* the load current. Figure 4.2.7 shows the functional arrangement of a shunt-connected active filter.

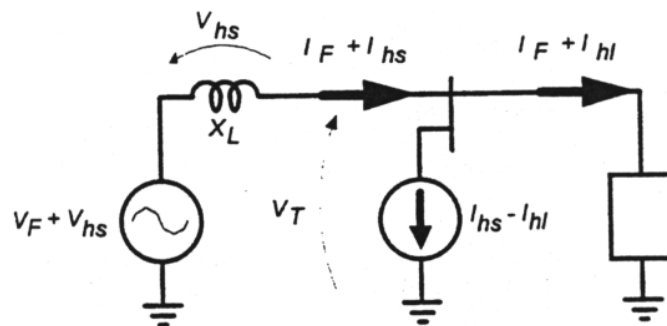


Figure 4.2.7: Shunt active filter functional arrangement

The series type of active power filter is the dual of the shunt active filter and serves to compensate a sensitive load for harmonic distortion that may be present within the ac power system. In this arrangement, an active voltage source is imposed between the primary ac source and the sensitive load. Its purpose is to insert a voltage in series with the load that is dynamically controllable to remove or oppose the voltage variations caused by ac power system voltage harmonics. The compensating voltage essentially cancels any harmonic voltages that are contained in the ac power system thus delivering a distortion-free, sinusoidal voltage to the terminals of the sensitive load. The degree of residual load voltage distortion is primarily a function of the bandwidth of the series active power filter and its power handling capability. Figure 4.2.8 shows the arrangement of the series-connected active filter connected as a controllable voltage source to compensate critical loads.

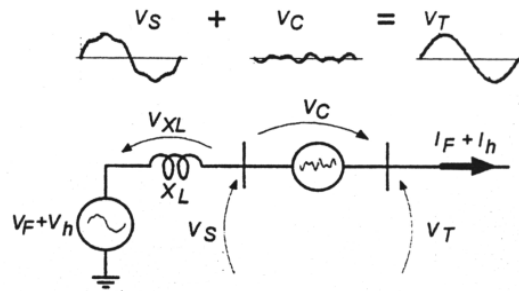


Figure 4.2.8: Series active filter functional arrangement.

Significant advantages arise from employing an active power filter rather than a conventional passive filter. Since the device can readily synthesize the magnitude, phase, and frequency of any harmonic component, it truly provides broadband compensation of the actual load currents. As is the case with the series active filter, practical limitations on operating bandwidth and power handling will restrict the overall effectiveness of the filter. However, an active filter will provide greater functionality and performance when compared to passive harmonic filters for a given application.

A typical series or shunt active power filter is constructed from a solid-state inverter that is configured as a voltage source inverter whose power switching elements are operated at a high switching frequency. A high switching frequency is a prerequisite to implement high bandwidth controls that enable the active power filter to compensate higher order harmonics. For similar reasons, PWM techniques are routinely employed to provide precise voltage control of the output waveform. Active power filters or line conditioners, as they're also known, are available commercially from numerous suppliers at ratings of up to hundreds of kVA.

4.2.4 Energy Storage Systems

Several energy storage systems may find application for custom power solutions. These include conventional battery energy storage as well as the emerging technologies of superconducting magnetic energy storage (SMES), flywheels and regenerative fuel cells (also called flow batteries). The following describes one form, the battery energy storage system (BESS), which has been deployed in practice. Extensions to other forms are discussed in general terms.

The two basic hardware components of the BESS are:

1. A power conditioning system (PCS), which provides bi-directional power conversion between the AC and DC systems and
2. The battery for energy storage.

A simple one-line diagram of a typical BESS system connection is sketched in Figure 4.2.9.

The Power Conditioning System (PCS) part of the BESS consists of a voltage sourced converter which is designed to operate as either an inverter when discharging the battery or as a rectifier when charging. Since the BESS may be required to support an isolated electrical load the PCS is

designed with self-commutating static switches capable of supplying the reactive power needs of the system. The high speed switches use pulse width modulation (PWM) to generate a controllable AC voltage waveform.

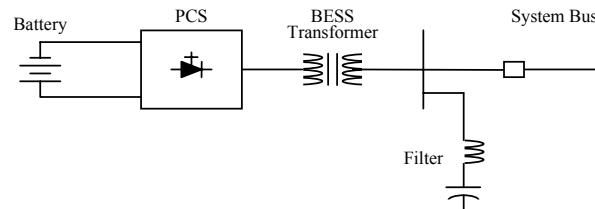


Figure 4.2.9: Simplified BESS one-line diagram

For most operating conditions the BESS is equivalent to a voltage source behind the transformer reactance (X_T) as sketched in Figure 4.2.10. The phasor diagram illustrates this essential feature of BESS system operation. Since the generated voltage is completely controllable within the current rating of the converter equipment, the AC current can be supplied at any phase angle relative to the terminal voltage (V_T). This permits the BESS to generate real and reactive power in all four quadrants as suggested by the capability curve. The BESS power generating capability is limited only by the thermal rating of the converters and the available battery voltage. Standard overload capability will permit operation at e.g. 110% for 60 seconds and 125% for 10 seconds. The active and reactive power controls are independent within the constraints of the converter capacity.

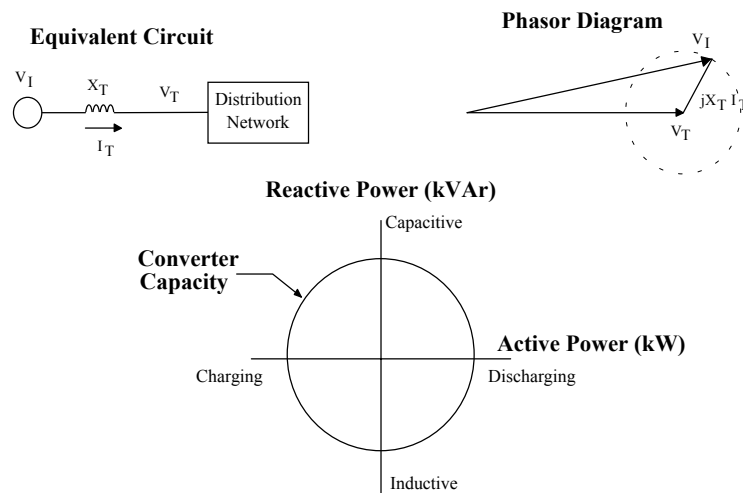


Figure 4.2.10: Active and reactive power capability

A common aspect among all energy storage systems is the need to vary the voltage or current associated with the energy storage element. Batteries typically vary in voltage from 65% to 100% as energy is added. A similar range is typical for capacitors or inductors used as energy storage. To accommodate this variation, a design decision is required whether to accept the inherent de-rating of a single conversion step as shown in Figure 4.2.9, or to add a second stage of conversion (e.g. dc:dc chopper). This is an economic tradeoff based on total system evaluated costs.

4.3 Shunt/Series Conditioners

As the name implies, an effective method to improve power quality can be obtained through the combination of both shunt and series compensation techniques. The benefits and performance attributes of active shunt and series filters, for example, can be aggregated with this approach to yield a unified method to simultaneously compensate both voltage and current in a local power delivery or distribution system. This enables current harmonics and voltage unbalance to be compensated in the load circuit concurrently with the compensation of voltage harmonics and unbalance at the incoming ac mains supply for the utmost in power quality enhancement.

This equipment has been discussed in the literature and is commonly referred to as either an active Power Line Conditioner (APLC) or a Unified Power Quality Conditioner (UPQC). Historically, shunt and series active filters found widespread use in local power delivery systems such as in office buildings or small industrial facilities. Typically, these systems were designed to operate at the prevailing voltage levels of 480 Volts ac or less. Recent advancements in technology now make it feasible to extend the concepts to distribution system potentials that is the target application of the Custom Power initiative. The underlying principles are, to some extent, embodied in technology associated with the STATCOM.

The combined series/shunt conditioner consists of two switching, voltage-source converters operated from a common dc link. These inverters feature high operating bandwidth and, consequently, wide dynamic range. One inverter is connected in shunt with the line via a standard coupling transformer while the other is connected in series. This arrangement functions an ideal ac-to-ac power converter in which the real power can flow freely in either direction between the ac terminals of the two inverters. Each inverter, in turn, can independently generate or absorb reactive power at its own ac output terminals. This arrangement resembles the shunt and series active power conditioners described elsewhere in this document. It also can be considered as being composed of two STATCOM-like devices with a common interconnection at their dc terminals when considering distribution-level applications. Each of them retain their individual operating character, but, when combined, assume a new dimension of operation and performance.

The series-connected inverter serves as a synchronous ac voltage in series with the line voltage having both controllable magnitude and phase angle. The line current flows through this voltage source resulting in real and reactive power exchange between it and the ac system. The real power that is exchanged at the ac terminal (the terminal of the insertion or coupling transformer), is converted by the inverter into dc power that appears at the dc link as positive or negative real power demand. Reactive power that is exchanged at the ac terminal, is generated internally by the inverter. The control system governing the operation of the combined shunt and series compensators dynamically controls the series voltage source to follow the harmonic voltage profile of the incoming ac supply lines, and removes unwanted voltage harmonics that may be present. This objective is somewhat different from the originally intended, and demonstrated, operation of another Custom Power device called the Dynamic Voltage Restorer (DVR) which is to inject voltage to compensate for transitory voltage variations on the supply lines. The need to compensate for voltage harmonics implies that the series converter must provide *continuous* voltage compensation of the ac mains in addition to its customary compensation.

The basic function of the shunt-connected inverter is to provide the harmonic current components demanded by the load, and to supply or absorb the real power demanded by the series-connected inverter at the common dc link. The dc link power is converted back to ac and coupled to the ac power system via the shunt inverter's coupling transformer. Like the STATCOM, this shunt inverter can generate or absorb controllable reactive power and thereby provide independent reactive compensation for the line. Unlike the real power flow which occurs in response to the series voltage injection and flows through both inverters, the reactive power exchanged is supplied or absorbed locally by the series inverter and does not flow through the line. This allows the shunt inverter to be operated with unity power factor or be controlled to have reactive power exchange with the line independently of the reactive power exchanged by the series inverter. This means that there is no continuous reactive power flow through the combined series/shunt device.

The availability of a combination series and shunt compensation device that retains all of the performance attributes of the APLC but functions at utility distribution power and voltage levels, would greatly enhance the Custom Power initiative, and provide the ultimate in power quality improvement.

4.3.1 Subcycle Static Voltage Regulator

A subcycle voltage regulator (SSVR) is a thyristor based voltage regulator. Thus, it acts like a combination of a series and shunt connected device. One possible configuration is shown in Figure 4.3.1.

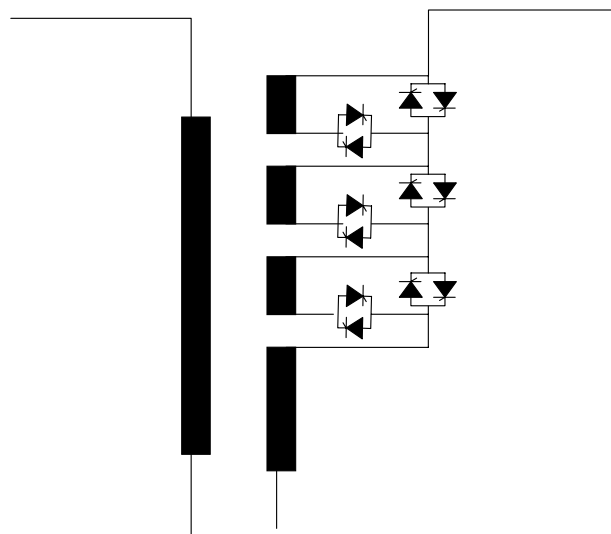


Figure 4.3.1: One Subcycle Static Voltage Regulator concept

The sketch shows a SSVR with fully insulated transformer windings with the thyristors placed on the secondary side of the transformer in line with the power circuit to the load. However, primary side switch locations are also possible. Concepts using a series transformer fed from a secondary winding of the transformer, in which the thyristor switches have been placed, have also been

shown. A number of other configurations are also possible. A few systems have been placed in service but no detailed information about the performance of any of these systems is available.

The SSVR operates as a fast load tap changer but with a tap range much larger than what is possible with a conventional tap changer. The scheme shown in Figure 4.3.1 can be used in for a binary tap selection scheme (1, 2, 4, 8, 16 etc.). If a reversing switch were to be incorporated, then the tap range would be +/- range of winding. If reversing is possible of each tap winding, then the taps could be arranged as 1, 3, 9 etc. and still provide a resolution equal to one per unit of the tap range.

The thyristor switches allow for a new tap selection at every current zero crossing. Thus, in theory, the SSVR will have an average, minimum, response time of a quarter of a cycle although if the disturbance begins right after a commutation has taken place, in a single phase application the next opportunity for a change of tap position will be one half cycle later. However, for a three-phase system, the switching will be sequential for all three phases so a minimum response time of close to one cycle can probably be expected.

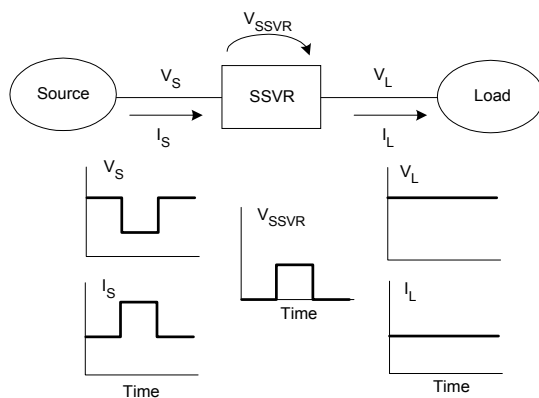


Figure 4.3.2: Example of SSVR response to voltage sag.

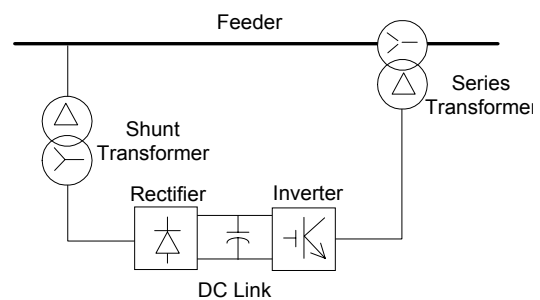


Figure 4.3.3: Main SSVR components.

A combination of voltage boost and buck tap selections is needed to produce a balanced three phase output voltage in response to a set of unsymmetrical input voltages with fault related phase angle changes on some or all of the phases. A realistic maximum voltage depression that can be corrected by means of an SSVR is probably on the order of 50% but the performance may differ for phase-to-phase, phase-to-ground and three-phase disturbances.

A second configuration of SSVR is shown in Figure 4.3.3. A series transformer couples the output of an inverter to the supply feeder to permit boosting when the source voltage sags. Normally, this inverter conducts load current while producing zero voltage. During a boost operation, the inverter creates the appropriate voltage to maintain load voltage at the desired set point. Energy to supply the boost voltage under load is provided via a simple rectifier connected to the line with a shunt transformer. Normally, this rectifier and shunt transformer carry no current. During a boost operation, the current drawn is as required to provide power to the inverter dc terminals. A significant point is that no energy storage is required in this scheme. Another important point is

that all main components are available from those widely applied in variable-speed motor drives and related industrial products.

CHAPTER 5

CUSTOM POWER SYSTEM SOLUTION

5.1 Shunt Reactive Compensation Applications

There have been 30 years of application of thyristor controlled reactors (TCR) and thyristor switched capacitors (TSC) for ac voltage and reactive power control. In more recent years, voltage sourced converters (VSC) with self-commutation have led to the development of the STATCOM which is the focus of this section.

5.1.1 BC Hydro STATCOM, Canada

Manufacturing Process

The manufacturing process includes a sawmill producing finished lumber and a whole log chipper (capable of chipping logs 24 inches in diameter) producing chips for the pulp and paper industry. Each chip is typically 2 inches or smaller.

The chipper utilizes three 400 HP motors connected to a belt driven blade. Depending on the log size, one, two or three motors may be running. The facility also has the capability of chipping multiple small logs at the same time.

Incoming Electrical Service

The lumber company is served by a 25 kV feeder that also serves approximately 800 other customers. Within the facility, the 25 kV service feeds five step-down transformers to 480 VAC.

Pre-STATCOM Power Quality

Logs entering the chipping process can cause current increases on the order of two to three times normal full load current. The cyclic inrush currents produce three phase running voltage flicker. Circuit measurement and simulation indicated voltage variations of approximately 6%. This level of voltage flicker is unacceptable to the 800 other customers (residential and commercial) that share the feeder.

STATCOM Installation

Rating: +/- 2 MVA
Feeder Voltage: 25 kV (14.4 kV_{L-G})
Trailer Mounted

The STATCOM is physically located adjacent to the lumber mill. It is connected in shunt to the 25 kV feeder.

Results

Figure 5.1.1 shows the uncompensated voltage flicker levels on the 25 kV distribution feeder due to the operation of the lumber mill (highlighted in red). The events shown were recorded over a 24-hour period with the STATCOM not in service. Figure 5.1.2 shows the same quantities for the subsequent 24-hour period but WITH THE STATCOM IN SERVICE. The resulting compensated flicker events are significantly reduced in magnitude demonstrating the effectiveness of the STATCOM.

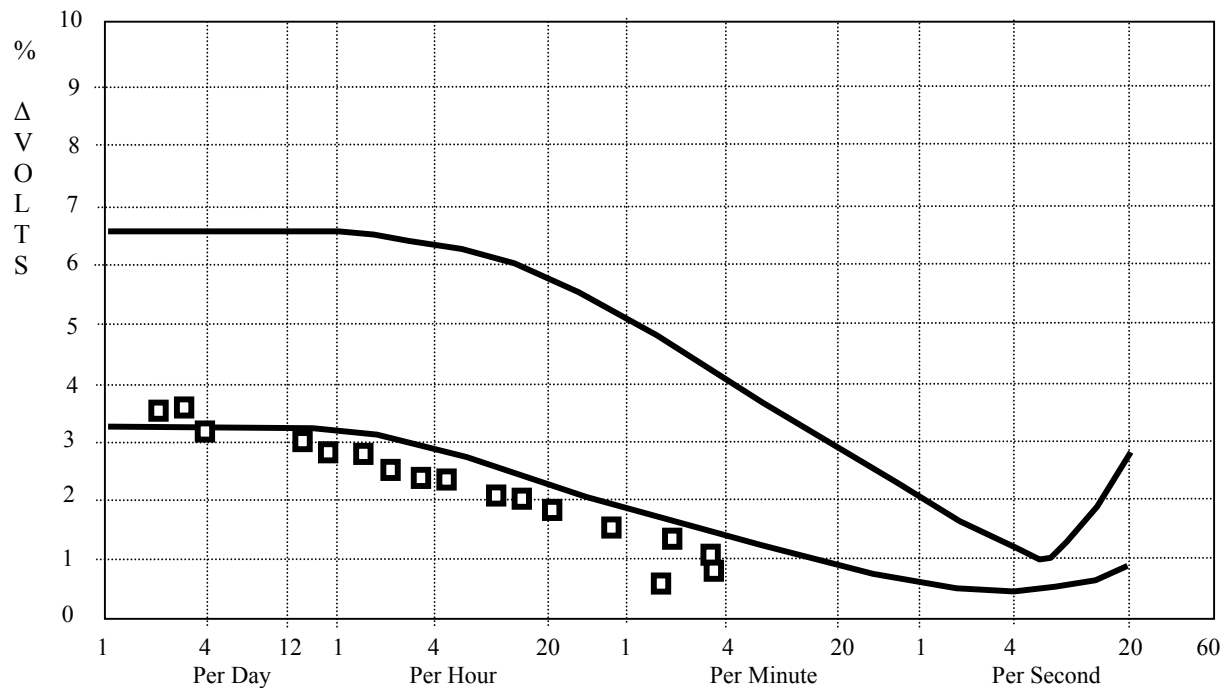


Figure 5.1.1: Voltage flicker events (small squares) recorded over 24 hours at lumber company service connection with STATCOM off-line compared with rural (upper) and urban (lower) utility distribution feeder allowable flicker standards.

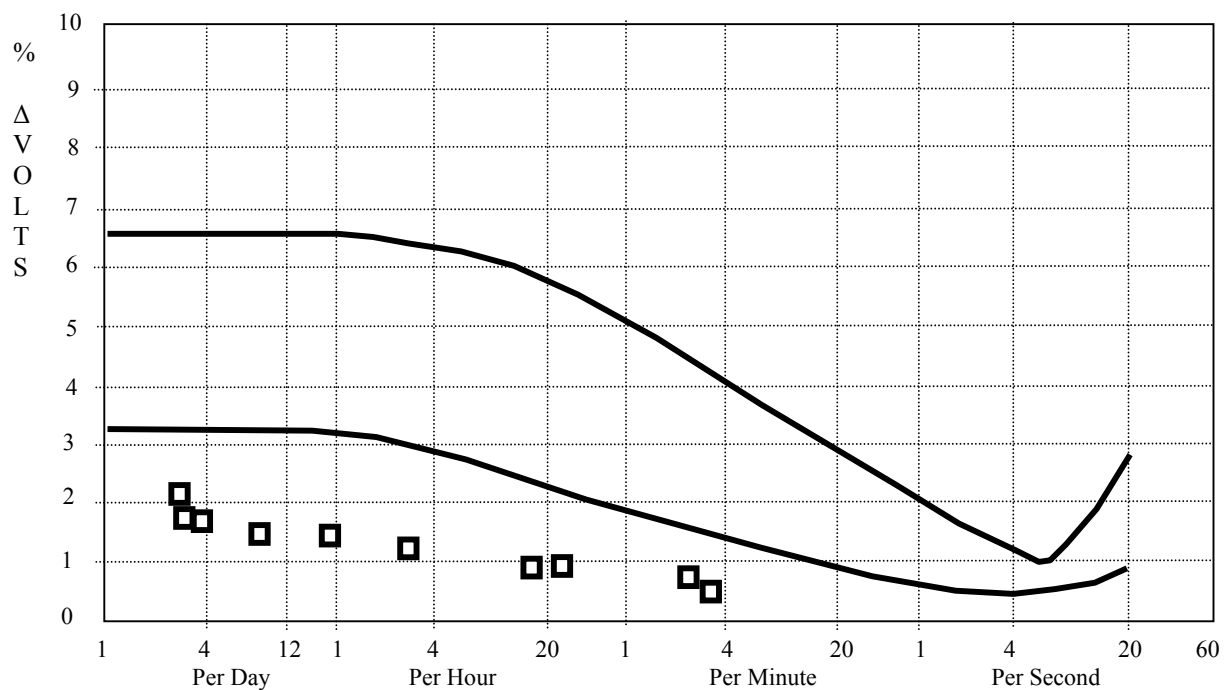


Figure 5.1.2: Voltage flicker events (small squares) recorded over 24-hour period (following period of Figure 5.1.1) showing improvement due to STATCOM operation.

5.1.2 American Electric Power STATCOM, USA

Manufacturing Process

This facility has two existing rock crushing operations with a third going into service. The operation produces minerals that are used in construction and agriculture. The crushing process reduces raw material from a foot or more in diameter to a final product that varies from five inches to powder, depending on the end use.

The first operation utilizes several motors of various ratings (1 x 250 hp, 4 x 200 hp, 1 x 250 hp, and 5 x 75 hp). The second operation uses two 200 hp motors and two 125 hp motors. The new third operation uses two-250 hp motors and many fractional hp motors. All of the multi-horsepower motors are 480 volt three-phase.

Electrical System

The site is served by an 11-mile long distribution feeder on a grounded wye system. Approximately 1000 other customers are connected to this feeder. The combined rock crushing operations are expected to have a maximum coincident running load of 3 MVA for all operations with a power factor ranging from 0.75 to 0.93. The inrush power factor is 0.28 when starting an individual motor.

Pre-STATCOM Power Quality

The first consideration was the effect on voltage at the point of common delivery created by starting the largest motor (1.8 MVA). However, because 17 multi-horsepower motors are involved, simultaneous starting of more than one motor was examined.

Simulations and site power quality monitoring demonstrated that unacceptable voltage flicker of approximately 8 to 12 percent would occur if the third rock crushing operation was connected. This level of flicker would exceed the acceptable utility criteria of approximately 4 percent and adversely affect other customers on the feeder.

STATCOM Installation

Rating: +/- 2 MVA

Feeder Voltage: 12.47 kV (7.2 kV_{L-G})

The installation also includes a parallel 2 MVA_c capacitor bank, producing a controllable reactive range of 0 to 4 MVA_c.

Results

To determine the STATCOM rating, the effect on voltage at the common point of delivery created by starting the largest motor (1.8 MVA Inrush) was simulated. Figure 5.1.3 shows the resulting voltage variation (per unit) at the point of delivery (y-axis) as a function of the locked rotor MVA (x-axis) imposed on the 3 MVA, 0.85 pf running load.

The dotted curve represents the uncompensated voltage, and the solid curve represents the effect of the +/-2 MV A STATCOM with a 2 MVA_c parallel fixed capacitor bank. The effect of the parallel fixed capacitor bank is to shift the controlled range of the STATCOM system to provide 0 to 4 MVA leading (capacitive) compensation.

The Figure 5.1.3 proves that two large motors (approximately 3.6 MVA of locked rotor current) may be simultaneously started with the STATCOM system maintaining 1.0 per unit voltage at the common point of delivery, largely reducing or eliminating flicker concerns. Voltage variation (flicker) is limited to less than 4% with nearly 4.3 MVA of motor starting inrush. Actual operation of the STATCOM with the rock crushing equipment corroborates the results from the simulation.

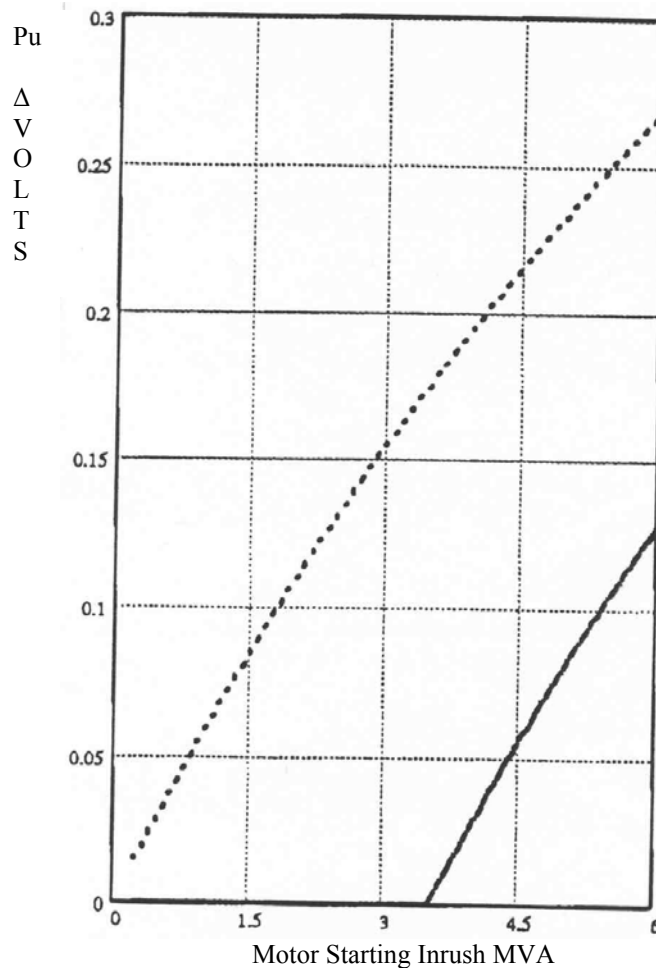


Figure 5.1.3: Per unit Δvolts at Common Point of Delivery vs Inrush MVA with (solid curve) and without (dotted curve) STATCOM system. Running load (3 MVA) @ 0.85 pf. Power factor at the point of connection is controlled to unity.

5.2 Series Dynamic Voltage Restorer Applications

To the knowledge of the WG, the first series dynamic voltage restorer based on inverter technology was installed in 1994. Since then several more have been installed throughout the world. The applications have been on both low-voltage and medium voltage applications, with load ratings from 1MVA to 6.5MVA. Configurations have included both energy storage types and those that draw extra current from the source during the voltage sag.

A selection from around the world is presented here.

5.2.1 PSE&G SSVR, USA

The Public Service Electric and Gas Company (PSE&G), located in Newark, New Jersey, was concerned about the increasing sensitivity of customer facilities to temporary voltage sags. To address this concern, PSE&G sponsored development of a device termed a “Static Series Voltage Regulator (SSVR)”, and installed the initial unit in their Central Division headquarters building in Somerset New Jersey. This facility includes many computer loads that were PSE&G’s primary concern, since a large number of their customers are large commercial office buildings.

The initial unit was rated for a load of 1.2 MVA with a maximum series voltage injection of 50%. The configuration consists of a shunt transformer supplying a dc link via a diode rectifier, with a pair of inverters on that dc link coupled via a series transformer between the supply and load. This was accomplished using two standard motor drive units, each rated 400kva.

A thyristor crowbar was used in the SSVR to transfer current from the inverters during a severe overcurrent event. During commissioning several load-side fault tests were performed to verify proper protective action.

This SSVR was commissioned in September 1994 and has been operating continuously since then. During the first year of operation, monitoring indicated many voltage sags on the supply side of the SSVR, but no disturbances were apparent on the load side proving that the device was operating properly. Although the monitoring program was stopped after the first year of successful operation, qualitative assessment indicates that the device continues to perform as desired to isolate the load from supply-side voltage dips.

5.2.2 Duke Power DVR, USA

Manufacturing Process

The Orian Rug Co. plant is a highly automated facility with two main processes. Yarn is manufactured from polymer chips by a high-speed extrusion and yarn winder (godet) process. The selected yarns are then supplied to automated looms that produce the final rug product.

Both manufacturing processes utilize many critical mechanical and electrically sensitive components. Among them are: godets, extruders, spin pumps, heaters, air compressors, and special tools for checking product acceptance and quality.

Incoming Electrical Service

The Orian plant is served by a single 12.47 kV feeder that is served by a 20 MVA substation transformer four miles away. The feeder has a 600 kVAr switched capacitor bank and 450 kVAr permanent capacitor bank. The Orian facility has two main transformers serving the yarn plant and the weaving mill. The total Orian load is approximately 3500 kVA at 0.8 pf.

The yarn mill transformer is rated at 2000 kVA, has a secondary voltage of 480 V and is connected wye-wye. Similarly, the weaving mill has a 1500 kVA transformer with secondary voltage of 480 V and wye-wye configuration. Several 480 to 380 Volt transformers are utilized within Orian because most of the process equipment is European and operates at 380/220 Volts.

Pre-DVR Power Quality

The feeder supplying Orian typically experienced about two voltage sags per month capable of tripping plant production. Those sags were often 30 cycles or less and caused the voltage to dip to around 40% of nominal.

With Duke Power's assistance, Orian had initially hardened their power system by increasing capacitance on drives prone to tripping or replacing them with less sensitive equipment. Equipment installed after 1991 was found to be more sensitive to voltage sags than older equipment.

Problems in the yarn plant caused by sags resulted from the drop out of motor drives or contactors. Even with partial loss of process, the entire batch may be scrapped. Yarn quality is highly dependent on the system remaining in precise synchronism.

DVR Installation

Unit #1: Online, August, 1996

2 MVA Inverter Rating

Energy Storage: 600 kJ

Feeder Voltage: 12.47 kV_{L-L} (7.2 kV_{L-G})

Maximum Inserted Voltage: 50% of Line to Ground Voltage (3,600 Volts)

The DVR is physically located at the Orian plant. It is connected in series between the Duke Power 12.47 kV feeder and Orian plant. The energy storage is capable of maintaining maximum voltage injection on all three phases for 30 cycles (½ second).

Anticipated Results / Results

It was determined that a voltage sag to less than 90% of nominal voltage could trip some plant equipment. Power quality monitoring over six months by Duke Power and analysis by Westinghouse determined that Orian experienced approximately 25 sags per year that were capable of tripping the plant off line. The DVR would have eliminated more than 80% of previously recorded sags.

The waveform below is the first half of a 26-cycle voltage sag that occurred in 1997. Power quality monitoring records show that the DVR corrected over 40 similar events during 1997.

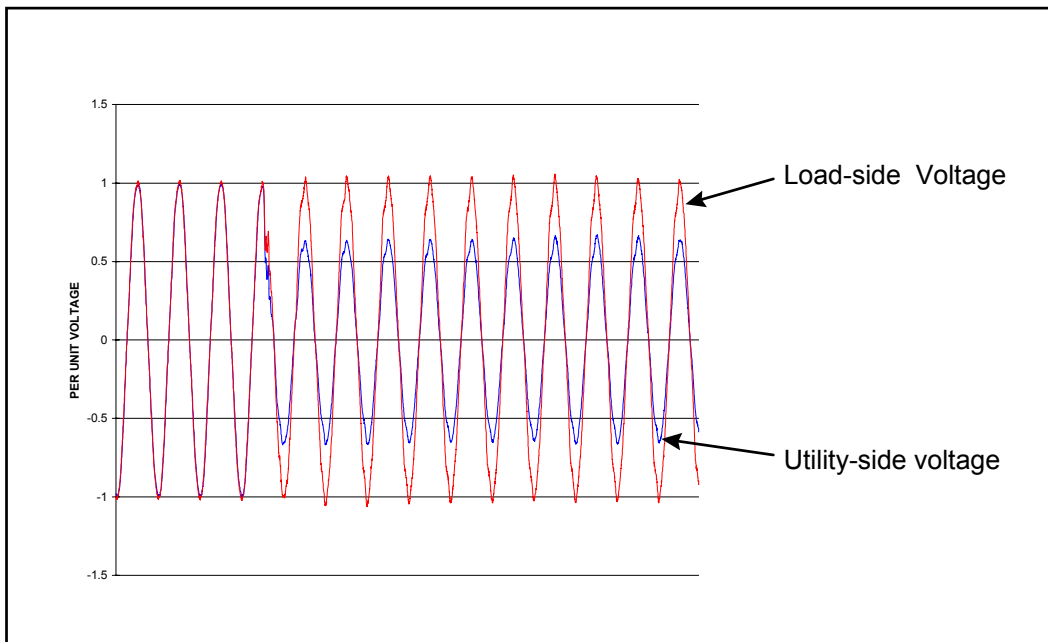


Figure 5.2.1: Recordings of DVR response to a voltage dip

5.2.3 Powercor, Ltd. DVR, Australia

Manufacturing Process

The Bonlac Foods Ltd. Stanhope Dairy has three main processes: 1. Producing whole milk from farmers' milk. 2. Producing milk powder from farmers' milk. 3. Producing cheese from farmers' milk.

The most electrically sensitive process is powdered milk production. Specialized Niro dryers are used during the powdered milk process. The flame control valves on the Niro dryers are extremely sensitive to voltage drops and momentary losses of milk supply. Niro dryers consist of an inlet fan, gas heated drying chamber, and outlet fan.

Incoming Electrical Service and Inplant Distribution

Bonlac is served by a 22 kV feeder from Powercor's Kyabram substation 11 miles away. Kyabram has three 66-22 kV transformers that supply 40 MVA at 0.8 pf for six feeders.

The Bonlac plant has six main transformers (22 kV to 415 V), five are 1 MVA transformers and one is a 1.5 MVA transformer. The total Bonlac load is approximately 5 MVA at 0.8 pf. Inplant production equipment is European and operates at 415 Volts.

Pre-DVR Power Quality

Fault rates on Kyabram feeders rise during the summer due to storms and bird nesting. The 22kV feeders from Kyabram average 20 to 25 faults annually. On the 66 kV line supplying Kyabram, 15 to 20 faults occur annually. About 60% of the 22 kV and 66 kV feeder faults cause voltage sags sufficient to disrupt production at Bonlac. In an average year, 20 to 27 faults on the Powercor system cause Voltage sags that disrupt production at Bonlac.

In the powdered milk process, Voltage sags of less than 90% of nominal voltage cause relays controlling the flame control valves to drop out and the milk supply to the dryers to be disconnected. Sags have also caused blower motors to trip which also disconnects the milk supply.

Often, voltage sags result in a product being below specification. However, some sags cause long process downtimes if the dryers need cleaning. Unscheduled long downtimes result in the destruction of incoming farmer's milk because it cannot be stored on site and must be used within 24 hours. Advance notice of a plant outage allows plant operators to divert milk to another plant or make alternate arrangements.

DVR Installation

Unit # 2: Online, February, 1997

2MVA inverter rating; Energy Storage: 600 kJ

Feeder Voltage: 22 kV_{L-L} (12.7 kV_{L-G})

Maximum Inserted Voltage: 40% of Line to Ground Voltage (5080 Volts)

This unit is the first 50 Hz Unit. The energy storage is capable of maintaining maximum voltage injection on all three phases for 25 cycles (½ second). The DVR will be located at the Bonlac site.

Results / Anticipated Results

A voltage sag of less than 90% of nominal voltage can trip some equipment at Bonlac. Power quality monitoring by Powercor and Siemens (formerly Westinghouse) determined that Bonlac has experienced as many as 30 sags per year capable of tripping the plant off line. The DVR would have eliminated more than 80% of the previously recorded sags. A cost-savings summary calculated by Bonlac Foods is provided below.

Operations Cost Savings To Date

The operations savings arising from the DVR Trial have been calculated from the list of operation interruptions recorded prior to the trial. This 2-year period gives a better statistical view than the partial year operation covered to date under the trial. (NOTE: All costs are in Australian \$.)

Costings have been calculated for a 5 hour production interruption that has been caused by a short duration voltage dip.

Local Operations

◇ Lost product / wasted raw materials	<i>Average loss \$1,250</i>
◇ Labor to clean / strip down production plant fouled due to loss of supply	<i>Recorded time @ \$25 per hour for 10 staff, totals \$1,250</i>
◇ Unproductive labor during equipment cleaning / restart time	
◇ Waste material treatment and plant utilities restarting	<i>Average cost of \$4,000</i>

Transport Costs

◇ Diversion of tankers to neighboring plants	<i>6 tankers @ \$980, average cost</i>
◇ Additional transport costs in shipping product to other plants	

Strategic Planning

- ◇ Opportunity Cost includes : *A value of \$75,000*
- ◇ Higher plant utilization *per event has been*
- ◇ Production of higher value product mix *calculated*
- ◇ Greater confidence for multi-plant operations

Total cost of 5 hour production interruption \$87,000

A total of 44 supply events that could have been treated by a DVR were recorded from March 1995 to the end of January 1997. Not all such events resulted in a 5 hour production loss, with a typical profile following:

20 hour	1 event	}	
5 hour	15 events	}	Total production
2 hour	18 events	}	loss = 141 hours
1 hour	10 events	}	

Using the calculated value of \$87,000 for a 5 hour event, an hourly rate of \$17,400 applies. Had a DVR been available during the recording period prior to the DVR installation, a production saving of \$2,453,400 would have accrued.

5.2.4 Scottish Power DVR, Scotland

Manufacturing Process

Caledonian Paper produces high quality paper for the commercial publishing industries. The process begins as logs are mechanically pulped and then chemically treated, forming a slurry. This is fed onto the moving wire of the paper machine to form the “web”. This is then dried and coated with china clay to give it a shiny finish. To achieve the necessary degree of gloss, the paper is then passed through supercalenders. Lastly, the rolls of paper are cut to size and the finished reels are dispatched. The finished paper weight ranges from 30 to 70 pounds.

The operation utilizes one paper machine that is intended for continuous operation. The process will often run for several weeks or months without interruption. The web is over 25 feet wide and is rolled up to a rate greater than 55 mi/hr. The weight of the paper determines the maximum speed at which the web can run.

Incoming Electrical Service

Scottish Power serves the Caledonian Paper mill at 132 kV stepped down to 11 kV within the site using two 40 MVA wye-delta connected transformers. The Caledonian Paper total plant load is approximately 50 MVA, of which 8.3 MVA is considered critical (see figure on reverse). The system includes capacitors for power factor correction and passive filters for harmonic cancellation. Plant equipment operates at 525 VAC.

Pre-DVR Power Quality

Voltage sags below 0.90 p.u. of nominal voltage for a duration of 5 cycles can cause motor drives to malfunction resulting in plant production problems. The drives were manufactured by a European company. Changes were made to desensitize the motor drives, the largest being 1300hp (994KW). These changes decreased plant sensitivity, but at the expense of reduced production of a premium product, which was unacceptable.

Voltage disturbances can cause damage to plant machinery. The felts that carry the paper on the rollers are set very close together to produce a single layer of paper. In the event of one motor drive tripping, a clump of paper can be forced through the gap between the felts causing damage. There can also be damage to the head box which contains the pulp mixture. Furthermore, it can take many attempts to restart the paper machine once it is off-line.

DVR Installation

Rating: 4 MVA

Energy Storage: 800 kJ

Feeder Voltage: 11 kV_{L-L} (6.35 kV_{L-G}), 50 Hz

Maximum Inserted Voltage: 46% (2.92 kV_{L-G})

The DVR is physically located within the Caledonian plant. The 8.3MVA critical load was segregated from the remainder of the plant feeders and the DVR connected in the 11kV feed to the critical bus bar. The energy storage is capable of maintaining maximum voltage injection on all three phases for 14 cycles (280msec).

Anticipated Results / Results

The 4 MVA DVR will be capable of providing approximately 46% voltage injection (2.92 kV_{L-G}). The DVR would have restored approximately 84% of previously recorded voltage sags to a minimum of 0.90 p.u. voltage.

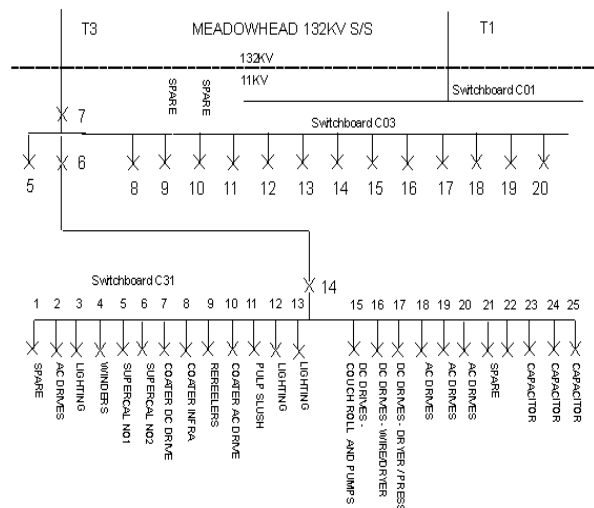


Figure 5.2.2: Caledonian Paper Mill 11kV distribution system

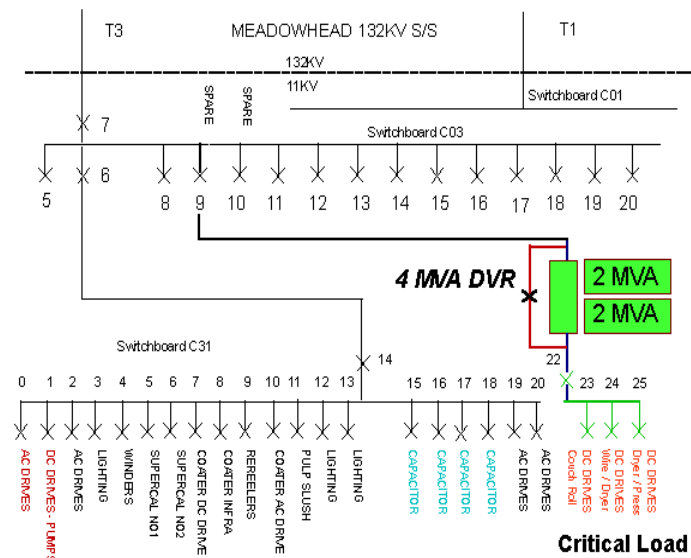


Figure 5.2.3: Caledonian Paper Mill 11kV distribution system modified to provide DVR protection for the plant critical load

5.2.5 Singapore DVR Demonstration

Manufacturing Process

Because of its nature as a demonstration project, the DVR has not been specified for a specific industrial process, though the operational experience aims to prove the suitability of the DVR concept for highly sensitive manufacturing processes such as computer chip manufacturing. Typically, this industrial process supports voltage sags of duration not exceeding a half cycle, which means a maximum of 8 to 10 milliseconds. Any voltage disturbance beyond this limit will cause an interruption to the process with substantial production losses due to a mandatory re-calibration of tools.

Incoming Electrical Service

The DVR is connected to a 21 kV, 50 Hz distribution bus. The design load to be protected from voltage sags is 4 MVA.

Pre-DVR Power Quality

The specification requires compensating voltage sags of up to 150 millisecond duration, and magnitudes of 50 percent and 38 percent below nominal for single phase and three phase events, respectively. The maximum response time was to not exceed 8 milliseconds from start of the voltage sag until full restoration of nominal load voltage.

DVR Installation

Rating: 4 MVA

Energy Storage: 600 kJ

Feeder Voltage: 21 kV_{L-L} (12.12 kV_{L-G}), 50 Hz

Maximum Inserted Voltage: The DVR control establishes an area protection function, i.e., it compensates even higher voltage sags than specified for a reduced duration.

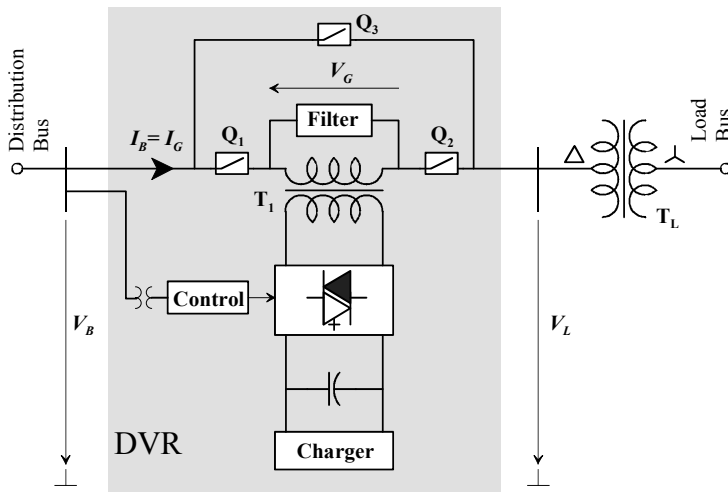


Figure 5.2.4: Basic Configuration of the DVR

This principle works independently of the type of ac fault, provided that the whole system remains connected to the supply grid, i.e., the line breaker does not trip. The DVR only compensates the positive and negative sequence components of the voltage disturbance seen at the input of the DVR. This option is justified because the zero sequence part of a disturbance will not pass through the step down transformer, since the effective impedance for zero sequence becomes infinite. In Figure 5.2.4, this zero sequence blocking function is achieved by the delta winding of the line step down transformer T_1 . The dc capacitor between the charger and the converter serves as the energy buffer to the DVR, generating and absorbing power during voltage dips and voltage swells, respectively.

For most of the time, the DVR has virtually “nothing to do” except to monitor the bus voltage. Under normal steady state operation, no voltage ($V_G = 0$) is injected and remains so independently of the load current. Therefore, it is important to focus on the losses of a DVR during regular hot standby operation. Two specific features addressing this loss issue have been implemented in this concept, which are the transformer design with low impedance, and the semiconductor devices employed.

The booster transformer's low voltage winding is shorted through the converter in the DVR's stand-by mode (left side in Figure 5.2.5). No switching of semiconductors occurs in this mode of operation, because the individual converter legs are triggered such as to establish a short-circuit path for the transformer connection. Therefore, only the comparatively low conduction losses of the semiconductors in this current loop contribute to the losses.

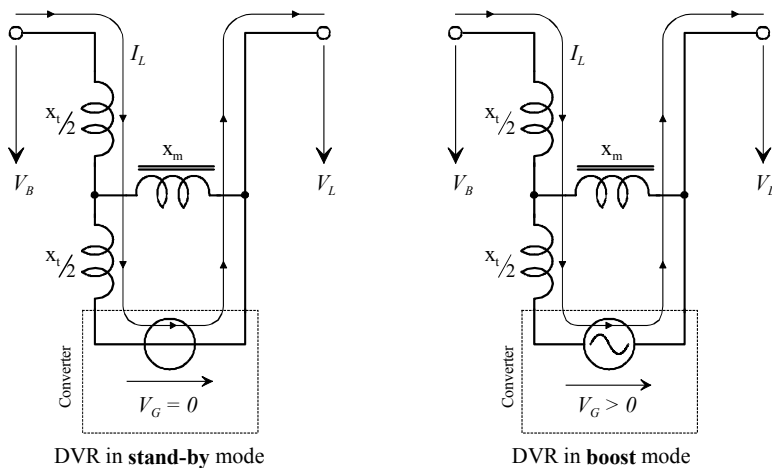


Figure 5.2.5: Effective transformer connection in stand-by and boost modes

As shown in Figure 5.2.5, the DVR transformer in standby mode resembles a shorted current transformer. Another loss reduction results from the IGCT technology (Integrated Gate Commutated Thyristor) utilized in this converter. These novel semiconductor devices combine the low conducting losses of a GTO (Gate Turn Off) thyristor with a switching performance similar to a transistor. With turn-off times in the range of a few microseconds, high-power IGCT type converters show approximately 30 percent lower losses than conventional GTO-type systems.

Dynamic properties of the DVR

Thanks to its voltage injection principle and a pure feed-forward control architecture, the DVR demonstrates superior dynamic performance. The attainable dynamic response of the DVR is linked to the following parameters:

- ◆ The sampling time of the feed-forward control hardware,
- ◆ The effective switching frequency of the converter, and
- ◆ The trigger threshold at which a bus voltage excursion becomes critical to the load.

Sampling times far below one millisecond is standard for today's control hardware, and therefore do not constitute any practical limitation to the system. The same is valid for the switching frequency of the converter. An effective switching frequency of approximately 2 kHz is adequate for a dynamic response of the DVR in the sub-millisecond range. In fact, the decisive parameter for the dynamic performance of the DVR is the trigger setting and its associated filtering time constant, because the control needs to distinguish between harmonic distortion and real sags in the fundamental voltage.

Operational Experience

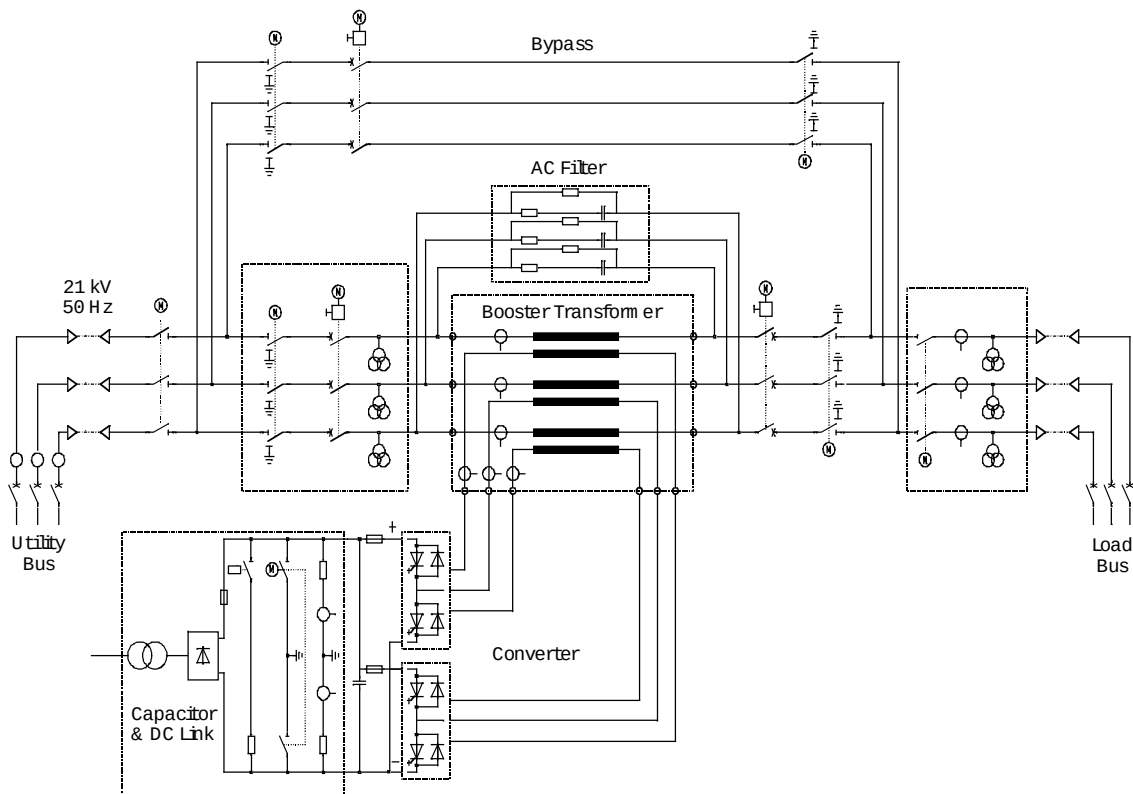


Figure 5.2.6: 3-line diagram of the 4.0 MVA Dynamic Voltage Restorer DVR

The diagram in Figure 5.2.6 shows the DVR's main components including bypass and grounding switches required for installation and maintenance. The communication between the control system and the power electronics part consists of fiber optic cables and is thus immune to any electromagnetic interference. Because of the short duty cycle of 150 milliseconds for the converter, forced air cooling is sufficient for the semiconductors. The converter consists of two 6-pulse units (on top of the capacitors in Figure 5.2.8), in Twin connection, and is rated for a dc voltage of 2.3 kV, optimizing cost and performance of the main components. For the subject duty cycle, a capacitor bank as energy storage device is most economic, although the feasibility of batteries has been investigated but waived for maintenance and life expectancy reasons.



Figure 5.2.7: DVR Container with transformer in background

All the power components except for the transformer and the filter circuit, fit into a standard 7.8-by-4.1 meters (25.5' x 13.5') container. All live parts are protected with transparent acrylic plates, hence the system is accessible for visual inspection without prior shut-down. Because of the low losses, active cooling of the container can be accomplished by three standard air-conditioning units, of which one is redundant. Because of the high humidity in the area, particular attention has been paid to the thermal insulation of the container to avoid condensation on electrical parts. The containerized design shows substantial advantages regarding installation and commissioning time spent at site. Setting up the whole system and bringing it into operation takes only a couple of weeks, because all wiring and sub-system testing is done at the factory.

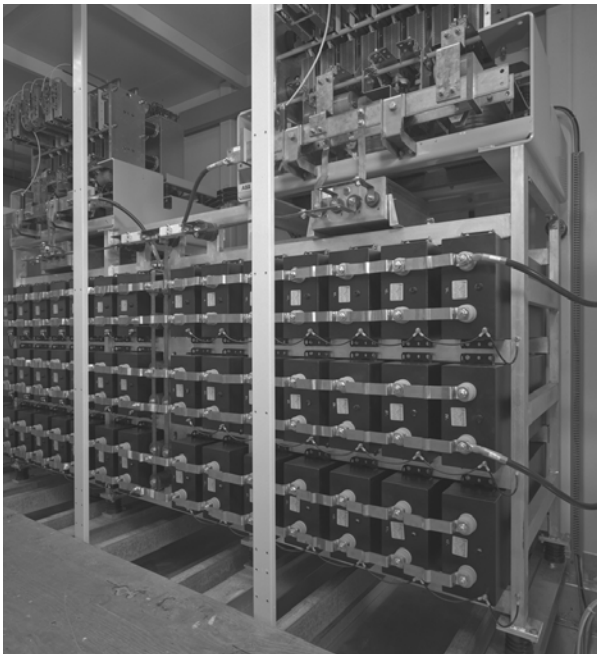


Figure 5.2.8: DVR energy storage capacitor & converter

The control hardware is based on a digital, modular multi-processor architecture with a real-time data acquisition and monitoring device. The latter, called "Dip Monitor", runs on a standard personal computer with an RS-485 interface to the controller, and allows on-line monitoring of

the DVR performance and downloading of event data. The acquired data are stored in standard ASCII file format for easy viewing and further processing. Updates to the control software can be implemented remotely from the manufacturer's location, including system checks and trouble shooting via a telephone modem.

The customer's specification called for a response time of no more than 10 milliseconds, and the design goal has been set to less than 6 milliseconds; thanks to the feed-forward control topology and the use of IGBT semiconductors, the response time of the actual system is less than 1 millisecond. During the initial commissioning, the trigger levels on the bus voltage have been set with too tight margins, causing the DVR to operate several times per hour, although the customer utility regarded the bulk of these events as insignificant to the connected load. Therefore, the thresholds eventually have been set to $\pm 5\%$ of voltage magnitude and $\pm 2\%$ of voltage phase displacement.

Performance records

Since the DVR became operational in spring 1998, several events have been recorded and are presented in the figures below. To avoid confusion, it has to be noted that the numerical values of the graphical data for voltages and currents (left part in the figures) indicate r.m.s values calculated over the entire visible time span. The fast and accurate response proves that the DVR performs beyond expectations and that this device is a cost effective and viable remedy for industries suffering from transients in their supply voltage. The technical concept is easily scalable to larger power ratings up to several tens of MVAs with the same dynamic performance and using the same IGBT converters as for the subject DVR.

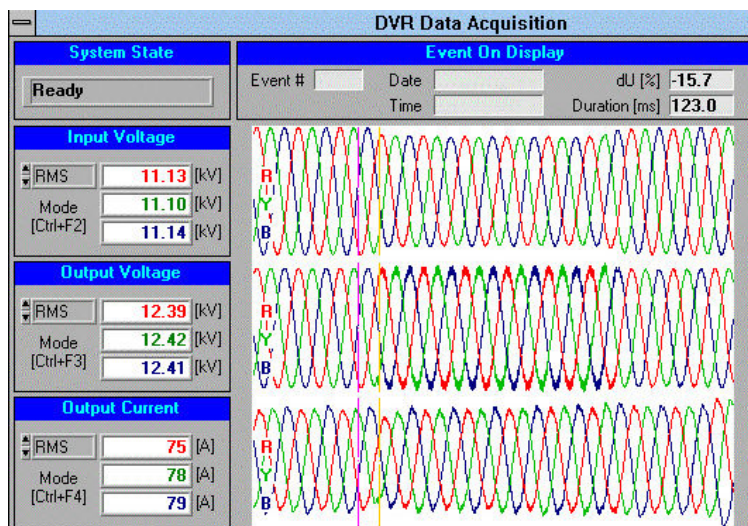


Figure 5.2.9: Compensation of a 16 percent voltage sag

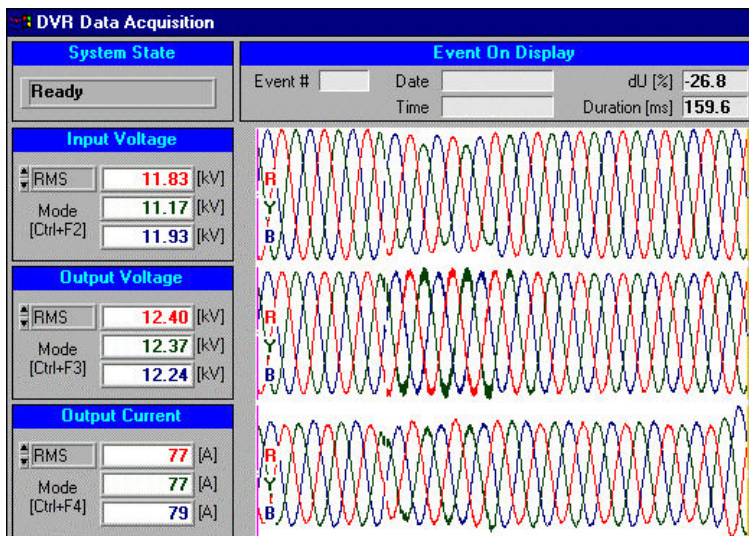


Figure 5.2.10: Compensation of a 26 percent voltage sag

5.3 Active Filter Applications

5.3.1 Active Filters for Harmonic and Flicker Mitigation, Japan

Since 1983, many active power filters have been put into practical applications in Japan. Figure 5.3.1 shows the number of active filters put into practical usage in Japan from June 1991 to 1995. The investigation was conducted by the Study Committee of the Institute of Electrical Engineers of Japan (IEEJ) on Power Conversion Circuits and Systems with Active Power Filtering Function. The total number of active power filters installed in these years is 355 sets. The ratio of active filters less than 200kVA is 69%. The number of active filters rated less than 50kVA are increasing rapidly over these years due to increased requirement for harmonic compensation. Note that the first active power filter in Japan was installed in the substation of a subway in Sapporo, Japan, in 1983. According to another investigation, approximately 100 sets of active power filters were installed from 1983 to May 1991 and approximately 450 active filters were installed from 1983 to 1995. According to another investigation, it is estimated that more than 100 active filters have been installed since 1996. Therefore, the total number installed up to April 1998 is more than 550, and it is still growing.

Figure 5.3.2 shows applications of active power filters in Japan. Approximately 40% of the total number has been used for compensation of harmonics from adjustable speed drive inverters for pump loads in water processing plants. Others are for buildings, factories and so on. As for circuit configuration, 351 out of 355 sets are shunt type and four of them are series type with passive LC filters. Although the first active filter used current source type GTO bridge circuit, recent application use voltage source type bridge circuit using IGBTs or GTOs. IGBTs are applied except for high power applications in the MW class. Among recent active filters installed, approximately 15% of them have fundamental reactive power compensation capability.

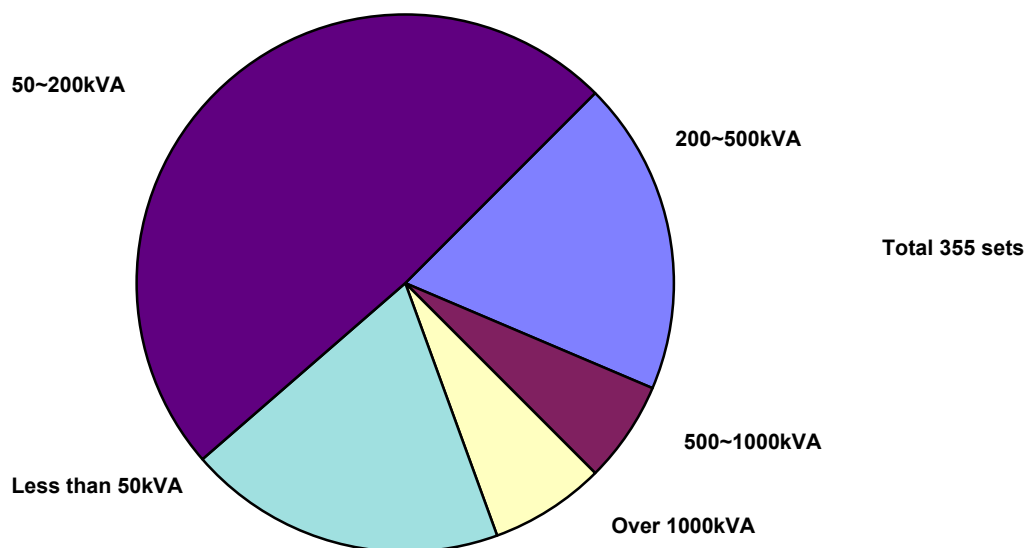


Figure 5.3.1: Installed number of active power filters in Japan from 1991 to 1995

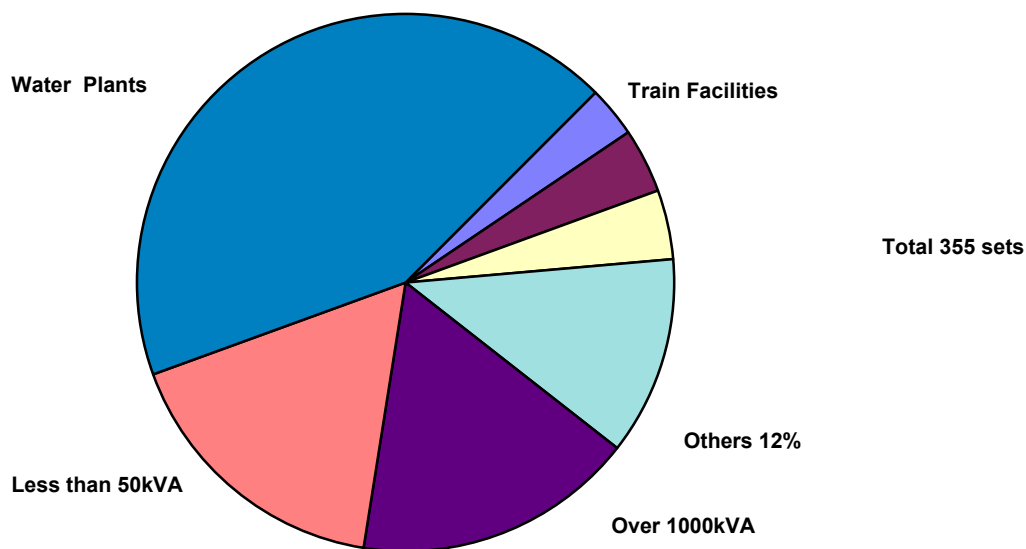


Figure 5.3.2: Applications of active power filters

Examples of practical applications are listed below with some features of their systems.

1) Application in a substation of subway in Sapporo (Figure 5.3.3)

- The first practical application in Japan in 1983
- Current source type circuit using GTOs, and 200kVA compensation capacity

- Solved problems of heating capacitors due to 4-th order harmonics from three phase full-wave half controlled bridge rectifiers.

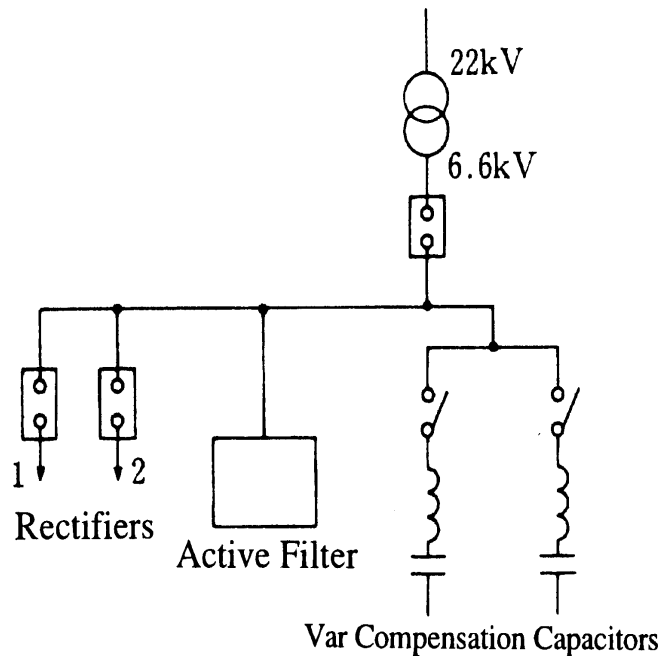


Figure 5.3.3: Active power filter in a substation of a subway

- 2) Application in a water plant (Figure 5.3.4)
 - Harmonics from diode rectifiers of adjustable speed drives for water pumps are compensated
 - A 300kVA shunt active power filter is installed for three sets of 240kVA VVVF (Variable Voltage Variable Frequency) inverters for adjustable speed drive.
- 3) Application in a building (Figure 5.3.5)
 - A 200kVA shunt active filter for 2,000kW loads in a building
 - Total Harmonic Distortion (THD) of input current to the building was reduced to 2% from 10%.
- 4) Application for voltage regulation (Figure 5.3.6)
 - Flicker compensation from arc furnaces
 - 20MVA active filter with reactive power compensation capability using 4.5kV, 3kA GTOs.

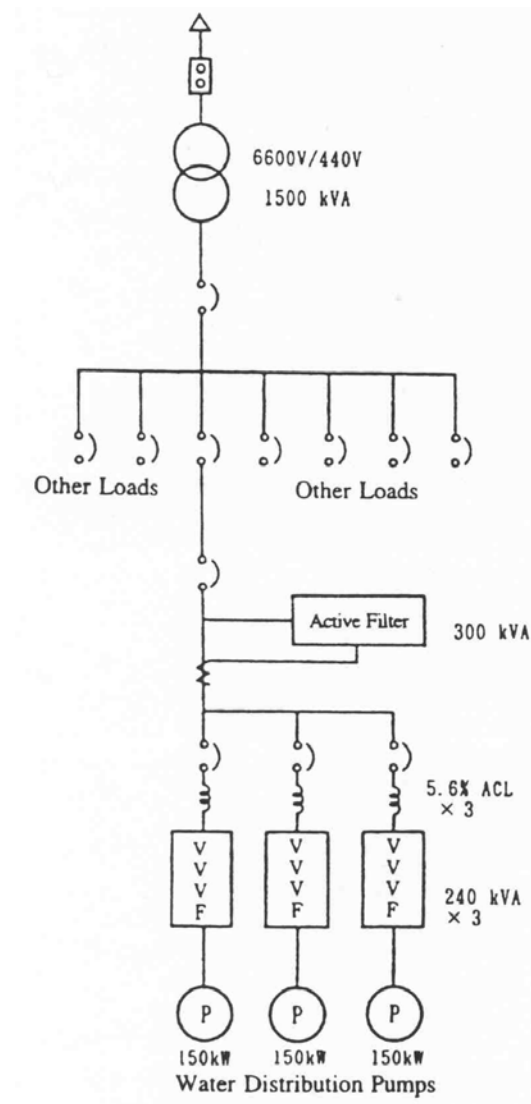


Figure 5.3.4: Active power filter in a water plant

5) Application of series active filter (Figure 5.3.7)

- Application in Yamanashi maglev train test line
- Avoiding the harmonic current magnification phenomenon caused by resonance (The resonance is generated between LC filters and the short-circuit impedance seen from the load bus)
- Smaller inverter ratings (1.6MVA) for compensation capacity (5MVA)
- Act as equivalent resistor for harmonics frequency

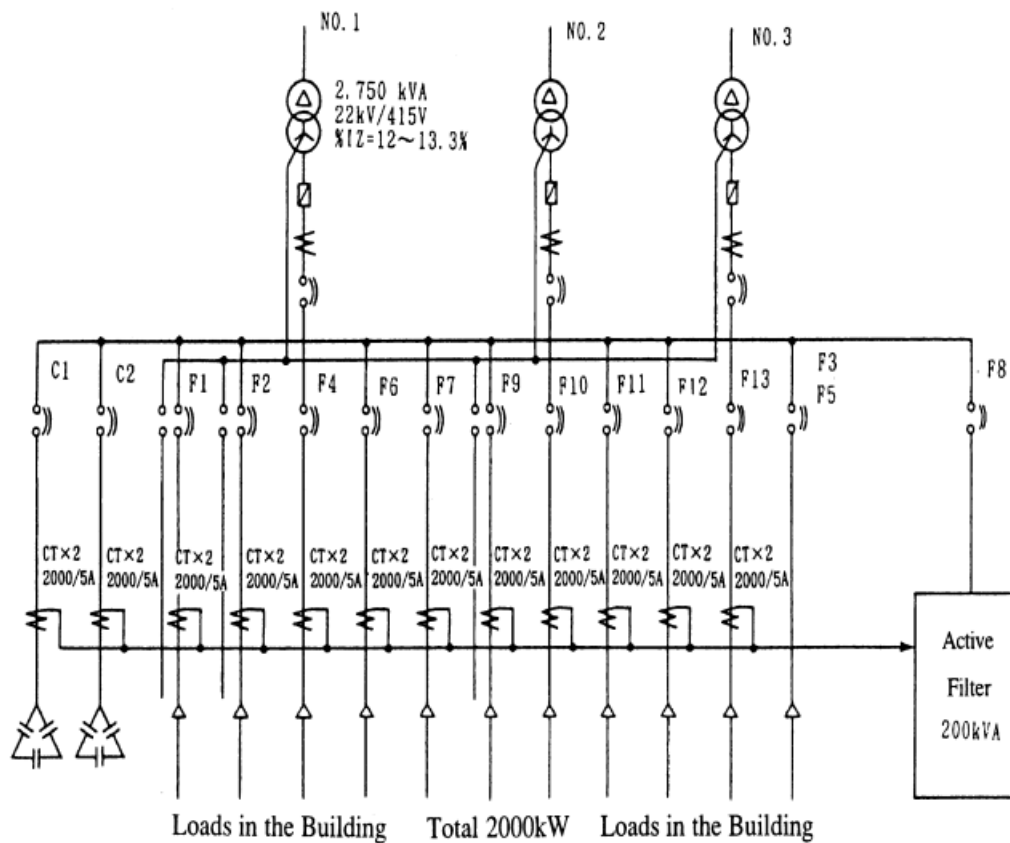


Figure 5.3.5 Active power filter in a building

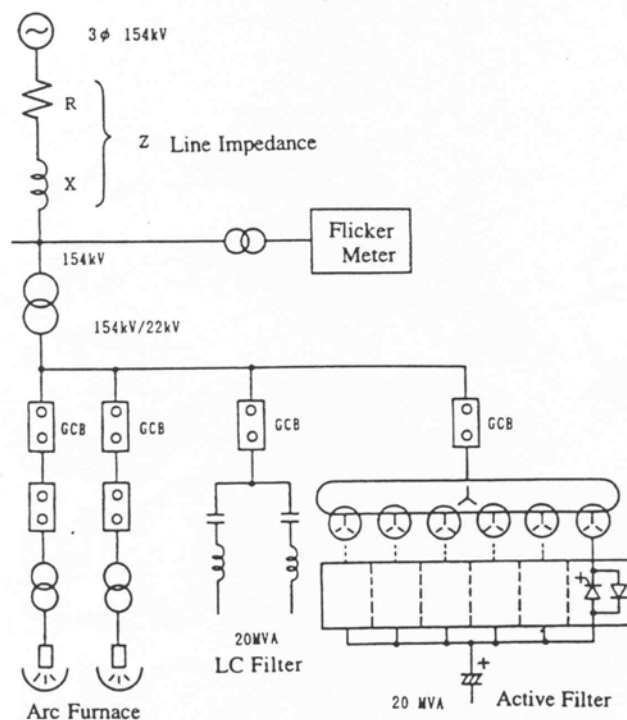


Figure 5.3.6: Active power filter in an arc furnace facility

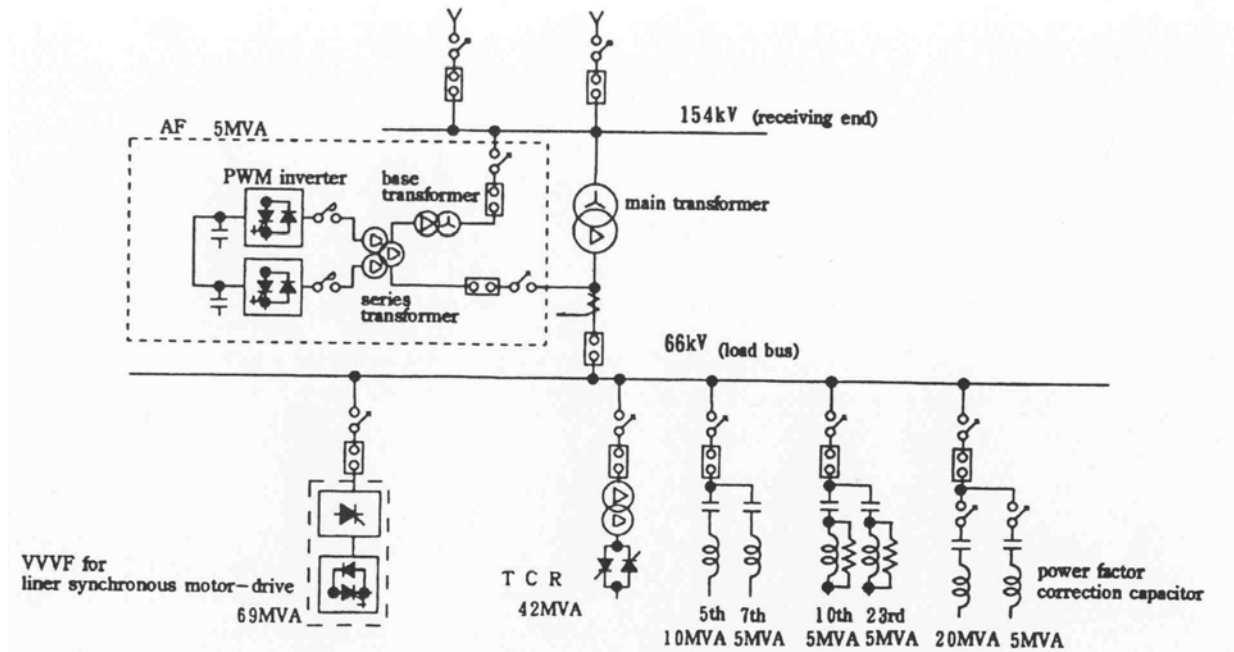


Figure 5.3.7: Active filter in Yamanashi maglev test line

5.3.2 Active Filter for Carrier Signal Solution, France

Overview

On EDF distribution networks, tariff transmission is performed by a centralized ripple control generator that is located after the HV/MV transformer in the utility substation. This transmitter injects a signal at a frequency of 175 Hz (or 188 Hz) with a nominal amplitude equal to 2.3% of U_n (50 Hz voltage on the MV busbar) (Figure 5.3.8). The level of the 175 Hz signal on the MV busbar of the substation is given by the following formula:

$$\tau_{175 \text{ Hz}} = 2.3\% * \frac{|Z_{\text{downstream}}|}{|Z_{\text{downstream}} + Z_{\text{upstream}}|}$$

where $Z_{\text{downstream}}$ represents the down stream impedance of the network seen from the transmitter and Z_{upstream} , the upstream impedance.

Ripple control signals are correctly received by customers connected to the MV busbar, provided the amplitude is higher than 1.4%. To prevent interference with neighboring utility substations, the 175 Hz upstream level on the HV side of the HV/MV transformer must not exceed 0.4%. To meet this condition, the system relies on the fact that the upstream impedance of the system is much lower than the downstream impedance.

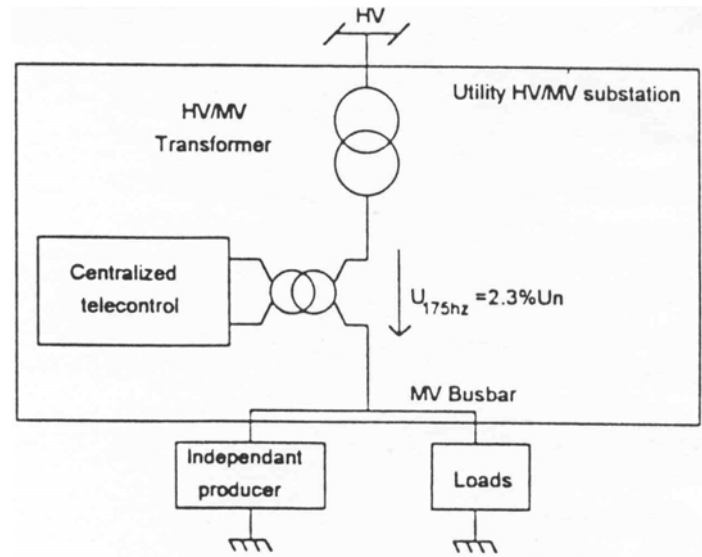


Figure 5.3.8: Location of a ripple control transmitter

Causes of Interference with the Ripple Control Signals

When an independent producer is connected to a substation busbar, the downstream impedance is lower; this alters the impedance balance, causing the 175 Hz signal level to increase on the HV side and to fall below the required threshold on the MV side of the ripple control system. Under these conditions it can no longer be guaranteed that consumers connected to the substation busbar will receive accurate tariff signals.

Prevention of Interference with Ripple Control Signals

There are a number of ways for preventing the interference caused by connecting independent producers (Figure 5.3.9)

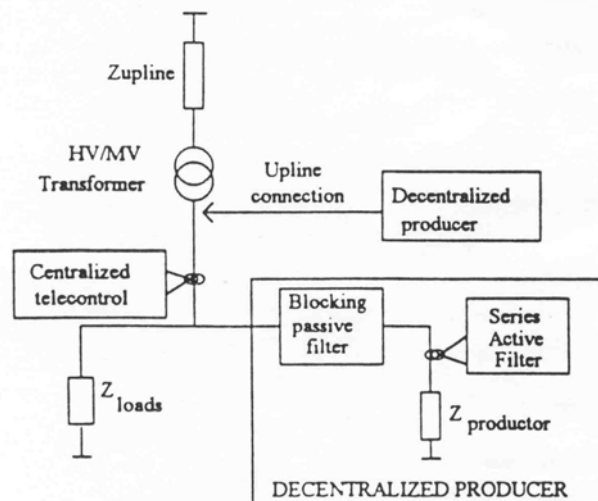


Figure 5.3.9: The different solutions against the interference caused by independent producers.

They can be connected to the upstream side of the ripple control system, allowing rebalance of the upstream and downstream impedances ratio. This is technically efficient but very costly. A blocking passive filter can be connected in series in the independent producer's feeder. This filter has serious disadvantages:

- it is not adaptive to network changes
- it is prone to component variation and resonance phenomena
- the device is bulky
- two devices are needed to handle the 175 Hz and 188 Hz frequencies
- there is no built-in capability for monitoring system efficiency
- it is necessary to perform frequent operations of checking and maintenance.

Below, a new system has been developed to overcome these disadvantages. It is an active 175 Hz/188 Hz series filter for an independent generator plant. Experiments have been conducted on this new filter installed in a 6 MVA independent generator plant.

Active 175 Hz/188 Hz Series Filter for Independent Producers

Principle of Operation

The active 175 Hz/188 Hz series filter increases the amplitude of ripple control signals on the busbars. This system takes the form of a voltage inverter connected to the network via a series injection transformer located between the independent transformer located between the independent producer's generator plant and the network connection point. It injects a 175 Hz (or 188 Hz) signal, which is identical in phase and at least as high in amplitude as the initial ripple control signal, to ensure that the tariff signal remains at least as powerful as when the network is operating without the independent producer. (Figure 5.3.10).

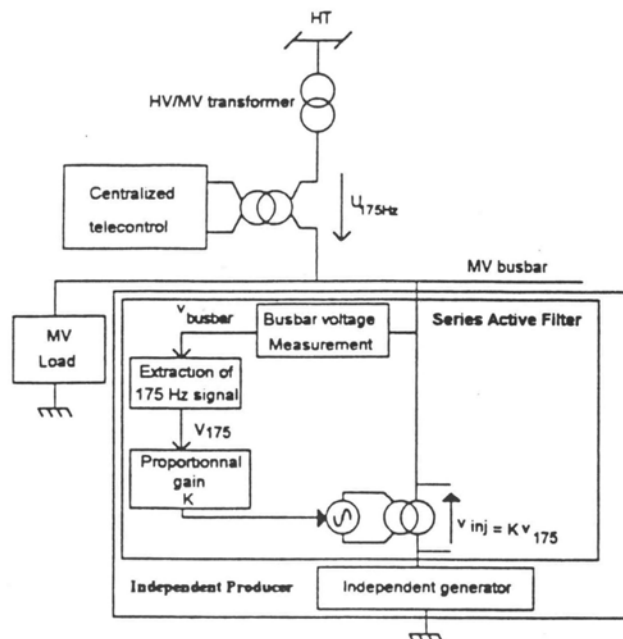


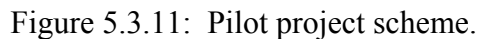
Figure 5.3.10: Connection of 175 Hz/188 Hz series active filter.

In 1995, experiments were conducted on a prototype filter at a decentralized 6 MVA fuel-driven plant connected to an utility substation (see Figure 4). The HV/MV utility substation of the pilot site is equipped with two 63kV/20kV transformers with a nominal power of 10 MVA each and a 2.4 Mvars capacitor bank on each busbar. The thermal power plant has a maximum power of 4.8 MW.

Series 1: Substation normal operating conditions. Short Circuit Power (Psc) on HV side is 650 MVA.

Series 2: Degraded operating conditions, with one transformer out of operation and all load taken by the other transformer. Psc on HV side is 650 MVA. The load transfer from one transformer on the other ones is not favorable as the transformer in operation reaches its nominal load.

Series 3: Degraded operating conditions. Psc on HV side is 280 MVA.



These three test series have shown than:

- 5.25

- The 175 Hz active filter allows to reach and even to exceed the signal level obtained without the independent producer in all network configurations thanks to an appropriate adjustment of the injection gain.

The active filter works efficiently and permits: to recover good level of ripple control signals on MV busbar.

Results of Test Series 1

Test Conditions		$\tau_{12\%}$	$\tau_{23\%}$	$\tau_{31\%}$
A	Independent producer plant not connected	2.05	2.01	2.13
B	Independent producer plant connected without active filter	1.59	1.51	1.6
Low production power (1 MW)				
C	Independent producer plant connected without active filter	1.59	1.51	1.6
Maximum production power (4.8 MW)				
D	Independent producer plant connected with active filter	2.17	2.05	2.15

Results of Test Series 2

Test Conditions		$\tau_{12\%}$	$\tau_{23\%}$	$\tau_{31\%}$
A	Independent producer plant not connected	1.7	1.64	1.72
B	Independent producer plant connected without active filter	1.3	1.26	1.3
C	Independent producer plant connected with active filter	1.7	1.6	1.64

Results of Test Series 3

Test Conditions		$\tau_{12\%}$	$\tau_{23\%}$	$\tau_{31\%}$
A	Independent producer plant not connected	1.58	1.48	1.54
B	Independent producer plant connected without active filter	1.23	1.16	1.21
C	Independent producer plant connected with active filter	1.62	1.5	1.57

Conclusion

As decentralized electricity generation becomes more common, new methods must be found for ensuring correct ripple control signals transmission. This device should ensure that customers continue to receive accurate tariff messages when independent producers are connected to the network. We also note that since this experimentation, twenty devices were commissioned in generating plants between 5 MW and 10 MW.

5.4 Battery Energy Storage Application

Battery energy storage systems (BESS) provide essential energy to loads when the power supply is temporarily disrupted.

5.4.1 BESS for Emergency Support of Industrial Plant

A 5 MVA, 2.5 MWh Battery Energy Storage System (BESS) was placed in service at the GNB Battery Recycling Plant, Vernon, California in November, 1995. The system was provided by a team of GE and GNB.

The primary function of the Vernon BESS is to maintain the critical process loads during outages resulting from disturbances external to the plant. To accomplish this, it is installed at the 4160V level of the plant power distribution system, in parallel with the existing loads.

The BESS is designed to work with the existing plant control system to automatically shed all non-critical loads as soon as possible after an incident. This permits the critical loads of up to 2.5 MW (mostly large induction motors) to operate for up to one hour. This time is necessary for the plant to safely shut down its critical processes. Provision is made for transfer back to the utility feed if utility power is restored before the end of the one hour period.

A secondary function of the system is to reduce the plant demand charges. This is accomplished by utilizing a portion of the battery capacity to supply energy to the plant during peak load periods.

5.4.2 Overview of the Installation

The system consists of the following major items:

- 1 A dedicated Battery Energy Storage System building.
- 2 Two strings of batteries, complete with manual disconnect switches and fuse protection.
3. Battery monitoring control cabinet providing peak shaving and state-of-charge control.
4. Personal computer interface to the battery monitor for data display, battery maintenance and data acquisition.

5. A power conditioning system (PCS), which provides bi- directional power conversion between the ac and dc systems.
6. Station control for sequencing and control of the power converters.
7. Remote operator's panel located in the plant control room.
8. Fused main BESS disconnect switch.
9. Power factor correction capacitors and harmonic filter to meet IEEE 519. [I]
10. Relay panel responsible for detecting a utility outage and supervising the operation of the main plant service breaker.

Three key modes of operation exist:

- **On Utility** -which defines the normal state when active power for the plant loads is supplied by the utility and the BESS is idle, charging or peak shaving and managing reactive power for the plant.
- **Isolated** -which defines the emergency state when power for the plant loads is supplied by the BESS and the utility is disconnected.
- **Resynchronizing** -which defines the process whereby the isolated plant is reconnected to the utility.

A simplified one-line diagram of the system is shown in Figure 5.4.1.

The entire Vernon BESS, including the batteries is enclosed in a 131' x 25' building with the filter, transformers and disconnect switch located outdoors.

System Rating

The system is designed to operate for 10 seconds at a maximum plant demand of 5 MVA immediately after the transition to isolated mode. This capacity exceeds the total existing and projected loads at the plant with some margin.

Table 5.4.1: Summary of System Ratings for the GNB Vernon BESS

Base Voltage	4160 Vrms L-L
Nominal Current Rating	348 A rms
Nominal Power Rating	2500 kVA one hour 5000 kVA for 10 sec.
Nominal Dc Voltage Rating	756 Vdc (660 – 900 Vdc range)

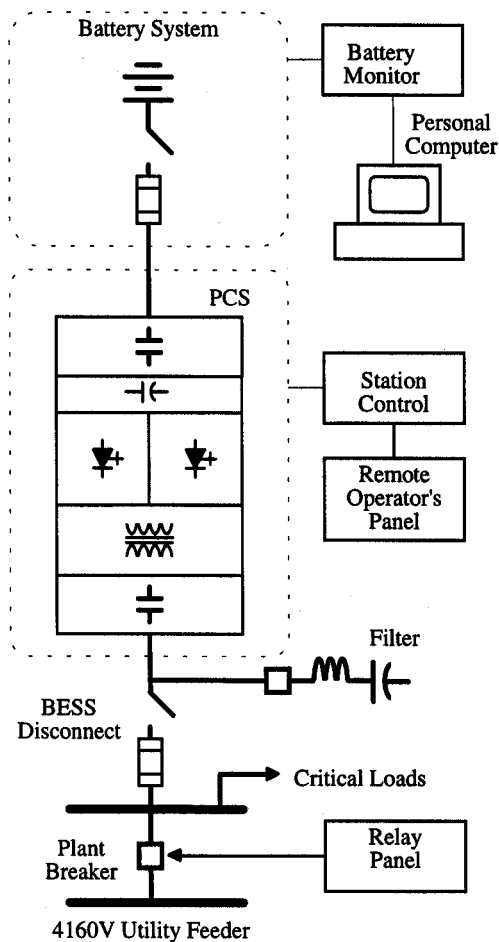


Figure 5.4.1: Simplified BESS One-line Diagram

Power Conditioning System

The PCS part of the BESS consists of a voltage source inverter which is designed to operate as either an inverter when discharging the battery or as a rectifier when charging. The PCS is designed with self-commutating static switches capable of supplying the reactive power needs of the system.

Station Control

Control of the PCS to meet the various modes of operation is provided by the station level control. The control consists of a microprocessor controller for regulator functions and a PLC for sequencing and protection.

When operating on-utility, the voltage order is derived from a closed loop var regulator which maintains the PCS at a desired power factor. The power order follows the charging needs of the battery or the operator can schedule the system to automatically reduce the plant demand charges.

When isolated from the power grid, the voltage order is adjusted to maintain nominal plant voltage (4160V) and the power order is dynamically adjusted to hold rated frequency (60 Hz).

Upon sensing a loss of utility voltage:

1. The incoming circuit breaker is opened,
2. The existing plant control system will shed all but the critical load, and
3. The BESS will carry the critical loads, up to 2,500 kW for one hour.

When re-synchronizing, voltage order is adjusted to match measured utility voltage and plant frequency is adjusted to match measured utility frequency and phase-angle. Synchronizing with the utility is supervised by a standard synchronism check relay.

Battery Monitor Control

The battery monitoring control performs five major functions:

1. Calculates the state-of-charge of the battery,
2. Provides for battery charging and discharging control,
3. Monitors the health and status of the battery,
4. Records battery operation for future optimization and warranty management,
5. Detects ground faults.

The Battery Monitoring function is implemented in a PLC, working with the Operator Interface Computer. The computer consists of an industry standard PC running a graphical interface program for data storage and display.

Batteries

Valve regulated lead-acid (VRLA) maintenance-free batteries are used. Two battery series strings are connected in parallel to provide a nominal amp-hour rating of 2.5 MW-hour. Each string includes a fused disconnect sized to allow operation with one string out-of-service. The electrical center of each battery string is high resistance grounded.

A string consists of 378 modules, each rated 2V and connected in series to make a nominal 756V string. The modules are arranged in stacks. A single stack of batteries consists of eight modules separated and supported by 4' steel "1" beams. Each module measures 42.5" x 26.4" x 8.6" for an overall stack height of about 6'. Each stack assembly has a standing weight of about 6360 lbs. A total of 48 stack assemblies arranged in two rows are required for each string. A typical stack assembly is shown in Figure 5.4.2.

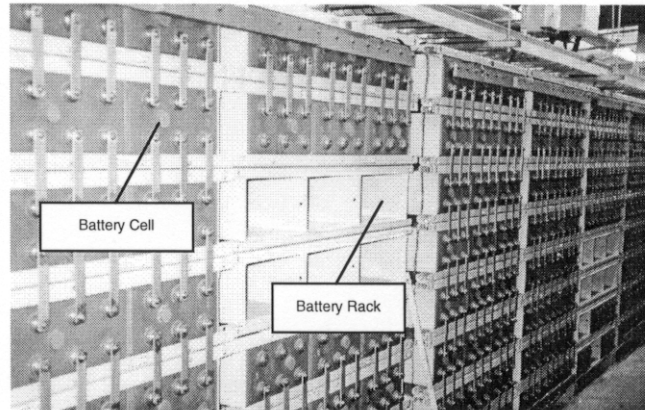


Figure 5.4.2: Close-up of battery string.

5.4.3 Final Commissioning Test Results

Acceptance tests of the Vernon system were completed on November 5, 1995. The tests included a total interruption of the utility power feeding the plant. The critical plant loads, totaling 2100 kW, were transitioned to the battery system and ran in isolated mode for about 30 minutes. The plant loads were then automatically resynchronized with the utility feeder.

The critical load consists of about 25 induction motors plus lighting and control. Four of the motors, totaling 1600 hp, are connected at the 4160V bus. The remaining motors, totaling about 1400 hp, are connected at 480Vac.

Figure 5.4.3 is an oscillogram that shows the response of the system during the breaker trip test. The battery was initially charging at a low rate corresponding to about 480 kW. While charging, the BESS is also compensating the reactive component of the plant load to maintain unity power factor at the point of utility connection. This is done to maximize the power available for charging the battery. The total reactive compensation while charging, including the filter component, is about 2200 kvar. The total plant load prior to the test is about 3000 kW (excluding the BESS charging kW) and includes about 2100 kW of critical loads.

To simulate a power interruption, the plant breaker was manually tripped. Notice that the critical plant loads immediately transition to the BESS following the manual breaker trip. To support these loads, the battery string current increases to about 1300 amperes and the battery voltage drops slightly.

Since the BESS regulators maintain the proper voltage magnitude and frequency, the power output naturally follows the needs of the plant loads. From the plant perspective, the breaker trip test was essentially bumpless. All critical loads including sensitive electronic equipment such as PCs were unaffected by the transition.

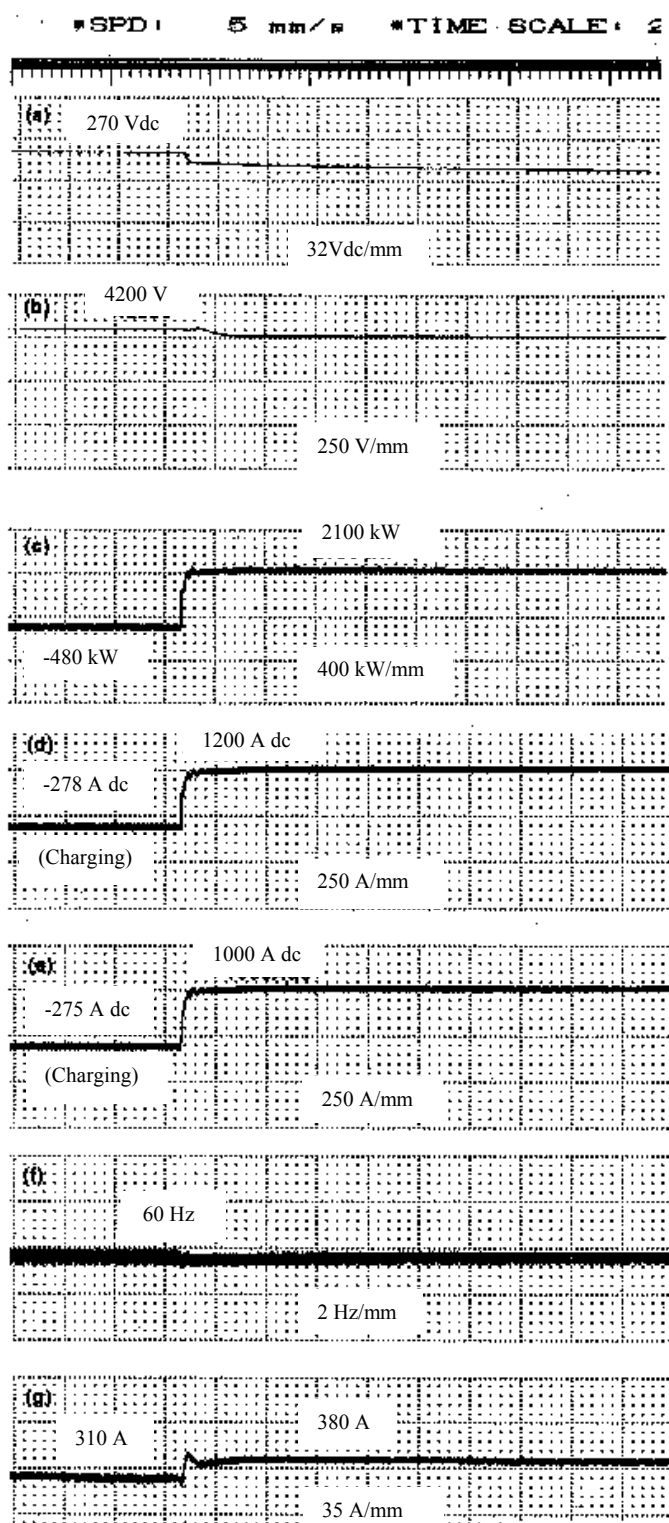


Figure 5.4.3: Response of BESS and plant during isolation from the system.

- | | |
|-------------------------------|------------------------------------|
| (a) Battery Voltage | (e) Battery String #2 Current |
| (b) Plant Voltage | (f) Plant Frequency |
| (c)...PCS Watts | (g) BESS Line Current at 4160V Bus |
| (d) Battery String #1 Current | (includes filter) |

5.5 Medium-Voltage Static Transfer Switch Applications

This section describes some of the applications of a 15 kV class sub-cycle transfer switch system. This Medium-voltage Static Transfer Switch (MVSTS) allows the fast transfer (up to 4 ms) of power from one source to another. This switching time is sufficiently fast to preserve the operation of even the most sensitive equipment loads during disturbances.

5.5.1 MVSTS Operation

A single line diagram of the MVSTS system is shown in Figure 5.5.1. The MVSTS system consists of three main components:

- Sub-cycle Transfer Switches
- Mechanical Bypass Switches/Breakers
- Isolating Switches/Breakers

The sub-cycle transfer switch consists of two ac thyristor switches. Under normal conditions, the ac switches allow the fast transfer of power from one source to another. The mechanical bypass and isolation switches/breakers enable the MVSTS to be protected, bypassed and isolated under the conditions of maintenance, testing, emergency overload, or as required by system operations. Under normal conditions the customer load is fed through ac sub-cycle switch #1 by the primary source of power. The bypass switches are open and the preferred/alternate source switches/breakers are in the closed position.

The MVSTS protects the connected loads from experiencing problems due to voltage sags, swells, and momentary or sustained electrical power interruptions by transferring from one incoming source to another in the total sense and transfer time of four milliseconds or less. (Note that for voltage swells, the total sense and transfer time may take up to 8 ms to allow for the sine wave to reach the zero crossing.) In any circumstance for which the MVSTS is “off-line,” a sophisticated digital signal processing (DSP) controller will provide a fail-safe return of control to the electromechanical switchgear in order to protect the load from sustained interruptions and permit bypass operation.

The MVSTS will inhibit transfer under the following conditions:

- Load side faults or overload conditions.
- Voltage of alternate source is outside programmed limits.
- Both sources are out of phase more than programmed limit.

5.5.2 Actual Transfer Result – Voltage Sag

Under normal conditions, ac switch #1 is turned on and current flows from the primary source to the load. When a disturbance, such as the voltage sag shown in Figure 1 is detected by the MVSTS the gates are removed from ac switch #1 and the gate of the ac switch #2 is then energized. Since ac switch #2 has a higher voltage potential, when it turns on, the SCRs of switch # 1 will be forced to commutate.

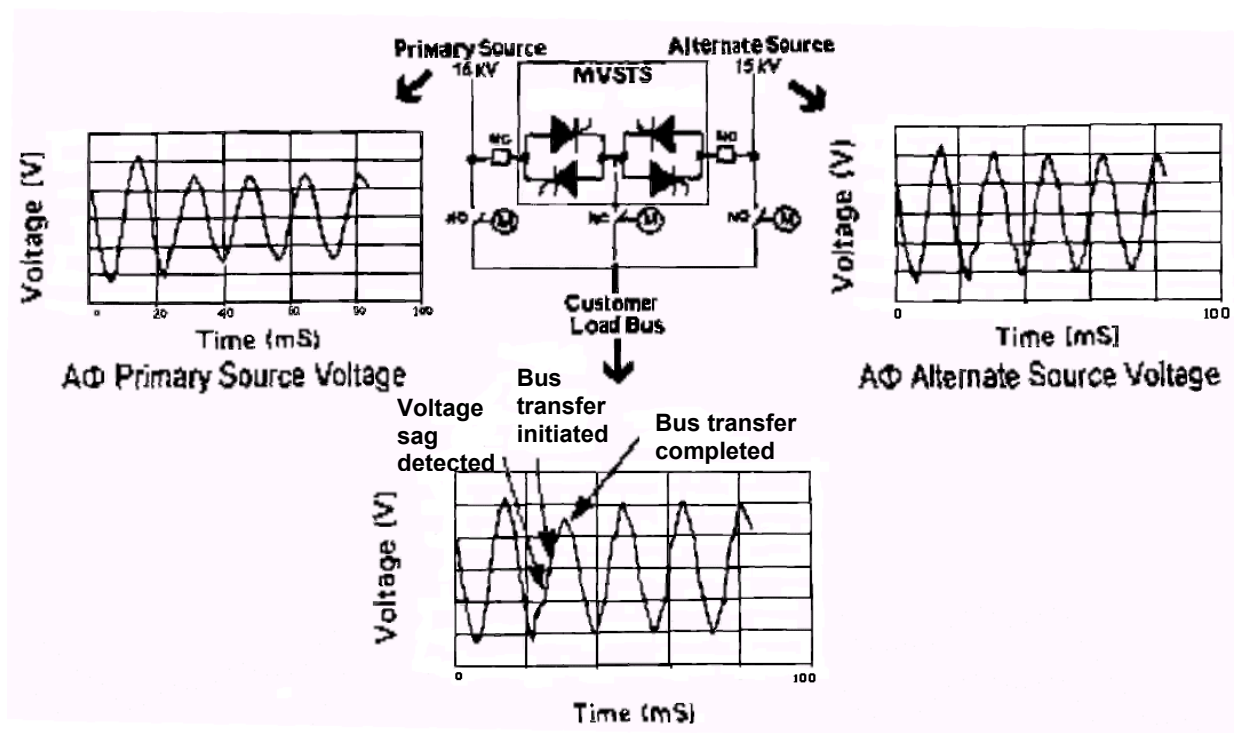


Figure 5.5.1: One-Line Diagram of MVSTS and Actual Transfer Waveshapes.

5.5.3 MVSTS Design and Electrical Ratings

The MVSTS is available in either a single switch, preferred/alternate, or split-bus configuration. It has been designed to meet the following electrical ratings:

- Rated voltage 5kV to 38 kV_{rms} phase-to-phase
- Normal Continuous Current 200A to 1200A_{rms}
- Fault Current Cycle up to 18 kA symmetrical, offset to 45 kA crest for 15 ride-through
- Impulse voltage withstand up to 150kV crest

The design of the 15 kV MVSTS includes the following requirements:

Voltage Rating of each Switch

Each ac switch must be able to block 8.66 kV_{rms} (12.25 kV_{peak}) phase-to-neutral voltage under normal operation and up to 3 pu voltage under transients such as capacitor switching.

Power Dissipation of Thyristors (99.5% efficiency)

The conduction losses of the thyristors is relatively large compared to conventional load break switches and circuit breakers, but compares favorably to low-voltage systems such as UPS. The heat generated by the SCRs must be removed. The thermal cycling of the power semiconductor components must be limited to maintain a long operating lifetime.

Surge Current Ratings of Thyristors

The MVSTS is designed to conduct a fault current of 18 kA symmetrical (45 kA crest) for 10 cycles to allow either upstream or downstream protection devices to operate.

Impulse Voltage Rating of Sub-cycle Switch

The low-voltage control system must be isolated from the high voltage switch elements to withstand an impulse voltage of 110 kV for a 15 kV switch.

Gate Drive System

Since the thyristors of the ac switch must conduct for the complete 180°, the thyristor gate drives need a source of continuous power, also the power source - which is located at ground potential - must be insulated from the thyristor level to withstand a voltage impulse of 110 kV for a 15 kV switch.

The design of the MVSTS also incorporates N+1 redundancy, a modular building block component design for easier maintenance, and internal diagnostics.

5.5.4 Front Street Office Complex

In September of 1995, after only 11 months of development design, engineering, and construction, the “World’s First” Medium-Voltage Sub-cycle Transfer Switch was installed on Baltimore Gas & Electric Company’s 13.8 kV Distribution System. The Preferred/Alternate MVSTS is rated for 600A and 18 kA fault current withstand (45 kA peak). The PQ Node data in Figure 1 was collected at Front Street during a voltage sag in March of 1996. An “A” phase to “C” phase to ground fault occurred on a circuit adjacent to the preferred feeder which resulted in approximately 60% of voltage on source 1 as well as 85% of voltage on source 2 due to a nearby transmission line. The MVSTS’s sophisticated digital signal processing controller made the decision that this event was significant enough to transfer to the alternate source and completed the transfer within 4ms after the event started, keeping the sensitive computer equipment within the office complex in service. (Note that the user programmable threshold settings within the controller software enabled the switch to determine that the alternate source was acceptable to the building load even though it was simultaneously experiencing a 15% voltage sag.) Since its installation, the MVSTS has

successfully transferred the entire load. of the six story office complex over 500 times, whether through live demonstrations held in the facility or through actual transfers due to voltage disturbances on the preferred source. The MVSTS was integrated with PowerCon switchgear to isolate the transfer switch for maintenance and provide seamless transfer to a bypass ATC package with automatic transfer backup.

With the installation of the World's First MVSTS, PowerDigm SystemSM, Inc. demonstrated that the fast transfer of 15 kV loads from one source to another can be achieved within 4 ms.

5.5.5 CONDEA Vista Company

On September 9, 1996, PowerDigm[®] SystemsSM, Inc. placed their second commercial MVSTS system in service at CONDEA Vista Company, a process oriented customer on Baltimore Gas & Electric's utility distribution system. The 15 kV, 600A, 9 kA system is an outdoor unit integrated with an S&C Electric Company metal enclosed bypass switchgear package. The switch has successfully transferred over 50 times, including the event shown in Figure 5.5.2. Figure 5.5.2 shows a 2-cycle fuse operation on "A" phase of the preferred feeder. Figure 5.5.3 is the condition of the alternate feeder at the same time. Figure 5.5.4 shows the resulting load voltage waveshape as a result of the nearly seamless 4 ms transfer. CONDEA Vista Company was unaffected by the event which, before the installation of the MVSTS would have cost them 12 hours of plant downtime. Prior to the installation of the MVSTS, eight to twenty events per year were typical. A remote monitoring system allows for constant monitoring of the condition of the MVSTS.

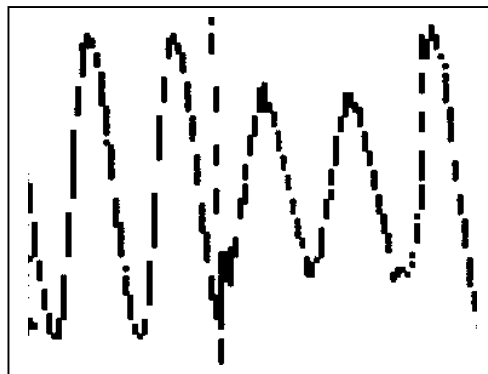


Figure 5.5.2: Vista Preferred Feeder.

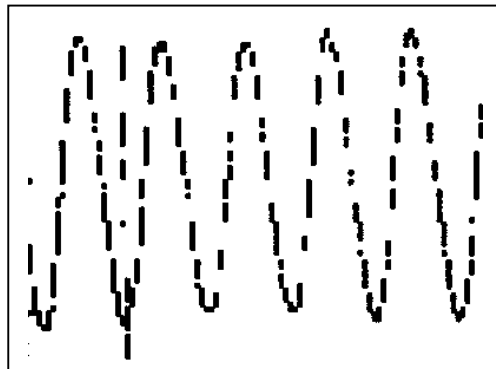
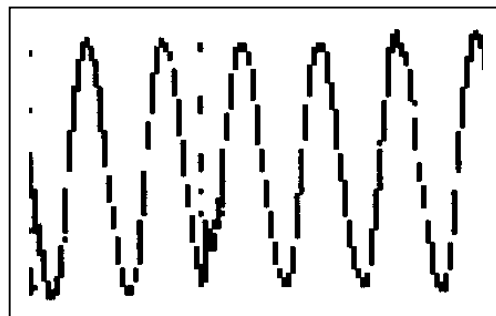


Figure 5.5.3: Vista

Alternate Feeder.



5.5.6 Detroit Edison Electric Company

On November 10, 1996, PowerDigm[®] SystemsSM, Inc., placed another MVSTS system in service at Ford Motor Company for Detroit Edison (DECO). This unit is a 15 kV, 600A, 18 kA system integrated with S&C Electric Company switchgear. EPRI is demonstrating this unit at Ford's Sheldon Road Plant. This facility, which has a load of 9 MVA, is fed from DEC's 40 kV subtransmission system through two 40/13.8 kV transformers. The transfer switch is expected to protect the plant from costly power interruptions. The customer was included in the team to look for an answer to the scattered power quality problems that were occurring within the customer's Sheldon Road Plant. After a detailed study, it was concluded that the solid-state transfer switch, in conjunction with circuit improvements to provide more isolation between the two feeds into this facility from the Detroit Edison system, was the best solution. The customer estimates a voltage disturbance causes a 1 to 2 hour production loss while the production process is restarted.

Load transfers were made to test the impact on the facility. These were accomplished both by manual operations of the transfer switch and by opening the circuit breaker on the primary source to the plant. This testing was performed on weekends when the plant was not in full production. During these operations of the transfer switch, up to 3 MVA was transferred while critical loads were running at the Sheldon Road Plant. No disruptions to the plant or the processes occurred.

Since the MTSVS system was installed, there has been one occurrence of a voltage sag where the switch correctly did not transfer since the voltage of the alternate source was also outside of the programmed limits. This particular sag was a result of a fault on DECO's 34 kV system. In addition, there have been five other transfers. If the test operations and SCADA testing are included, a total of 12 operations have occurred. No plant disruptions have been observed for any of these operations.

CHAPTER 6

VISION OF FUTURE PRACTICES

Since the problems relating to voltage sags and short interruptions was first recognized many years ago, industry on both sides has moved a long way from blaming one another to the realization that the problems are real and the solutions involved require a collective effort.

For the domestic customers, retail businesses and small service companies, the problem related to sags and short interruptions, will by and large cease to exist, because the appliances, computers and clocks will have ride-through capability and will not produce significant harmonics and EMI for others. Incorporation of voltage regulators and storage within the appliances as well as availability of low cost UPS, surge suppressors and filters will form the basis of ride-through or safe shut down.

Thus the issues of voltage sags and interruptions and corresponding solutions will relate to the manufacturing and large commercial sector. With the age of automation, computers, process controls, drives and robotics, the number of outages and voltage dips and their duration is much more important than the cumulative outage time per year.

The trend will continue towards realization that the problems are real and the solutions are available. This trend of mutual respect for the other side will continue to evolve in appropriate infrastructure and business opportunities for the Custom Power equipment and services. Not all of the industrial/commercial customers will call for solutions by Custom Power, in fact many customers will have a few critical loads and would have a few low-power conditioning solutions for control and protection.

On one hand customers will understand that the faults and sags are here to stay. Their causes are numerous and while improvements can be made in the utility systems, there are going to be several tens of sags per year that could impact customers' productivity. On the other hand the utilities will understand that sags as the most important criteria of reliability for automated and high-tech production and will evolve new standards for reliability of supply at the premises or large customers.

It is interesting to note that Custom Power solutions represent a wide range of cost. The lowest cost solutions may take care of a large percentage of the sags, while eliminating the last 10% of the events may cost 10-20 times the cost for the first 90% of the sags. This aspect of diminishing returns will not change significantly. Thus economical Custom Power solutions are a function of the loss of business per sag or interruption event. It is therefore reasonable to expect that each type of industry ie, chip manufacturers, paper mills, dairy product companies, refineries etc. will through their professional organizations evolve generic guidelines for their type of production corresponding to each type of production, there is a need for appropriate computational tools.

There will evolve business entities that offer limited services for evaluation studies, to those that offer at-the-fence Custom Power equipment, and to those that offer full services including evaluation, at-the-fence investment and guarantee service that carries rewards and penalties, and even provide services inside the production facilities. These services can be available on the basis

of an individual, large customer, industrial/commercial park or a supply for a high tech community on a wide area basis.

Those companies that provide services of building new manufacturing plants for whom the quality of power is the last thing on their mind at the design stage of the plants will pay much more attention to integrating Custom Power solutions as part of the design requirement.

The industrial parks that are established to attract new businesses to appropriate sites will in the long run establish Custom Power Parks that offer different grades of power quality to different businesses.

In the following sections a concept of a Custom Power is described.

6.1 Custom Power Park Concept

There can be a variety of Custom Power concepts, this section covers one suggested scenario for a Custom Power Park.

The customers are better served if they receive a comprehensive solution to their power supply problems from the power supply service providers. Although most of the voltage reductions and interruptions result from events that involve the utility system, some of the voltage dips will result from faults in other customer's loads, passed through the utility substation.

Within the context of the Custom Power Park, one would expect to accommodate:

1. Small to medium size industries and commercial organizations with load requirements in the range of hundreds of KWs up to say about 10MW.
2. Businesses that need a degree of improvement in the reliability/quality of service.
3. Businesses that are willing to pay a premium in lieu of the investor having to own and manage their power supply conditioning equipment.

6.2 Types of Power Supply Services in a Custom Power Park

In a Custom Power Park all customers will benefit from a basic supply that is a cut above the normal power supply from a utility. This basic supply can be obtained by provision of two incoming feeders along with Solid State Transfer switches (SSTs) that will reduce the duration of most voltage dips to 4-8ms by rapidly selecting the feeder with the highest voltage. It is also clear that most of the customers generate moderate to high harmonics, and therefore need an active filter service. Thus the lowest grade supply should involve use of two incoming feeders, SSTs and an active harmonic filter.

As an example, the following loads are assumed for the Custom Power Park. (Figure 6.2.1).

MaxLoad PQNeed (explained below)

Semiconductor Chip Co.	10 MW	CP-AAA
Biotech Co.	2 MW	CP-AAA
Computer Hardware Co.	1 MW	CP-A
Software Development Co.	1 MW	CP-AA
Plastics Co.	3 MW	CP-A
Hospital	10 MW	CP-AA + CP-AAA
Data Processing Center	2 MW	CP-AA + CP-AAA
Office Building	2 MW	CP-A
Shopping Mall	2 MW	CP-A + CP-AAA
Total	33 MW peak load	

In addition, there would be small common power needs for parking facilities and driveways.

The key issue is how many grades of power should be available, and how the choices are determined and managed. Consideration of the value to different type of customers suggests that three grades of qualities (CP-A, CP-AA, and CP-AAA) with appropriate value-added premium cost, can serve the need. As a minimum, all customers would receive power CP-A with a quality superior to the regular power. Custom Power Park Control system will play a key role in the real-time and offline management of services.

6.2.1 Custom Power A (CP-A)

This is the basic value-added power at the Park. Its higher quality, compared to the regular power, arises from the fact that the Park has two incoming feeders, which can be designed with improved grounding, insulation and arresters, and better maintenance that reduces the chance of nearby lightening and other faults. With single phase tripping and reclosing, the interruptions and major voltage dips are greatly reduced. In addition, the Solid State Transfer Switching ensures that the feeder with superior voltage is selected in less than half a cycle. There will still be voltage dips that are common to both feeders resulting from faults and dynamic swings in the transmission network. Dips from transmission line faults usually last for 4-10 cycles, and occasionally the system swings may cause 20-50 percent dips for about 1 second and then repeated if the power system is unstable. There is also the possibility that a circuit breaker after clearing the fault will reclose into a fault, and the voltage dip and system oscillations will be repeated. Nevertheless, improvement over and above the normal power is substantial and may be characterized as follows:

1. 60-80 percent reductions in voltage dips.
2. Rare occurrence of interruptions.
3. Active harmonic filters.

6.2.2 Custom Power AA (CP-AA)

Over and above grade CP-A, grade CP-AA receives the benefit of a standby generator which can come up to speed in about 20 seconds in case of a power loss.

6.2.3 Custom Power AAA (CP- AAA)

Over and above grade CP-AA, Grade CP-AAA receives the benefit of a DVR with storage, which precisely adds the right amount of voltage including harmonics to the feeder voltage to ensure virtually dip free, interruption free, and harmonic free voltage to the customer.

It is assumed that under emergency conditions (loss of DVR), CP-AAA may degrade to CP-AA. For unavailability of backup power, it would still receive superior quality power and priority customer service attention.

On the left side of the CP bus in Figure 6.2.1, is shown a distribution bus for Custom Power A and AA. Both receive the same service as either of the two feeders is available. If and when both feeders are lost, the circuits of all customers A and AA are disconnected at both ends by their circuit breakers. The differentiating feature between customers A and AA is that when the standby generator is up and running (perhaps 10-20 seconds after the loss of both feeders), the circuit breakers for customers AA are closed to restore power to those customers. This means that customers AA do not lose power for more than 10-20 seconds in the case of loss of both feeders. However the customers A do not receive power until one of the feeders is back in service.

The standby generator may normally stay off and disconnected from the CP bus. When both feeders are off, the generator is started up immediately, brought up to speed, synchronized and connected to the CP bus. It should take about 20 seconds for the generator to come on line, and pick up the load of both AA and AAA customers. It is reasonable to assume that CP Control will supervise this fully automated diesel-driven or gas turbine generator of 5-10 MW size. When only one feeder is off, CP Control will alert all the customers and also the utility to confirm that the generator is available, has adequate fuel supply, and to ensure that the utility is extra careful in its system operation.

Under peak load conditions and/or when one circuit off, the CP Control may even bring the generator up and connected. It can become a co-generator, even if both incoming feeders are intact. Furthermore co-generation may be used as often as economic conditions are favorable for co-generation.

In order to ensure that the CP- AAA customers are not deprived of power during the period that the generator is brought up to speed and on line, and to supply them power without dips, distortion and imbalance, a combination of Active Filter, Dynamic Voltage Restorer, and hot standby storage is provided as shown on the right hand side of Figure 6.2.1.

In addition, connection to the AAA customers can also be made through solid state current limiting circuit breakers (SSCI.) This can ensure that the fault current resulting from faults in the CP-AAA customers own system does not exceed, say, 2 times their peak load for about 1 or 2

seconds before tripping. This will further ensure that other CP-AAA customers are not affected. SSCLs can provide coordination with the downstream protective relays of the CP-AAA customers. These SSCLs will also limit over loading on the DVR. Another alternative would be to provide a separate series converter (DVR) for each customer or a CP super-AAA customer, etc.

The active filter can filter exactly the amount of harmonics it is ordered to filter. Thus with current measurement on its AAA customer side, it can ensure that the AAA customers' harmonics are filtered. CP Control will supervise such an operation, as well as monitor harmonics from other customers. On the other hand, it can also sum the measured current of select customers, and filter the harmonics of these customers. The overriding considerations will be to ensure that the active filter is not overloaded, harmonic voltage on the CP-bus is not excessive and that the total harmonics entering the feeders is reasonable. Because the harmonics from various customers may cancel each other to some extent, it may be best to order the active filter to minimize harmonic content in the common busbar connection between the two SSTs and the CP bus. As mentioned earlier, practically all customer facilities generate harmonics and need active filter support.

Each customer's waveforms are monitored by the CP Control. All power quality events are captured, logged, and managed for periodic assessment of the service being provided. It is also necessary to evaluate specific events for continued improvement, and collect the information required dispute resolution, performance-based payments/penalties, etc.

It is obvious that there can be a variety of scenarios for a Custom Power Park. The scenario presented in this paper provides only the basis for further discussion.

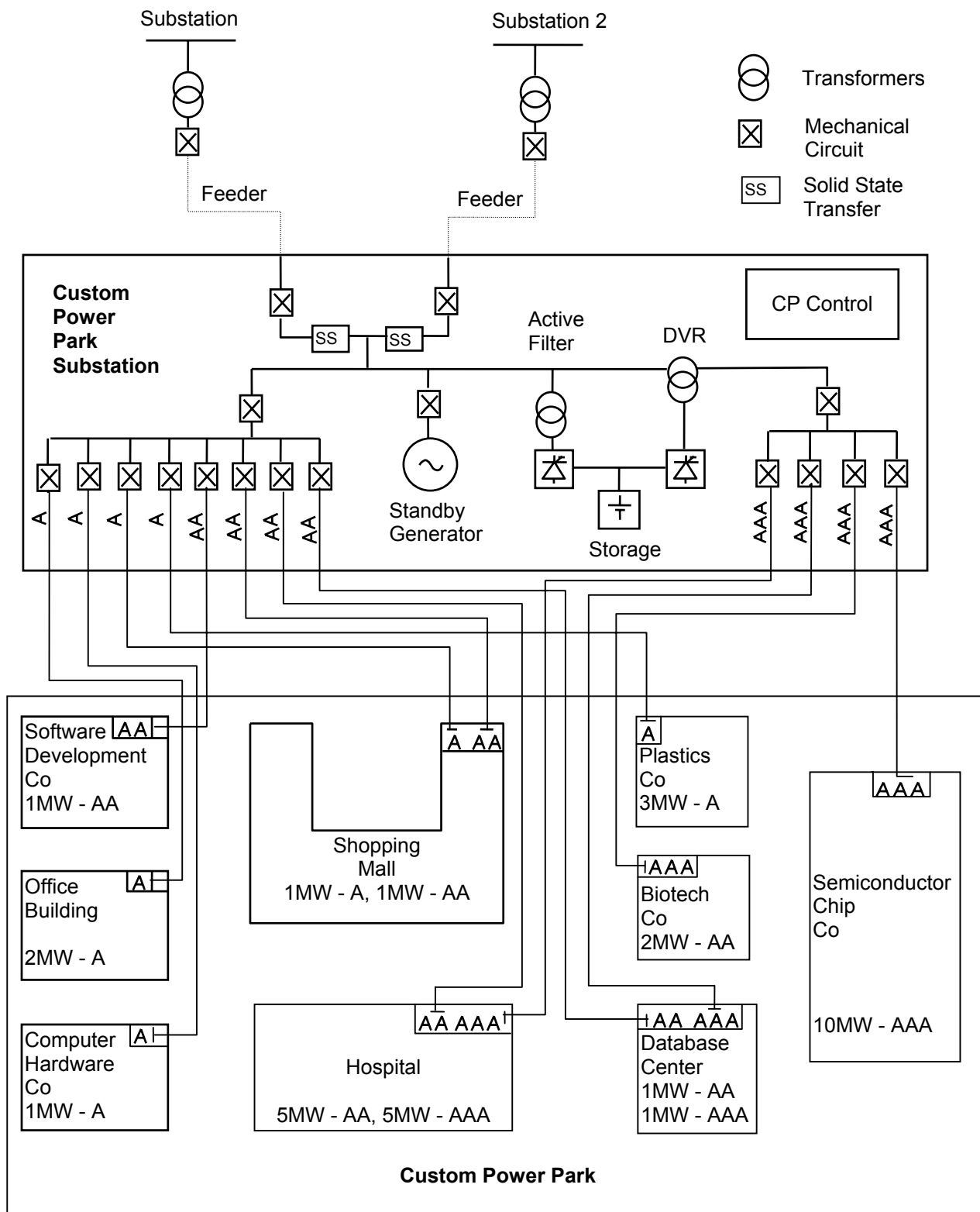


Figure 6.2.1: Custom Power Park concept

REFERENCES

- [1] Glossary of terms and definitions concerning electric power transmission system access and wheeling, IEEE Power Engineering Society, 96 TP 110-0.
- [2] J. Knijp, T. de Zwart, Quality of power supply becomes measurable, PQA 97 Europe, Session 4B, Stockholm, 16-18 June 1997).
- [3] Quality of service and its cost (UNIPED, 91en50.3, 1991).
- [4] Reliability assessment of large electric power systems (R. Billinton, R.N. Allan, Kluwer Academic Publishers, 1988).
- [5] R.C. Dugan, M.F. McGranaghan, H. Wayne Beaty, "Electrical power systems quality" McGraw-Hill, 1996.
- [6] Power interruption costs to industrial and commercial consumers of electricity (M.J. Sullivan, T. Vardell, M. Johnson, IEEE Transactions on Industrial Applications, Vol. 33, No. 6, November/December 1997, pp 1448 - 1457).
- [7] "Requirements for dynamic voltage restoration to relieve distribution system voltage sags", by R.J. Nelson et al., APC 1995 pp 1530-1534.
- [8] CEI 1000-2-1: "Compatibilité électromagnétique (CEM) - Partie 2: Environnement - Section 1: Description de l'environnement - Environnement électromagnétique pour les perturbations conduites basse fréquence et la transmission de signaux sur les réseaux publics d'alimentation" (1990).
- [9] CEI 1000-2-2: "Compatibilité électromagnétique (CEM) - Partie 2: Environnement - Section 2: Niveaux de compatibilité pour les perturbations conduites basse fréquence et la transmission de signaux sur les réseaux publics d'alimentation à basse tension" (1990).
- [10] EN 50160, "Voltage characteristics of electricity supplied by public distribution systems," European standard (CLC, BTTF 68-6, Nov 94).
- [11] "Application guide to the European Standard EN 50160 on Voltage Characteristics of Electricity Supplied by Public Distribution Systems" (UNIPED, Standardisation Specific Committee, Group of Experts: Electricity Product Characteristics and Electromagnetic Compatibility, July 1995).
- [12] "Measurement guide for voltage characteristics" (UNIPED, Standardisation Specific Committee, Group of Experts: Electricity Product Characteristics and Electromagnetic Compatibility, July 1995).

- [13] IEC 1000-3-6, "Assessment of emission limits for distorting loads in MV and HV power systems" (1996).
- [14] IEC 1000-3-7, "Assessment of emission limits for fluctuating loads in MV and HV power systems" (1996).
- [15] European Commission, "Amended proposal for a European Parliament and Council Directive concerning common rules for the internal market in electricity" (Official Journal of the European Communities, No C 123, 4.5.94).
- [16] Group of experts DISQUAL, "Draft report of the Group of Experts DISQUAL on availability of supply indices" (UNIPED, DISQUAL 44, May 1996).
- [17] R.C. Dugan, M.F. McGranaghan, H. Wayne Beaty, "Electrical power systems quality" McGraw-Hill, 1996.
- [18] G. Gufflet, P. Malkin, "Solid-state Medium-Voltage Contactor," IEEE Proceedings-B, vol. 140, no. 2, pp. 147-151, March 1993. [conference paper].
- [19] J. W. Schwartzberg, R. W. DeDoncker, "15 kV Medium-Voltage Static Transfer Switch," 1995 IEEE IAS Conference in Orlando, Conference Proceedings, pp. 2515-2520, October 1995. [conference paper]
- [20] D. Merrill, "Static Transfer Switch 'Litmus Tests'", Power Electronics International Cyber-Zine for the Power Electronic Industry, June 1996. [magazine article]
- [21] J. Lowery, "Pursuit of Premium Power", Rural Electrification, Solutions, p. 29, October 1996. [magazine article]
- [22] EPRI Power Delivery Group, "Value of New Systems Displayed Through Custom Power Demonstrations", Distribution Newsletter, Volume 1, Number 1, April 1996. [EPRI Newsletter]
- [23] Staff, "PowerDigm[®] Switch for Improved Power Quality", IEEE Power Engineering Review, p. 37, December 1996. [magazine article]
- [24] Y. Okamura and N. Okada, "Experiment on 6.6 kV Thyristor Switching Device for Power Distribution Line", CRIEPI Report T94021.

- [25] T. Ueda, M. Morita, H. Arita, J. Kida, Y. Kurusawa and T. Yamigawa, "Solid-State Current Limiter for Power Distribution Systems", IEEE 93 WM 009-1 PWRD, T-PWRD October 1993.
- [26] S. Sugimoto, S. Neo, H. Arita, J. Kida, Y. Matsui and T. Yamigawa, "Thyristor Controlled Ground Current Limiting System for Ungrounded Power Distribution Systems", IEEE 95 SM 374-9 PWRD, T-PWRD April 1996.
- [27] N.G. Hingorani, "Introducing CUSTOM POWER" IEEE Spectrum June 1995.
- [28] N.G. Hingorani, "Overview of Custom Power Meeting in San Diego. Copy of the presentation is available on the IEEE PES Working Group 1409 website.
- [29] N.G. Hingorani, L. Gyugyi, "Understanding FACTS," IEEE Press, 2000, ISBN 0-7803-3455-8
- [30] CIGRE Brochure No 139, "Guide to Specification and Design Evaluation of AC – Filters for HVDC Systems," WG 14.30.

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