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# Voltage Source Converter based Power Quality Solutions

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ABSTRACT: The voltage source converter is the all-round converter type in today's power electronics. Its characteristics allow building a wide range of power quality devices based on basic converter modules. Through combination of basic modules tailor made single- or multifunctional power quality solutions can be built to match the specific needs of individual customers. Applications based on voltage source converters can tackle power quality problems ranging from voltage flicker, harmonics, poor power factor, to voltage sags, swells and interruptions.

On the basis of two application examples this paper discusses the use of voltage source converters in industrial manufacturing processes. These two applications were developed for protection against short-time voltage disturbances (sags and swells). Subsequently a short overview about existing applications in the field of power quality concludes this paper.

Sags and swells in the grid voltage are a major threat to manufacturing processes of high-tech industries such as semiconductor or pharmaceutical companies. Single voltage sags can cause losses in the millions of dollars if hitting sensitive processes without appropriate protection.

Different solutions have been developed to protect sensitive loads against such disturbances. Two of those devices are the Dynamic Voltage Restorer (DVR) and Series Voltage Restorer (SVR). The DVR is usually installed at medium voltage level and is designed to protect complete facilities. Although a high-power, medium voltage level protection may be adequate for some applications, it is not for others. In some cases protection at low voltage level may be more appropriate. The SVR is a low voltage device intended to protect single low voltage feeders. Both devices compensate the "missing" voltage by series injection of the correct voltage vector. Since such voltage sags are usually in the range of up to 500ms, the DVR and SVR are designed to protect against short-term disturbances. In a typical grid such short-term power quality problems make up for the big bulk (80-90%) of voltage disturbances.

In addition to the dip compensation capability the SVR incorporates some additional features. This illustrates the real potential of voltage source converters. The topology of the SVR allows combining different power quality functions in one and the same devices. In addition to voltage sag correction the SVR offers power factor correction and continuous voltage regulation.

## POWER QUALITY

The term „power quality“ is widely used today when deficiencies of electrical transmission and distribution systems are described. Therefore it could mean various potential deficiencies, which can have various causes. Those for example are:

- Loads with a poor power factor have a large demand of reactive power. The transport of reactive power increases the line losses and dramatically increases the voltage drop. Undervoltage at the point where the load is connected may result. The conditions can be improved by reactive power compensation equipment.
- Non-linear loads (for example rectifiers) draw non-sinusoidal currents. These are currents with a considerable content of higher frequency harmonics. They in turn can cause voltage distortions, which may cause malfunctions of sensitive loads and overheating of rotating machines. In addition neighboring telephone lines may be disturbed. Remedies for such disturbances are passive or active harmonic filters.
- Large single-phase loads cause voltage asymmetries. If the asymmetries become too large rotating machines will be overloaded and overheat. The countermeasure is the installation of load symmetrizing (balancing) equipment.
- The switching on of large transformers or large motors cause inrush currents to flow temporarily, which can be a multiple of the nominal current of the equipment. This can result in temporary voltage sags to other loads, which are connected to the same or a neighboring bus. Sensitive loads may experience disturbances.
- Line faults in the distribution or transmission grid cause voltage sags of short duration. They last until the faulted line is disconnected from the grid. The typical duration is 0.1 to 0.3 seconds. Most loads are not disturbed if it happens. However, some manufacturing processes are rather sensitive to such voltage sags and may experience a considerable impact to production.

Voltage sags

Most complaints about poor power quality today seem to concern voltage sags. Why all of a sudden? Voltage sags are no new phenomena. They always happened in electric power grids. They always represented the majority of disturbances – much more common than the ultimate disturbance – the blackout.

Voltage sags are getting increased attention because manufacturing processes are increasingly becoming more automated and more integrated, and are moving from partial continuous towards fully continuous processing. These complex integrated processes show a higher vulnerability to power supply disturbances. Drives trip, distributed controls cease working, ultraviolet light sources dim. Even short time disturbances lasting for 100 ms only may result in several hours of production loss - the time needed to restart the process and to regain stable processing conditions.

Similar needs exist in the area of data processing and telecommunication and were recognized much earlier. The solution adapted there for protection against power supply disturbances including total loss of power is the Uninterruptible Power Supply (UPS). Today it is a booming market with a volume of about 3.5 billion $.

One might conclude now that the answer to the needs of the manufacturing industry could be UPS as well. This answer might be wrong. The major difference between data processing and manufacturing is the power demand and the power intensity of the process. For data processing and telecommunication the electric power needed is quite small compared to the value of the processing itself and the financial consequences of an interruption of the process. Energy efficiency only becomes an issue in view of the investments for waste heat removal and air conditioning. The cost of the energy itself and the investments to be made for reliable energy supply is generally regarded as a minor item. Thus, in case of the data processing and telecommunication industry, if a UPS can avoid a process breakdown only once within 2-3 years it is a worthwhile investment already.

In the manufacturing industry the cost consequences of a process interruption are usually not as disastrous as in data processing and the cost of energy including investments to be made for energy supply are not minor cost items. Furthermore the total loss of power is a rare event compared to the many transient voltage sags caused by remote faults somewhere in the electric grid. Fig. 1 shows the results of a long time recording done in a typical US distribution grid. This event coordination chart was prepared by EPRI. More than 90% of all recorded events lasted less than 0.5 seconds and had a remaining voltage magnitude higher than 50%. One further has to note that at least 80% of all faults in high voltage systems are single-phase faults. Considering this facts one can rightfully conclude that a power quality device which will not give a 100% protection but sufficient protection for about 90 % of all events is the appropriate device for protection of most manufacturing processes.

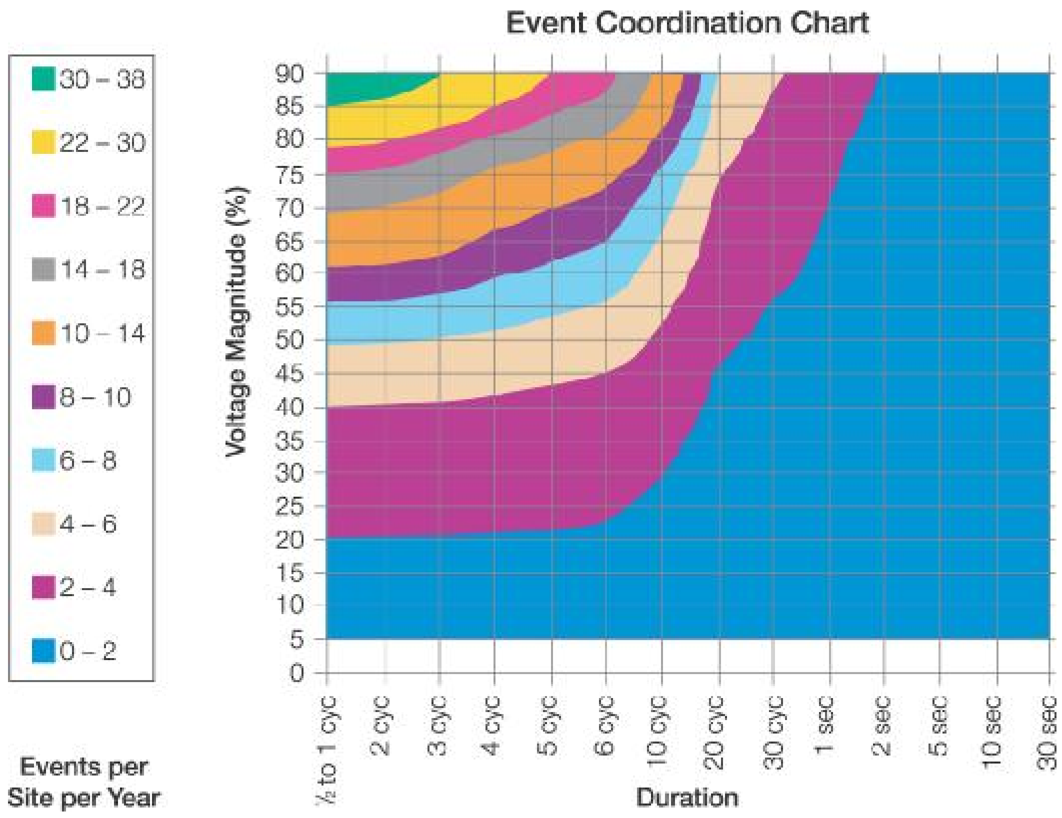


*Fig. 1: Typical distribution of voltage disturbances (EPRI event coordination chart)*

The average economic loss per voltage sag is highly depending on the sensitivity of the manufacturing process. The biggest losses were clearly reported in the semiconductor and pharmaceutical industry. However also the glass, plastics, textile and automotive industries have been confronted with severe damage due to voltage sags.

## DYNAMIC VOLTAGE RESTORER (DVR) – PROTECTION AT MEDIUM VOLTAGE

Several manufacturers of electrical equipment have developed and introduced devices for mitigating the effects of voltage sags. Today's probably most utilized and best-known device is the DVR. Fig. 2 shows a simplified single line diagram.

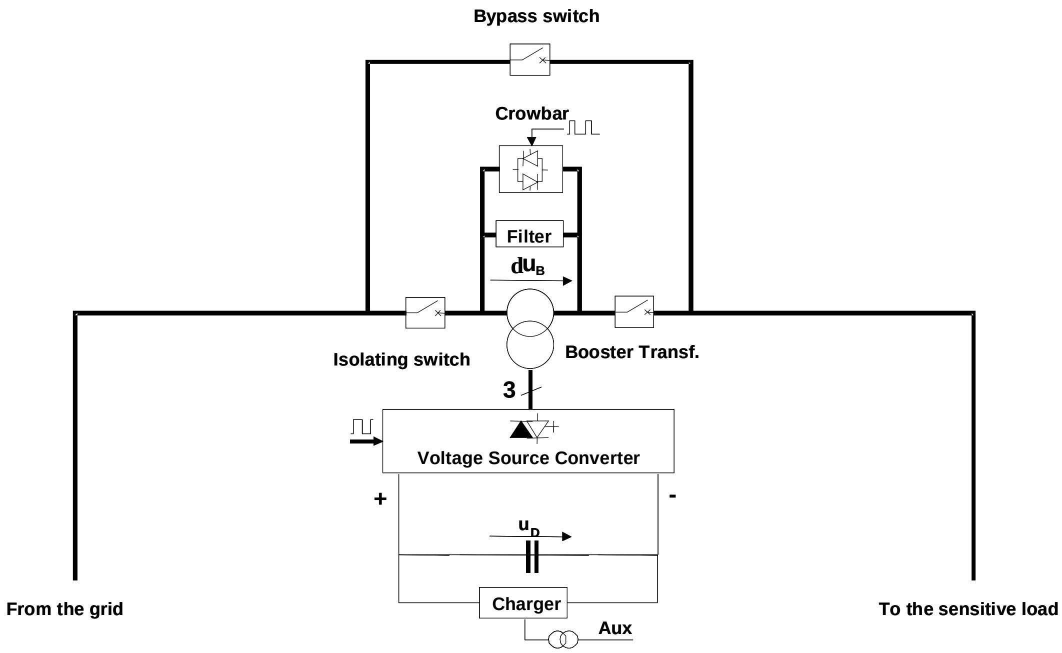


*Fig. 2: Single line diagram of voltage sag mitigation device (DVR)*

A voltage source converter is used to add the "missing" voltage during voltage sags via a booster transformer. A large capacitor bank provides the necessary energy storage. For start up the capacitor bank is precharged by a small charging rectifier. The thyristor crowbars enable fast bypassing; either in case of a downstream fault to assure that the downstream protection can work reliably or in the unlikely case of an internal defect of the voltage source converter. A mechanical bypass switch relieves the crowbar from its current carrying duty to avoid undue overheating of the thyristors. It will also be used to bypass the device for a longer time if maintenance work has to be done. For this purpose also the isolating switches will be opened to allow safety grounding.

DVRs are usually installed at the distribution voltage level (typical voltage range 10 to 30 kV) and can be built up to power ratings sufficiently high to protect not only a voltage sag sensitive process line but also even a whole plant. ABB's deliveries belong to the biggest DVRs ever installed.

Typical requirements are to compensate single-phase voltage sags down to 50% remaining system voltage and three-phase sags down to 65% remaining system voltage for a duration of about 300 milliseconds. The voltage at the load shall be restored back to normal voltage levels within less than a quarter cycle.

Especially the restoration speed requirement is very demanding for the control system, but it can be achieved with a fast acting feed forward control. In practice voltage restoration times down to about 1 millisecond have been achieved.

Fig. 3 shows an event (voltage sag), which occurred at a semiconductor factory.

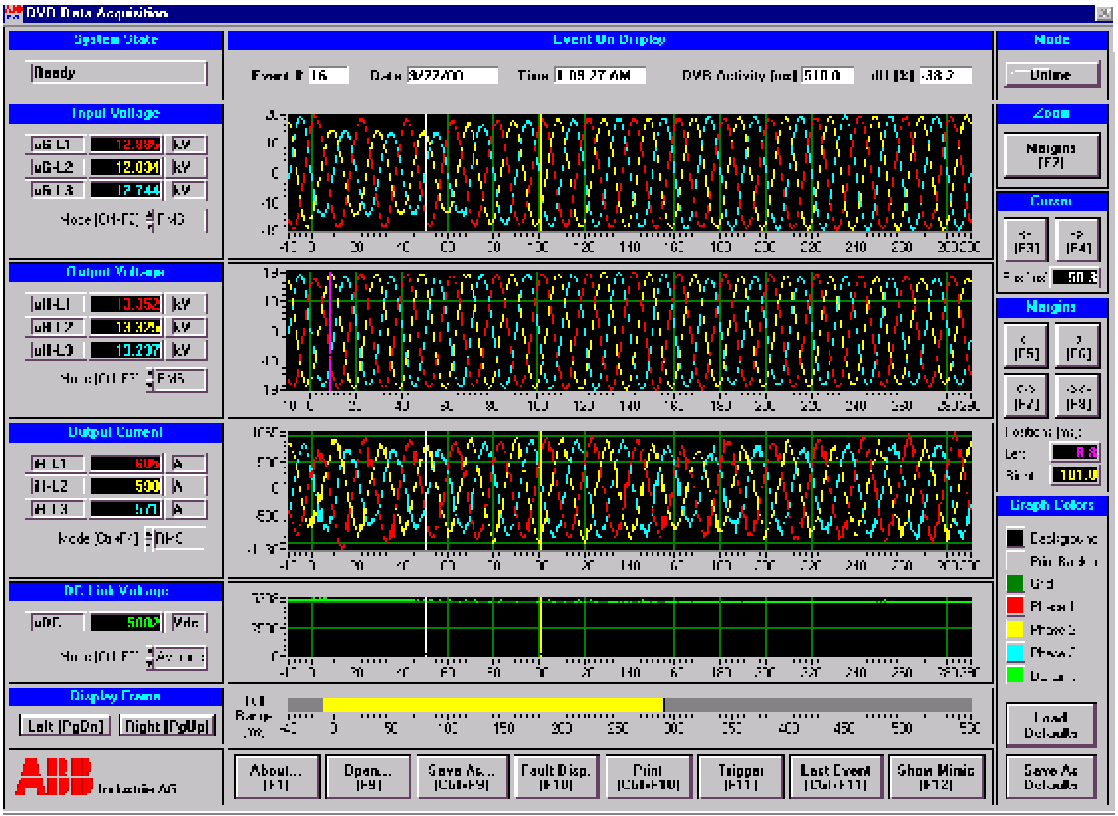


*Fig. 3: Screenshot of the recording of a voltage sag.*

The top window displays the power grid voltages, the second window from the top shows the load voltages, in the third window the load current is displayed, and in the window at the bottom the voltage across the DC energy storage capacitor is monitored. A voltage sag of about 38% happened at two phases. The load side voltage was restored within less than 1 millisecond. ABB engineers downloaded this screen shot via modem connection over the phone. This remote monitoring functionality permits access to the control and monitoring system from virtually everywhere in the world. It allows for remote trouble shooting in cooperation with engineers and technicians at the plant and tremendously reduces downtime if any disturbance at the device should occur.

Voltage Source Converter based on IGCT technology

For the DVR, ABB employs an advanced derivation of the common GTO (Gate Turn-Off) semiconductor, which is the IGCT (Integrated Gate Commutated Thyristor). This element represents state-of-the-art in high-power semiconductors, and combines both the advantages of the GTO and the IGBT (Insulated Gate Bipolar Transistor), the low conducting losses and controlled state transition, respectively.

The IGCT allows for a snubber-less design of the converter, i.e., for a phase module only a single snubber circuit is required instead of a single snubber per GTO previously. Besides reduced cost due to fewer components, the snubber-less converter excels in efficiency, less maintenance and therefore higher availability and reliability. IGCT converters are especially suited for medium and high power applications.

The PowerStack converter module used for the DVR is based on a very compact, standardized valve design (see Fig. 4). The converter is water cooled, which yields an optimized cost versus performance ratio, and is virtually maintenance free. The control interface is established via fiber optics, thus eliminating any contingent electro-magnetic interference. Though compact, the valve allows for exchange of failed components within two hours (round up time excluded).

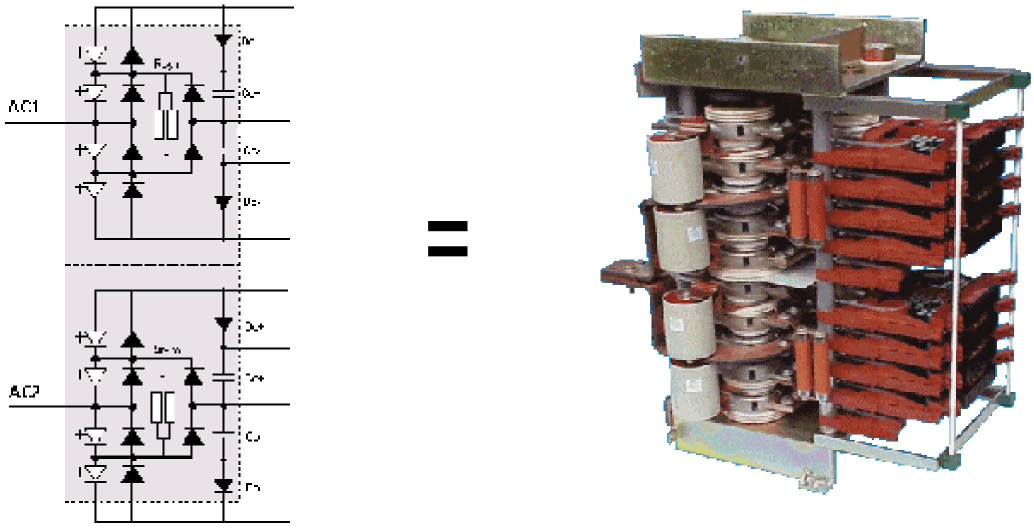


*Fig. 4: IGCT based PowerStack converter module as used for the DVR*

The PowerStack module is the basic element (Power Electronics Building Block – PEBB) of the voltage source converter. Depending on the application and power required several PEBBs are combined. This modular design allows covering the entire range of power quality applications with the same basic converter module. A standard DVR is equipped with three Power Stacks. Depending on the power rating the number of stacks can of course be different.

<u>Physical layout and arrangement</u>

An impression of the physical layout and arrangement of the DVR's main components is given in Fig. 5. All components are installed in a container suitable for outdoor installation. By completely installing, wiring and testing the units in the factory prior to shipment, on site installation time is reduced by a minimum and the time needed for commissioning is also significantly reduced. The container shown is 12.5 meters long, 3 meters wide and 3 meters high. Most of the energy storage capacitor bank is housed in a second container of similar size.

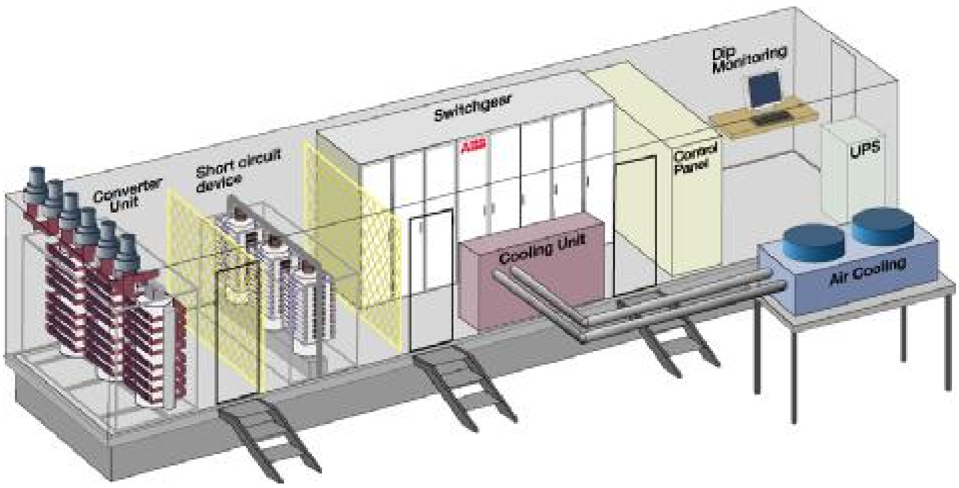


*Fig. 5: Physical layout and arrangement of the DVR's main components*

## SERIES VOLTAGE RESTORER (SVR) – PROTECTION AT LOW VOLTAGE

After the DVR ABB developed a new voltage sag mitigation device, called Series Voltage Restorer (SVR). The goal was to develop a device based on the experience and functionality of the DVR but aimed for low voltage applications in order to protect single sensitive production lines at typical voltage levels between 400V to 600V, instead of protecting entire plants. The topology of the SVR is shown in Fig. 6.

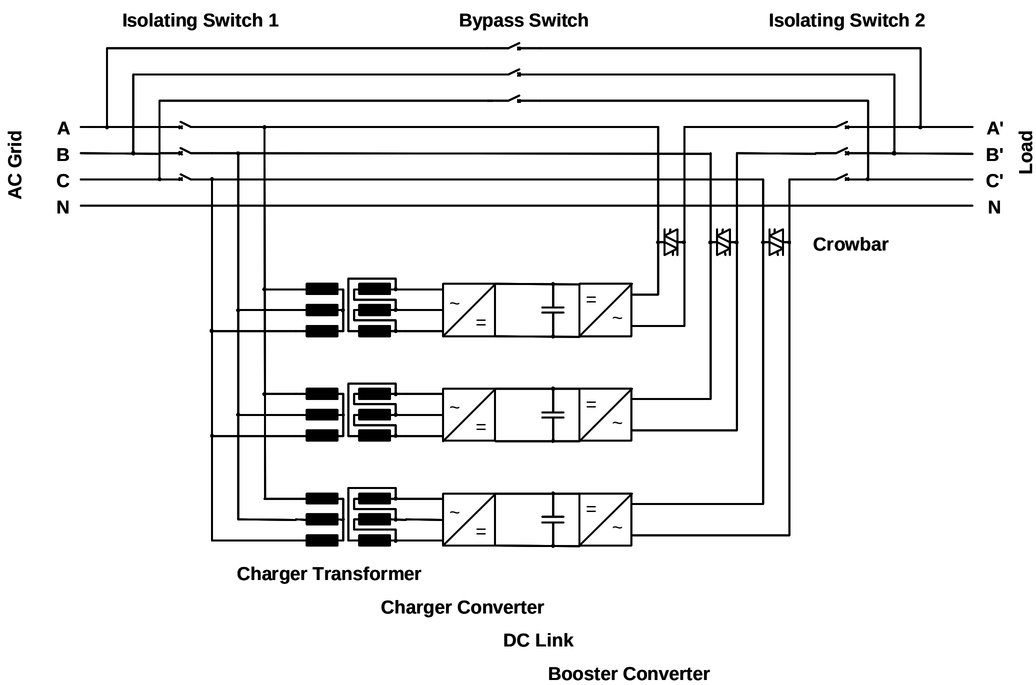


*Fig. 6: Principle diagram of the SVR*

This topology is similar to the DVR but differs from it in two major aspects.

- Restriction of the application to the low voltage level allows omitting the booster transformer. Instead of a common DC link, three individual DC links are installed in order to provide single-phase protection. It was concluded that the advantage of a booster transformer does not offset its disadvantage. The main disadvantages of a booster transformer are the cost of it, the space demand and, last but not least, the additional losses.
- The large capacitor banks for energy storage are no more required if a charger converter supplies the power to the DC link needed for voltage compensation. With grid voltages down to about 50 to 60% of nominal voltage this is still possible and results in additional space and potential cost savings. Furthermore the duration of voltage support is no more limited to the amount of energy stored and voltage sags can be compensated for as long as permitted by the overload capability of the charger transformers. This design can also be applied to the DVR.

Additional functionality of the SVR

The topology of the SVR renders itself to provide additional functionality what may result in additional customer benefits. Two functions are incorporated in the design of the controls. The first one is continuous voltage regulation. The device controls the output voltage of the single phases within a selectable and narrower band than the usually slightly fluctuating grid voltage provides. This is useful if the process to be protected benefits from a very stable voltage. The other function is reactive power compensation or power factor control. It is useful if the load to be protected has a very poor power factor. Whether or not this results in a financial benefit depends mainly on the contract with the electric power supplying utility, in particular whether there is an additional charge for reactive power delivery.

Another potential option is active harmonic filtering. The topology of the SVR would permit it, but it is not implemented at present, since there is not yet enough demand in the market today. As consumers and utilities get more power quality conscious, this option might become more important in future.

Voltage Source Converter based on IGBT technology

The modular low voltage power electronic platform is called PowerPak. It is a power electronics building block (PEBB) with three integrated Insulated Gate Bipolar Transistor (IGBT) modules. Each IGBT module consists of six switches forming three phase legs. Various configurations are possible. For example three individual three-phase bridges on one PEBB, one three phase bridge plus chopper(s) etc. The PowerPak is easily adaptable for different applications. The IGBT modules used are the ABB LoPak type.

Fig. 7 shows one Power Pak as it is used for the SVR. It consists of one three-phase bridge (the three terminals at the right hand side), which provides the input to the DC link (one IGBT module is used for it) and one output in form of one single phase H-bridge (the two terminals to the left) acting as the booster converter. For the latter two IGBT modules are used with three paralleled phase legs per output terminal. By paralleling such PEBBs adaptation to various ratings is possible.

*Fig. 7: IGBT based PowerPak converter module as used for the SVR*

Physical layout and arrangement

The basic mechanical modules are shown in Fig. 8

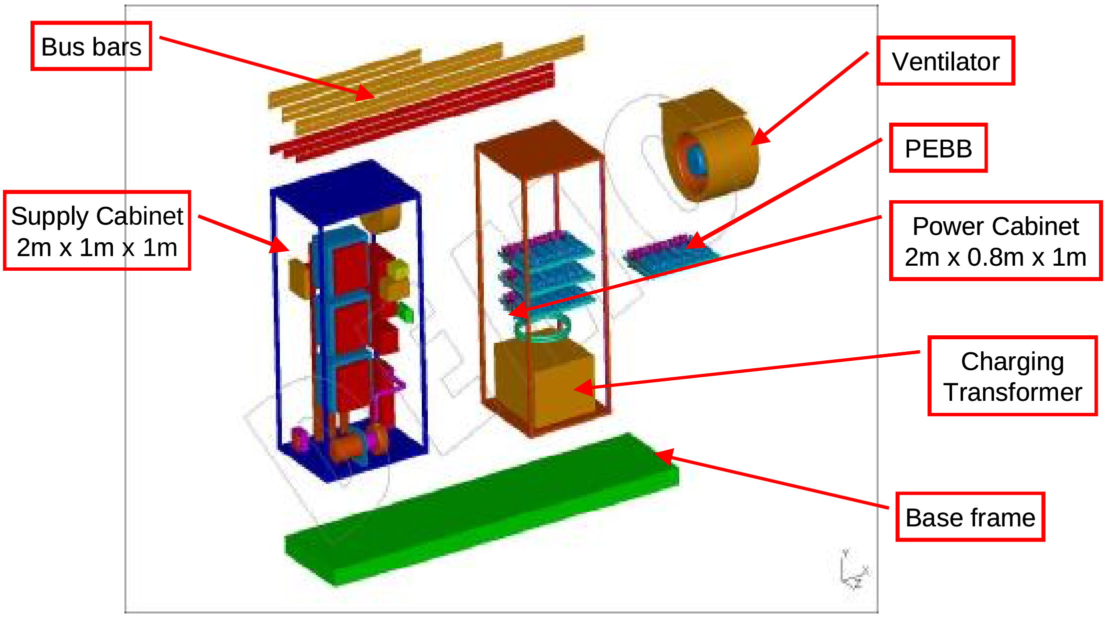


*Fig. 8: Basic mechanical modules of the SVR family*

Fig. 9 shows the mechanical design of an SVR designed to protect a load of 1500 kVA at a nominal voltage of 480 V. Each of the three phases has its own cabinet. Three PEBBs are connected in parallel per phase and provide charger as well as booster converter functions.

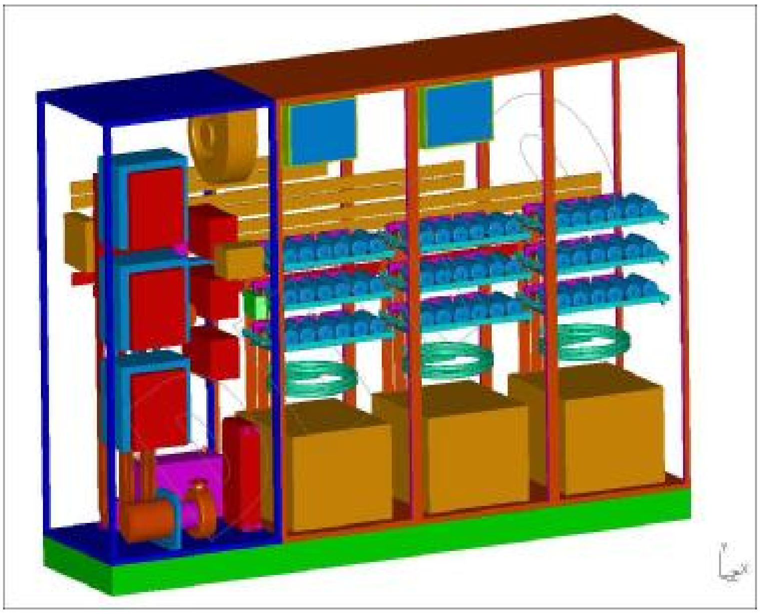

*Fig. 9: Mechanical design of a SVR rated 1500kVA at a nominal voltage of 480V*

A photograph of the same device is shown in Fig. 10

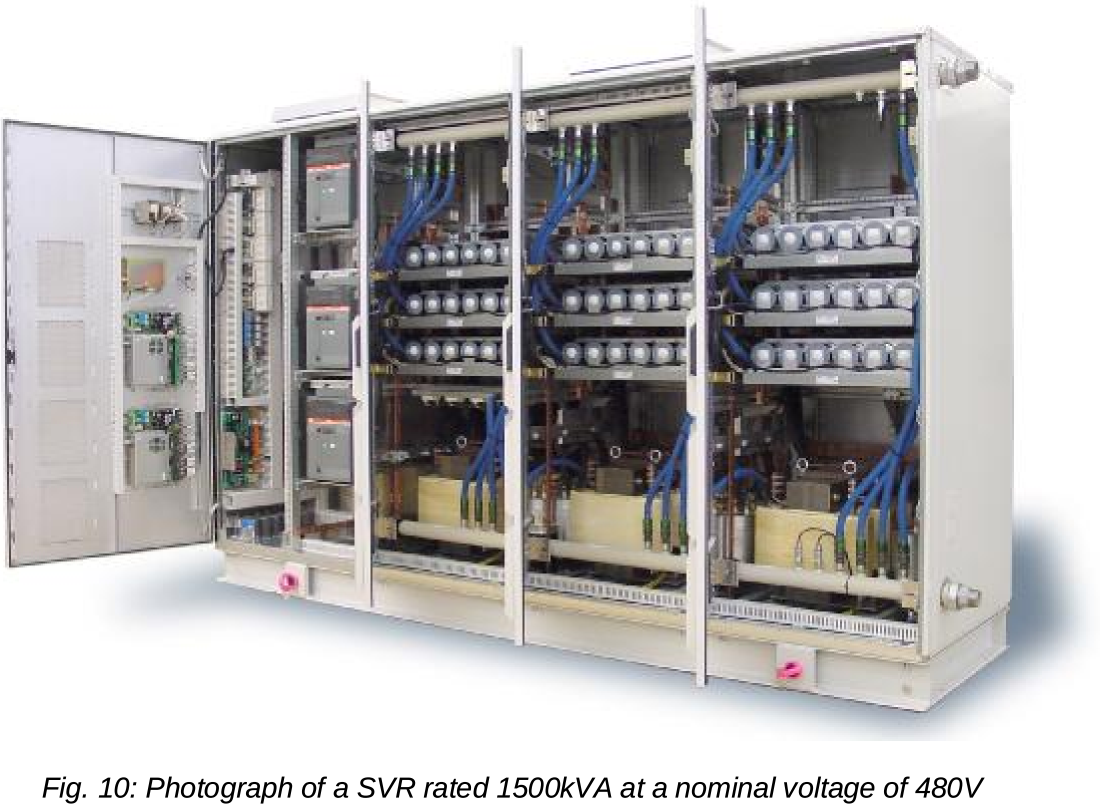

*Fig. 10: Photograph of a SVR rated 1500kVA at a nominal voltage of 480V*

## OTHER POWER QUALITY SOLUTIONS BASED ON VOLTAGE SOURCE CONVERTERS

In the precedent chapters two specific power quality solutions have been discussed. The DVR and SVR are however only two examples of applications, which can be built with voltage source converters. With the modular IGCT and IGBT converter concept, ABB has created a platform, which allows building an entire range of power quality solutions.

IGBT applications cover the lower power range, while IGCT solutions are aimed for the medium and high power range. The power level where to change from one to the other is somewhere in the range of 2-5MVA depending on the application. IGBT based solutions can even reach higher power ranges, if several units are paralleled.

All systems have one thing in common. They are all based upon standard components. The heart of each system is the voltage source converter together with the control platform. Most applications will require a transformer to connect to the corresponding voltage level. Further, each device comes with a cooling system. Other components such as the capacitor bank or the breakers of the DVR depend on the requirements of the specific application.

Hereafter power quality solutions other than the DVR and SVR are shortly discussed.

STATCOM, Harmonics and Flicker Compensation

The configuration for reactive power compensation (STATCOM) is basically the same as needed for Harmonics Compensations. The main difference is in the programming of the control algorithm. In fact both applications can be easily combined in one and the same device. Since injecting or absorbing reactive power is also the remedy to correct flickers, the same device can be used for Flicker Compensation. Fig. 11 shows the simplified single line diagram for these applications.

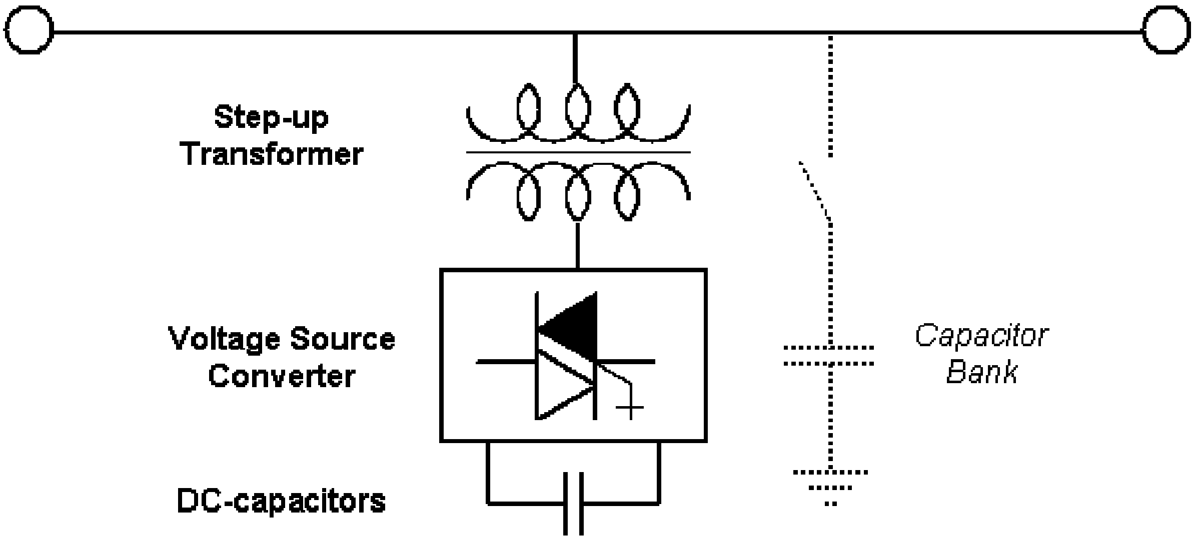


*Fig. 11: Topology of STATCOM, Harmonics and Flicker Compensation*

This configuration allows compensating positive or negative reactive power up to the converter rating (e.g. +/-5MVAr). By adding a capacitor bank in parallel as shown in Fig. 11 the range can even be extended. If the capacitor bank is sized to contribute an additional 5MVAr the range will increase to –5MVAr to +10MVAr. The control of the STATCOM will make sure that no step in reactive power occurs when the breaker of the capacitor bank is opened or closed. The 5MVAr step applied by adding or removing the capacitor back are immediately compensated by the STATCOM.

Since a voltage source converter can generate voltages of any required frequency it can also be used to compensate harmonics. Harmonics of predefined order will be measured and compensated by the device.

Battery Energy Storage System (BESS) and Unbalanced Load Compensation

The basic topology of a BESS is very similar to the one discussed before. The main difference is that instead of the capacitor bank batteries are connected to the secondary of the voltage source converter as shown in Fig. 12. Like this it is possible not only to control the reactive power, but also to inject or absorb active power. The most common application example of a BESS is of course the Uninterruptible Power Supply (UPS). Another example is to serve as spinning reserve to ensure stable operation of a power grid. Obviously this topology also incorporates all functions discussed above, like Harmonics and Flicker Compensation.

One interesting feature is the possibility to inject or absorb power individually for each of the three phases. This can dramatically improve the quality of the voltage supply in grids with large unbalanced loads.

It is also possible to connect other energy storage systems to the secondary of the converter. For example, ABB has recently built a converter system to connect to fuel cells on the dc-side.

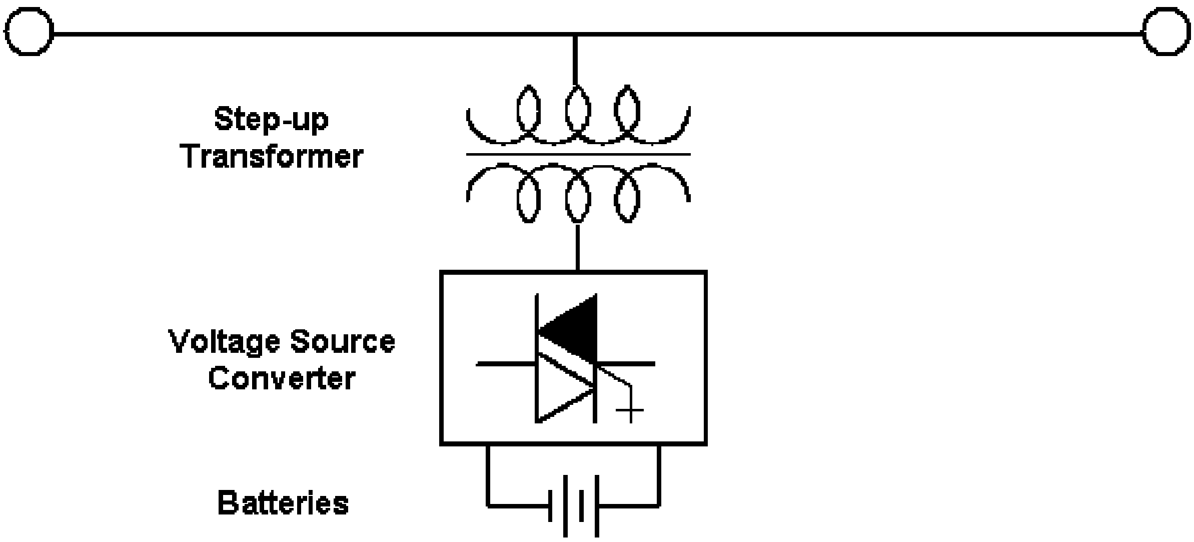


*Fig. 12: Topology of a Battery Energy Storage System*

Static Frequency Converters

Static Frequency Converters have a very wide application range. The best-known applications are of course drives for motors. But the drives business does not belong to what is generally regarded as the area of power quality. However there are a number of applications with Static Frequency Converters, which clearly belong there.

For example, such converters can be used to interconnect two grids (e.g. two weak island grids) with both helping to stabilize each another. Often direct connection of two grids is not possible. The reason can be manifold. It might simply be that the two frequencies are different, or that they are not synchronized, or that voltage fluctuations on one side are so big that a direct connection via transformer would cause problems on the other side. In these cases a Static Frequency Converter is the right solution, since it decouples the two sides, but still allows transmitting power from one side to the other.

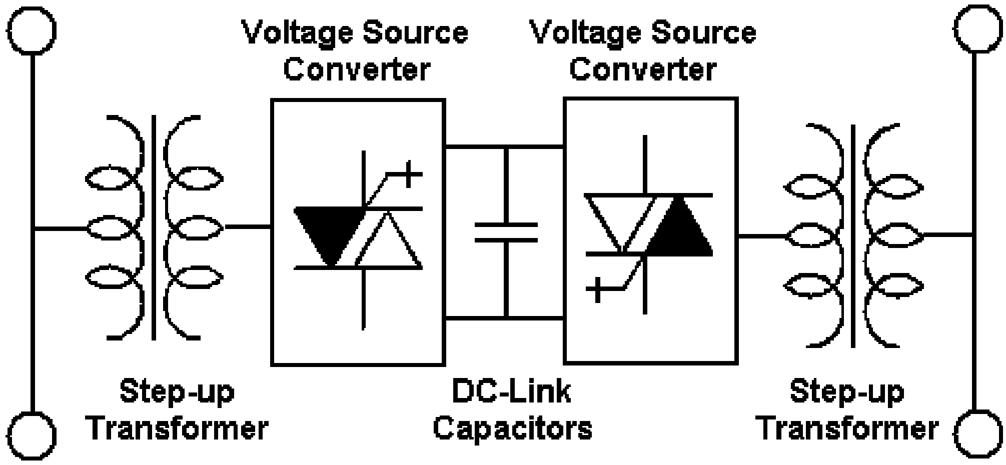


*Fig. 13: Topology of a Static Frequency Converter*

The behavior of the Static Frequency Converter as seen from the connected grid is the same as for the BESS. The main difference is that the batteries with their limited capacity are replaced through an unlimited energy source (another grid), meaning that injection or absorption of active power is not limited to the size of the batteries. Static Frequency Converters are always bi-directional, meaning that the power can be transmitted from one grid to the other or in opposite direction depending on the requirements. The functionality of the system however, is the same as the one described for the BESS. Even UPS functionality can be achieved, if some batteries are connected into the DC-link.

## CONCLUSIONS

The voltage source converter is a universal device, which allows building many different power quality solutions. ABB has built and commissioned many such systems based on a modular converter platform. Two different platforms are available, one based on the IGBT for the lower power range and the other based on the IGCT for the medium and high power range.

This paper discussed in details two power quality applications for voltage sag mitigation: the DVR based on the IGCT platform and the SVR based on the IGBT platform. Both devices are of a modular design permitting easy adaptation to various ratings with the same key components. Other power quality solution such as STATCOM, Harmonics and Flicker Compensation, BESS and Static Frequency Converters can be built based on the same modular converter systems.

Given the great potential of the voltage source converter and its capability to integrate multiple functions in one device, power quality systems based on theses converter platforms will get more and more popular in future. Especially since consumers and utilities are getting more power quality conscious.