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INCREASED SYSTEM EFFICIENCY BY USE OF NEW GENERATIONS OF POWER SEMICONDUCTORS

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Increased system efficiency by use of new generations of Power Semiconductors

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1 Overview

1.1 Introduction

The background of this Working Group (WG) report is the rapid development of power semiconductors with respect to lower losses, higher switching frequency and the trend towards converter modularization as building blocks (see Figure 1-1). Even though the application of power semiconductor based devices for FACTS and Power Quality applications has become a regular measure to solve grid problems the aforementioned trends will open up possibilities for new applications in both transmission and distribution systems. The overall objective of the WG is to follow the development of the power semiconductor development and its new application areas in order to propose and evaluate new or enhance equipment for increased system efficiency in a broad sense.

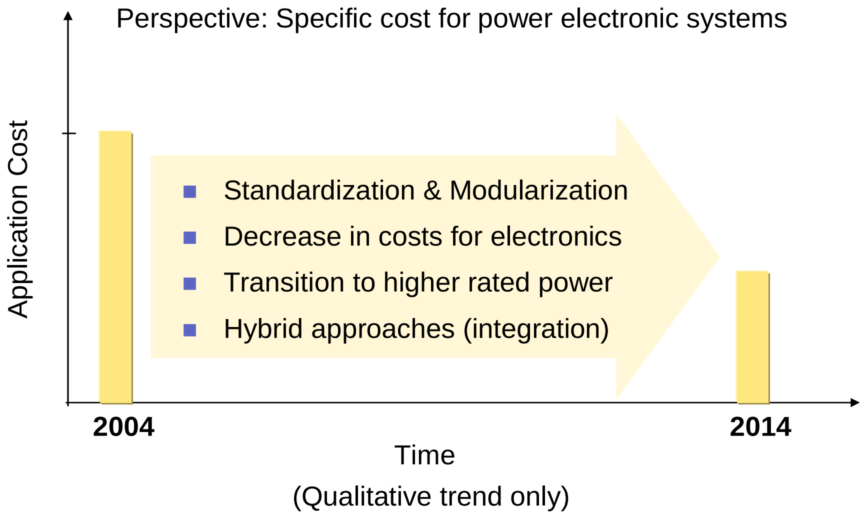

Figure 1-1: Major trends in power electronic applications driven by new generations of power semiconductors

In general, the objective can be discussed from two different perspectives. On the component side (component view) power electronic equipment will influence more and more devices which are built within a substation. This topic refers to the direct integration of single or multiple semiconductor devices into substation equipment like circuit breakers, transformers, etc. From this perspective those application areas are considered where power semiconductors are used instead of mechanical switches and contacts. Consequently, the target is to identify the application areas for power semiconductors, to evaluate existing concepts and to specify the application boundary conditions.

From the substation perspective (station view) the objective is to evaluate the impact of new generations of power semiconductors on power electronic device like FACTS and Power Quality (PQ) devices which are referred to as a part of a substation to fulfill a certain function in the network. With the increase of FACTS and PQ applications and the more and more modular design of those, it needs to be evaluated how the typical functionality can be improved and how the design will change or even whether power electronic systems become part of conventional primary equipment in substations. Examples are a transformer that has an ”inbuilt” voltage source converter for power flow control and/or voltage control, an integrated bay with breaking and controlling capabilities, etc. These concepts will address new or better devices for FACTS and PQ applications.

The different angles from which the power semiconductor development can be considered may lead to confusions when discussing the various application areas. Therefore the following definition for components, modules and systems are the reference for the discussions within this report:

Table 1-1: Definitions: Device, Modules, and Systems

Device	The Semiconductor device as such (IGBT, GTO, etc.)
Power Electronic Module	Converter, Valve, etc. I.e. the subsystem of a power electronic system
Power Electronic System	Operational device with a certain function for the power system comprising power electronic modules. I.e. FACTS device, Power Quality device or even a potential future substations with power electronic building blocks or modules
System	Entire Power System

Based on this definition the aforementioned “component view” is related to devices whereas the “station view” comprises power electronic modules and power electronic systems. Both categories will be analyzed with respect to their system behavior.

Within this report the focus of interest is the application of power electronic modules and power electronic systems to a network node. The network node is be considered as system element having the function of a present-day substation within a transmission or distribution system (see Figure 1-2). In general, there is no limitation to either transmission or distribution systems.

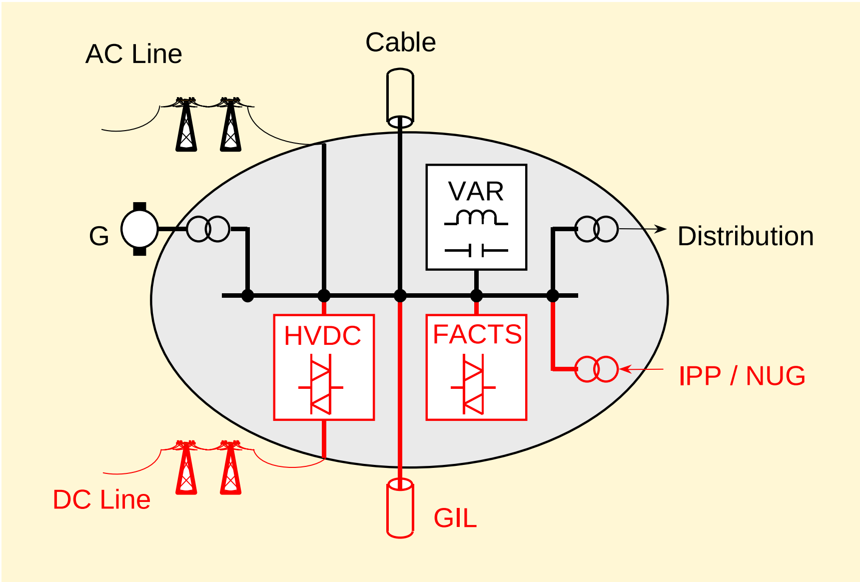

Figure 1-2: Network node consideration with power electronic systems and / or modules

The next generation(s) of semiconductors with considerably lower losses and higher switching frequencies will have properties which make new types of FACTS equipment economically interesting for system optimization, for better use of equipment and/or for possible postponement of extensions and refurbishments. It is also probable that new concepts will come up for connection of dispersed generation, DC/AC and AC/AC conversion as well as new power quality applications. These areas will only be considered with respect to new functions and device topologies. The overall power system economic perspective of new power electronic devices integrated in substations will be covered by the activities of other working groups.[1]

All the new power electronic systems have to be introduced into substations. In many cases it is likely to make them more complicated both in layout and operation plus control. On the other hand new and more reliable switching devices can lead to substation simplification giving a decreased number of apparatuses. Current control and fault current limiting devices can enable cheaper and simpler dimensioning of the substation equipment. Power electronic systems integrated into substations do not only need to be considered from an electrical perspective but also with respect to their mechanical integration. In particular foundations, gantries

[1] See WG reports and activities from Study Committee C1: System Economics and Development

etc. may be impacted by a changed design on device level. These areas are not considered in detail. Here, the focus lies on the electrical behavior and design of power electronic systems.[2]

Besides the transformation of voltages and currents, transformers are important network controllers in power systems. With the availability of highly efficient power semiconductors, transformers will benefit from the increased applications of directly integrated power electronic modules for control applications (e.g. tap changers etc.). Since further combinations of power electronic modules and transformers will become feasible (e.g. direct connection of voltage source converters to transformer star points for network control and power quality issues), this report summarizes the application areas. Detailed considerations regarding e.g. magnetic core design or insulation coordination are not considered here.[3]

Power semiconductors with lower losses and higher ratings are considered as enablers for faster and more reliable generations of circuit breakers and other switching devices and controllable fault current limiters. Faster breakers are needed for limitations of energy in devices for voltage dip and interruption mitigation. Even though theses devices are touched by some considerations within this report the detailed analysis of potential new switching equipment is not considered here.[4]

1.2 Considered technology

The evaluation of new power electronic system applications enabled by new generation of power semiconductors affects almost all areas of transmission and distribution systems. Following the hypothesis that future generations of semiconductors enable many AC applications which are not feasible today this report focuses on technologies which are referred to as AC technologies today. The area of today's DC systems either with thyristor technology or with voltage source converters will not be considered here.

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[2] These design aspects are directly related to substation construction and primary design. In particular this topic is covered by a WG from the Substation Study Committee B3 (WG B3.1, Multifunctional substations: Impact of new functionalities on substation design).

[3] These detailed investigations are part of the work of the Transformer Study Committee A2.

[4] The consideration of new switching equipment is done within the Switching Equipment Study Committee A3. In particular working group WG A3.12 is focussing on changing network conditions and system requirements.

As mentioned above, in AC technology the following two application areas have to be considered:

- Power electronic devices used for substituting mechanical switches and contacts
- Power electronic modules and systems comprising valves and / or converters for controlling network parameters by producing / consuming reactive power and / or injecting voltages or currents in parallel and / or in series with a network branch.

The first application area will be considered with respect to a state of the art mapping and the projection of future ratings of already existing and / or known application concepts.

In the second AC technology area today, two generations of power electronic systems for various applications can be identified and classified according to the first and second generation of power electronic systems (Figure 1-3).

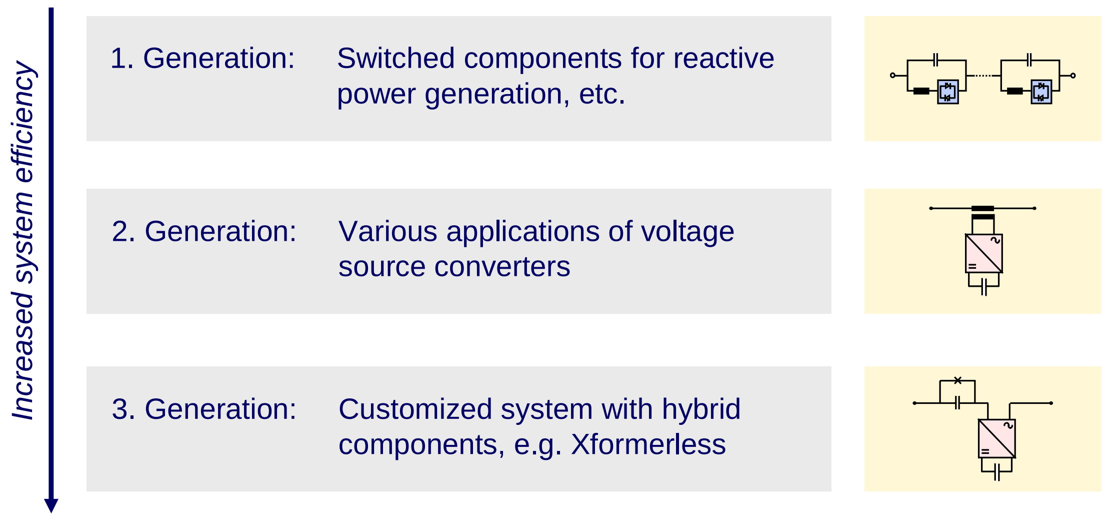


Figure 1-3: Evolution of power electronic systems for controlling the parameters of power transmission and distribution system

According to this classification the 2nd generation of power electronic systems has been enabled by a new generation of power semiconductors. Thus it is very likely that this development continues and the 3rd generation is enabled by the next generation of power semiconductors.

Consequently, this evolution is the main focus area of this report. For example, the 3rd generation of power electronic systems is featured by fewer primary components, new converter topologies, integration of power electronic modules and systems with conventional primary equipment and higher ratings, lower losses and additional functionalities.

In summary the technology and application areas which are considered in this report are

- AC applications
- Applications where semiconductors are substituting mechanical switches and contacts with respect to as-is-mapping and future ratings.
- Applications with power electronic modules and systems with respect to existing topologies, new converter topologies, new device concepts, modularized approaches, future ratings and the corresponding impact on network node design.

1.3 Method & criteria

The above-mentioned technology applications areas are considered in a four step approach (Figure 1-4). In the first step the actual existing applications and application concepts are mapped according to the following criteria:

- Analysis of existing realized and non-realized applications with power electronic devices substituting mechanical switches and with power electronic modules and systems
- Analysis of the used semiconductor type and rating
- Analysis of converter topologies enabled by future semiconductor technology

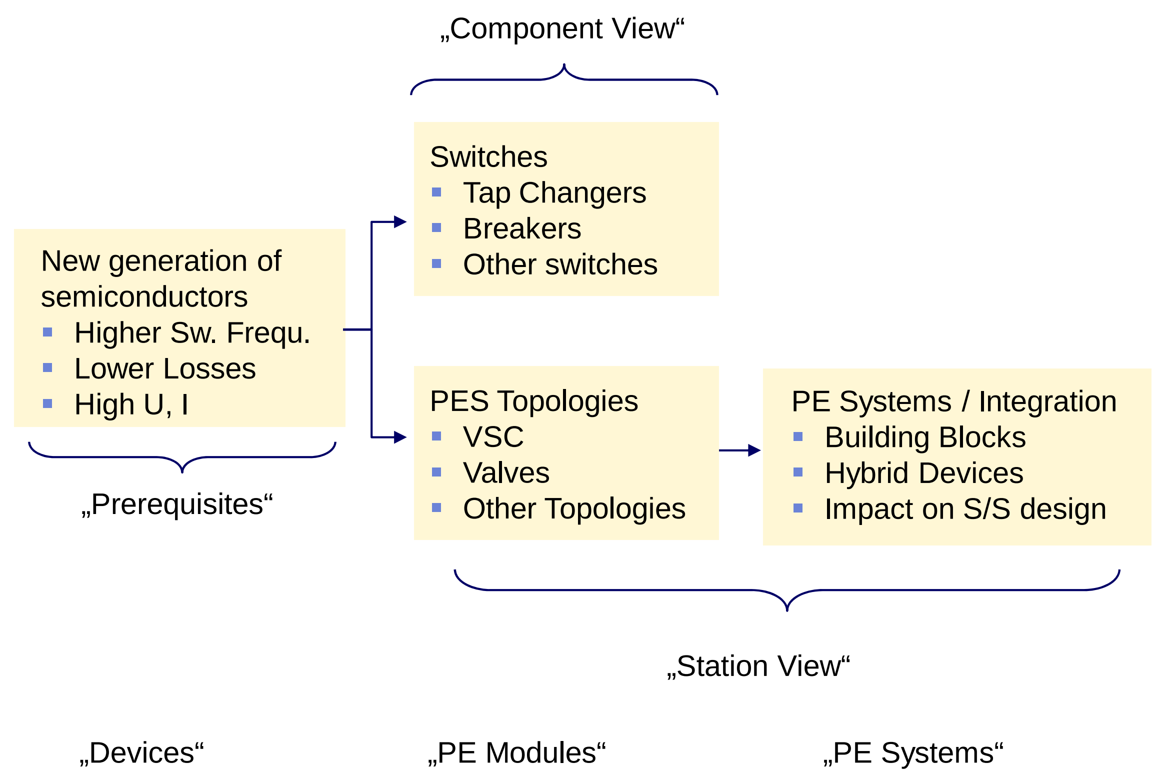


Figure 1-4: Overview on four step approach guiding this report

Based on this result future device ratings and topologies can be projected. Since new generations of semiconductors are considered to be "enablers" for more modularized power electronic systems potential application concepts will be described in the context of power electronic building blocks in a third step.

The application of the next generation of power electronic systems might lead to completely new device concepts. All of them need to be integrated into either existing or new substations to provide certain functionality. In the last step the impact of new power electronic system based functionalities on substation design is considered.

2 New generations of power semiconductors – general trends

Generally, high power semiconductors can be classified in diodes and switches i.e. controllable devices. The switches can be subdivided into devices without turn-off capability (thyristors) and on the other hand with turn off capability. Current-sourced converters require switches with symmetric blocking capability whereas voltage-sourced converters require switches with reverse conducting capability, with no requirement for reverse blocking.

2.1 Devices without turn-off capability

Based on the experience of the last years the total market for high-power devices without turn off capability seems to be stable. Nevertheless a shift can be seen in applications and in technical requirements of the devices within the market.

2.1.1 Diodes

Rectifier diodes

Rectifier diodes are mostly used as uncontrolled rectifiers for converters. Because of the big demand of low power converters the demand of diode modules is very high and still increasing. Concerning higher power ratings press pack diodes are available on the market up to four inch pellet diameter, 9kV blocking capability and more than 4kA average current. The market of rectifier diodes for high power applications is stable. One trend in these devices is a development towards higher blocking voltages. This can be achieved by higher blocking capability of the silicon wafer of more than 10kV. Another trend targets towards bigger diameters to reduce the number of parallel connected devices in galvanic applications. In addition there is a small demand for high power rectifier diodes used as anti-parallel devices (protection of dc capacitor against undesired voltage) for crow bars in voltage source converters and pulsed power applications.

Freewheeling diodes

The introduction of fast power switches such as IGBTs or hard-driven GTOs results in switching transitions at high di/dt and dv/dt values requiring freewheeling diodes with soft recovery behavior and low recovery losses. This finally led to the development of improved designs for fast freewheeling diodes in order to prevent limitations of the whole system’s overall performance. It is well known that the most efficient concept of an improved diode performance is controlled by on-state excess carrier distribution in the device using electron irradiation and implanting techniques. Driven by the growing market for inverters, there are several companies that offer many different freewheeling diodes for the different applications. Current and future developments of freewheeling diodes are driven by the switching and blocking capabilities of new switching devices. Some further incremental improvements can be expected.

Snubber diodes

Snubber diodes are mainly used in applications with GTOs, or with IGBTs in series connected stacks. The technical requirements of these kinds of devices (essentially hard commutation) have not changed over the last years. A high demand of these diodes lasts longer than was expected a few years ago, because converters with GTOs are still built in high quantities.

2.1.2 Thyristors

Electrical triggered thyristor (ETT)

In 1960 the development of SCRs (silicon controlled rectifier) was started; since that time many development steps followed. The main aim of the developments was the desire of increasing the blocking voltage and the current capability of the devices. Silicon material developments, fabrication process development, improved package design and improved emitter designs have all led to superior performance and higher voltage. Also improvements concerning trade off between on-state and turn-off parameters have been achieved due to the introduction of charge carrier life time adjustment by electron irradiation. ETTs have been produced in small quantities for experimental or demonstrator applications with blocking voltages of up to 12kV and diameters of up to 6 inches; however, for a few years, the maximum repetitive blocking voltage commercially available has been about 8kV, with a wafer diameter of 5 inches. Significant markets exist for large drives, electrochemical rectifiers and special power supplies, but the biggest markets for ETTs are HVDC and FACTS. Here thyristors with high blocking capability are used in the rectifier and the inverter to reduce the number of series connected devices. Because of the large active area of the silicon wafer, the surge current capability and low on-state voltages (resulting in low total losses in line frequency applications), thyristors are the benchmark for semiconductor device with turn-on capability. Some further adaptations like further improvements of trade-offs, reduction of electrical parameters and the introduction of alternative life-time-control measures (such as ion-implantation) are seen in future developments of these devices.

Light triggered thyristors (LTT)

LTTs are directly turned-on through a light pulse applied to the first stage of an amplifying gate structure. The only difference between an ETT and LTT is the gate design of the two types of thyristors. In the case of an ETT the thyristor is triggered by an electrical pulse applied to the gate. Direct light triggered devices were developed for HVDC applications. Since 1970, many semiconductor manufacturers have developed direct light triggered thyristors. However, the numbers of such devices commercially available today is limited. Driven by the HVDC application, a Voltage Breakover (VBO) protection has been designed into LTTs (also called **B**reak **O**ver **D**iode). The BoD triggers the LTT if the voltage is getting too high in forward direction. By using LTTs with integrated protection functions the number of external electronics assigned to the thyristors is reduced and accordingly, the reliability of the converter can be increased. In principle, it is also possible to design the forward recovery protection (FRP) function into an LTT. Such a device would give a further reduction in the complexity of external electronics required for an HVDC application. Several manufacturers have produced LTTs with in-built VBO and FRP for demonstrator applications, but these require many more processing steps than even LTTs with VBO only, and it is not clear whether such thyristors can ever be truly economic.

Besides the HVDC application, further applications are FACTS, medium voltage drives and pulsed power. Especially in applications requiring high valve voltages with many devices stacked in series connection, essential advantages are offered by LTTs.

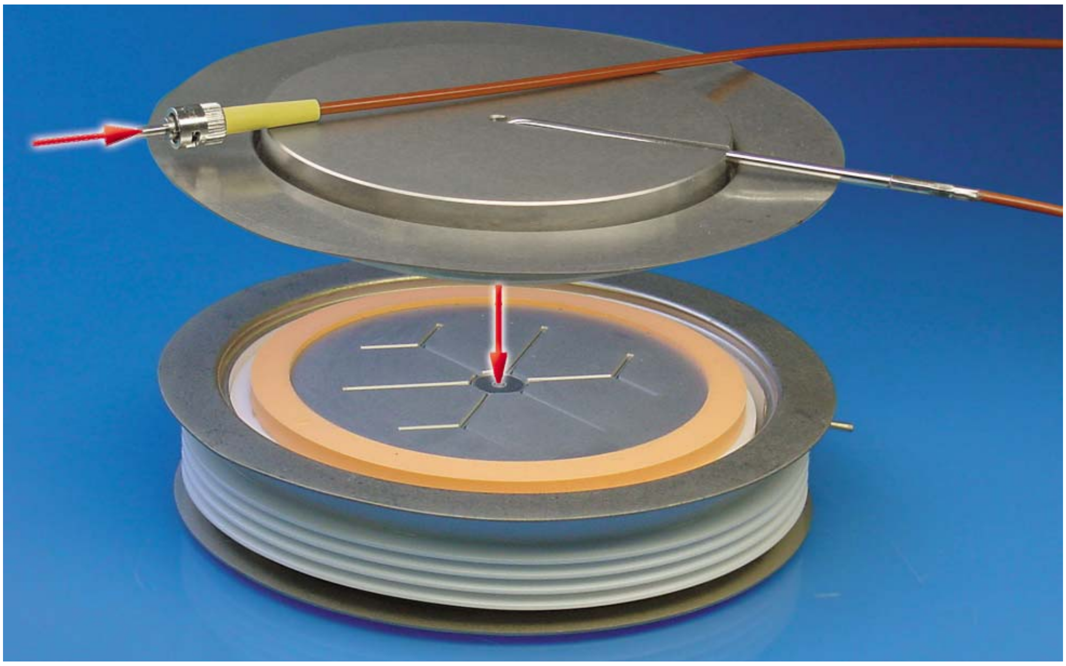


Figure 2-1: Picture of a light triggered thyristor [5]

Bi-directional thyristors

Bi-directional thyristors were developed for AC applications, where usually two thyristors in anti-parallel connection are used. In this kind of device, two thyristors are designed into one wafer achieving a symmetric blocking bidirectional switch. The active area for current transport in one direction is about half of the wafer area, which limits the current capability. Two gates are designed into the device, each one assigned to one thyristor for each current direction. Using this device for AC switches the number of heat sinks and mechanical equipment for clamping can be reduced. Bidirectional thyristors are available on the market up to 5 inch pellet diameter and blocking voltages of 6.5kV.

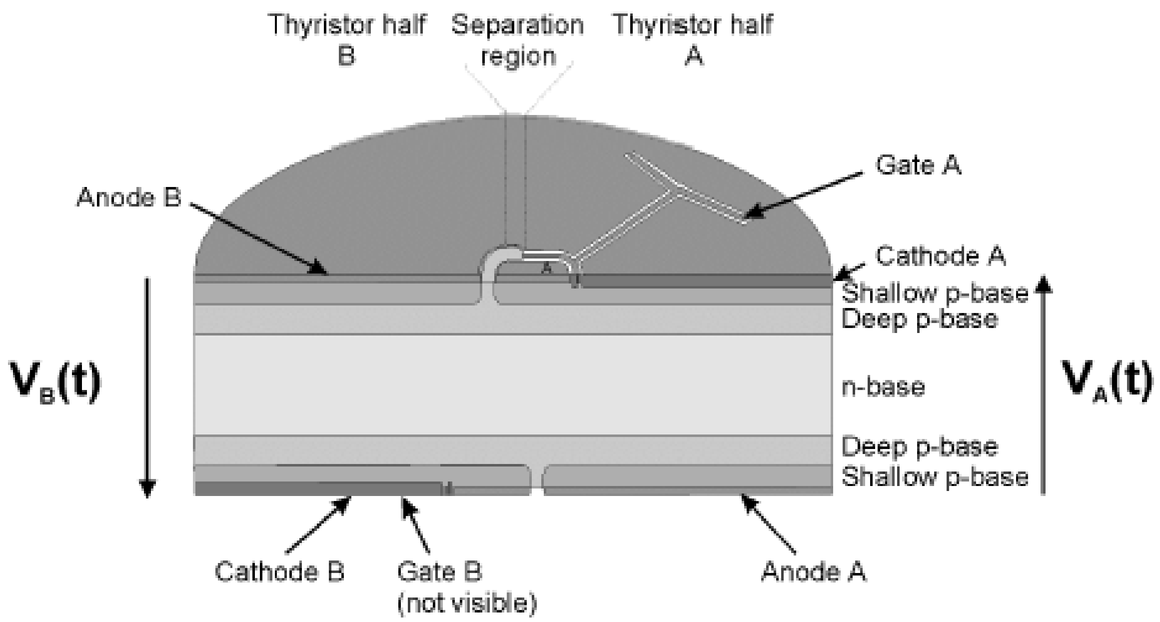


Figure 2-2: Cross-section Bi-directional Thyristor [6]

2.2 Devices with turn-off capability

2.2.1 GTOs and IGCTs

The GTO can be turned off by a strong gate pulse, with a typical turn-off current gain of 3-5. During turn off the dv/dt has to be limited by a RCD (rectifier, capacitor, diode) snubber. During turn on the di/dt has also to be limited. In addition, most GTOs are asymmetric and have no reverse blocking capability; hence they require an anti-parallel freewheeling diode. Although a lot of converters are still built today, especially in traction, there are no new developments of these converters with GTOs. Therefore, no big developments were made based on GTO technology, recently. In the future GTOs will be replaced by IGBTs and IGCTs, depending on the application. Only a few suppliers of the devices are left on the market. GTOs are also in use in pulsed power applications with high currents and di/dts.

The GCT (Gate Commutated Thyristor) was developed out of the GTO-structures. The limitations of GTO switching were solved by designing the GCT, which differs from the GTO by having a turn-off current gain close to unity. This means that, at turn-off, virtually the whole load current is commutated into the gate circuit for a period of a few microseconds (hence the name “Gate Commutated”). To reach this goal, a very strong gate pulse with very high di/dt of the gate pulse has to be applied (up to 3000A/µs and higher). To achieve these high values, the inductance between the gate driver and the GCT has to be very low. This resulted in a new gate unit design.

Although GCTs have found only limited application, a further development, the IGCT (Integrated Gate Commutated Thyristor), has been quite successful. In contrast to the GCT, which still uses a separate gate drive connected via a lead, in the IGCT, a modified housing is used, allowing the gate drive circuit to be integrated very closely with the semiconductor device, achieving exceptionally low values of gate inductance.

Like the GTO, because GCTs and IGCT are asymmetrically blocking devices, a freewheeling diode is needed. In some IGCTs the freewheeling diode is integrated, but to achieve high current capability the diode has to be externally connected. This diode has to have a soft recovery turn-off behaviour. Blocking voltages up to 6.5kV are available on the market, IGCTs with 10kV are under development [7].

Figure 2-3: Picture of an IGCT [8]

2.2.2 Transistors

Bipolar transistors

Bipolar transistors are well known in consumer applications where low power transistors are used to amplify the current by factor 100 or more. In the 1980s, high power bipolar transistors were used in a few applications to amplify the current to be switched. But due to the low amplifying factor of 10-20 the bipolar transistor wasn't an appropriate device for high-power applications. Today, bipolar transistors are only used in very special applications, having been largely replaced by the IGBT. Only a few manufacturers of this kind of device are left on the market.

IGBTs

In the late 1980s Insulated Gate Bipolar Transistors, IGBTs, were introduced to the market. Since that time the world of power electronics, especially industrial drives, forces the development towards new IGBT-generations to reduce the losses and increase the efficiency. In contrast to high-power inverters using SCRs or GTOs as power switches, IGBT inverters are mainly meant to work at higher PWM frequencies. To operate the power stage at high PWM frequencies, the IGBT has to be switched as fast as possible to reduce the overall power loss and to increase the efficiency of the system. Especially as far as high-power inverters are concerned, high PWM frequencies cannot easily be realized because of the large mechanical set-up and the resulting stray inductance of the wiring. This stray inductance limits the switching speed of the IGBT due to several well-known effects. Nevertheless, to increase the PWM frequency, snubber networks which are connected to the IGBTs should reduce the maximum collector voltage and should keep the dv/dt and di/dt slopes within an acceptable limit. In IGBT inverters those snubber networks show disadvantages. They generate high power losses even in partial load operation of the inverter and the snubber resistor has to be cooled [9]. In order to lower the losses in different applications, developments of IGBTs in different variants were made in the last years (e.g. low saturation voltage, low switching losses).

The popularity of IGBTs in a wide range of industrial power conversion applications is a direct result of the technological advances that have been achieved. The development over the last years has made the IGBT a power switch with rugged switching characteristics, low losses, simple gate drive and the possibility to control the device at any time (turn off of short circuits). Improvements in the IGBT performance have generally been achieved by optimized surface patterns and optimized diffusion profiles. A significant performance advantage was obtained by employing trench gate cell structures for the IGBT combined with the field stop technology. The trench IGBT provides a low on-state voltage compared to conventional IGBTs. Very important is proper chip packaging including the following issues: Low inductance, low impedance, internal wiring yields, low on-state and switching losses. Furthermore, small thermal impedance between chips and base plate to guide the heat from the power chips is of high significance [10]. For most commercially available IGBTs, these challenges are solved by the "module" construction (figure 2-4).

Figure 2-4: Picture of IGBT IHV Module [5]

For high power inverters, IGBT modules are available on the market up to 6.5kV 600A and 1200//1700V 3600A. The current rating is realized by parallel switching of IGBT chips in the module. The trend for IGBT modules is to reduce the overall losses and hence reduce the size of IGBT modules. Also the method way of triggering should become easier and the complexity of the trigger board should be reduced.

Only a few types of IGBTs are built in press packs. These kinds of devices are mainly used in special applications like voltage sourced HVDC and Pulsed Power applications. For the last two years no big developments were carried out based on PPIs (Press Pack IGBTs). The max voltage for a standard PPI is 4.5kV. One supplier developed a housing especially for direct series connection (see Figure 2-5), whereas the clamping force of the stack is taken from the housing itself and thus the force is not applied to the chips. The contact to the chips is realized by springs, which guarantee a uniform contact pressure and the ability to short in case of a failure [11].

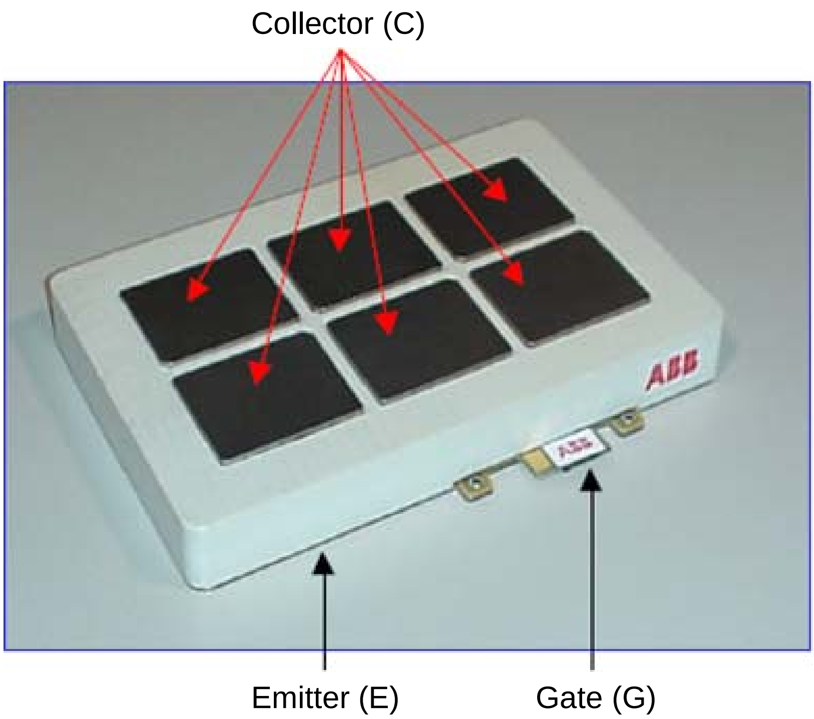


Figure 2-5: Picture of StakPak™ [14]

2.2.3 Advanced turn-off devices

Future advances in materials and devices will significantly reduce converter cost, size, weight, and losses. These advances include, thyristors with integrated gate technology, double-sided gates, bonded silicon, and optimized silicon design; leading to higher switching frequencies, higher controllable current capability, lower switching losses, and lower gate drive power etc. Some examples of future silicon based thyristors are:

- **The MOS Turn-off Thyristor (MTO)** uses transistors to bypass the gate-cathode junction to assist in turn-off. Compared to IGCTs, these devices have smaller gate drive as well as smaller gate drive losses. MTOs are an example of the further integration of gate drive with the device itself. However, MTOs have not been commercially introduced. These devices have the potential to be successfully deployed in medium to high power industrial and FACTS Controllers.
- **Emitter Turn-Off Thyristors (ETO)** are another variation on the GTO. They incorporate a very low voltage transistor (MOSFET) in series with a high voltage GTO along with another MOSFET to bypass the gate-cathode junction. Like MTOs, the ETO requires low gate drive power. Additionally, excessive anode currents cause partial GTO turn-off due to the voltage increase across the series MOS-

FET. This current limiting feature is useful for protection purposes. This device is in the research stage and has not yet been commercially introduced.

- **Super GTOs (SGTO)** are another GTO device which, like an IGBT, have a highly integrated gate-cathode structure. Also like IGBTs, they are made in small sizes (1-2 cm^2) on large wafers. For high power, several SGTOs are housed in a bonded silicon package. They require low gate drive power due to further integration of gate drive circuitry into the device resulting in lower impedance. These devices are being commercially introduced in low voltage transfer switches and have the potential for achieving high power ratings in the future.
- **MOS Controlled Thyristors (MCT)** includes integrated MOS gate structures for both fast turn-on and turn-off. These devices are also made in small sizes (1-2 cm^2) and packaged like SGTOs. MCT devices have been commercially introduced for use in very fast turn-on applications.
- **Next Generation IGBT.** The Next generation IGBT devices are introducing light punch through (LPT) or soft punch through technology (SPT) up to the highest voltage levels (6500V) to further improve their characteristics. In lower voltage devices (up to 1700V) this concept will be often combined with trench technologies. All this improvements are aimed at achieving lower saturation voltage, lower turn-off switching loss, rugged SOA and reduced gate charge, which consequently requires lower driving power.

2.3 Mechanical construction, housing technology

Press pack

Generally, the press pack solution offers copper contacts which are used for current transport and heat transfer. The devices are usually clamped into a stack offering the possibility for easy direct series connection. In case of a failure of a device, a defined short circuit ensures a safe operation if redundant devices are designed in the converter. The press pack technology is divided into two technologies: using the free floating technology the silicon wafer is not joined to any other material which fixes the silicon mechanically. On both sides of the silicon wafer, plates of a material with nearly the same thermal expansion factor as silicon, (usually molybdenum), are in pressure contact with the wafer. Two edge-bevel technologies can be used with this process: the “double-positive” and “double-negative” bevels (see figure 2-6).

In the second technology, the silicon is bonded to a carrier-disk to fix it mechanically. This technique can give improvements in thermal impedance and surge-current capability; however, differential thermal expansion between the silicon and carrier disk must be allowed for.

The carrier-disk must have nearly the same temperature coefficient as silicon. The best and most economical material for this kind of process is molybdenum. There are two different ways of joining the silicon wafer to the molybdenum. The first is an alloying process by which the silicon wafer is joined to a molybdenum plate by high temperature and low pressure. The second process is a low temperature joining process where the silicon wafer is joined to the molybdenum plate by low temperature and high pressure. This kind of processing reduces the bow of the molybdenum which reduces the stress for big diameter silicon wafers. With this technology, the thyristor requires a “positive-negative” edge bevel (figure 2-6). Bonding technologies are currently applied only on the anode side of the silicon, but future developments may see similar techniques being applied on the cathode side as well.

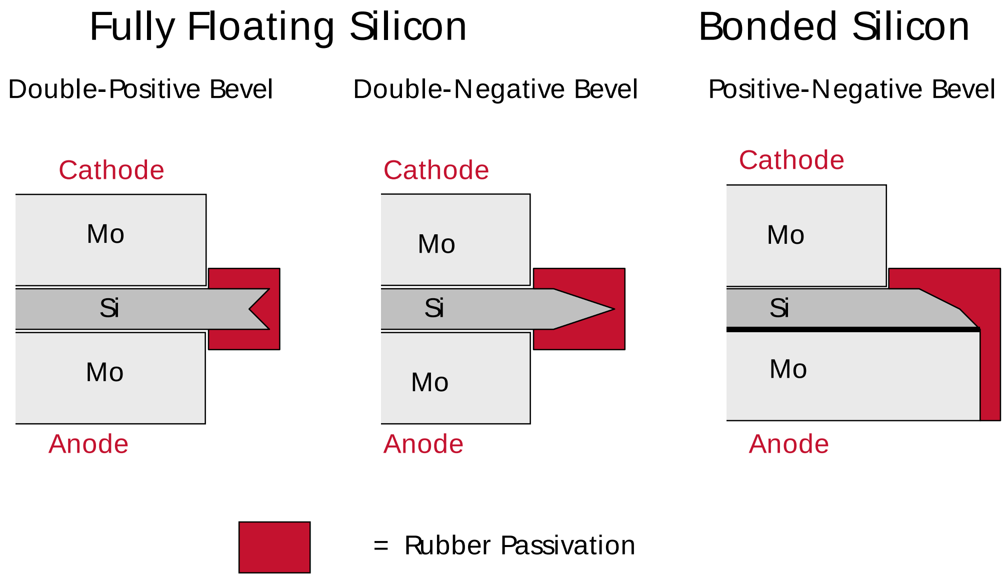


Figure 2-6: Drawing of free floating and joined silicon

Modules

The major difference between presspack and module construction is that the module is designed to be mounted onto a large, flat, heatsink at quite low clamping force. This makes it much easier to apply, although the low clamping force and the fact that only single-side cooling are possible, can reduce the efficiency of cooling. Another major advantage of the module technology is its flexibility. In contrast to the presspack, which generally only contains a single switching device, a module can be configured as a single switching device, phase-leg, H-bridge, Graetz bridge, bi-directional switch, chopper or many other possibilities. The design has to consider different thermal expansion coefficients of different materials being used in IGBT modules.

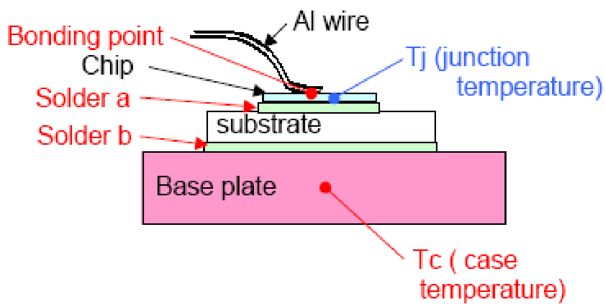


Figure 2-7: Drawing of IGBT chip

Thermal management is becoming increasingly important in power semiconductor applications as manufacturers and users attempt to extend the operating temperature ranges (upwards and downwards). These factors could become even more important in future as materials other than silicon are introduced.

Derivates

To reduce the customer's engineering costs and to increase the integration level of the supplier, parts like Skiip (Label of Semikron) and PrimeSTACK™ (Label of eupec) were developed. Such systems are also known as "Integrated power Modules" (IPM). With such modules, IGBTs in different layouts are integrated into a housing with a trigger board and with all sensors needed for current and voltage. The complete housing is connected to a heatsink. These modules are very easy to handle for the customers because the design of all components used is harmonized. Based on this feature, the need for these modules will go up in the future. By today such modules are available for different currents, voltages, and different layouts.

Figure 2-8: Picture of PrimeSTACK™

2.4 New developments

At this time, semiconductors of the highest power are made of silicon. Pure silicon is readily available on the market up to a diameter of 5 inches, although for special applications, wafers of 6 inch diameter are also available. The requirements of silicon for high power devices are much more demanding than the requirements of silicon needed for logic or memory production or similar devices.

Different semiconductor materials are under development. The biggest focus is on silicon carbide. Of interest are also Germanium, Gallium Nitride and Diamond, but only for very special applications.

Silicon carbide

Silicon carbide (SiC) is an emerging semiconductor material which is now finding widespread use in low-power applications in the automotive, telecommunications and opto-electronic sectors. The main research and development activities are focussed on these large-volume sectors. However, based on its exceptional physical properties, it has considerable potential for applications on the high-power/high frequency end of semiconductor devices. Replacing conventional silicon devices by SiC technology in the sector of electrical power distribution, for example, would reduce the electrical energy consumption by several percent. For this reason, there are considerable research and manufacturing activities worldwide in order to realize this potential. However, they are with few exceptions based on well-established procedures for crystal growth and semiconductor processing of SiC. Up to this time only small chip sizes of SiC are available on the market. The main reason for this is the damage of the SiC by “nano-tubes” during the production process. Once the production problems are solved, big chip sizes will possible, but then development of new production processes for diodes, thyristors, and IGBTs must be realized. And new housing technologies and materials must be developed, too. Resulting from this, the time needed for establishing SiC on the high-power market will be very long. Main advantages of SiC against Si are: Higher breakdown electrical field strength, higher thermal conductivity, larger band gap.

With respect to SiC devices suitable for power transmission applications discussions of both power devices and material defects in SiC wafers and epilayers are ongoing. Defects are the main issue. 1 kV is no problem to manufacture. 1 kA at > 1 kV is the main issue, especially if one needs reliable operation of devices with superior performance to silicon. There has been a laboratory breakthrough reported in SiC material quality that would make > 1 kA > 1 kV power devices much more probable [12].

Diamond

The major advantages of Silicon Carbide over silicon apply even more to diamond. Diamond has a much larger band-gap (5.5eV compared with 3.2eV for SiC and 1.1eV for Si) and exceptionally high thermal conductivity. Carrier mobilities are also considerably higher than either SiC or Si.

Small chips of diamond are now capable of being produced by Chemical Vapor Deposition (CVD). However, a major limitation to their use at present is that no suitable donor dopant has yet been identified. Bipolar devices are therefore not possible at present, although unipolar (Schottky) diodes have been produced as demonstrator components [13]. Because of the above limitations, diamond is likely to be many years from commercial application in high-power, high-voltage applications.

Intelligent Control and protection

The IGBT driver is the link between power electronics and control electronics. In this connection, the driver has more functions than turn-on and turn-off of a gate voltage. It has to cope with the complex switching behavior in combination with the required protection functions for IGBTs and deliver check back signals to the control unit. Especially with regard to applications in the medium and high power range further features like high noise immunity or special gate voltage waveforms are necessary. In some applications a supply of the gate unit from the emitter-cathode voltage has also to be realized. For the future the drivers for IGBTs will include more "intelligence" to ensure the best switching control for customers applications [20].

Figure 2-9: Picture of EiceDRIVER™ [5]

2.5 Conclusion and outlook

Because of the global demand of high power semiconductor, new developments based on new semiconductor materials (Silicon Carbide) will be made in the near future. Especially devices with small area demand (low power diodes and switching elements like JFETs) will be developed with new materials to lower the losses and improve the performance. Another challenge is the development of high temperature packages, in order to utilize the high temperature capability of some of these new devices.

One the other hand well-known devices, like high power diodes, SCRs, IGCTs, IGBTs etc. will have a fixed place in new high power applications. For these big area devices the change to new semiconductor materials will take longer because of challenges in fabrication of the semiconductor material (see also Figure 2-10).

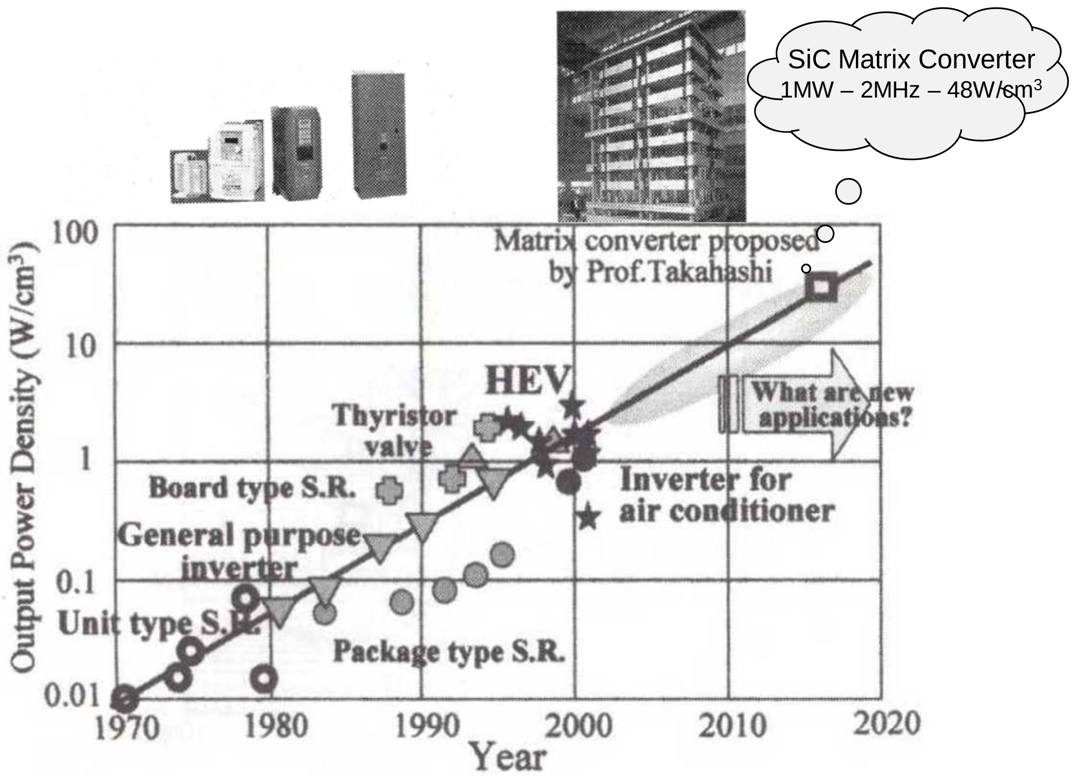


Figure 2-10: Progress in output power density of commercially available power electronics apparatuses over the past 30 years [21]

3 Conventional switching applications

3.1 Introduction

The aim of this chapter is gives the state of the art of power electronic switching equipment as direct alternatives for mechanical switches, including the work of other WG's, such as [3] and [4]. The content of this chapter is proposed as the following: Power electronic systems are applied in electric power distribution as well as transmission systems. The application requirements are however, different and therefore, the designs of the systems are different. In distribution systems, the objective is normally to improve the power quality. This includes reduction of voltage sags and swells as well as elimination of harmful harmonics and voltage flicker. In some cases it also involves ride-through of short outages.

The power electronic systems for distribution applications are sometimes referred to as custom power systems. In ac transmission systems, power electronic systems are used for voltage and transient stability enhancements and power flow control. These systems operate by controlling voltage, phase angle or the impedance of a line or a combination of two or more of these. Theses systems are often called FACTS systems since they enhance the flexibility of ac transmission systems to deal with unforeseen demands on key transmission systems often associated with system contingencies. However, in some long ac power transmission applications, the dynamic support provided by the power electronic systems might be needed to enable the transmission system to carry full load.

3.2 Transfer switches

There are a number of suppliers of sub-cycle transfer switches (STS) although to date not very many actual applications. An example of a transfer switch can be seen in Figure 3-2. The basis configurations are shown in Figure 3-1 and Figure 3-3 below.

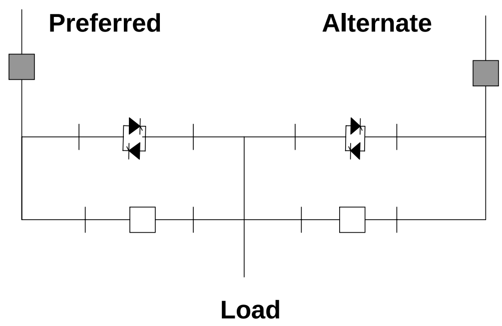


Figure 3-1: Preferred-alternate connections

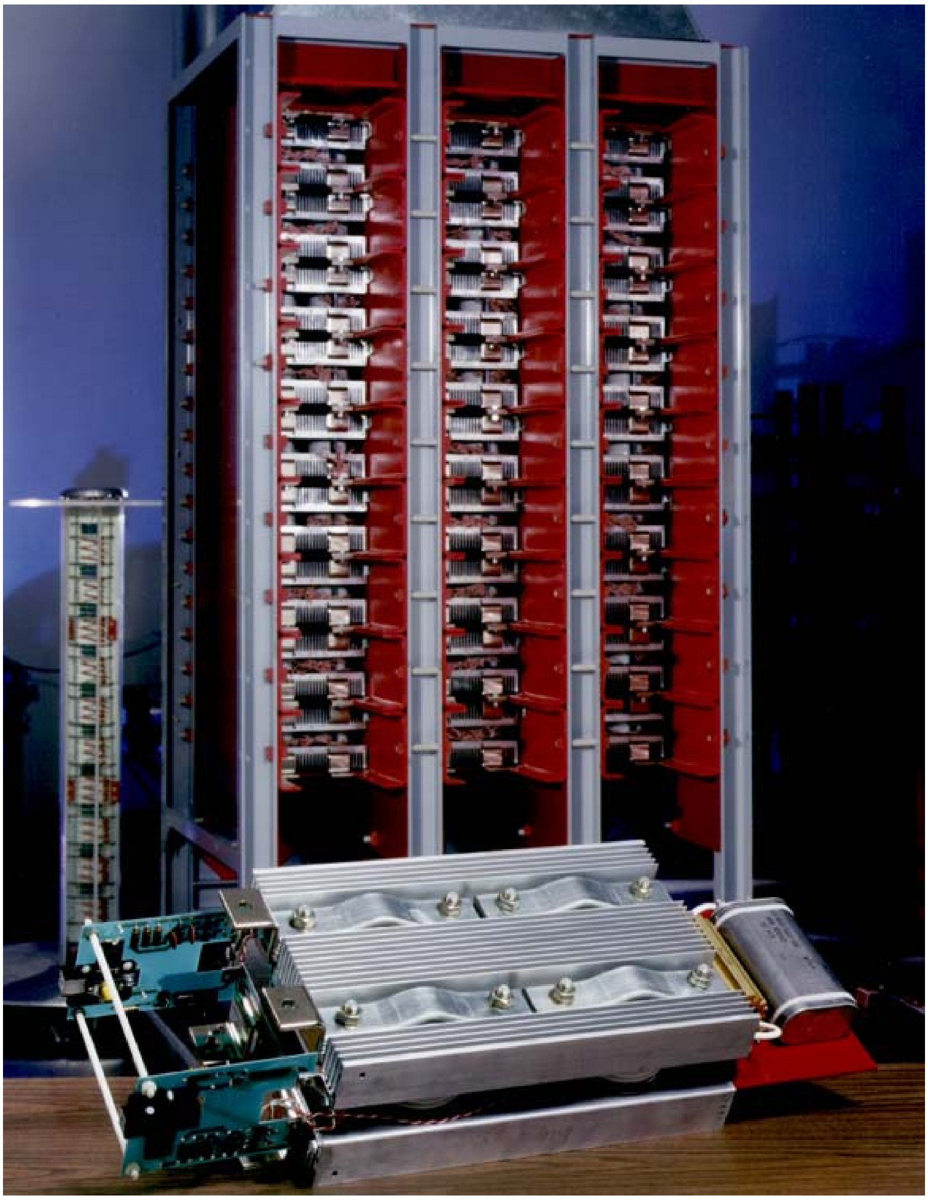


Figure 3-2: 15 kV transfer switch made by Silicon Power Corporation

In this configuration, the transfer to the alternate source takes place when the preferred source is disturbed and if the alternate source is available with normal voltage levels. Transfer back takes place when the preferred source has returned to normal. Typically, this transfer takes place with a time delay to ensure that the preferred source stays in service for some time before a transfer is allowed again. This is to ensure that typical trip-reclose sequences are completed prior to return to the preferred source. Otherwise, the load voltages would be disturbed repeatedly when the system closes into the fault again.

The STS part of the system is bypassed with conventional mechanical transfer switches. In this way, presumably until the technology is considered proven, the semiconductor switches can be taken out of service for maintenance and the system will then continue to function as a conventional transfer switch assembly. Disconnect switches are used to isolate the parts of the system to which access is required.

Transfer is prevented when there is a through fault. That is, a fault on the load side of the transfer switches. Through faults may cause the short circuit current to increase to the point at which the semiconductor device is no longer able to block the ac voltages. For this reason, there are breakers in the supply sides of the system, which will interrupt the fault current. In this way, the load side conventional fuses, protective relays and breakers can clear faults in the normal way. That is, no changes are required to the conventional requirement just because the transfer is fast. The semiconductor switches can be built to interrupt the fault currents, too. In that case, the devices must be rated for higher short circuit currents and the junction temperature of the devices must not be allowed to increase to the point where the devices are unable to block normal voltages. Another typical arrangement is the so-called split bus arrangement (Figure 3-3).

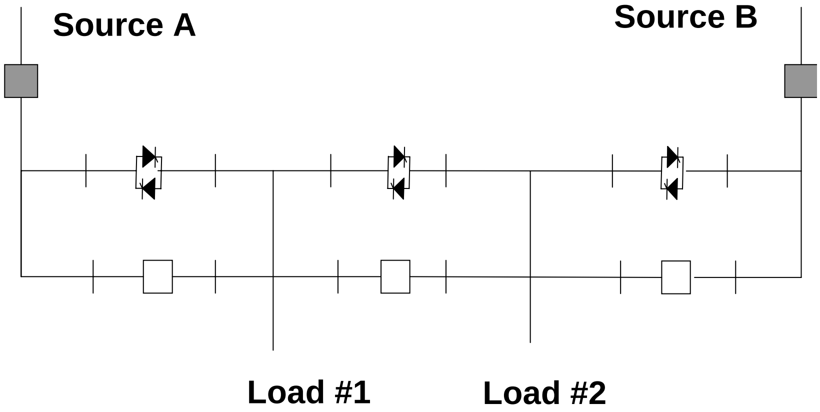


Figure 3-3: Single line representation of a split bus arrangement to serve to loads

The only difference is that there are two loads served from two different sources. In case one is disturbed, the transfer is made to the other source, which now feeds both loads. In other respects, the systems operate in much the same way as the one described above. Transfer switch applications are only feasible if at least one of the two sources is not significantly affected by a disturbance on the other source. Thus, the two sources must be electrically decoupled from each other. That is, transfer switches do not work if the predominant problem is to ride though transmissions system faults, in which case all distribution feeders in the same system are impacted by the same fault. Fortunately, many power supply disturbances involve only distribution the systems and are therefore relatively well isolated. Thus, transfer switches can work for a large number of possible disturbances and therefore, help to improve the availability of power.

Transfer from one source to another takes place sequentially. When thyristors are used in the switches, the semiconductors stop conduction first when there is a natural current zero. There could be a short interruption of the load before the alternate source switch is triggered. However, this is normally for a negligible short interval, which has no effect on the loads. When the first phase is transferred from the preferred to the alternate source, an unbalance arises in the ac system. Until the second and third phases are disconnected from the source, there is a path for unbalanced currents to circulate between the two sources. This is readily apparent by observing the zero sequence currents flowing in each source. If the transfer to the new source takes place before a current zero in the outgoing circuit, the two sources are connected together on the phase side. This can lead to fault currents flowing from the new source into the disturbed source. This situation is typically referred to as a loop though and is not a desirable state.

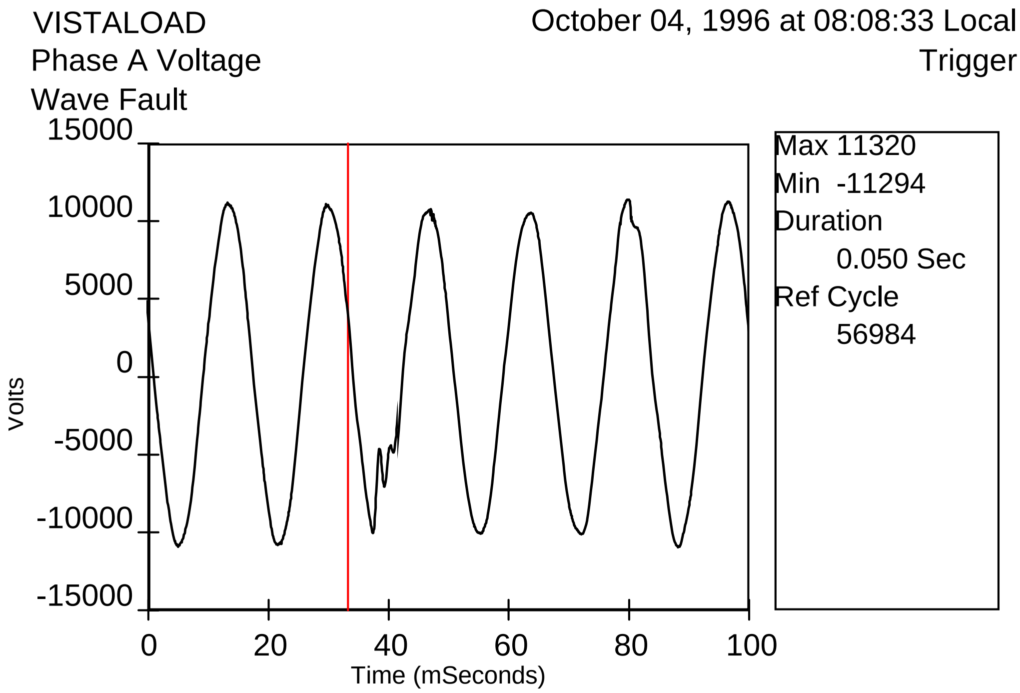


Figure 3-4: Load voltage during transfer of load from preferred to alternate source.

Transfers in the sub-cycle range are not well understood. However, one early finding is that motor loads will maintain voltage at the load bus for some time after interruption of the source. This is positive because it means that transfers do not have to be completed extremely fast. However, it also means that current reversals take place with power fed from the load side into the disturbed source. Functional testing of the switches must take this into account. Very small loads can be a problem, too. Thyristors normally require a substantial load current to latch so that they will stay conducting if the gate pulse is removed. Therefore, continuous gate pulses are required to prevent thyristors from switching off when the load current is small. A typical transfer is shown in Figure 3-4. As can be seen in the figure, there is a small delay in the transfer of source. This is necessary to allow for detection of the disturbance and then a transfer at the first current zero.

A through fault, that is a fault on or beyond the bus to which the transfer switches are connected, must be dealt with to enable normally applied short circuit protections to operate. In response to a short circuit, the transfer to the alternate source is inhibited. In some systems the thyristors are not fused to allow for fast removal of the short circuit. This is possible if the junction temperature in the thyristors does not rise above a level where the devices are damaged.

The thyristors in these systems cannot be blocked since the blocking voltage of the devices is significantly reduced at high junction temperatures. However, this is acceptable since the fault current is reduced to normal load current levels after the short circuit is removed allowing the devices to recover their blocking capability after a sufficient cool down period. The alternative where fussed semiconductor devices are used is to provide a mechanical bypass switch to re-energize the bus to enable the short circuit to be removed the unfaulted power system to be restored to service. This prolongs the disturbance.

3.3 Solid state breakers

GTO or IGBT -based semiconductor switches are capable of being turned-off by means of gate control and can therefore be used to interrupt an ac current before a natural current zero. However, if this is done in an inductive circuit, it can lead to high transient recovery voltages, which could damage the semiconductors if not controlled. These overvoltages are normally controlled using arresters or other overvoltage limitation techniques. Also, a fast interruption of a short circuit current prevents the normally applied fuses, and protective relaying systems for operating. Therefore, since these devices have limited overcurrent capabilities, means to enable conventional fuses and other fault isolation equipment or systems to operate must be included in the switch. This can be done by means of a parallel thyristor switch or a parallel mechanical switch, which is used to close into the fault after the GTO or IGBT switch, has stopped conducting.

3.4 Fault current limiters

A number of systems have been proposed for limiting the fault current in a network by inserting an appropriate impedance (resistive or inductive) in series with the fault path. Most such systems are based on passive components, and Superconducting Fault limiters have been proposed, but these are outside the scope of this report.

Fast semiconductor switches can be used to insert a fault limiting impedance very rapidly into the network when a fault is detected. Two types of such semiconductor fault limiter are briefly described below. The first type, described in [24] uses a GTO switch in parallel with a fault limiting impedance. The GTO switch is normally ON (ie the load current flows through the switch) but on detection of a fault, it turns OFF, forcing the fault current to flow through the parallel impedance (see Figure 3-5). The GTOs may require both series and reverse parallel diodes to protect them from reverse voltage. In addition, a non linear resistor (surge arrester) may need to be connected in parallel with the switch to limit the transient voltages occurring as the switch turns OFF. An advantage of this type of device is that the semiconductors do not need to be rated for the fault current. A disadvantage is the power losses occurring in steady state.

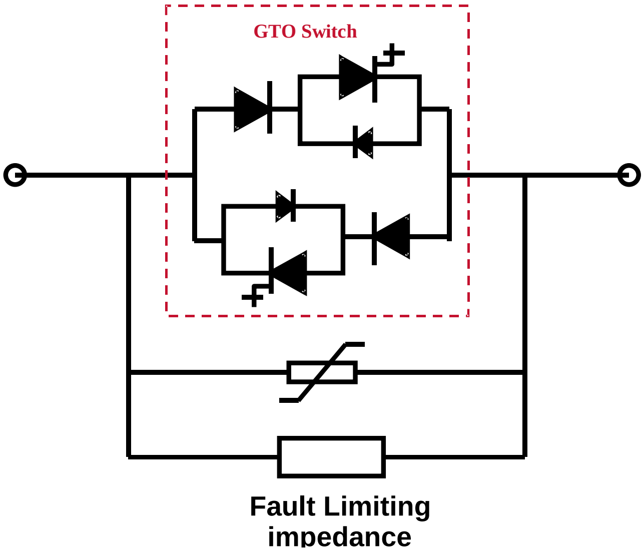


Figure 3-5: Fault current limiter based on GTOs (normally ON)

The second type, as described in [22] could be considered to be a variant of the Thyristor Switched Series Capacitor (TCSC). It consists of a series combination of a capacitor bank and a reactor, in series with the transmission line. The LC circuit is tuned to fundamental frequency so that, under normal operating conditions, it introduces negligible impedance into the circuit.

A back to back thyristor switch is connected in parallel with the capacitor (Figure 3-6). The thyristor switch is normally OFF, but on detection of a fault is turned ON. In doing so, the capacitor bank is shorted out so that the main current path is through the reactor only, which then becomes the fault limiting reactor (see also [23]). This type of circuit has the advantage that the thyristor switch does not incur conduction losses in normal steady-state operation. However, the thyristor switch does need to be dimensioned for a high value of short-circuit current (from the network) and di/dt (from the capacitor bank, at the instant of switching). In principle a second, smaller reactor could be connected in series with the thyristor switch to assist in achieving these ratings.

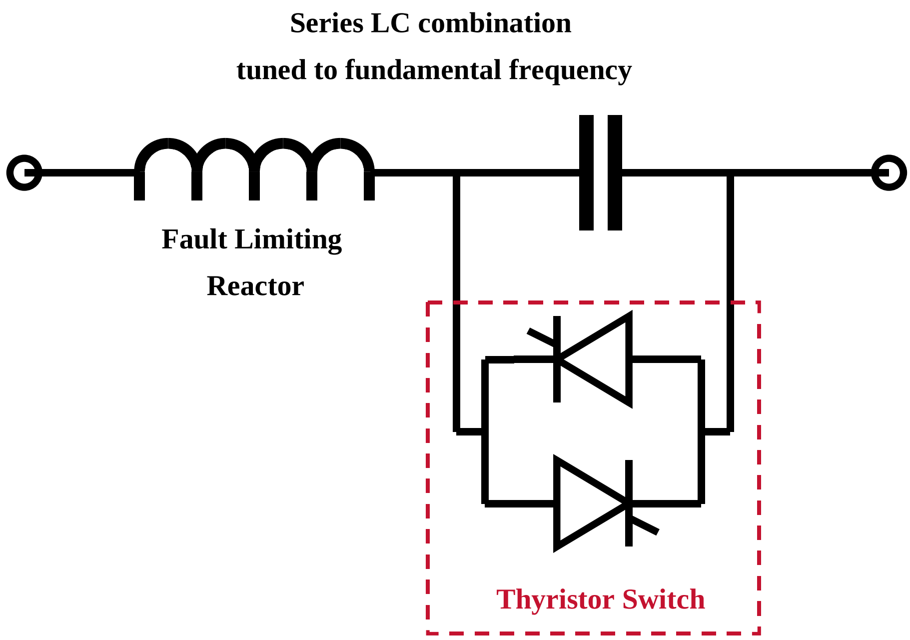


Figure 3-6: Fault current limiter based on thyristors (normally OFF) – this is expected to become the most probable application in the future

3.5 On load tap changers

On-load tap changers in power transformers are important for the proper operation of modern power systems, because they allow voltage levels to be adjusted to desired levels despite changes in load and generation dispatch. Although a mature technology, the conventional oil-immersed OLTC does have disadvantages that could be solved using power electronic switches.

- The tap changer operation, though adequate for normal steady state voltage regulation, is relatively slow. The speed of the diverter switch is in the range of 50-100ms, but the tap selector switch is slower and could take minutes to traverse the full tap range.
- Commutation of the current in the diverter is done by extinguishing an arc under oil. This leads to wear and erosion of the contacts, and contamination of the oil. Regular maintenance of oil immersed OLTCs is, therefore, needed. This is also a major cause of power transformer failures.

Several approaches to an OLTC with power electronic switches have been suggested, and some have been tested and used in practice.

Substitution of all mechanical switches with thyristors

This is discussed in detail in the final paper of Cigré WG B4-35 entitled "Thyristor Controlled Voltage Regulators". In that paper, several problems for such a device are highlighted, together with some possible solutions. These problems are:

- Because thyristors are line commutated devices, there may be problems commutating the thyristors on either the incoming or outgoing tap. Solutions to this problem are proposed in the paper, but all seem to be at the expense of technical performance.
- The losses in thyristors are very high compared to mechanical switches
- Using currently available thyristors, many devices are required for a typical application, and the tap changer would be large and costly.
- The optimal location of a thyristor tap-changer may be different to a mechanical tap-changer. Thus, a retrofit thyristor tap-changer may not be viable.
- There has been some concern over the fault current rating of thyristors for tap changer applications, but it is concluded that this is a result of unrealistic testing requirements. Thus, this is not really a problem.

The paper concludes: "*an all-static thyristor OLTC in which thyristors replace mechanical contacts of the conventional OLTC is not a viable practical proposition.*"

Hybrid tap-changer

This is also discussed in detail in the final paper of Cigré WG B4-35. Essentially, the hybrid tap-changer has a mechanical tap-selector, and a power electronic diverter switch. Several variants are presented, in broadly the following categories:

- thyristor diverter with transition resistors
- thyristor diverter without transition resistors
- GTO or IGBT diverter

The paper concludes that: "*hybrid OLTCs, thyristor assisted or GTO assisted, fail to live up to the promise of significant improvement in the speed of operation from static switching*."

Thyristor assisted diverter switch

This concept is presented in a 2002 IEEE paper entitled “A Novel Thyristor Assisted Diverter Switch for On Load Transformer Tap Changer”. It uses a mechanical tap selector and diverter, but replaces the transition resistors with thyristor valves. Commutation from one valve to the other is at the same current zero, so no interruption of current and no short-circuiting of tap windings occurs.

Aside from eliminating arcing in the diverter switch, this device seems to offer no performance advantage over a conventional OLTC. However, savings in maintenance and improvements in transformer reliability may make the device attractive.

Fully Static Tap-Changer with thyristors

This is a commercially available device by ABB, that has been discussed in several papers. The primary application seems to be voltage dip mitigation, and not precise voltage control.

The first installation was a single-phase device installed in the 16.5kV, 16 2/3Hz. system of Norwegian State Railways in 1986. The unit operated without problems, and in 1996, a three phase version of the device was put on the market, but there are no units in commercial operation. This is probably due to the price of the unit.

In concept, the device utilizes a small number of tap windings, with two thyristor valves per switched winding. One valve is in series to insert the winding and the other is in parallel to bypass the winding. Successful commutation between the series and parallel connected valves is achieved by installing an L-C circuit across the valves, and delayed deblocking of the incoming valves the turn-off time of the outgoing valves has expired.

Fully Static Tap-Changer with IGBTs

This concept was presented in a paper entitled “Electronic Tap Changer for 10 kV Distribution Transformer.” Like the previous device, this OLTC also uses a small number of tap windings, but precise voltage control is achieved with pulse width modulation (PWM). The test device in a 10 kV distribution transformer uses IGBTs, with a thyristor crowbar to protect the IGBTs against overcurrents. It remains to be seen whether this concept will be widely applied.

3.6 Conclusion

As long as the speed of power semiconductor based switching is not needed for a certain application even higher ratings and lower losses will not enable a widespread application of power semiconductors for conventional switching applications. The main reasons for this result from reliability and acceptance issues. Without a general shift in design paradigm, conventional switching applications without high speed switching requirements (e.g. short circuit current limiters) will be built with mechanical switches. There might be an increased application of semiconductor switches for applications like short circuit current limiters or other applications, where semiconductors do not determine the reliability of the entire device in normal operation mode – i.e. semiconductors are not in the current path.

4 Ratings and topologies of power electronic systems

4.1 Introduction

Based on application areas this chapter provides an overview on typical converter topologies used for network controllers for AC grids. Here, the focus lies on the topologies. More detailed information on application areas can be found in [20] - [27]. The second part of this chapter outlines actual developments in converter technology, which might become commercial applications with the increased system efficiency by means of new power semiconductor generations.

4.2 State of the art converter topologies

4.2.1 Topologies for distribution system applications

There are two basic types of equipment [32]:

- **Switchgear**: Transfer Switches, Solid State Breakers and Fault Current Limiters
- **Power Conditioners**: Shunt-connected Conditioners and Series-connected Conditioners. They are typically based on passive components (reactors, capacitors), line-commutated thyristors in case of SVC (Static Var Compensator) or on self-commutated IGBT- or GTO / IGCT-converters. SVC technology for reactive power compensation, voltage control and flicker compensation will be described in more detail in the following chapters.

This remaining part of this chapter will focus on Power Conditioning Equipment, since Switchgear Equipment is treated by a separate Task Force. A detailed description of Power Electronics Applications for Power Quality Improvement can be found in [33].

Power Conditioners in General

As shown in Figure 4-1 shunt- and series-connected Conditioners are typically applied for separate tasks in low-voltage or medium voltage networks:

- Shunt-connected Conditioners are mainly used for compensation of unwanted load current portions (active filter or reactive power compensation / power factor correction). Note: in case of reactive power compensation (power factor correction) or flicker compensation SVC-technology is widely used. SVCs are not depicted in the Figures. For harmonic current filtering and power factor correction passive filters and capacitor banks are often used. They are typically subdivided in separate units which are switched to the network by mechanical or power electronic switches (thyristors) depending on the required speed and frequency of operation.

- Series-connected Conditioners are typically applied when sensitive loads have to be protected against voltage sags originating in the up-stream distribution or transmission system.

Of course, series/shunt combinations are also possible although seldom used, since at the location of interest typically only one control task, such as voltage sag compensation, is needed. The remaining part of the chapter will focus on Power Conditioners based on Voltage-Sourced Converters (VSC), since they allow the design of most versatile equipment for improving the operation of distribution systems and will therefore probably be of major importance in the future.

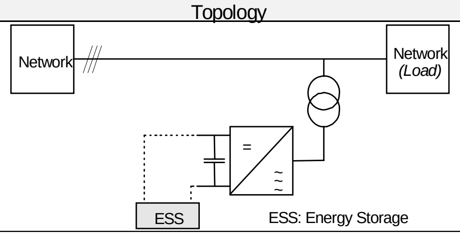
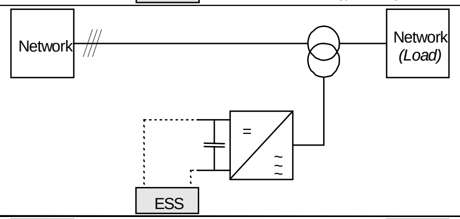
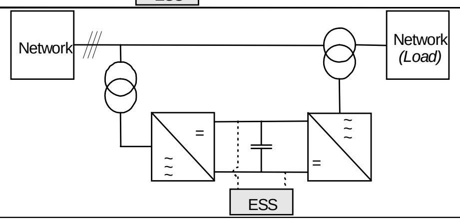
Name	Topology	Preferred Tasks: Transmission	Preferred Tasks: Distribution
STATCOM (DSTATCOM) Static Synchronous Compensator		• voltage control • oscillation damping • reactive power regulation	• flicker compensation • reactive power compensation • harmonic filter
S³C (DVR) Static Synchronous Series Compensator (Dynamic Voltage Restorer)		• power flow • transient stability • oscillation damping	• sag / swell compensation
UPFC (DVR) Unified Power Flow Controller		• power flow • transient stability • oscillation damping • voltage control	• sag / swell compensation • undervoltage / overvoltage compensation

Figure 4-1: Overview of VSC-based FACTS Controllers for Transmission and Distribution Systems

Figure 4-3 to Figure 4-7 explains the working principle of VSCs by illustrating the simplest type of VSC, the two-level inverter. The term “two-level” arises from the fact that each phase leg can produce an output voltage of only two values: +Vdc/2 and –Vdc/2 (Note however that when connected in a bridge arrangement such as a single-phase “H” bridge or three-phase “Graetz” bridge, the line to line output voltage of a two-level inverter has three possible levels: +Vdc, 0 and –Vdc). By applying PWM (Pulse Width Modulation) the VSC functions like a controlled three-phase voltage source similar as a synchronous machine.

A VSC can operate in all 4 quadrants of the P/Q-diagram and can exchange active and reactive power with the network independently (Figure 4-8). Depending on the switching frequency high frequency voltage portions can be superimposed. This is used in so-called Active Filters for example. More detailed explanations on Power Electronics are given in [34].

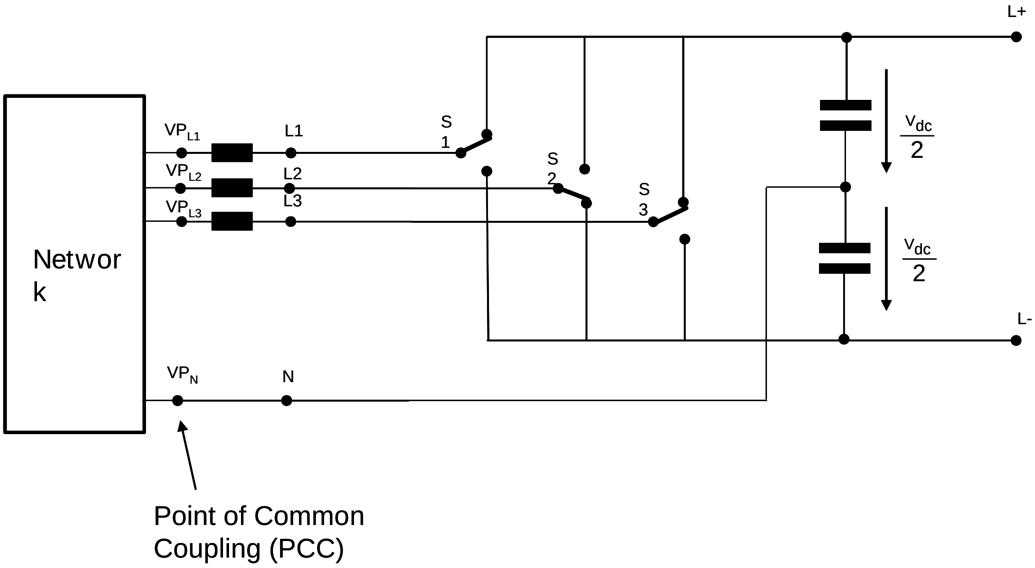


Figure 4-2: Working principle of Voltage-Sourced Converter (VSC): Two-level converter with switches

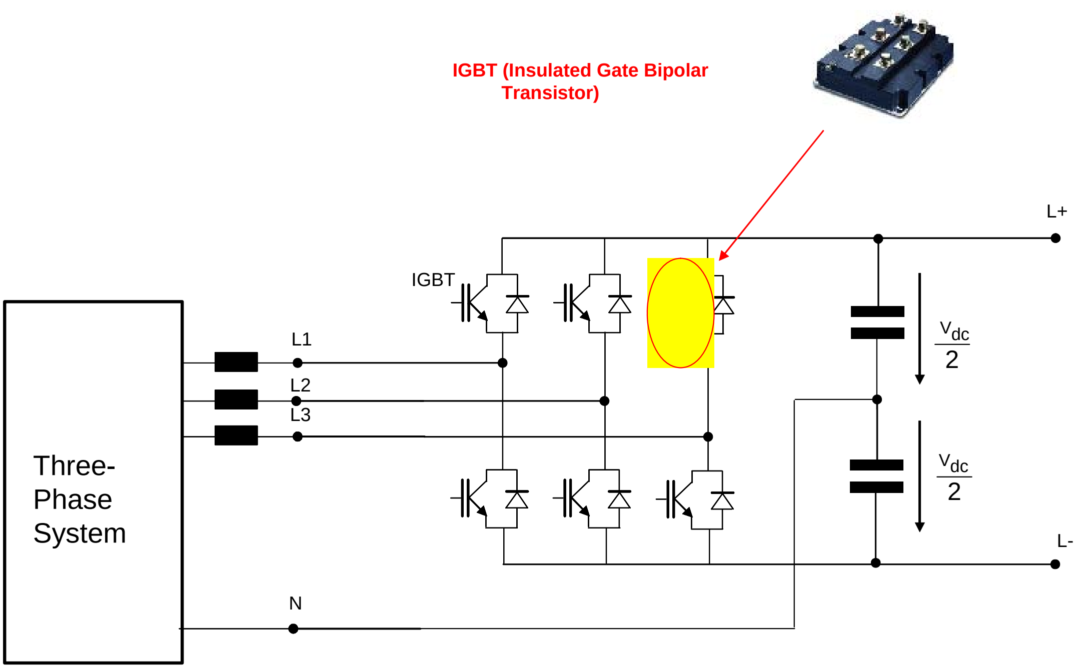


Figure 4-3: Working principle of Voltage-Sourced Converter (VSC): Three-phase, two-level converter with IGBTS as switches

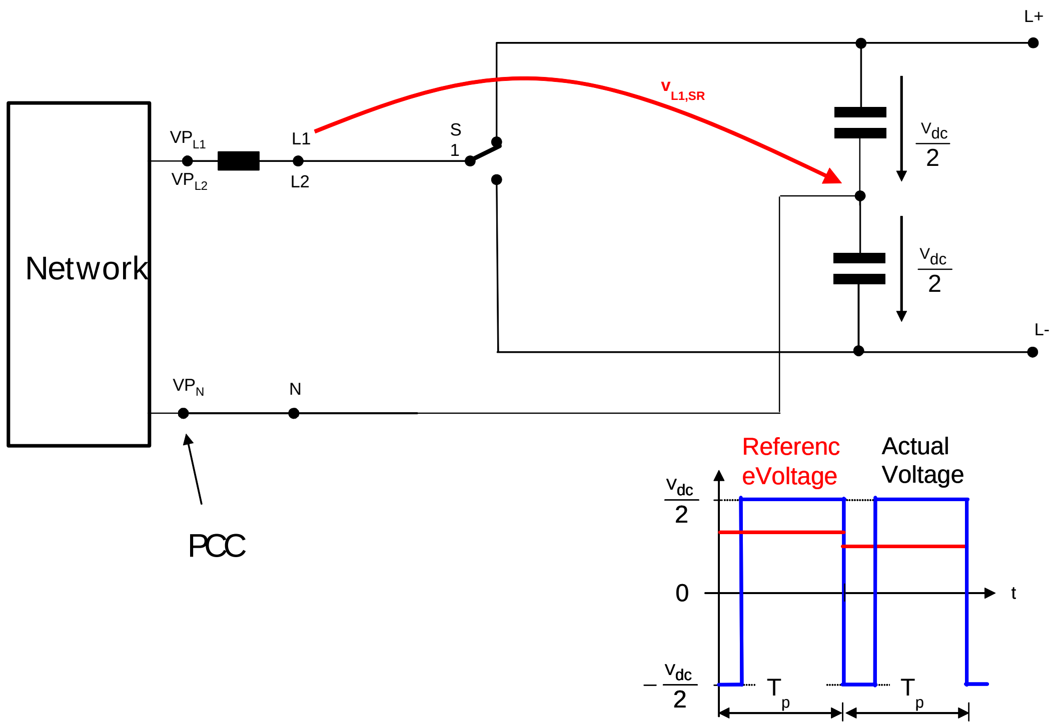


Figure 4-4: Working principle of Voltage-Sourced Converter (VSC): Two-level converter in single phase representation

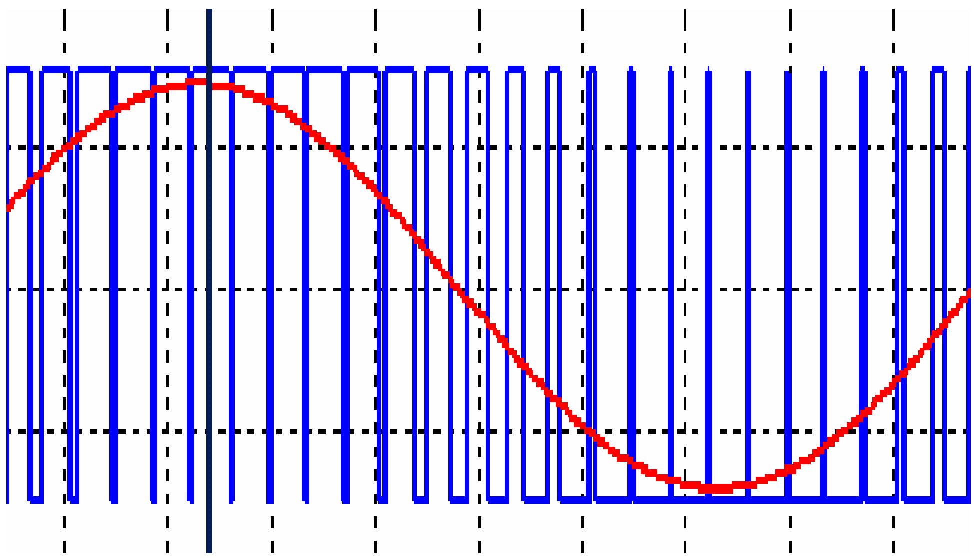


Figure 4-5: Working principle of Voltage-Sourced Converter (VSC): approximation of desired AC output voltage (red curve) via PWM

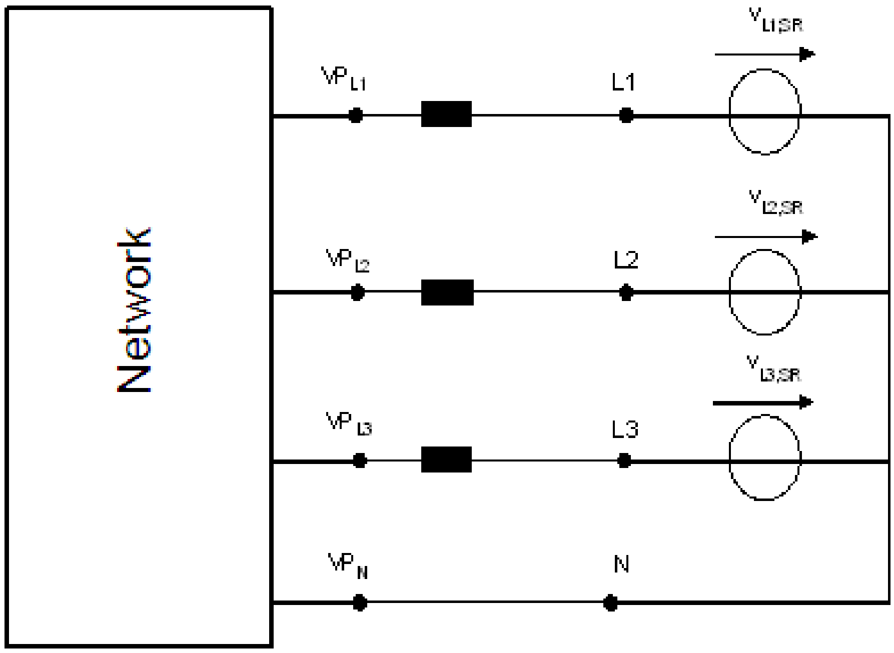


Figure 4-6: Working principle of Voltage-Sourced Converter (VSC): modeling of VSC by voltage source

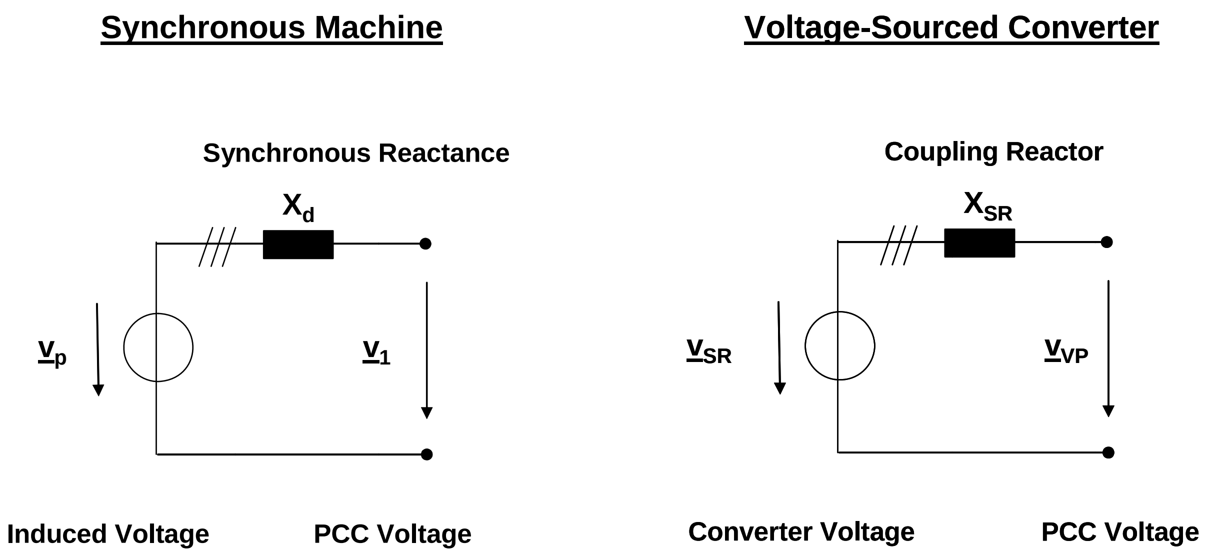


Figure 4-7: Working principle of Voltage-Sourced Converter (VSC): comparison to synchronous machine

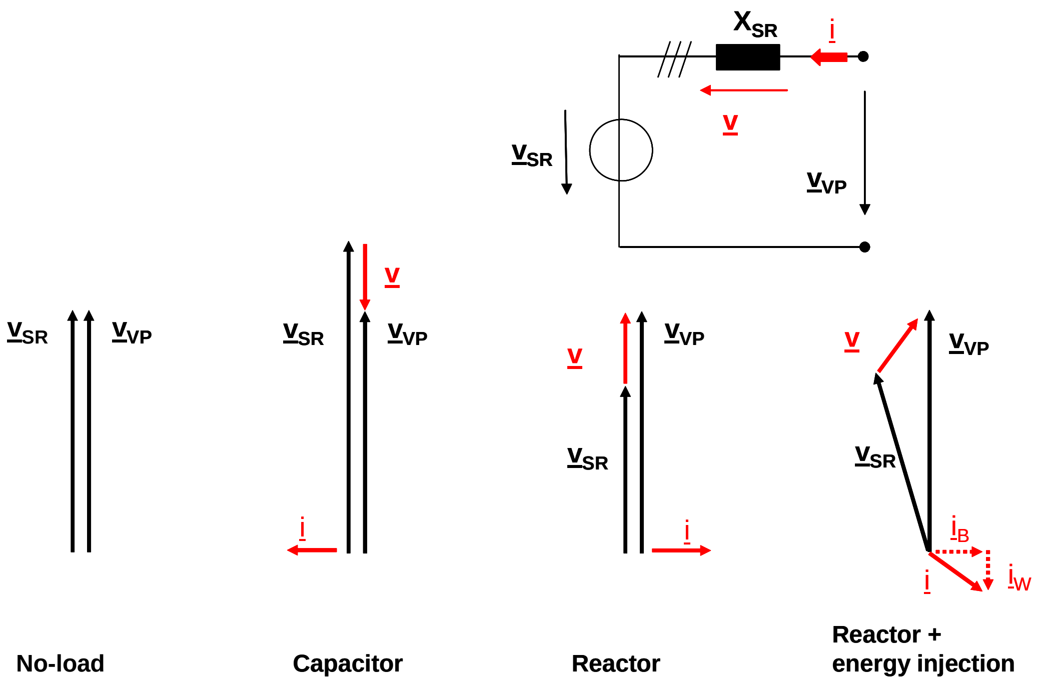


Figure 4-8: Analogy of VSC current and voltage vectors with Synchronous Machine: VSC can also operate in all 4 Quadrants of P/Q-diagram

Series-connected Power Conditioners

Series-connected Power Conditioners are typically operated as DVRs for voltage sag compensation (DVR = Dynamic Voltage Restorer). They inject such voltage portions, which are missing in the network voltage due to system faults for example and would cause sensitive loads to trip. The controller action / restoration time of DVRs is typically in the order of up to 4 Milliseconds. For restoration of the voltages to normal, the positive sequence system must be restored, which means that the negative and zero sequence components must be brought to zero.

Some DVRs only minimize the negative sequence system and allow the zero sequence components to go though the DVR, which is only acceptable for systems that do not have any connected single phase loads. Figure 4-9 depicts the operating principle. More details and working experience and are given in [35], [36] and [37]. DVRs are an alternative to UPS (Uninterruptible Power Supply), if no outage protection is needed. In order to block certain load current harmonics series-connected Power Conditioners may also be operated as Active Filters for example in conjunction with passive filters [38].

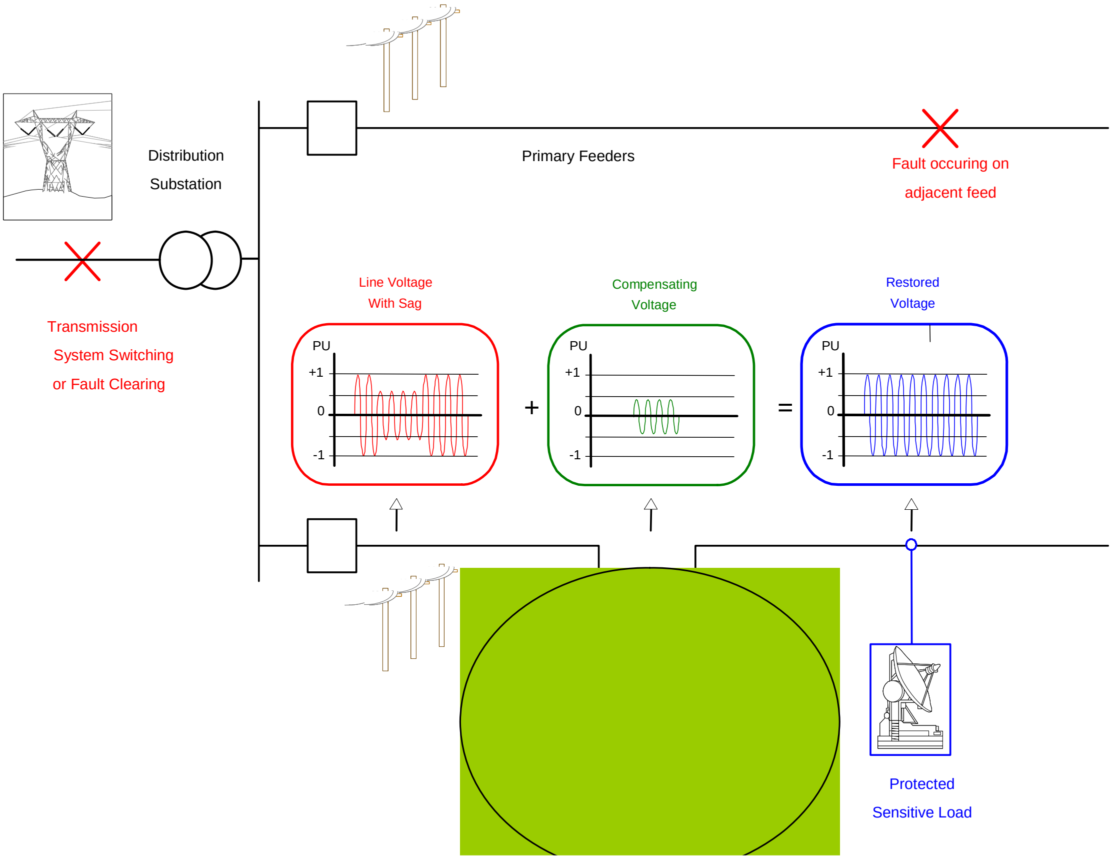


Figure 4-9: Operating Principle of DVR

Shunt-connected Power Conditioners

As Figure 4-1 points out, there are similarities in topology of distribution and transmission system FACTS Controllers. Therefore shunt-connected Conditioners based on VSC-technology are often called DSTATCOM (Distribution Static Synchronous Compensator) in order to point out the similarity in topology and control tasks to Transmission System STATCOMs [64]. In the following two examples for shunt-connected equipment based on VSC are given.

Active Filter

Active Filters are a competitive alternative to conventional passive filters for filtering harmonic current portions, especially if unwanted series or parallel resonance with the system impedance would result. Such an application is depicted in Figure 4-10. Details on control strategies and application examples are given in [39] and [40]. They have also been applied to HVDC systems as will be described in the chapter 0 about VSC-based Transmission System FACTS Controllers [72], [74].

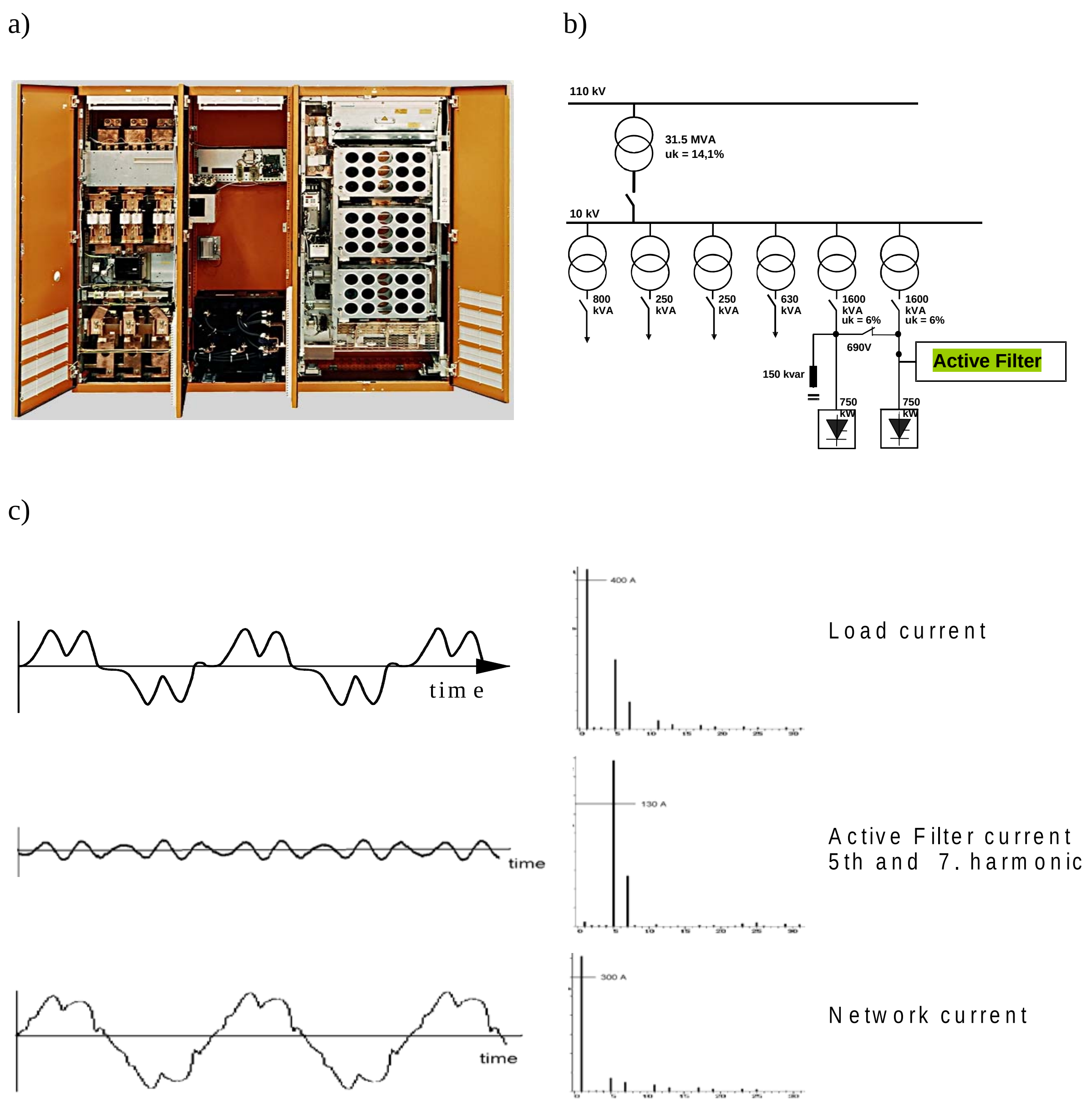


Figure 4-10: 630A low voltage Active Filter for 5th and 7th harmonic [Siemens AG]

Flicker Compensator

For compensating undesired current portions of an arc furnace, which would otherwise result in flicker and thereby disturbing neighboring loads, very fast controller action is needed. For many decades now SVCs (Static Var Compensators) have been successfully applied [41], [42]. From the 1990s on also VSC technology is being used [43], [44]. Figure 4-11 shows measurement results of a 22 MVA DSTATCOM [37]. Other working experience is presented in [45] and control schemes are discussed in [46] for example. A Cigré brochure gives an overview over theory and applications [65].

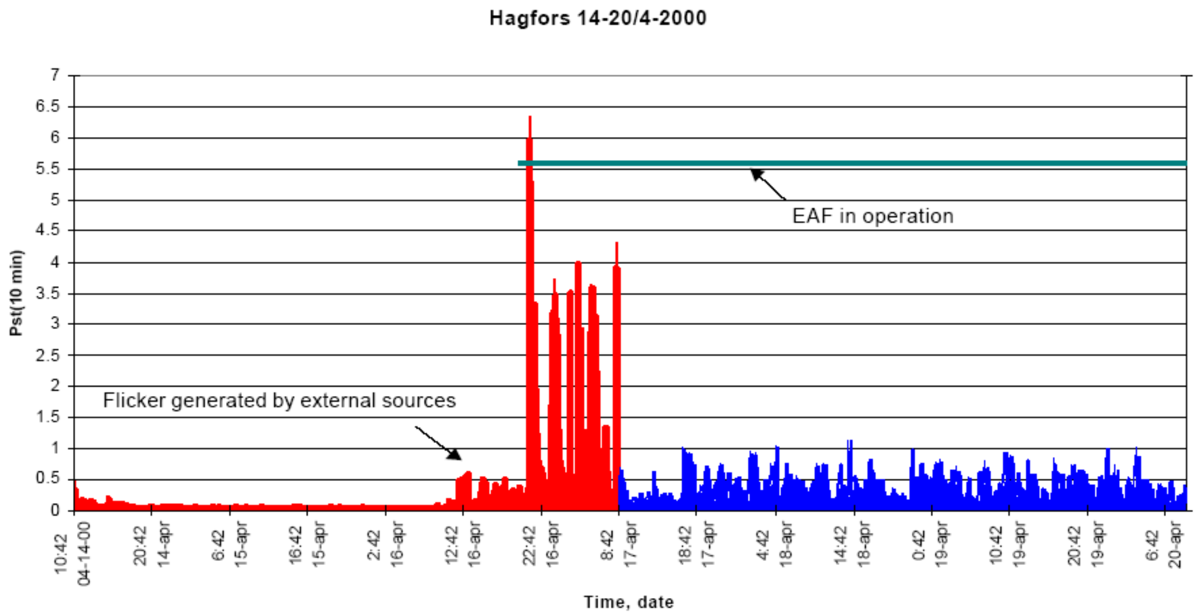


Figure 4-11: Measurement results of arc furnace flicker compensator based on VSC [60]

Back-to-Back Distribution System Coupler

Increasingly VSC-technology is also being applied for coupling of networks. As shown in Figure 4-12 they can transfer energy from one network to the other and at the same time generate reactive power independently at each terminal. Figure shows the technology of a 2 MVA coupler. One application scenario arises, if networks with different frequencies (Figure 4-12) or star-point treatments need to be connected or if the short circuit-level of networks to be coupled are already too high. Such couplers may also be applied, if back-up power supply is needed as shown in Figure 4-15. Other applications are optimization of energy cost, if energy can be purchased from separate utilities with different pricing. Such scenarios arise increasingly in the deregulated energy markets.

The big advantage of applying VSC-based Couplers is, that they do not increase the short-circuit level significantly. Depending on the control setting and design, the additional contribution is in the order of about up to 3 times the power rating of the VSC.

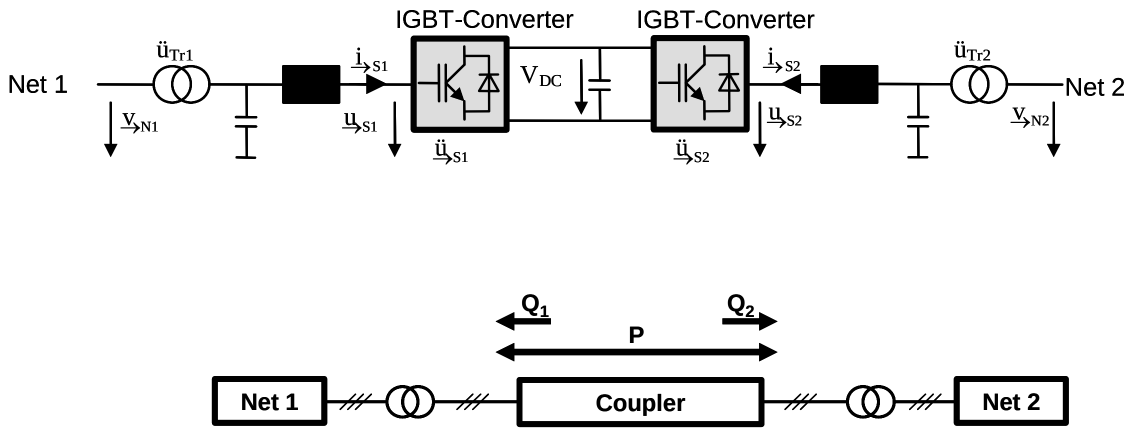


Figure 4-12: Back-to-back connection of VSC-converters for coupling of Distribution Systems

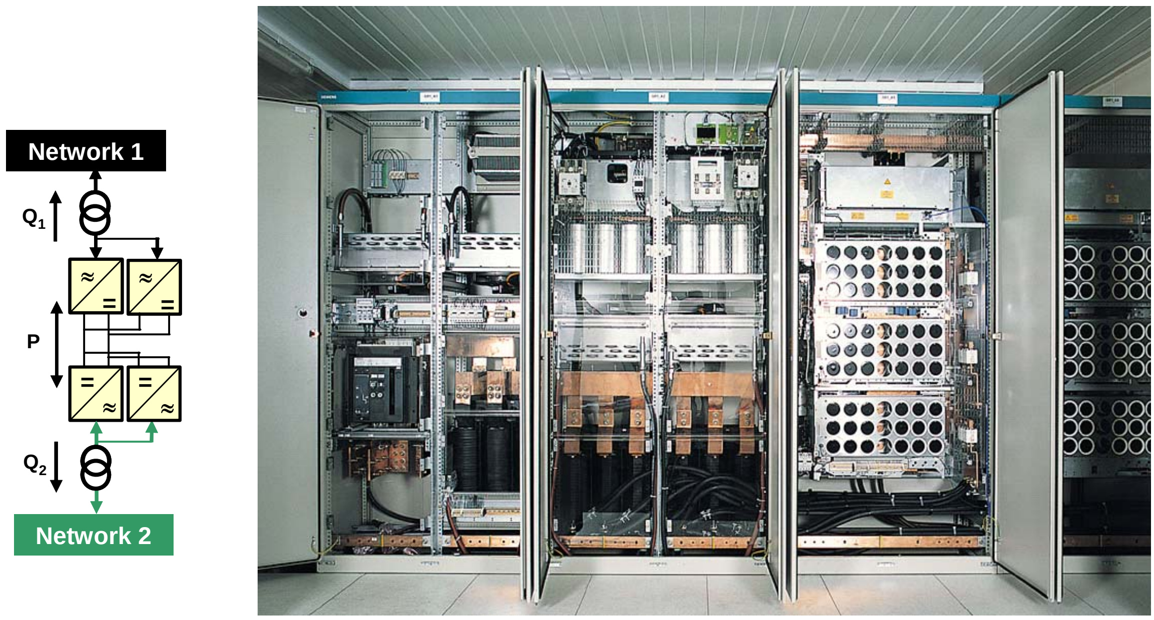


Figure 4-13: Photo of one back-to-back terminal converter system consisting of two 1-MVA-2-level IGBT converters [61]

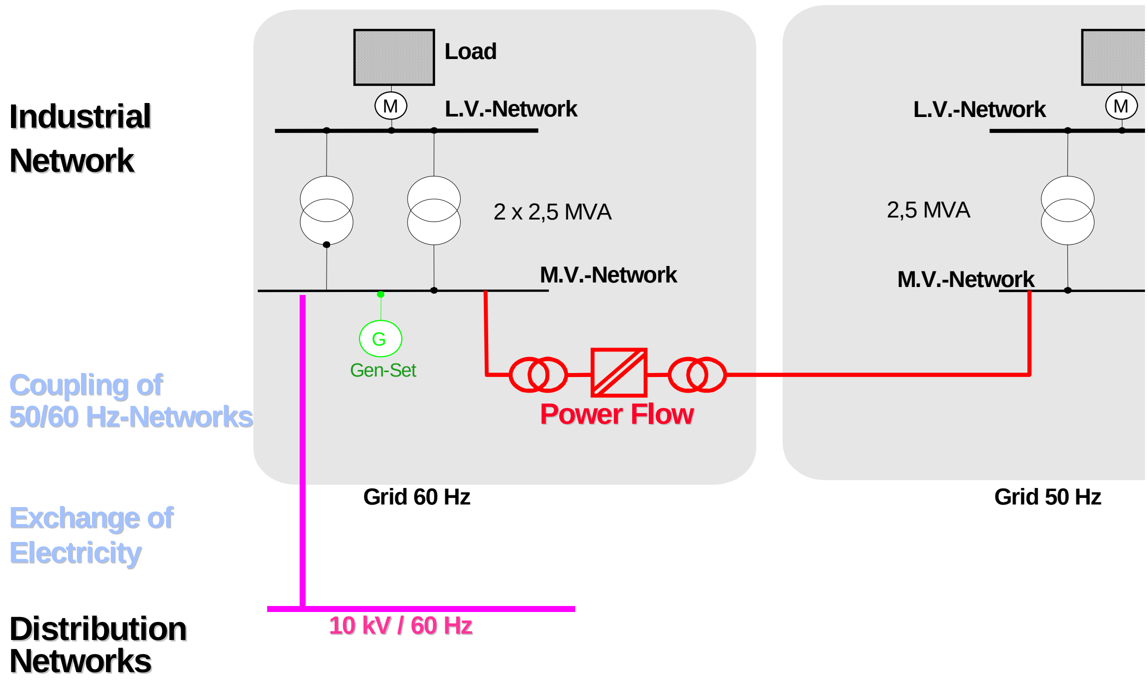


Figure 4-14: Application Scenario of Distribution System Coupler: connecting systems with different frequencies

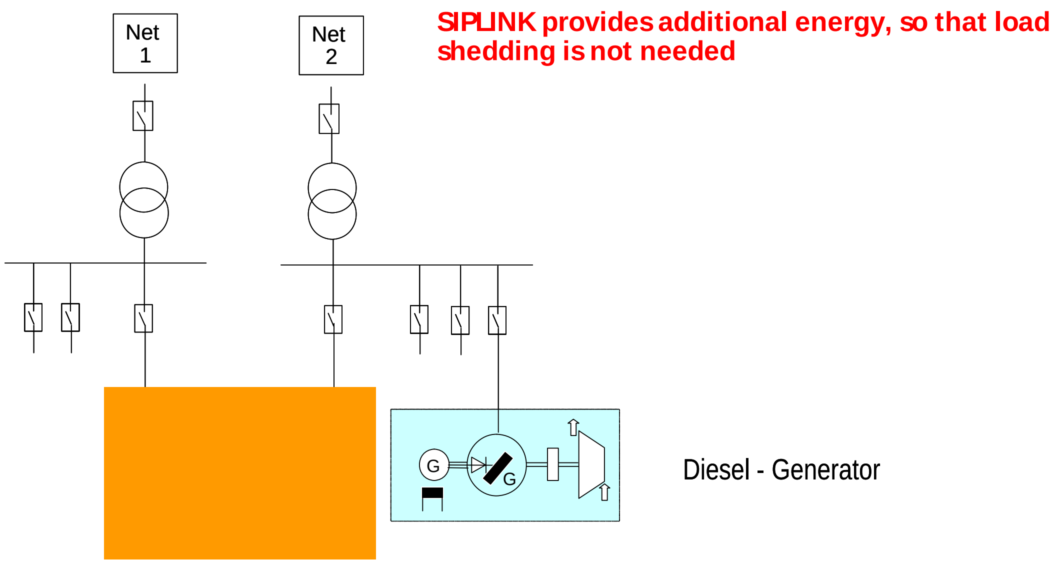


Figure 4-15: Application of Distribution System Coupler as backup power supply (SIPLINK = Siemens Multifunctional Power Link)

4.2.2 Topologies for Transmission System Applications

The development of transmission systems follows the task to transmit power from generators to consumers. The increased demand on energy and at the same time the construction of large generation plants built remotely from load centers makes it necessary to transmit large amount of electrical energy over long distances. Another challenging task for transmission system planning is the worldwide trend to build interconnections between existing power systems in order to achieve technical, economical and environmental advantages (pooling of large power generation stations, sharing of spinning reserve etc.). The resulting challenges and solutions with FACTS-Controllers and HVDC are well described and ranked in [48], [49] and [50].

Figure 4-16 gives the basic equation for active power flow in ac-transmission lines and Figure 4-17 shows the contribution of shunt- and series-connected reactive power compensators to short-circuit current, voltage profile and transmission phase angle. Further details on FACTS-Controllers can be found in [51] - [55]. In general power electronics-based FACTS Controllers can be subdivided in Controllers that make use of line-commutated converters and Controllers that make use of self-commutated converters. Similar to DFACTS Controllers, line-commutated converters being used are always thyristor-based and self-commutated converters being used are typically Voltage-Sourced Converter (VSC)-based.

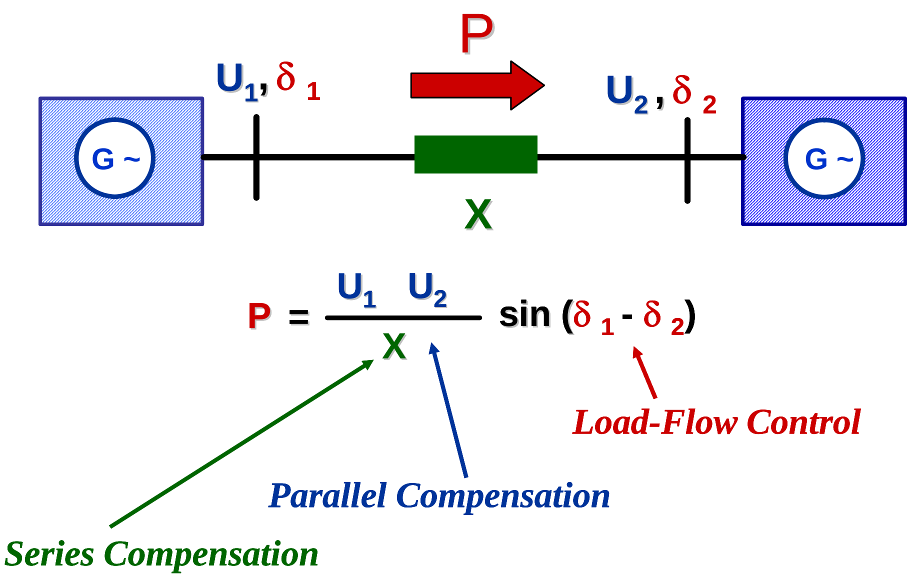


Figure 4-16: Basic Equation for Power Transmission

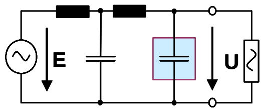
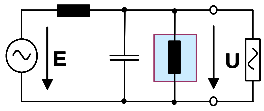
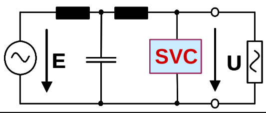
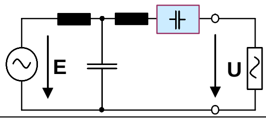
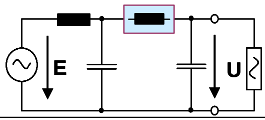
Compen-sation Element	Location	Short Circuit Current	Voltage Profile	Transmission Phase Angle	Remarks
Shunt Capacitor		small influence	Voltage Rise	small Influence	Voltage Stabilisation at high Load
Shunt Reactor		small influence	Voltage Reduction	small Influence	Reactive Power Compen-sator at Low Load, Limiting of Overvoltages.
Static Var Compen-sator		small influence	controlled	small influence	Reactive Power & Voltage Control. Damping of Power Oscillations, Improvement of System Stability
Series Capacitor		increased	improved	strong Reduction	Long Transmission Lines: Increase of Transmission Capacity
Series Reactor		reduced	degraded	strong Increase	Short Lines, limiting of Short-Circuit Current Level

Figure 4-17: Applications of Reactive Power Compensation

Thyristor-based FACTS-Controllers

Thyristor-based Equipment was first introduced in Thyristor Controlled Reactor (TCR) and Thyristor-Switched Capacitor (TSC) installations in the 1970s. They are often used together and/or in conjunction with Mechanically Switched Capacitors (MSCs). The equipment has been named Static VAR Compensator (SVC) [56], [57]. Figure 4-18 depicts the principal SVC-topology and control tasks and Figure 4-19 shows an example. The series-connected Thyristor Controlled Series Capacitor was introduced in the 1980s [58]. Its principal topology and control tasks are shown in the example depicted in Figure 4-20. It is typically used in conjunction with Fixed Series Compensation (FSC). From the late 1990s on other applications of thyristors have resulted in the following equipment:

- Thyristor Protected Series Compensator (TPSC) [59]: instead of MOVs the thyristor takes over the bypass current thus preventing the long cool-down time of MOVs. As a result the Compensator can be put into operation again much faster after Fault Clearing in the network.
- Thyristor-based Short Circuit Current Limiter (SCCL) [62]: an LC-circuit tuned to the grid frequency is rapidly detuned by short-circuiting the capacitor through an parallel-connected thyristor. The resulting and current-limiting impedance is the inductance of the reactor. See also section 3.4 above.

The description of this equipment will be covered in more detail by another task force of this working group dealing with power electronics-based switchgear. The thyristors were initially electrically triggered, but since the mid 1990s also light-triggered thyristors are being used.

a) b)

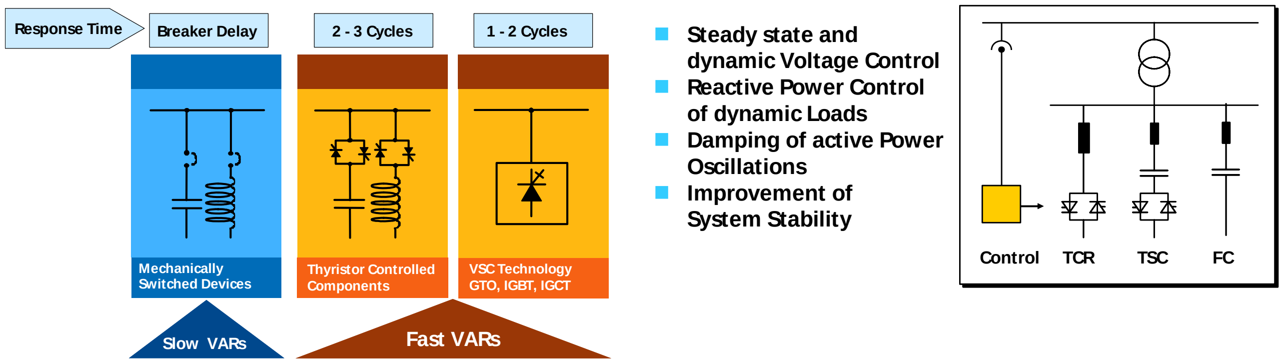


Figure 4-18: Reactive Power Compensation: a) general overview of reaction speeds; b) principal topology and tasks of SVC

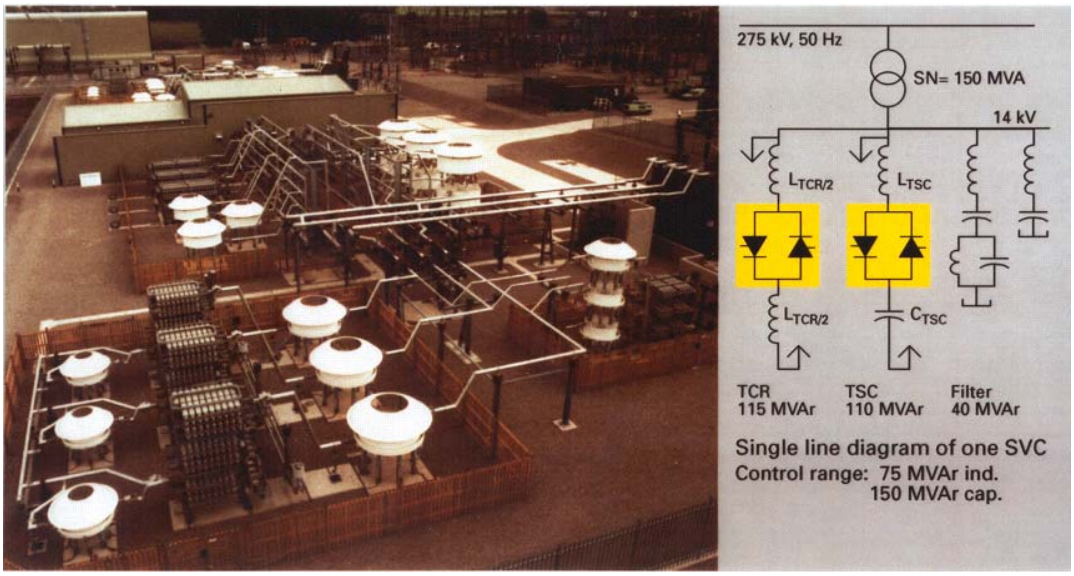


Figure 4-19: Example for SVC [61]

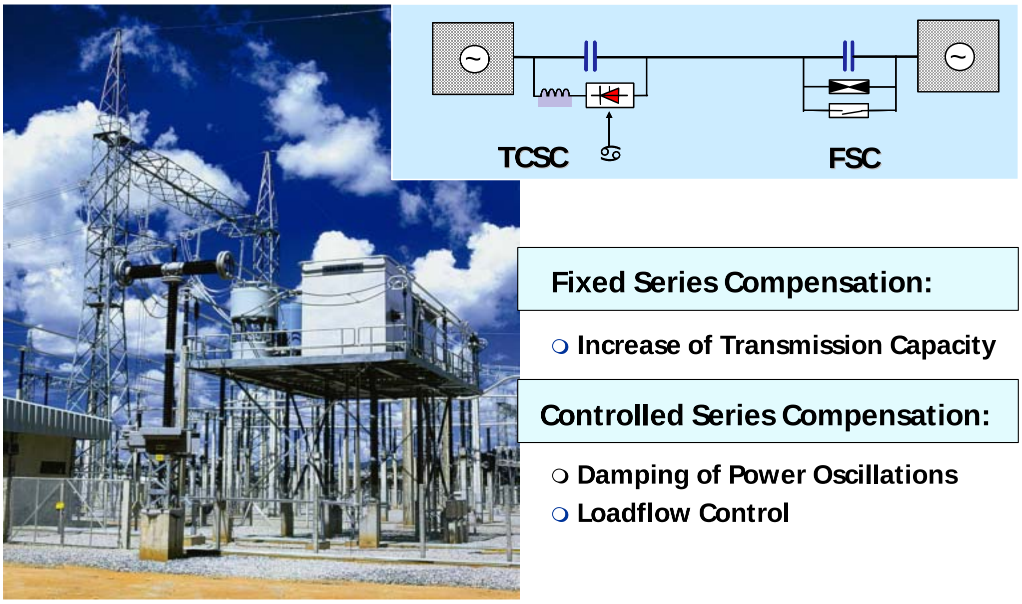


Figure 4-20: Basic Topology and Example for series compensation with TCSC and FSC for VSC-based FACTS-Controllers

Shunt-connected FACTS Devices

In the 1990s shunt- and series-connected FACTS-Controllers based on GTO-technology (Gate Turn Off Thyristors) have been introduced. The first units to be built were shunt-connected and are called Static Synchronous Compensator (STATCOM) [50], [64], [65], [66], [67]. As discussed in Chapter 0 they have been applied to Flicker Compensation of Arc Furnaces. Other applications have been balancing of single- or two-phase railway in-feeds. STATCOM may also be used to couple energy storage equipment such as Batteries or SMES to the network.

Series- and Shunt-/Series-connected FACTS Devices

The combination of shunt- and series connected VSC results in the Unified Power Flow Controller (UPFC) [68], [69]. If only the series part of the UPFC is operated, the resulting FACTS-Controller is called Static Synchronous Series Compensator (SSSC or S^3C). The most versatile FACTS Controller built so far is the so-called “Convertible Static Compensator (CSC)”. It was commissioned end of 2003 [70], [71] and contains two converter system which can be reconfigured via circuit breakers to several shunt- and series-connecting topologies.

Active Filters for HVDC and Transmission Systems

In conjunction with HVDC systems self-commuted converter-based Active Filters are being used [72]. The development was initiated in the middle of the 1980s. They are either connected at the AC-side or the dc-side of the HVDC system and provide more flexibility in filtering unwanted current and voltage portions [74].

Transmission System Couplers

In the power range of up to about 300MW new technologies have been introduced which offer cost-efficient alternatives to the well-known conventional HVDC Back-to-Back or long distance transmission systems. They incorporate additional functionalities like reactive power or voltage control, which justifies their mentioning in this chapter.

Connecting the dc-links of two VSCs results in back-to-back coupler with similar topology and capabilities as discussed in Chapter 0. Figure 4-21 shows such a Coupler. VSC-technology can also be used for long-distance transmission [75], for example to connect off-shore wind parks to the network [76]. As described in Chapter 0 VSC-converters can black-start a network and are therefore quite attractive for connecting remote loads or isolated networks without significant generators to an existing network. VSC-based transmission DC transmission has been built up to power ratings of about 300MW. An overview of VSC-based DC transmission is given in [77].

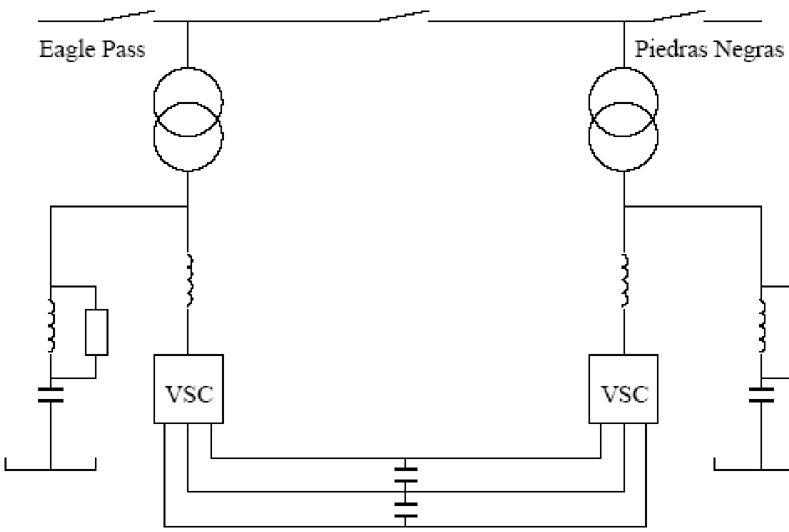


Figure 4-21: Basic Topology of Back-to-back Coupler based on VSC-technology [73]

Up to about 300 MW cost-efficient HVDC links can be built, which make use of conventional AC power transformers instead of converter transformers. This makes AC transformers less expensive and faster to deliver.

The design of such a Back-to-Back system is described in [78]. In this system the dc bus bars are isolated from ground, which avoids the use of converter transformers and also prevents zero-sequence current harmonics from flowing. By either switching capacitors or reactors or by adjusting the dc-voltage the reactive power exchange with the network can be altered (note: in B-to-B schemes the transmission losses are negligible and therefore the dc voltage can be adjusted to any level within the specified limits.)

Fault Current Limiters

An overview over Fault Current Limiters (FCL) is given in [63]. The usage of power electronic equipment in conjunction with FCL is discussed in Chapter 3.4 of this document.

4.3 Trends in converter technologies

The development of high power converter technologies is driven by medium drives applications. Generally a reduction of the number of components and losses, an improvement of voltage and current quality and of course a reduction of costs is aspired. Also a further improvement of reliability, fast commissioning and easy maintenance is desired.

Line-commutated converters are applied for voltage- and current-sourced converters. The highest power ratings of current-sourced converter systems are realized in HVDC-terminals (nowadays up to about 3 GW). HVDC and SVC technologies are the market driver for high power thyristors. In drive converters typically smaller device ratings are used. High power ratings for voltage-sourced line-commutated converter systems are realized in static railway frequency converter systems in the terminal that interfaces to the three-phase ac-system (at the single- / two-phase railway-side typically self-commutated GTO- or IGCT-converters are being used). Line-commutated converters, equipped with conventional thyristors without turn off capability, have reached a reliable and powerful technical standard. Changes in the basic converter topologies (e. g. 6-pulse bridge) are not seen in the future due to the well-engineered and well-proven design with experiences of tens of years. Improvements can be achieved by more powerful components and by a further reduction of components, e.g. integration of protection functions in the power semiconductor itself. In general the line-commutated converter is attractive due to its inherent advantages, such as simplicity, robustness, overload capability, lower losses and high reliability. As indicated before, due to trends in the development of power systems, the need for self-commutated converter technology will increase.

Self-commutated converters require switches with turn on and turn off capability [80]. Today most of such converters are built with GTOs, IGCTs or IGBTs, whereas GTOs are increasingly substituted due to higher snubber losses and, as a consequence thereof, a worse partial load behavior. Self-commutated converters are widely used for adjustable speed drives (especially induction machines) and as indicated in the previous chapters, they have already been introduced in distribution and transmission FACTS Controllers.

Generally, self-commutated converters can be classified in three types:

- Voltage sourced converters,
- Current sourced converters and
- Matrix converters.

4.3.1 Voltage sourced converter

Voltage sourced converters in two or three level technologies are popular solutions for various industrial drives applications equipped with GTOs, IGCTs or IGBTs. Such converters have reached a wide market share in medium voltage drives applications due to the rapid development of the switching power semiconductors. The power range of a single converter without direct series connection of high power semiconductors goes up to about 10MW. Today two- and three-level topologies are also used for energy distribution and transmission applications. In these applications, direct series connections of high power semiconductors are often necessary to achieve the required valve voltage. In that case IGBTs offer some advantages compared to other switching semiconductors and are therefore the preferred solution:

- It is possible to connect the devices in series without dv/dt-snubber.
- di/dt limiting reactors and associated snubbers are not required
- IGBTs can be controlled via gate signal at any time.
- The required control power is very low.
- Short circuits are limited by the IGBTs itself and can be turned off.
- IGBTs can be connected in parallel to increase the current capability of the inverters.
- Active balancing in series connections by short turn-on pulses is possible.
- High voltage IGBTs up to 6.5kV are available on the market.

The basic design of a three phase two level voltage sourced converter design is shown in Figure 4-22, the output voltage of each phase is either switched to + $\frac{VD}{2}$ or - $\frac{VD}{2}$. Applying this standard topology, the standard control methods and pulse width modulations which are used in medium drives applications can also be used for FACTS applications.

In converters with direct series-connected devices attention has to be paid to achieve uniform static and dynamic voltage distribution, and if needed, small snubbers have to be utilized.

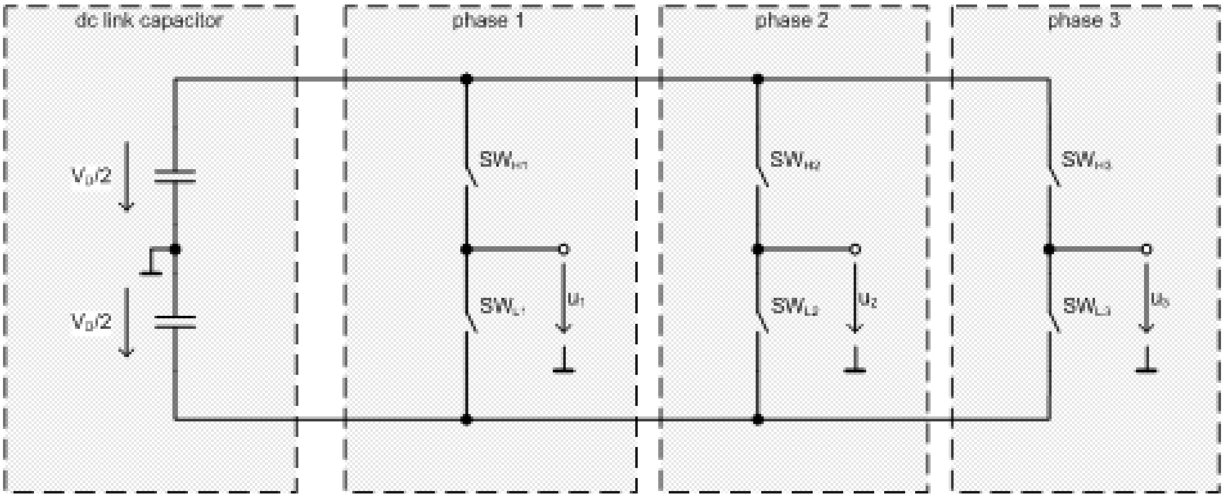


Figure 4-22: Conventional three-phase two-level converter

Based on the capability of the semiconductors, the switching speed of the IGBTs which is adjustable by the gate pulse and gate circuit, usually has to be limited for two reasons:

- The switching speed of the IGBTs has to be adjusted to the turn-off capability of the freewheeling diodes.
- In applications with direct series connections the maximum rate of rise of valve voltage has to be limited due to displacement currents through stray capacitances (e.g. bushings, transformers) and to meet EMC requirements of the converters.

The required limitation of the switching speed has to be paid with higher losses of the IGBTs. Due to the constraint of rate of rise of valve voltage it would not be possible to exploit the performance of high power switches and diodes made of SiC, which may be available in a few years, when conventional voltage sourced converter topologies are used for FACTS applications.

New voltage sourced converter concepts were proposed which are able to overcome these limitations. Furthermore new topologies can help to reduce harmonics of the converter and to reduce converter losses. The most important concepts are presented in the following chapters.

As indicated in the following, some of these concepts are already used in drive converter and FACTS Controller applications.

4.3.2 Multilevel converter concepts

By the use of multilevel converter concepts (three levels and more) it is possible to realize an amplitude modulation of the converter voltage by smaller voltage steps, i.e. a good approximation of sine waves can be achieved. The number of devices in series connection, which switch at the same time, is reduced, resulting in lower dv/dts of the valve. Furthermore the pulse frequency of a single device can be reduced.

Based on the same switching frequency and equal dv/dt per switching device, harmonics and EMC emission are lower compared to conventional designs. Thus filter circuits can be much smaller. These advantages have to be paid by more complex converter designs and higher control efforts. In the following the three main concepts to achieve multi-level voltage sourced converters are presented:

Diode clamped multi-level inverter

In this topology the dc link capacitor of an n-level inverter is split up in (n-1) series connected capacitors with the same voltage rating. Each voltage between the series connected capacitors can be switched to the phase output by using clamping diodes. The required blocking capability of the clamping diodes depends on the tap voltage. Figure 4-23 shows the design of one phase leg of a 5-level voltage sourced converter.

In that case the diodes D_1 and D_{-1} need to have the same blocking capability like the switches and the freewheeling diodes. D_2 and D_{-2} require the double blocking capability and D_3 and D_{-3} the threefold value. When semiconductors with same blocking capabilities are used, direct series connections of clamping diodes are necessary. This would to lead a minimum number of clamping diodes of (n-1)·(n-2) = 12 for a five level inverter [81].

The mechanical design of a three-level converter compared to a two-level converter is possible with acceptable efforts whereas multilevel designs with more than three levels become quite complicated due to the required blocking capabilities of the clamping diodes. The arrangement of the clamping diodes and the requirement of low-inductive current paths is the main difficulty of the realization of diode clamped multi-level converters with more than three levels. Special efforts have also to be made to achieve a symmetric voltage distribution of the discrete capacitor levels.

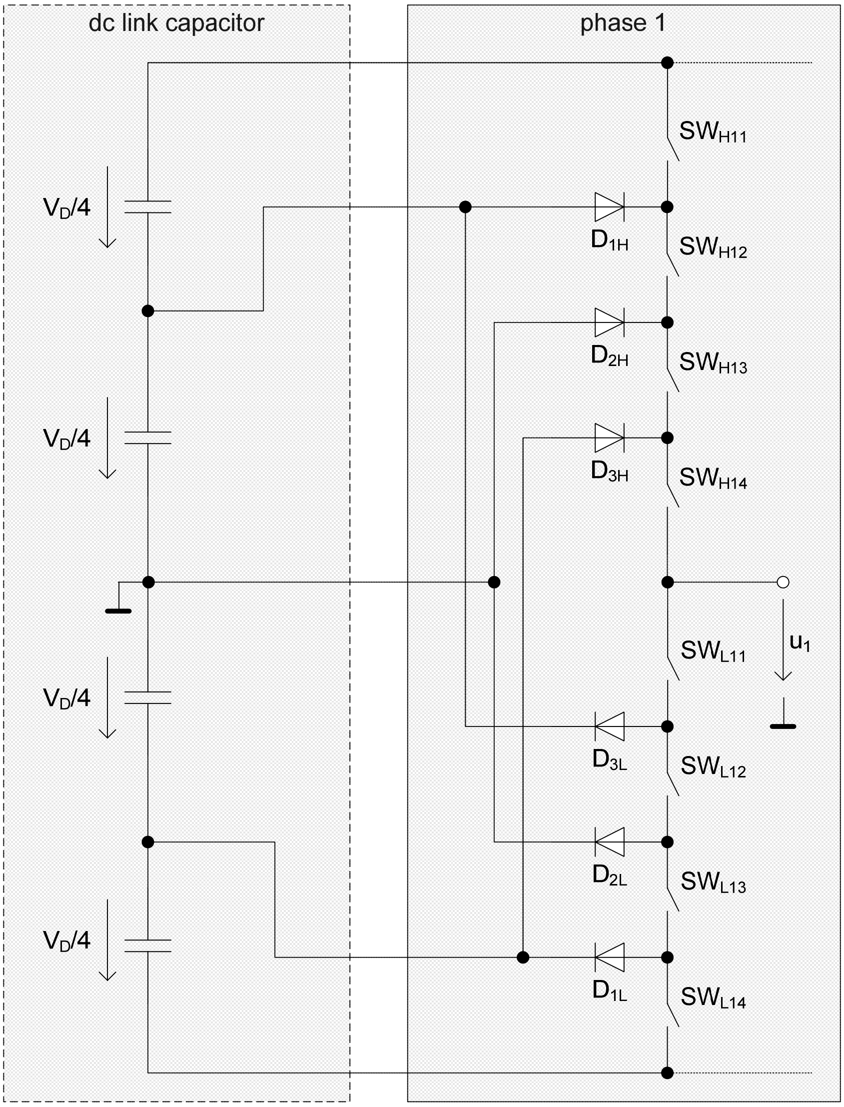


Figure 4-23: Phase leg of a 5-level diode clamped voltage sourced converter

Flying capacitor converter (Figure 4-24)

Additional capacitors enable an amplitude modulation of the output voltage in this topology. For a n-level inverter (n-1) capacitor cells are necessary. All semiconductors have the same blocking capability in this type of multilevel converter, whereas the capacitors must have different voltage ratings [81]. For output voltages except $+\frac{V_D}{2}$ and $-\frac{V_D}{2}$ different switch combinations are possible. For example the following conduction switch combinations result in an output voltage of $+\frac{V_D}{4}$:

- SW_{H11}, SW_{H12}, SW_{H13}, SW_{L14}
- SW_{H11}, SW_{H12}, SW_{H14}, SW_{L13}
- SW_{H11}, SW_{H13}, SW_{H14}, SW_{L12}
- SW_{H12}, SW_{H13}, SW_{H14}, SW_{L14}

Under consideration of the different possible combinations and adequate trigger pulse logic, the capacitances of the discrete capacitors can be minimized. Furthermore it can be shown that it is possible to achieve stable capacitor voltages with equal capacitances when appropriate pulse sequences are applied.

Disadvantageous of this topology is that a large number of DC-link capacitor units are required. Assuming that all capacitor units are built with the same discrete capacitors, i.e. by series and parallel connections of capacitors, the minimum number of capacitors for a five level inverter is 30 to achieve the required capacitances.

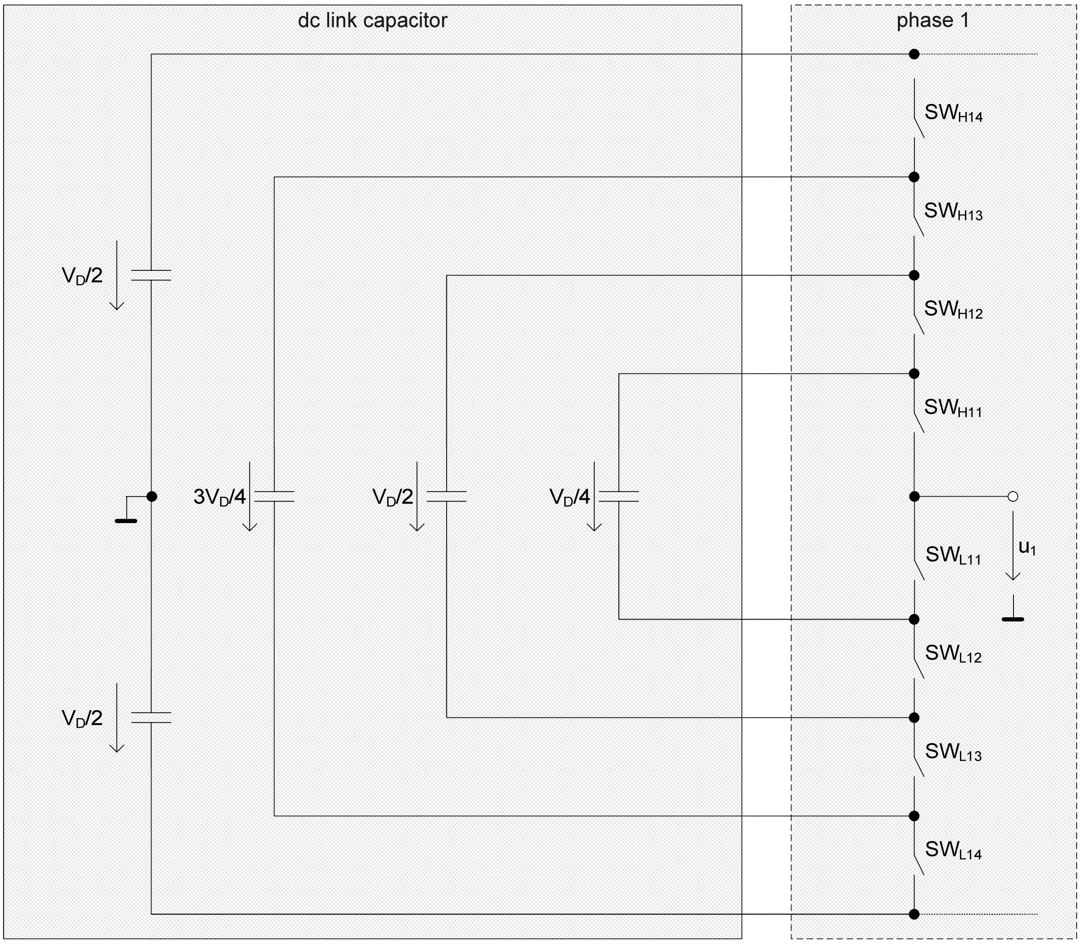


Figure 4-24: Phase leg of a 5 level flying capacitor converter

Series connected H-bridge cells

Multilevel output voltages can be achieved by multiple series or parallel connection of single-phase, 2-level "H-bridge" cells [81], [86]. In the case of parallel connection different H-bridges can be supplied with one common DC-link. The outputs of the H-bridges are connected to primary windings of a transformer; the secondary windings are connected in series. The principal topology of one phase leg of this converter type is shown in Figure 4-25. The output voltage of each cell can be switched either to $+V_D$ or $-V_D$. Depending on the transformer design, the secondary voltage outputs can be equal (symmetric design) or non-equal (asymmetric design). When an asymmetric design is used, it makes sense to choose a scaling factor three. In that case, 27 equal voltage levels can be achieved with three series connected cells like shown in Figure 4-25. In that case, the power semiconductor currents of the different H-bridges are different. By using a symmetric design, 7 levels can be achieved with this arrangement with equal currents of the power semiconductors. On the one hand, a converter can be built with components of medium voltage drives, but on the other hand, the transformer design is quite complex. This design principle has been used in high-power static frequency converters for railway systems [82], [83].

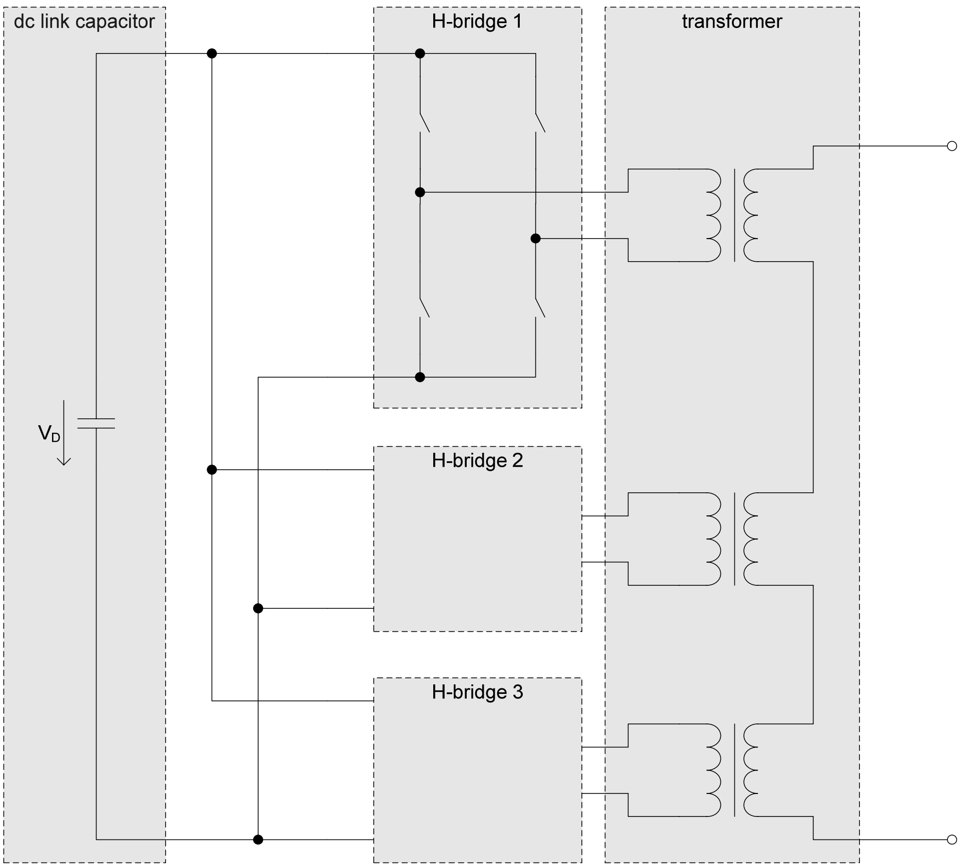


Figure 4-25: Phase leg of series connected H-bridge cells with common DC link

When no active power has to be delivered by the converter, it is also possible to connect insulated H-bridges, each connected to an own DC link capacitor, in series (Figure 4-27). This is an advantageous design for applications where only reactive power is required, since the capacitors need not to be externally supplied and many components of standard medium drives can be used. Such a concept is being used by one FACTS Controller manufacturer [66], [91], [92].

This approach is readily scalable to different connection voltages and MVAr outputs, simply by varying the number of H bridge cells in series per phase. Figure 4-xx shows a single phase for a commercial installation using 16 bridge cells (or “chain links”) in series per phase, at a connection voltage of 15.1kVrms, giving a rated output of +/-25MVAr per phase.

An additional advantage of this circuit is that, because it is inherently single-phase, it is very effective at dealing with unbalanced systems.

Figure 4-26: Single phase of a STATCOM based on series-connected H bridges

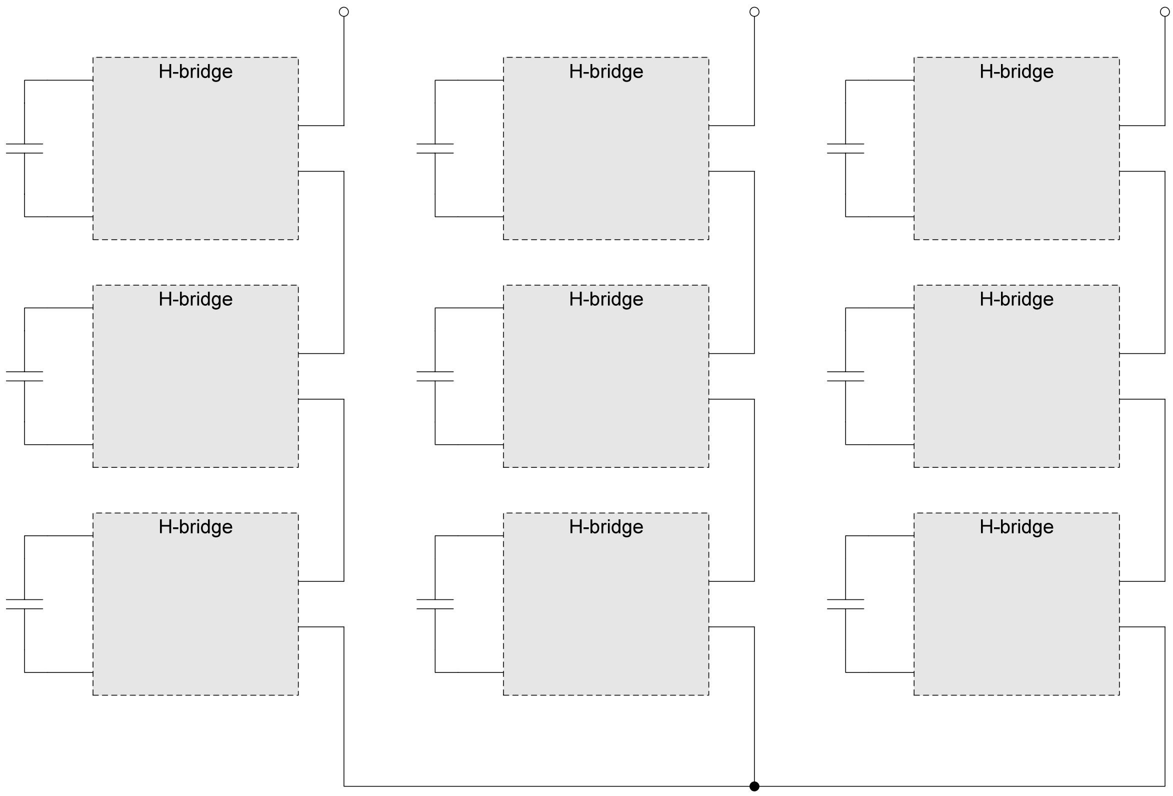


Figure 4-27: Converter with series connected chain link with assigned non-supplied DC link capacitors to each cell

Of course, the cells can be supplied individually, realized for example in medium voltage drives (such a concept is being used by one drives manufacturer [79]). In that case, isolated DC power supplies need to be provided for each DC capacitor. Depending on the design of these DC power supplies, active power transfer in both energy flow directions may be possible.

Other Multi-Level Converter Types

Although the preceding sections have covered the major types of multi-level converter that have found practical application, many other hybrid arrangements are possible. Two are worthy of a brief mention:

- The principle of magnetically combining the outputs of several bridges sharing a common DC capacitor, mentioned in the preceding section in the context of the H-bridge circuit, can also be extended to other circuit topologies. One manufacturer has installed STATCOM equipment based on magnetically combining the outputs of several three-phase, two level inverters based on GTOs.

- In principle, the series-connected H-bridge ("Chain") circuit can be enhanced by using multilevel phase-legs (3-level or 5-level, neutral-point clamped or flying capacitor) instead of the basic two-level phase leg shown.

4.3.3 Resonant converters

In voltage-sourced converters as discussed in chapter 4.3.2 the switches operate in a mode, where current through the device and the voltage across the device overlap and thus generate high switching losses. The rate of rise of voltages has to be limited resulting in higher switching losses in the IGBTs. To overcome these problems, i.e. to reduce switching losses and to achieve a moderate steepness of voltage at the switches, resonant converters were proposed, also designated as **A**uxiliary **R**esonant **C**ommutated **P**ole **I**nverter (ARCP or ARCPI). The main principle of the resonant converters is based on resonant auxiliary circuit elements, which avoid an overlap of voltage and current of the switching devices. Figure 4-28 illustrates that behavior.

One possibility to realize a resonant converter is shown in Figure 4-29. The principal function is as follows: The two resonant capacitors, connected in parallel to each switch, are recharged during every commutation process, resulting that the turn on and turn off occurs at zero voltage. The auxiliary switches S_{H1} and S_{H2} are used to enable a complete reload of the resonant capacitors (Figure 4-29).

Assuming that the load current flows through S_1, S_{H1} is turned on short time before S_1 is turned off. After turning off S_1, the energy in L_r of the resonant circuit consisting of L_r and C_r leads to a quite soft charge of C_{r1} to U_d.

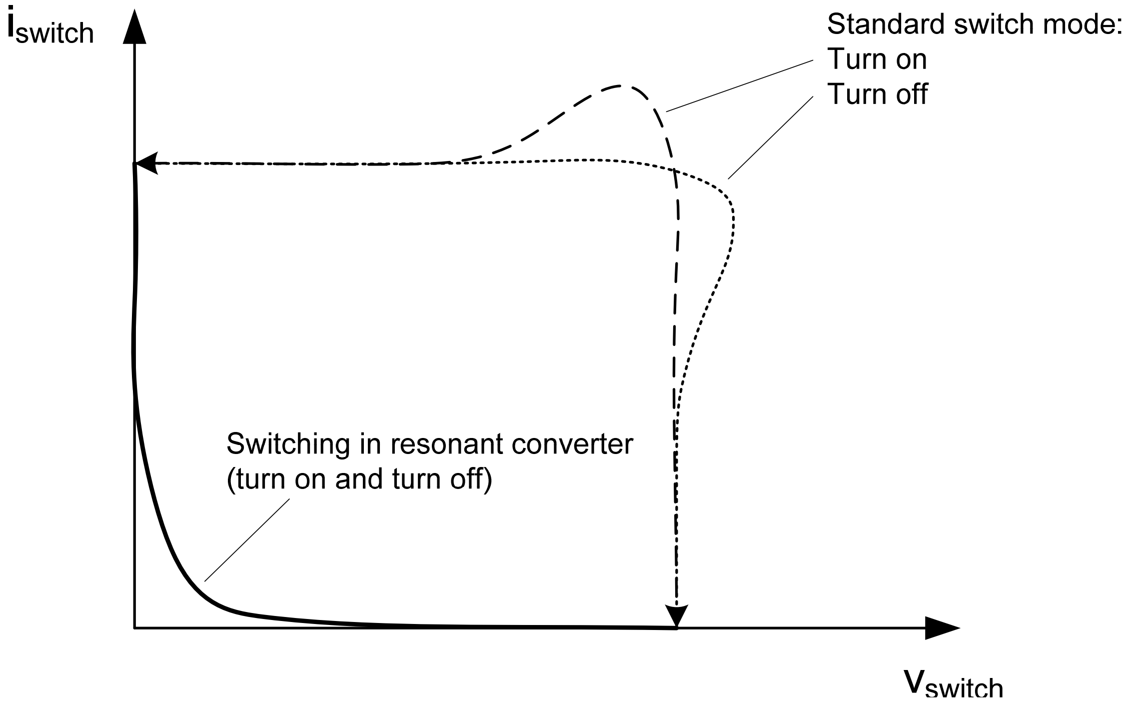


Figure 4-28: Comparison between standard switch mode and switching in a resonant converter

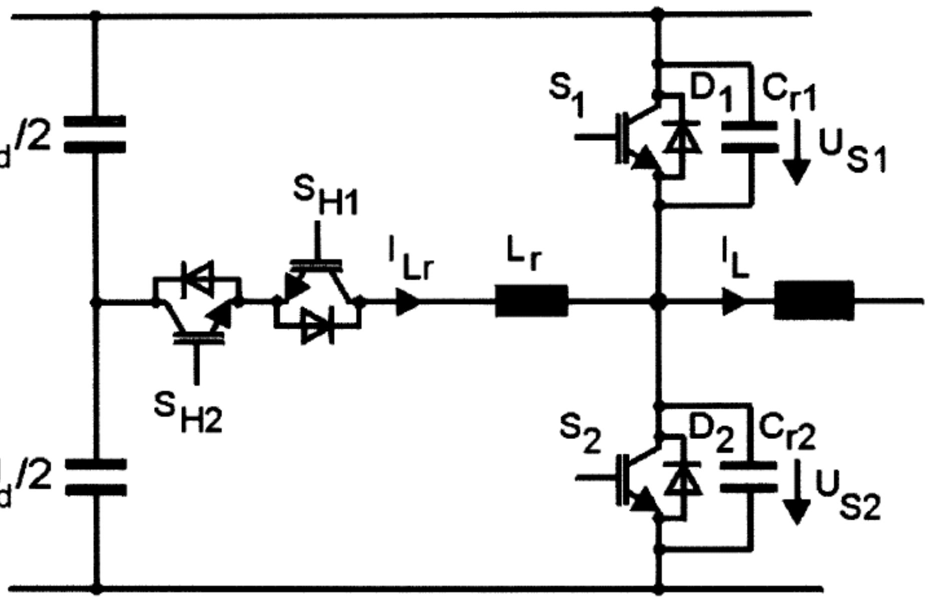


Figure 4-29: One Phase leg of a two level resonant converter

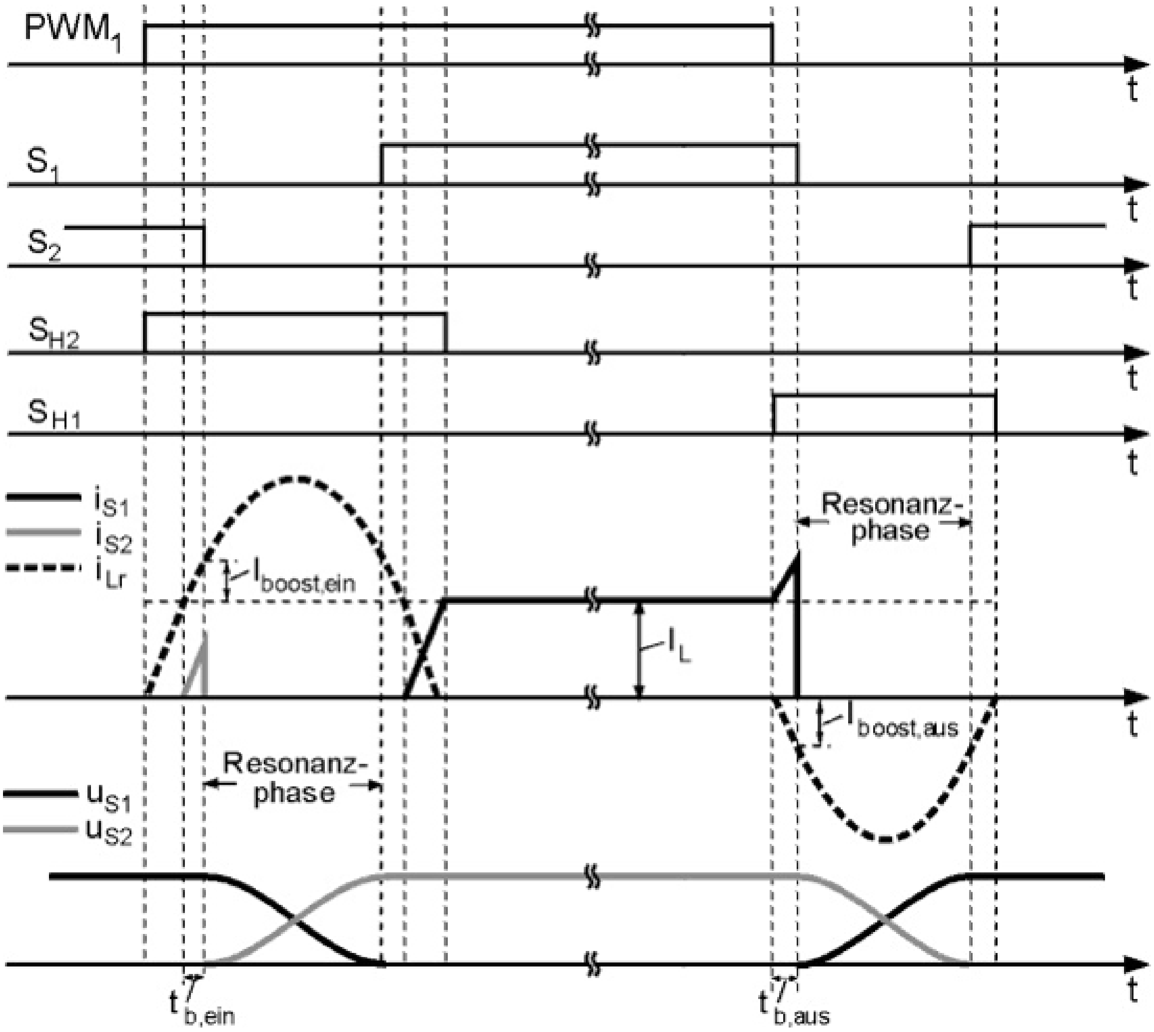


Figure 4-30: Waveforms of the ARCP inverter

To built a resonant converter like shown in Figure 4-29 an additional bi-directional auxiliary switch, consisting of S_{H1} and S_{H2}, with a voltage rating for $\frac{V_D}{2}$ is required. This causes a more complex design of the converter. Another difficulty is the more complex control regarding the triggering of main and auxiliary switches. On the other hand, the switching losses and thus the total losses of the converter can be drastically reduced although additional losses are generated by the auxiliary switches. Even the semiconductors can be optimized to low on-state losses in this design resulting in a further reduction of switching losses. At this time the resonant converter is still in the emerging technology stage.

4.3.4 Self-commutated current sourced converters

In a voltage-sourced converter the energy is stored in the dc link capacitor whereas in the current sourced converter (CSC) it is stored in a reactor. Self-commutated current sourced converters require power semiconductors with reverse voltage blocking capability. Since such devices are not very common they can be achieved by a series connection of asymmetric IGBTs and diodes (see Figure 4-31). Compared to line commutated current sourced converters with conventional thyristors, the utilization of switches with turn-off capability enables an operation in all four quadrants.

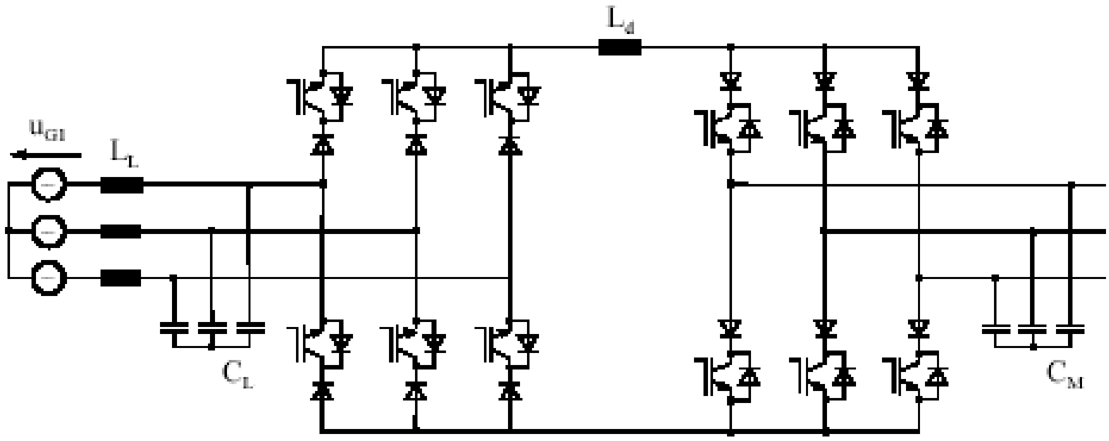


Figure 4-31: Self-commutated Current Sourced Converter

When a valve is turned off, an alternate current path is required. If ac capacitors are connected between the phases (C_L and C_M) a rapid commutation of the turn off device to the turned on IGBT can be achieved. The ac capacitors also limit the rate of rise of voltage of the valves. The required size of the capacitors might be quite large. Compared to voltage sourced converters short-circuit currents are limited by the dc reactor and therefore are much lower. Destructive short circuits can thus be avoided. On the other hand the losses generated in the reactor are much higher compared to the generated losses in the dc link capacitors of voltage sourced converters. The widely used asymmetric switching devices for voltage-sourced converters, driven by the drives market, have led to improvements concerning power capability, losses and costs of these semiconductors and converter types. The further development of symmetric devices is therefore in the background, resulting in a drawback of self-commutated current sourced converters.

4.3.5 Matrix converters

In contrast to voltage sourced and current sourced converters matrix converters do not have passive energy storage components like DC link capacitors or reactors. In this topology each of the input phases can independently connected to each output phase at any instant, i.e. the switches must have turn on and turn off capability.

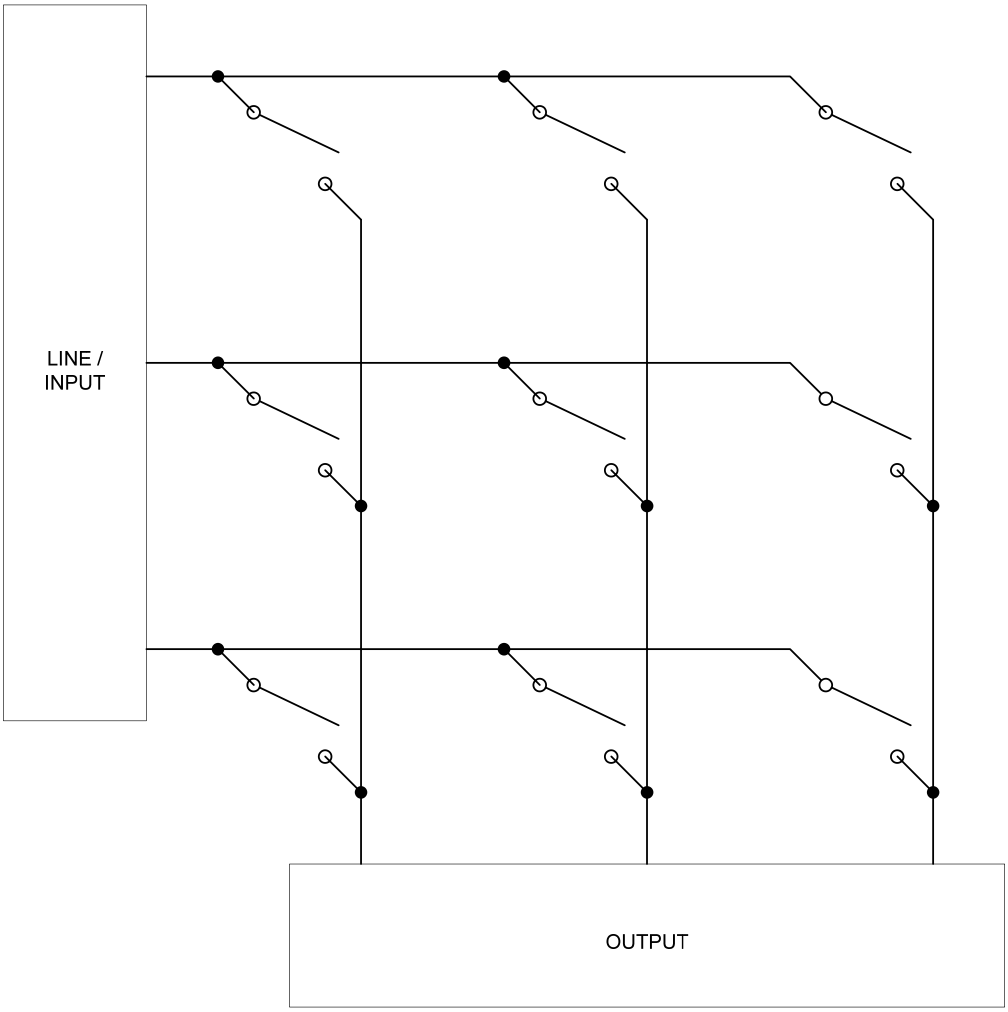


Figure 4-32: Principal topology of a three phase to three phase matrix converter

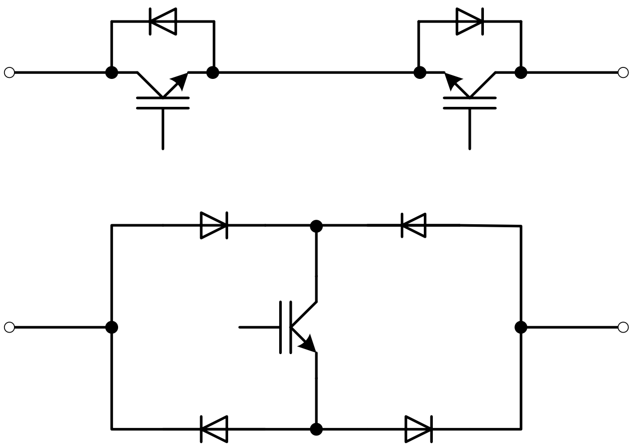


Figure 4-33: Possible arrangements of semiconductors to build up a symmetrical bidirectional switch

As seen in Figure 4-32 the switches must be able to conduct the load current in both directions and must have symmetrical blocking behavior. Since such semiconductor devices are not available as single monolithic devices at the moment, the switches can be built up with standard semiconductors as seen in Figure 4-33.

When a turn on trigger pulse is applied to one of the IGBTs in the upper circuit (two-transistor based configuration), the circuit has the character of a diode. In the lower arrangement this diode character cannot be achieved, here conducting or non-conducting states are possible. During on-state, the upper configuration has two conducting elements whereas the one-transistor based configuration has three.

Compared to voltage sourced converters, the trigger sequences to achieve a commutation from one phase to another are more much more challenging because no freewheeling paths exist in this topology. During the commutation short circuits between two phases on the one hand and an open inductive circuit on the other hand have to be avoided. Therefore it is reasonable to use a switch arrangement shown on top of Figure 4-33 and to perform the commutation process in different steps by adequate pulse sequences [88]. However, this requires high control efforts and a higher energy charge capability of the gate drivers, compared to voltage sourced converters.

To cope with faults and subsequent turn off of all switches several clamp configurations have been proposed, resulting in more complex designs as shown in Figure 4-33 [89]. Converters with energy storage elements can only partly be substituted by matrix converters, because in some FACTS applications the energy storage capability is required for its functionality. Similarly, in drive technology the energy storage facilitates the ride-through capability in case of a network fault.

5 Power Electronic Building Blocks

5.1 General motivation

"Power Electronics Building Block (PEBB) is a broad concept that incorporates the progressive integration of power devices, gate drives, and other components into building blocks, with clearly defined functionality, that provides interface capabilities able to serve multiple applications. This building block approach results in reduced cost, losses, weight, size, and engineering effort for the application and maintenance of power electronics systems. Based on the functional specifications of PEBB and the performance requirements of the intended applications, the PEBB designer addresses the details of device stresses, stray inductances, switching speed, losses, thermal management, protection, measurements of required variables, control interfaces, and potential integration issues at all levels". When designing Distribution-FACTS or FACTS Controllers it is beneficial to make use of existing devices and widely used converter concepts in order to benefit from the advantages a mass-market application offers, such as maturity, reliability, serviceability and cost.

The Power Electronic Building Block (PEBB) concept meets these requirements. It is being promoted by manufacturers and organizations, such as the US Office of Naval Research (ONR) in order to develop standardized and universally applicable intelligent power modules. However the universal applicability will in practice only be achieved to some extent due to dependency of the PEBB characteristics on devices and topologies for example.

The PEBB design approach is as follows:

- PEBBs have a standardized *power interface* and a *control & protection interface* allowing the flexible usage in different applications. They also need to fit to the cooling system and environmental conditions of the converter system.
  Via the power interface they are connected to the other PEBBs and via the control & protection interface they communicate with the supervising control & protection system of the overall converter system.
- PEBBs must already contain a certain amount of "intelligence" implemented in digital and analog electronics in order to carry out fast control, protection and monitoring routines. Therefore they can also be described as fully operational and intelligent building blocks.
- PEBBs may be single-phase, two-phase or three-phase depending on the application. The converter type may be line-commutated or self-commutated. PEBBs may be connected with or without magnetics (reactors, transformers). The connection may be in parallel or in series.

As described in the previous sections there will be various increasing applications for FACTS-Controllers in distribution and transmission systems. This requires easy adaptability of the power electronic system to the specific needs (power rating, redundancy, reliability, electromagnetic compatibility, etc.). Due to its inherent flexibility the PEBB concept is especially well-suited to offer necessary platforms. Development time and engineering work can be reduced. The PEBB concept will also promote the usage of standardized control schemes in the overall converter control & protection system. The control software will have to be compatible to major simulation programs being used for control- and system-studies. In line-commutated converter applications such as SVC or HVDC the thyristors are grouped together in modules on a per-phase basis. In HVDC applications modules are connected in series in order to realize the required high dc-voltage. These modules may be regarded as PEBBs, since they fulfill major prerequisites according to the PEBB-definition.

As already shown in several Figures, the PEBB-concept can be applied to realize a high-power multi-pulse converter system, which causes very low distortion currents in the network. The reason is that a desired voltage waveform can be approximated very closely in a stair-case-wise fashion. Examples are shown in Figure 5-1 and Figure 5-2; see also [50], [82], [83], [91] for applications in static frequency converters for railway systems. This is in contrast to the approximation via PWM with a two-level converter as presented in Figure 4-3, which in general requires filter circuitry in order to assure network compatibility with respect to network current and voltage distortion. As stated before, due to their versatile operational characteristics, such as operation in all 4 quadrants of the p/q diagram, black-start capability and capability of active filtering and load / voltage balancing Voltage-Sourced Converters (VSCs) consisting of self-commutated devices and therefore PEBBs based on VSC-technology will be of increasing importance.

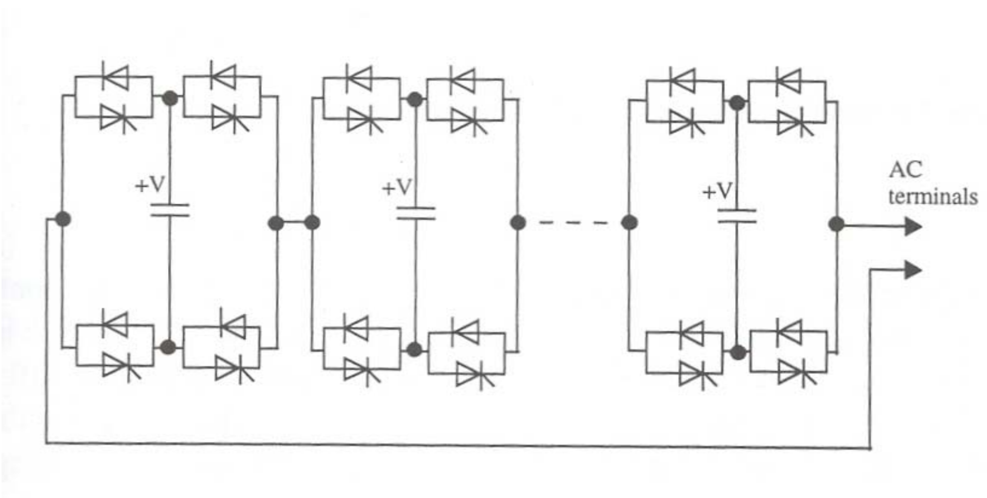


Figure 5-1: Direct series-connection of PEBBs (“chain-link”)

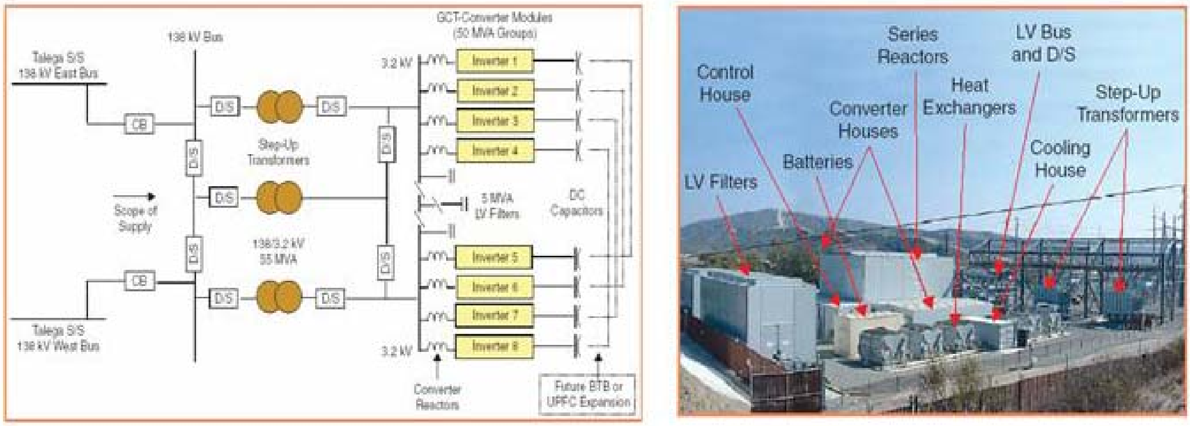


Figure 5-2: 2x50MVA STATCOM consisting of eight 12,5 MVA 3-level VSCs [50]

5.2 Definition of the Power Electronics Building Block (PEBB)

One important PEBB concept is promoted by manufacturers and organizations, such as the US Office of Naval Research (ONR), in order to develop standardized and universally applicable intelligent power modules [95] - [98]. The concept of this concept is outlined in the following paragraphs.

The “Power Electronics Building Block” (PEBB) concept incorporates the progressive integration of power devices, gate drives, and other components into building blocks, with clearly defined functionality and interface capabilities able to serve multiple applications. This building block approach results in reduced cost, losses, weight, size, and engineering effort for the application and maintenance of power electronics systems.

Based on the functional specifications of PEBB and the performance requirements of the intended applications, the PEBB designer addresses the details of device stresses, stray inductances, switching speed, losses, thermal management, protection, measurements of required variables, control interfaces, and potential integration issues at all levels”.

5.3 Power Electronics Building Blocks: A platform-based approach

High level of R&D investments are linked to power semiconductor innovation, which explains why the power semiconductor industry focuses its efforts in this power range on the most promising turn-off power semiconductor technologies, i.e. the IGBT and the IGCT.

Another demanding R&D effort is linked to the PEBB development itself, i.e. the application of power semiconductor in combination with the topology choice. Again the high volume applications try to optimize this step. The variety of different topologies is kept low with the dominant designs being 2-level or 3-level VSC design in the low to medium power range.

Many industries have adapted successfully a platform-based approach for their products. Perhaps the best-known example is the automotive industry. By means of the platform-based approach this industry, operating in a highly competitive environment, successfully reduced the complexity in the design process and enabled effective partnerships on subsystem level due to clearly defined building blocks with their functionality and interfaces.

A platform-based approach requires the definition of basic building blocks with defined functionality and interfaces. Therefore, when taking this approach with any power electronics system it is desirable to separate a power electronics system into its key functional components (basic building blocks), i.e. control and power conversion. The power of the platform-based approach can be deployed, if these basic building blocks are consistent with one another, have a defined functionality and defined or even standardized interfaces. Regarding the power electronics part the Power Electronics Building Block (PEBB) is one of these key functional components, which enables a platform-based approach in power electronics. The other key functional component to reach an efficient platform-based approach is the control (Power Electronics controller), which includes the control hardware and software.

The platform approach serves to reduce the costs a) in mature applications (like adjustable speed drives and rail propulsion drives) due to the achieved standardization, and b) in emerging applications (like distributed power generation and FACTS) due to lower development costs. The R&D can focus on the “missing” application knowledge by using already developed and field-proven building blocks in the power conversion and control area, rather than developing everything from scratch for every new application.

5.4 PEBB based power electronics systems

The goal of PEBB based power systems is to make it possible to integrate identical basic building blocks as major components of the final application. Interconnecting PEBB units creates specific system configurations with various power level ratings. Together, the aggregate of these basic building blocks form a complete PEBB based power electronics system, including mechanical, cooling, power, auxiliary power, and controls system interconnections.

The functionality of a PEBB, as a basic building block, can be defined as power conversion (single phase or multiple phases) including

- power supply for gate drives & sensors
- stack or module assembly including gate drives
- voltage, current and temperature sensors incl. A/D conversion of sensor signals
- switching control incl. pulse generation for gate drive
- communication with control and primary protection.

The interfaces of a PEBB can be defined as follows:

- auxiliary power interface
- control interface
- cooling interface and
- power interfaces.

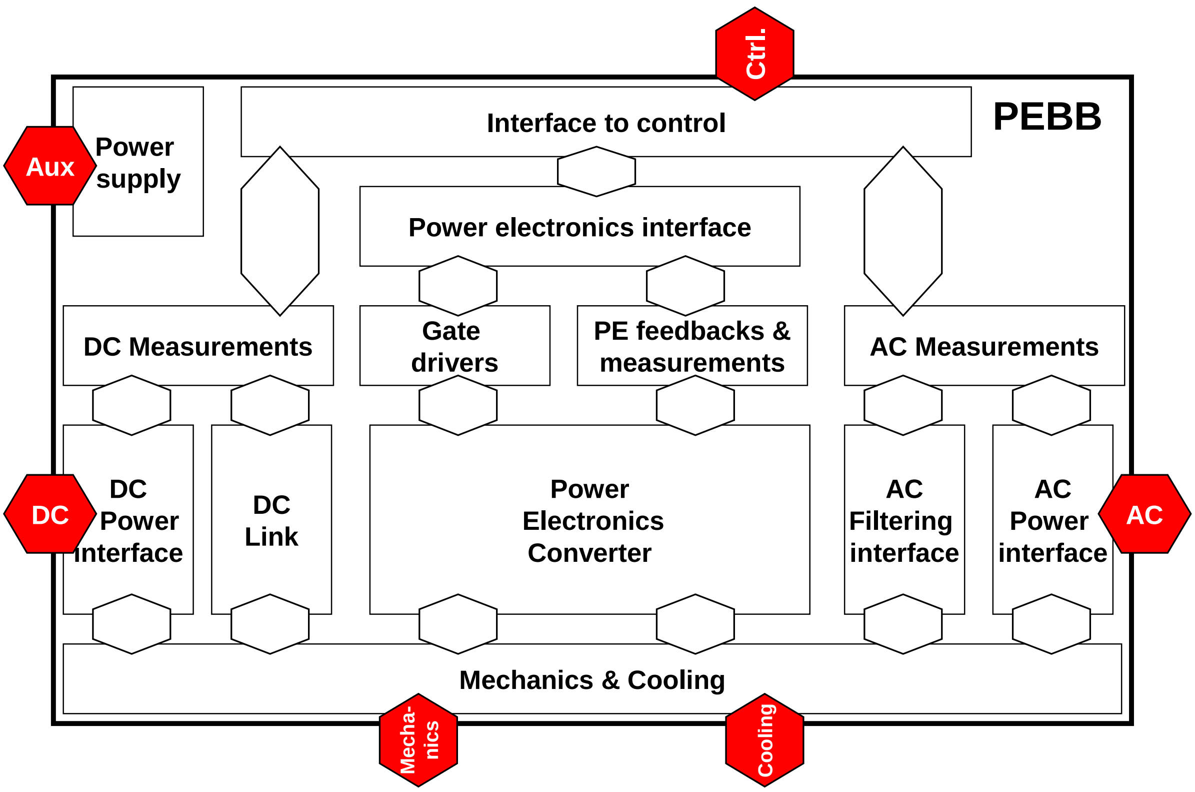


Figure 5-3: PEBB functionality and interfaces

With this proposed definition the complexity of power electronics systems can be reduced due to basic building block and interface definitions. It is important, that the overall PEBB systems control architecture has the inherent capability of supporting the integration of these multiple blocks, regardless of their configuration.

When the control functions of many different power electronic systems are investigated and evaluated, a significant degree of common functionality emerges, irrespective of the target application. Using the concept of system levels (or layers), it is possible to develop a hierarchical control architecture for the PEBB based power electronics systems.

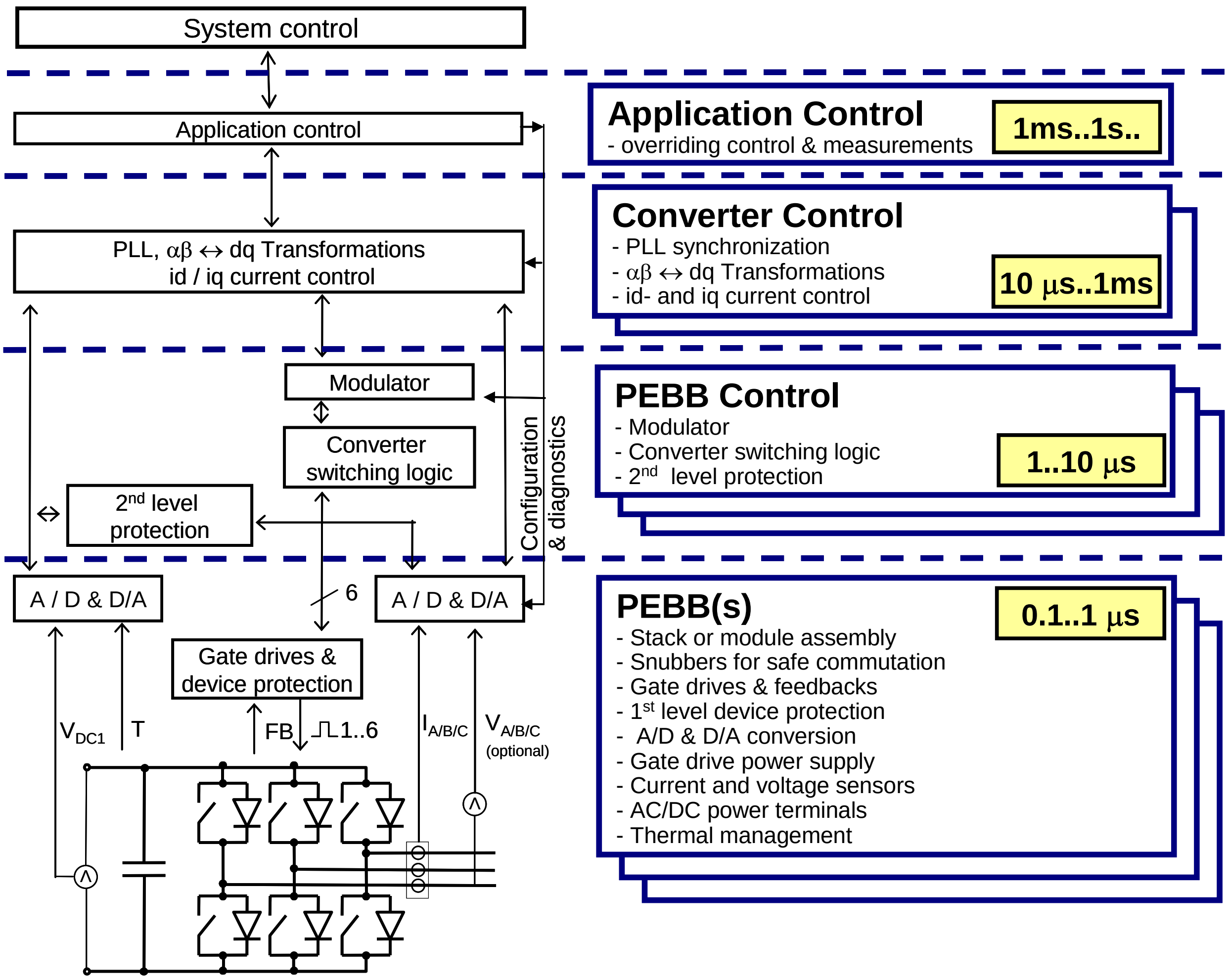


Figure 5-4: PEBB functionality and interfaces

In order to exploit commonality in the architecture of PEBB based power electronics systems for multiple applications, consider the division of the PEBB based system architecture into four distinct layers.

System Control Level

Includes overall operational control and coordination of this particular power electronics based PEBB system within a complete system or network.

Application Level

The application level determines the overall mission of the system. This level is specific to the application and establishes the objectives and goals for the system. There may be some common elements at the systems application level, such as the measurement and calculation of voltages, currents, and power levels.

Convertor Control Level

The convertor control level is responsible for maintaining such functions as synchronous timing (PLL), current and voltage filtering, measurements, control, and duty cycle calculations. The functional controller level will have some common functions depending on the particular target application.

PEBB Control Level

The PEBB control level will contain the many common functions irrespective of the final applications. The functions include switching or modulation control, and pulse generation

PEBB (s) Level

The PEBB (s) level includes the power electronics and may exist as a multiple modules depending on final power configurations. Gating, measurements, galvanic isolation, safe commutation (limits of di/dt dv/dt etc.), and 1st level protection are functions of the PEBB level and will be common for virtually any PEBB based target application. The partitioning of a system into these levels is illustrated in Figure 5-5. This clear definition of functionality and interfaces is the base for the targeted platform based approach to power electronics systems.

For applications from 1 MVA upwards the definition of a PEBB in a power electronics system should include the PEBB and the PEBB control level. This concept includes the standardization of the demanding control interface of a PEBB and its implementation in a cost-efficient way by means of a serial bus interface. Future Work, especially in IEEE Working groups, is targeting the further standardization of the interface between the intelligent PEBB and the control system.

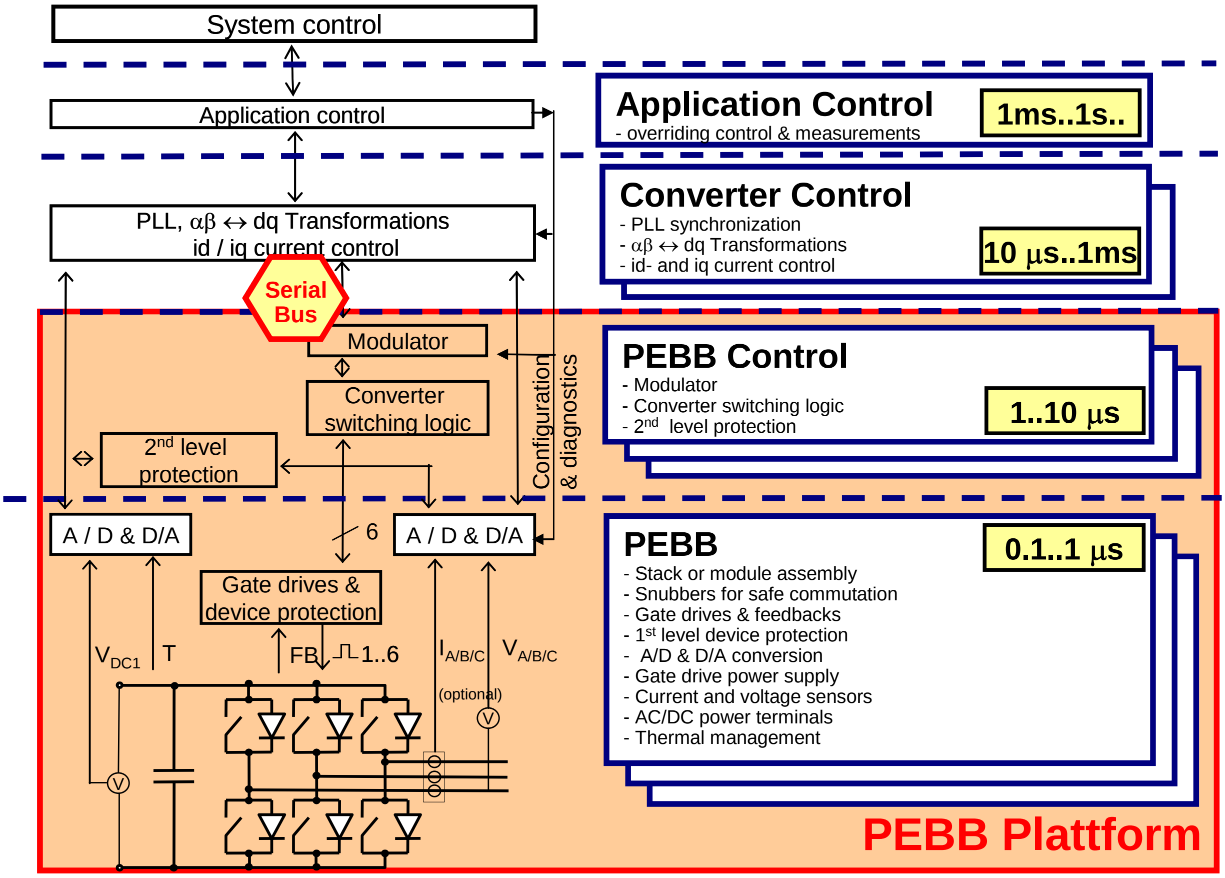


Figure 5-5: PEBB functionality and interfaces

5.5 NPC IGCT PEBB technology and FACTS applications

5.5.1 The NPC IGCT PEBB

Based on the IGCT technology a NPC IGCT PEBB, serving multiple medium-voltage applications, has been introduced to the market and the first commercial installations were commissioned in the year 2000.

The maximum output power of the water-cooled NPC IGCT PEBB in a 3-phase configuration is in the range of 9 MVA. The NPC IGCT PEBB is a highly compact, highly reliable and efficient medium-voltage design, which defines the basic metrics for any competitive solution in this field. The system voltage with the 4500 V or 6000 V IGCTs is limited to 3300 V or 4160V correspondingly.

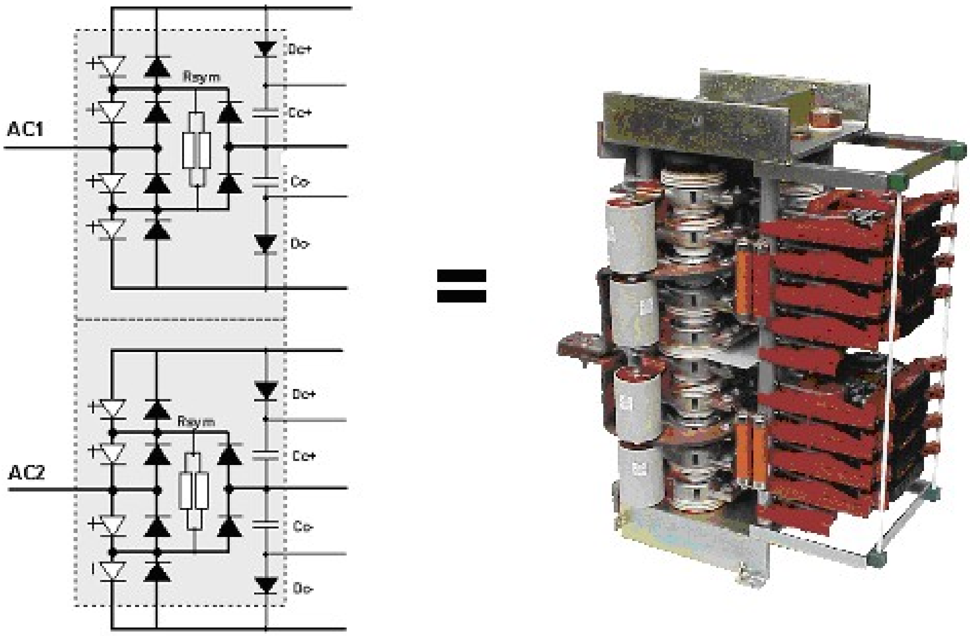


Figure 5-6: NPC IGCT PEBB – a leading edge PEBB based on medium-voltage IGCT press pack technology [87]

5.5.2 Applications of the NPC IGCT PEBB

The NPC IGCT PEBB has been successfully introduced into the market to serve highly demanding medium voltage drives applications. It is successfully used in a 9 – 27 MVA modular medium-voltage drive product, i.e. ACS6000, for various applications including rolling mills, marine propulsion and other demanding industries.

Figure 5-7: ACS6000 – Modular Medium Voltage Multi-Drives [87]

Derived from the high volume medium voltage drive products, the NPC IGCT PEBB technology has been successfully transferred to multiple FACTS applications, i.e.

- 15 MVA back-to-back inter-tie to connect the 50 Hz grid and the 162/3Hz grid of European traction systems,
- 60 MVA energy storage systems based on NiCd battery technology to enhance grid stability
- 22 MVA Dynamic Voltage Restorers to safeguard the highly critical processes of a semiconductor plant.

These new FACTS applications have benefited from substantially lower development costs. The R&D was able to focus on the "missing" FACTS application knowledge by using already developed and field-proven building blocks in the power conversion and control area, rather than developing everything from scratch again.

Figure 5-8: Back-to-back intertie based on the NPC IGCT PEBB [87]

5.6 Importance of the PEBB concept to FACTS controllers

As described in the previous chapters there will be various increasing applications for FACTS-Controllers in distribution and transmission systems. This requires easy adaptability of the power electronic system to the specific needs (power rating, redundancy, reliability, electromagnetic compatibility, etc.).

Due to its inherent flexibility the PEBB concept is especially well-suited to offer necessary the power platforms:

- low voltage IGBT PEBBs, based on IGBT module technology, can be used up to 2-4 MVA. At higher power level the current are getting high, and the short-circuit currents are getting critical to handle.
- Medium voltage IGCT PEBBs, based on press pack technology, have commercially proven their usability up to power levels of 60 MVA.

In the ultra high power field above 100 MVA the utilization of PEBBs established in other high volume applications is much less likely. Special PEBBs are developed for these applications, but nevertheless the standardization of the PEBB concept is visible in many of those.

5.7 Summary and outlook

In summary, the important question in connection with the PEBB approach is, how the development of new technologies might impact the different application areas and engineering disciplines. Table 5-1 gives an overview on factors and issues related to PEBB.

Table 5-1: Summary of driving factors in the context of PEBB

Factors promoting Modularization of Power Electronic Systems	**Factors detracting from Modularization of Power Electronic Systems**	**Issues relating to Power Semiconductor Devices**
Maintainability of systems – replacement of the smallest replaceable module		*Utilities desires replacement of semiconductor devices from multiple sources to enhance maintainability of systems and to avoid being forced to buy all future replacement parts form one vendor*
Reliability: N-1 or N-2 system design		

Factors promoting Modularization of Power Electronic Systems	Factors detracting from Modularization of Power Electronic Systems	Issues relating to Power Semiconductor Devices
	Losses – design optimization meeting the users' loss evaluation criteria (different fuel mix or trade-offs between capital resource demands and operating costs) often leads to quite different product designs	*IGBT or similar devices in PWM systems operating at high switching frequencies but at higher losses versus lower loss thyristor based systems are part of these tradeoffs*
Standardization of dc voltage and current ratings, as well as insulation test levels	*Relatively few systems being built does not lead to economies of scale and relative ease of tailoring semiconductor devices to meet power and ac system requirements enablers the buyers and suppliers to optimize the system design for overall economic benefit to booth parties*	*R&D leading to constant improvement of the performance of semiconductor technologies/devices requires the suppliers to use the latest technologies for every new project to stay competitive*
	Utilities' practices of developing comprehensive specifications for competitive solicitations and use of consulting firms for this sometimes leads to overly detailed specifications and over-design of system	
A small set of experienced consulting firms tends to promote similar specifications for projects enabling the manufacturers to better plan products offerings		

6 Enabled new devices and design impact on substations

The discussion of system integration and design impacts on substations, driven by new generations of power semiconductors, is a broad area that requires an interdisciplinary consideration from both perspectives: *what is possible and what are the implications on substation design.*

This chapter starts with two application examples on the question "what is possible" on a high level. Here it will be outlined how the combination of power electronic components with conventional equipment, station cost can be saved and existing facilities become integral component of tailor-made FACTS devices. Two examples for tailor-made FACTS devices, the Hybrid Power Flow Controller and the Unified Voltage Controller, show the efficiency of the proposed approach. In comparison to full-size equipment the „thyristor assisted substation solution" appears to be superior since control tasks can be optimally met with less equipment. The control systems for a tailor-made FACTS device comprises field proven components of conventional FACTS device controllers and those of mechanically switched facilities. Only a few modifications are required to ensure a coordinated operation.

Some applications within substations of new power electronic devices have been discussed already – they will be mentioned within the next chapters. However, the major contribution for this chapter comes from WG B3.01 TF 4 which is looking on the future requirements from the substation perspective [99]. In this chapter it is assumed that power electronic systems based on new generations of power semiconductors can provide new functionalities in the grid and can increase the overall system efficiency. However, substations are needed in any case to provide grid integration to new technologies. Subsequently, the discussion on the design impact on substations focuses on how to deal with new functionalities in substations. Major references for chapters 6.2, 6.3 and 6.4 are [100] - [105].

6.1 Hybrid approaches – Example FACTS devices

Much research has been directed to point out the operational benefits of Flexible AC Transmission System (FACTS) controllers as a "stand-alone" device [106]-[109]. A well known FACTS device concept is the Unified Power Flow Controller (UPFC) [106], [107] which provides unique capabilities of controlling active and reactive power flow as well as line voltage. The inserted series voltage can be controlled independently of the terminal voltages of the UPFC, although for power flow control only a subset of the achieved control region is required. This over dimensioning can be avoided by more detailed diversification of the required functionality which leads to more tailor-made FACTS devices. This concept is enabled by new generations of power semiconductors.

In this chapter tailor-made FACTS device solutions are presented for which device functionality can be optimized by the combination of basic converter modules. Furthermore, effective network utilization with tailor-made FACTS devices can be achieved while incorporating existing primary equipment in substations. The numerous controllable devices available today (i.e. switched series compensation, tap changer etc.) whose control capabilities can be improved by adding FACTS device components indicate the potential for hybrid FACTS solutions. To underline the design philosophy two examples for hybrid tailor-made FACTS devices are given, namely the Hybrid Power Flow Controller and the Unified Voltage Controller.

6.1.1 Technological basis

Hardware

The technological basis for the development of tailor-made FACTS devices is assumed to be a voltage source converter (VSC) with high power ratings. By converting direct current to alternating current quantities, with respect to magnitude and phase, a VSC acts like a voltage source injecting an AC-voltage or AC-current in series or in parallel to transmission devices. Resulting from this technology the UPFC serves as benchmark device. Prior to the UPFC concept much research effort has led to a technique of series compensation superior to switched capacitors or controlled reactors. VSC operation is almost independent of the line current. As a result of the progressive developments in the field of power semiconductors series connected stacks are possible. This technology heralds the third generation of FACTS devices which do not require bulky components like booster transformers or large filters [111].

Additionally, this technology opens new possibilities with the combination of conventional equipment and power electronic based components for rapid power flow and voltage control (Figure 6-1) and hence functionality of existing devices can be optimally extended. The VSC modules can also be placed on high voltage potential as well as on low voltage potential which will reduce the insulation level and hence equipment cost. The overall size of additional apparatus can be reduced due to hybrid control schemes, comprising mechanical tap changers or switched capacitors as well as fast acting VSC equipment.

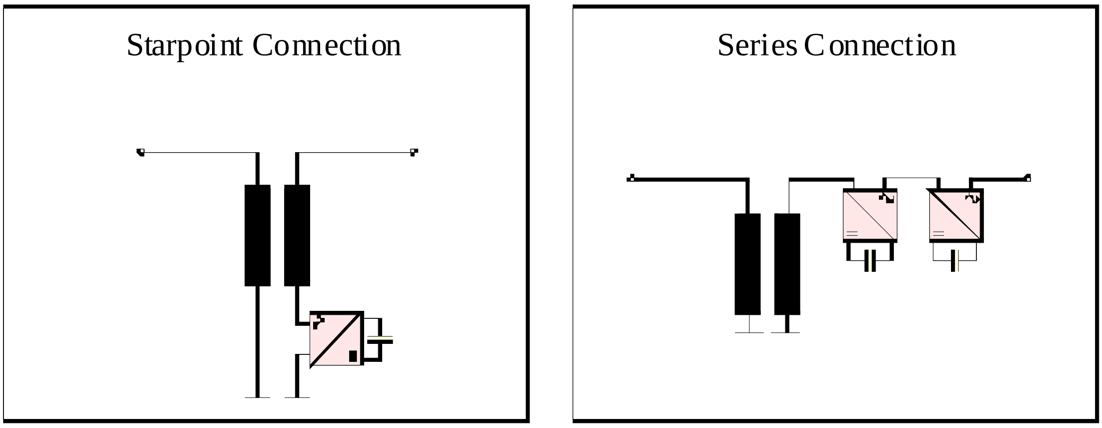


Figure 6-1: Examples of transformerless VSC configurations

The three phase transformerless infeed at the starpoint of a transformer is one example for a cost effective solution for series voltage injection. For the case of retrofitting a transformer to enable control actions in the short term time range, only small modifications are required. In case of large single phase transformer units the VSC modules can be directly connected.

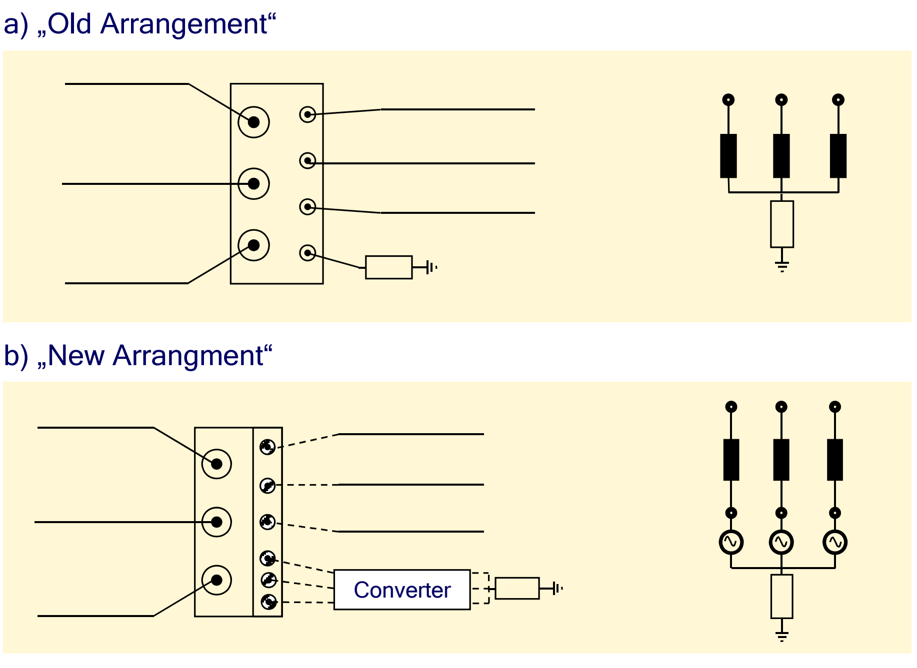


Figure 6-2: Principle sketch of a starpoint connection of a converter

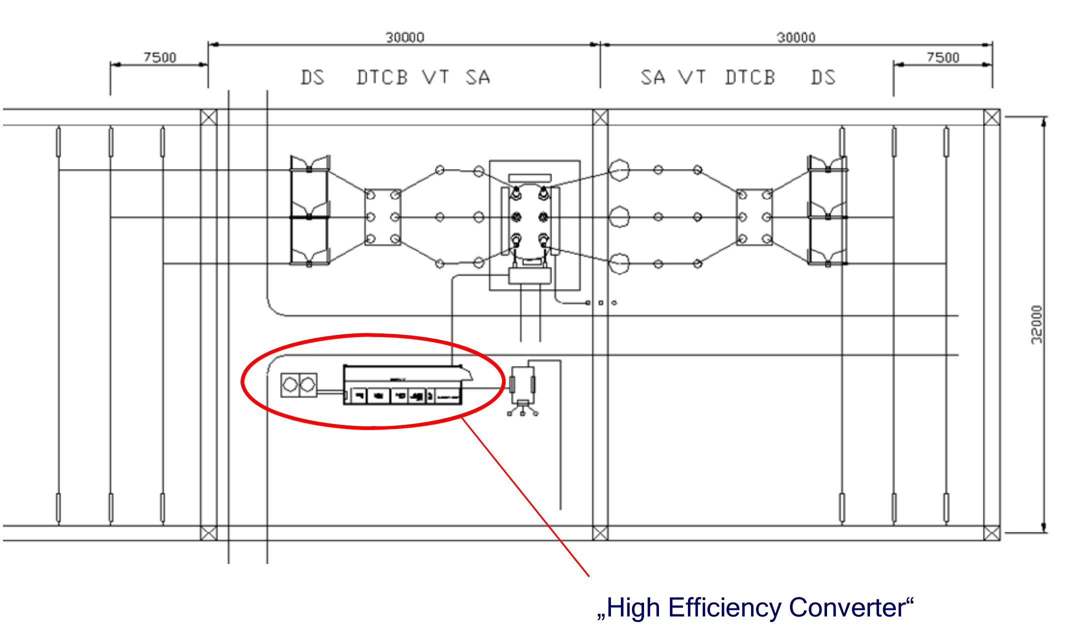


Figure 6-3: Example of a footprint of a station layout with hybrid power flow controller with a converter based on new generations power semiconductors

The economical benefit is achieved through savings resulting from reduced equipment requirements for specific control. This measure is not limited to series voltage injection into the neutral point of the secondary winding. For example, VSCs as external circuit elements of the tertiary winding are suited to control the DC-Voltage of a secondary winding connected VSC. This is mandatory in case of active power infeed into the controlled winding. This concept can be applied to three phase systems as well as to single phase systems even in terms of refurbishing existing plants.

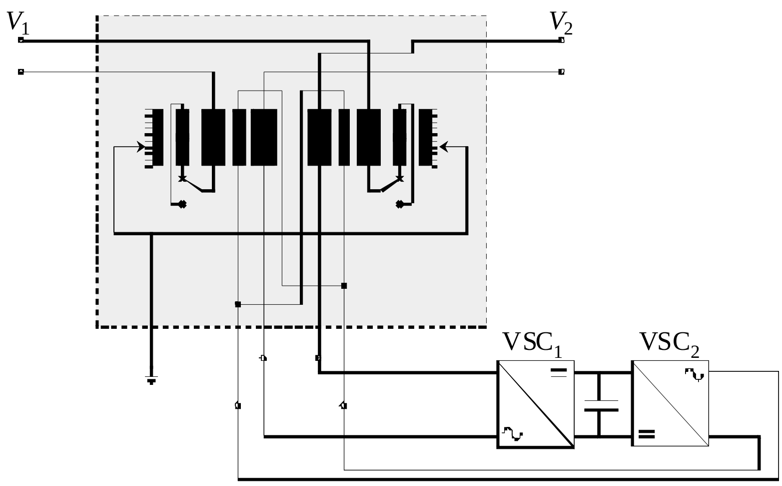


Figure 6-4: Transformerless voltage injection

Against this background the definition of Flexible AC Transmission System devices is expanded to encompass intelligent network nodes. These are optimized power electronic assisted substation systems aimed at power flow control as well as voltage control and active filtering for more effective network utilization in a deregulated environment and large system extensions projects.

Operational Objectives

Power flow control by means of VSC technology is based on a series injected voltage that can be controlled in phase and magnitude. In terms of vectorized quantities the in-phase voltage injection affects the reactive power flow, while quadrature injection allows for active power flow control or phase angle control. In networks with small R/X-ratio the active power flow through voltage angle control is decoupled from control of reactive power by means of voltage magnitude control. High R/X-ratios prohibit decoupled active and reactive power flow control for the same reasons mentioned above. Decoupled control of active and reactive power then requires the simultaneous control of angle and magnitude.

The decisive factor for active or reactive power output of the series connected VSC is the phase angle between the line current and the series injected voltage. In case of series voltage injection perpendicular to the line current only a power exchange between AC and DC circuit with the double network frequency takes place. Assuming a load angle with $\cos\phi \approx 1$ this operating mode represents pure quadrature control.

In combination with, for example, a mechanical tap changer, angle control and hence decoupled active reactive power flow control becomes possible. If the series injected voltage is not perpendicular to the line current the VSC feeds active power into the line. The active power output is taken from the DC circuit and affects the magnitude of the DC voltage. Since the VSC operation depends on an almost constant DC voltage the active power has to be taken from an additional source, e.g. the tertiary winding of a transformer as shown in an application example in Figure 6-4. Although the dimensioning procedure for both steady state flow control and transient stability enhancement differ from each other, the basic ratings can be obtained by estimating the impact of voltage magnitude on active power flow shift [112].

6.1.2 System design issues

The most important control tasks in power systems with enhanced flexibility are active power flow control and voltage control. As an example of tailor-made devices fulfilling the requirements for control tasks resulting from specific operational improvements the Hybrid Power

Flow Controller and the Unified Voltage Controller are discussed in more detail. Both controllers comprise VSC modules which are optimized in terms of number and ratings and are ideal for integration with conventional equipment even in case of retrofitting.

Hybrid Power Flow Controller

Series voltage injection for power flow control purposes is in conjunction with series power injection. The operational devices which are suitable for rapid active power flow control are theoretically well studied. However, for practical application one has to evaluate these approaches with respect to their economic benefits. On the one hand devices like the UPFC appear to be over dimensioned for the task of pure active power flow control. On the other hand power flow controllers based on VSCs for series compensation like the voltage sourced series compensation appear to be dependent upon the phase angle of the line current. Mechanically switched phase angle controllers will not fulfill the rapid response time requirements.

An optimum solution for this problem is a hybrid power flow controller which can be realized by means of conventional equipment i.e. on load tap changers and optimized VSC modules. For this approach the fast control action required is provided by starpoint connected VSC modules. Independence from the current angle can be assured by adding further VSC modules feeding the DC circuit. The steady state power flow is controlled by a combination of changing the tap position and the magnitude of the series injected voltage (Figure 6-5).

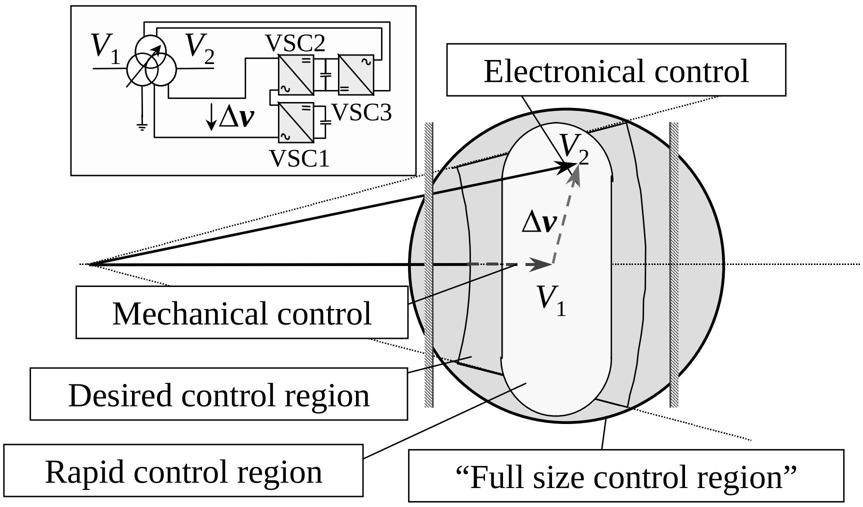


Figure 6-5: Hybrid Power Flow Controller

The desired control region is specified by maximum angle and maximum magnitude variations of the secondary voltage of the transformer. The VSC modules provide for suitable series injected voltage independent from the line current angle for fast control action. The rapid control region allows for power system damping as well as for steady state pure active power flow control. This control region can be shifted along the direction of the primary voltage by changing the tap position and can be temporarily enlarged due to the overload capacity of the VSCs. The „Full size control region“ would be achieved by means of a UPFC. In comparison to the UPFC the Hybrid Power Flow Controller fulfills the basic demands by its tailor-made system design and is proven to be the more economic solution. Furthermore, the hybrid solution provides control capabilities - even in the case of a failure in the power electronic modules - and hence has an increased availability.

Unified Voltage Controller

Despite the possibilities made available by rapid power flow control voltage control is also a very important countermeasure for reactive power conditioning as well as for disturbances in the system voltages. Originally developed for balancing unsymmetrical voltages the Unified Voltage Controller’s (UVC) control capabilities allow also for rapid power flow control (Figure 6-6).

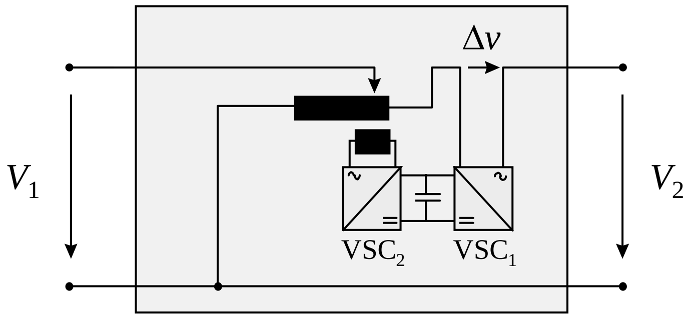


Figure 6-6: Unified Voltage Controller

The basic components of the UVC are an auto transformer with galvanic decoupled tertiary winding and two VSCs. VSC_1 is connected directly in series in order to act as a series injecting voltage source. VSC_2 caters for active power provision to the DC circuit. The rated power of VSC_1 is typically higher than the rated power of VSC_2. The maximum control range with respect to the voltage control magnitude is determined by the winding ratio of the auto transformer. For large control regions, the auto transformer can be equipped with an additional thyristor or mechanical tap changer. The combination of a high speed tap changer with VSC modules provides smooth control operation in the short term time range within a wide control region (Figure 6-7).

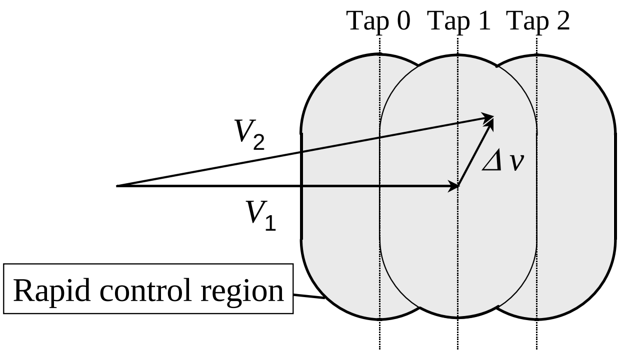


Figure 6-7: Vector diagram UVC with high speed tap changer

With only three tap positions a 100% increase of the rapid control region is achieved without loosing the smooth control capability. The control philosophy is equivalent to the above mentioned scheme realized for the Hybrid Power Flow Controller.

For economical reasons the structure of the UVC appears to be superior to „full sized" equipment. In comparison to the well known equipment for decoupled power flow control, only an auto transformer is needed instead of booster and shunt transformers.

6.1.3 Control system

The control tasks related to power flow control are solved according to their time range. In the control centre, algorithms within the short term optimization procedures serve to determine suitable set points for the decentralised FACTS device controllers [115], [116]. The set points are expected to be determined according to the short term optimization being performed every 15 minutes in the control centre. Locally, the control system provides set point control as well as power system damping. The latter task requires rapid controller response which is possible within milliseconds. For tailor-made FACTS devices the general structure of the control is similar to full-size FACTS devices like UPFC or voltage sourced series compensation. Due to hybrid solutions the control system has to be designed for achieving the control demands resulting from electronic and mechanical components. As an example, the basic control scheme for a Hybrid Power Flow Controller comprises shunt and series converter control as well as a tap change control.

Control systems for different solutions can be derived from this structure. The core components of the proposed control system are couplings between the tap changer controller and the converter control. During steady state operation the power output of the series connected VSC is minimized in order to maximize control capability during the transient operation mode. Furthermore, this device operates at minimum converter losses since in steady state operation the series converter feeds only reactive power into the line and the shunt converter is adjusted to minimize thyristor currents.

Under steady state conditions, the shunt controller is responsible for controlling the DC voltage. The tap position is optimally adjusted and the shunt converter has to compensate for the lag between the discrete tap positions. For dynamic purposes, the shunt controller can be included into the control concept of the underlying damping circuit. Limited to the maximum converter power, the controller outputs are sent to the pulse width modulator and gate control unit which then directly feeds the trigger signals to the converter modules.

6.2 Generalized Impact of new technologies on substation design [99]

The providers of new functionalities and substation designers are challenged to provide interfaces and application hints for ensuring optimal integration into substation design. This task however aims at opening the door towards a more modular design practice for faster and easier adaptation to changing needs as well as optimized design practice to take full advantage of new technologies.

However, there are both technical and cultural challenges to address before these technologies become more readily accepted,

- Resolving the complexities of interfacing between new and legacy technology, particularly for secondary systems.
- Need for solutions and techniques to minimize outage duration
- Impact of new technology on existing substation access practice and maintenance regimes.

As outlined in the previous chapters the rapid development of power electronics technology provides plenty of opportunities to develop new power system functionalities and equipment to address new needs of the grid or to mitigate existing challenges. During the last decade a number of functionalities and technologies have been proposed and implemented.

While system aspects of new functionalities (that can be provided by new generations of power semiconductors) and technical details of solutions have been broadly investigated, there is still an information gap regarding how to integrate new functionalities into a substation. One of key futures for power electronics will be to provide the interface between the existing power system and many of the emerging applications such as PV, energy storage and superconductivity.

Power electronics conjures a number of concepts namely Flexible AC transmission systems (FACTS), HVDC and Custom Power, which employ voltage and current source converters based on silicon switching to provide a variety of functions.

The new functionalities within substations that might require drastic changes in engineering philosophy, processes and operation are expected to come – as far as power electronic applications are of concern – out of the following areas:

- FACTS and HVDC in general
- Custom Power devices
- Reactive compensation with power electronic components
- Dynamic compensation
- Mixed technology switchgear
- Fault current limiter
- Energy Storage
- Superconductivity

6.3 System impact on substations [99]

New functionalities are either designed to control the basic parameters of the system (to give control over voltage, fault level, power flow or even short term frequency support), or in the case of distributed generation inherently make major changes to the way in which an existing distribution system will behave.

Dispersed generation may be constituent of many different types, such as wind power, photovoltaic, small diesels, fuel cells etc. The generation may be connected at different voltage levels within the distribution network and may be three phase or single phase connected. This gives rise to a whole range of impacts upon the performance of the system including voltage regulation, voltage unbalance, harmonics, frequency variation, power flow direction, short circuit current levels and fault detection.

From the above it is clear that the changing nature of generation will have a profound impact upon the design of substations remote from the immediate point of connection of the new devices. Studies will be required to investigate the transient conditions on these networks to ensure that hunting does not occur when the system is disturbed.

The increase of remote generation (possibly even offshore) is going to require additional reactive compensation to enable transmission to the load centers, this may be a an area where power electronic solutions become popular whether it's HVDC in either form or dynamic compensation to provide fault ride through capability.

All this reactive compensation could increase the risk of resonances on the network and the drive for low loss equipment is reducing the overall system damping. Generally the corrective measures should be connected locally to the device which is causing the effect so that the substation affected will be the one which includes the new device. The more advanced applications with sophisticated control system should be designed to neutralize any potential resonance effects

The developments in wide area control and protection will also start to emerge as system operators are faced with more dynamic networks and large scale interconnection. The communication necessary to support these developments will require secure and reliable infrastructure.

The existing infrastructure is also going to have to cope with these increased power transfers, so networks will be trying to increase circuit capacity through either series compensation or real time monitoring to enhance ratings all, of which stresses the system more than ever.

New technologies and integrated applications will affect the insulation coordination dynamics. Application of surge arresters and controlled switching to ensure satisfactory surge protection will be required. This is particularly important for electronic components, which have a very low tolerance to overvoltages.

6.3.1 The impact on the single line diagram

If we look at the effect upon the single line diagram (SLD) of the substation then one of the immediate effects may be the short circuit rating required for the plant within the substation. Depending upon the device being connected this may require an increase in short circuit level or in some cases (fault current limiters) may enable simplification of the SLD by allowing greater bussing of equipment without too many sections.

The increase in harmonics on the network may give rise to a greater need for filters, either passive or active. For substations incorporating new technologies consideration needs to be given to the operation and running arrangement when the device has to be disconnected for maintenance or under fault conditions. Reducing the duration of outage or bypass arrangements may be required and care needs to be taken with the protection arrangements to cover both conditions. Any element of wide area protection will also need to coordinate with these changes.

6.3.2 Bay level changes and design trends

While new functionality is employed to affect system level attributes fault level, power flow etc, it is invariably going to have a significant impact at the bay level.

Environmental factors

Once the SLD is defined, consideration has to be given to the detailed design requirements of all aspects of the substation and equipment. Space is an obvious limitation in most substations where new equipment needs to be installed. The space requirements need to consider the connectivity required with other plant items, the required electrical clearances, clearance required for electromagnetic effects, access for initial installation and maintenance. The impact on civil works may include oil containment and fire requirements if the new devices introduce oil immersed transformers and if air cored reactors are present care has to be taken with the reinforcing bar arrangements, structures and earthing to avoid heating from closed loops.

Metering for tariff purposes must not be adversely affected. The control system connections, cable and fiber optic must be designed to ensure that they are immune to interference. Special care is needed in the design of the earthing system, to ensure safety whilst avoiding interference into control circuits and avoiding large circulating currents from flowing due to electromagnetic induction.

Operation

Maintenance techniques and procedures may need to be reviewed, when novel technology is introduced into a substation. This will also require training. Where diagnostic tools are employed such as condition monitoring or analysis provision for maintenance or calibration of these services will need to be made (exchanging one maintenance intensive system for another), albeit the latter does not tend to incur outages.

New skill sets required by substation staff, particularly in the field of information systems and possibly software programming. Staff will need to be IT literate, to interrogate secondary systems, implement test procedures and perform diagnostics on substation automation.

Increased pressure on auxiliary systems. Largely forgotten until too late, but there is an increasing demand and dependency on DC supply. Additional AC supplies will be required for cooling of components, additional DC supplies for the control and protection. The protection design needs to consider the particular requirements of the new types of device and also the impact these devices may have upon the performance of existing system protections such as distance relays. Interlocking may be required for both operational and safety reasons.

Secondary systems

Substation automation will see the greatest of changes including interfacing new to old legacy wiring, requirement for DC supplies and isolation from instrument transformer secondary's (high impedance) rate of technology obsolescence. Implementation of IEC 61850, utilities need to develop their application requirements and the associated interfaces to any system management tools. Substation communication systems are a major concern. Before many of the new initiates can be considered rules about ensuring secure portals, management of firmware changes, software version control and access must be resolved. Ensuring that utility personnel can interrogate and download fault recorders or setting is necessary, while at the same time preventing unauthorized access.

6.4 Examples for impact analysis of new devices [99]

This chapter deals with custom power technology. Custom power technology is the name given to a group of devices dealing with power quality issues associated with customers. There are various issues associated with power quality at the customer's point of connection to the network. These can broadly be divided into two major groups, namely the effect that a customer's load may have on the network and secondly the effect that poor quality of the network can have on the customer's load. In the first sector the most common problems are flicker and harmonics. In the second sector the most common problems are short term voltage dips associated with fault clearance and also pre-existing harmonics.

There are three devices most commonly classed as custom power devices, one dealing with the first aspect namely the distribution STATCOM (D-STATCOM) and two dealing with the second aspect these being the dynamic voltage restorer (DVR) and the solid state transfer switch.

The idea behind the solid state transfer switch is that the customer's load is fed from two totally independent infeeds. Then if a problem occurs in one of the infeeds the load is transferred to the other infeed in less than one cycle by means of the solid state transfer switch. As the instances where totally independent infeeds are available for a customer such that the event affecting infeed 1 does not also affect infeed 2 are very rare and consequently we do not have any feedback on the usage of this particular device.

The chapter is therefore divided into two parts, one part dealing with the D-STATCOM and the other dealing with the DVR. It looks at the impact that the installation of the device within a substation will have on the system, then on the single line diagram and finally on the detailed substation design.

D-STATCOM

The tables and paragraphs below list a standard set of possible impacts. This chapter explains the impact and provides guidelines on the aspects which may need to be considered. The structure is as follows:

- Basic system changes (Table 6-1)
- Sing line diagram impact (Table 6-2)
- Detailed substation design (Table 6-3)
- Further remarks

Table 6-1: Basic system changes

Impact Index	*Impact*	*Important Notice*
Fault level	none	
Power flow	minor	D-STATCOM can support voltage under steady state and dynamic conditions
Frequency	none	
Voltage	high	The D-STATCOM can vary the VAR injection rapidly and thus compensate for voltage fluctuations including flicker.
Thermal rating	none	
Unbalance	high	D-STATCOM can be used to balance unbalanced loads. If the D-STATCOM is used for this purpose then the impact on unbalance is very high.
Harmonics	high	Design of D-STATCOM using multilevel inverters to reduce harmonic generation should be considered.
Impedance	none	
Resonances	none	
Losses	minor	The transformer and the power electronic components add losses.

Table 6-2: Single line diagram impact

Impact Index	***Impact***	***Important Notice***
Short circuit rating	none	
Operational switching	none	
Filtering	minor	Depends upon the acceptable level of harmonics and the exact type of inverter.
Compensation	high	The D-STATCOM is a form of voltage compensating device.
Installation	high	The D-STATCOM needs to be housed in containers. The design may be modular.
Maintenance	high	The D-STATCOM adds new components which will require maintenance
Bypass	none	
Commissioning	high	Commissioning of the D_STATCOM requires specialist skilled engineers
Insulation coordination	minor	May need protecting by surge arresters if connected in an over-head line circuit

Table 6-3: Detailed substation design

Impact Index	***Impact***	***Important Notice***
Protection (external)	minor	No significant change required to existing circuit protection
Protection (internal)	high	The D-STATCOM itself needs to be protected. Much of this is built into the control circuitry for the device.
Control	minor	The only impact on the S/S control is the operation of the circuit breaker and additional alarms and indications required. Internal control of the device is complex.
Communications	minor	
Land & layout	high	Requires space for the transformer and containers

Impact Index	***Impact***	***Important Notice***
Visual impact	minor	Depends on the site.
External pollution	none	
Audible noise	minor	Additional noise from the shunt transformer and the cooling for the electronics.
EMC	minor	Firing circuits need to be hardened against interference
Electrical clearances	none	
Safety clearances	none	
EM fields	minor	
Civils	high	Requires space for the containers and the transformer.
Containment	none	
Auxiliaries	high	Requires auxiliary power to cool the transformer and the electronics
Equipment ratings	minor	
Busbar layout	none	
Earthing	minor	Equipment requires earthing
Monitoring	minor	In built monitoring with device
Testing	high	Commissioning of the D-STATCOM requires specialist skilled engineers
Relocatability	high	Should be relatively easy to relocate
Spares requirement	minor	Spares required for electronic components
Hazards	none	

Impact on Power Flow

A D-STATCOM is a shunt connected device and its main purpose is to control voltage. However, by injecting VARs at the receiving end of a circuit it has the capability to increase the power transfer capability of the circuit. It can also assist in avoiding voltage instability under outage or fault conditions.

Impact on Voltage

The D-STATCOM is effectively a shunt connected compensation device and has the capability of injecting or absorbing VARs. This means that it can be used to control the voltage at the point of connection generating VARs to increase the voltage or absorbing VARs to reduce the voltage.

Impact on Unbalance

If the D-STATCOM is being used for voltage or flicker control then there will be no effect upon unbalance. However, if the load is unbalanced and this is likely to cause a problem on the network, the D-STATCOM can be used as a static balancer using the Steinmetz principle for balancing unbalanced loads. When used in this mode the balancer can convert any unbalanced load, even if varying continuously with time, to a balanced unity power factor load.

Impact upon harmonics

As the D-STATCOM is a power electronics device it will inherently generate harmonics. Using higher order bridges and multilevel converters can mean that the harmonics occurring at the lower orders is minimal.

Impact on Losses

The D-STATCOM is a power electronics device and there are losses inherent in these devices. Furthermore, there may be fans required or water cooling pumps and these will also increase the losses. Finally if a transformer is required to connect the power electronics then this will also add both no load and load losses.

Filtering

Usually the level of harmonics created by a D-STATCOM is of a significantly lower magnitude than those from a conventional SVC and it is not normally necessary to have filter circuits to deal with these. The acceptable level of harmonics and the pre-existing harmonics will need to be considered and the levels predicted after the connection of the D-STATCOM discussed and agreed with the network operator.

Compensation

The D-STATCOM is a form of compensation device. It will not require any compensation to allow for its connection to the network. If a number of compensation devices exist in close proximity on the network it may be necessary to look at coordinated control to avoid hunting between devices.

Installation

The power electronics will be accommodated in a building or a container. It may have been designed in a modular format so that higher power levels can be created by connecting modules in parallel. If a transformer is required to connect the equipment the space for it will have to be found.

Maintenance

Maintenance will be required in accordance with the manufacturer's instructions. The frequency of maintenance may be reduced if there is redundancy built into the design of the power electronics. Co-ordination of the maintenance periods for the D-STATCOM with those for the load which it is associated with should be considered.

Commissioning

Commissioning tests in accordance with the manufacturer's instructions will be required. A full factory acceptance test (FAT) should have been completed before the device is shipped to site and this will help to reduce the amount of tests required during commissioning. The tests will usually include a functional test to prove that the device is responding correctly to changes in the system voltage.

Insulation Co-ordination

The insulation levels of the components should be chosen according to the network conditions in the usual way. If the device is to be connected to an overhead line network susceptible to lightning strikes it will probably require the use of surge arresters to protect it.

External Protection

The D-STATCOM has no effect upon the external protection other than connection of current transformers into the associated busbar or connections protection.

Internal Protection

The shunt transformer will normally have the usual protection. The power electronics devices are usually protected by the control equipment. Protection is provided to prevent the devices from experiencing excessive voltage or excessive current.

Control

The impact on the substation control is limited to the control status indication and alarms arising from the device. The D-STATCOM will have its own control system which will take in system parameters such as voltage, current, real and reactive power depending upon the exact function of the D-STATCOM. In certain circumstances where there are other compensation devices in proximity it may be necessary for the control system to be coordinated with the others.

Land and Layout

Space needs to be allocated for the containers for the power electronics and for the transformer if required.

Visual Impact

The measures necessary to be adopted will depend upon the particular site. Although containers may be the cheapest housing for the power electronics it may be necessary to consider a building to blend into the surroundings in certain locations. Alternatively the color of the containers may be carefully chosen for the same reason.

Audible Noise

There is likely to be additional noise from the cooling equipment associated with the power electronics. If a shunt transformer is used then this will also contribute significantly to additional noise.

EMC

Screening of the control circuits to the power electronic components may be required to protect them from interference.

Civils

Allowance needs to be made for the foundations for the transformer if required. If the power electronics are in a container rather than a building then compacted hardcore may suffice as the base for the container. Cable trenches may be required between the transformer and the container.

Containment

If an oil filled transformer is used then oil containment will need to be provided. It may be necessary to consider a fire barrier between the transformer and adjacent equipment on other circuits to prevent a fire on the transformer from damaging equipment on the other circuits.

Auxiliaries

The D-STATCOM will require auxiliary ac supplies to feed the cooling equipment for the power electronics. Additional dc supplies will also be required for the control and protection.

Earthing

If the device is star connected earthing of the star point will be required. Earthing of all of the metalwork associated with the device such as containers, panels etc. will require to be earthed. It may be necessary to consider instrumentation earthing in association with the control circuitry.

Monitoring

Usually the control associated with the D-STATCOM will have its own monitoring equipment to ensure the safe and continuous operation of the device.

Testing

In addition to the commissioning testing the device and particularly its control system should undergo a thorough factory acceptance test to ensure that it is functioning as intended.

Relocatability

Since privatization it is becoming an increasingly common request that the equipment should be relocatable. As this device lends itself to a modular construction then it should be a relatively simple exercise to relocate it.

Spares requirements

As the power electronics will be different from any other components already existing on the site it will be necessary to hold additional spare parts. Advice should be sought from the supplier on the quantities of spares to be held.

DVR

The tables and paragraphs below list a standard set of possible impacts. This chapter explains the impact and provides guidelines on the aspects which may need to be considered. The structure is as follows:

- Basic system changes (Table 6-1)
- Sing line diagram impact (Table 6-2)
- Detailed substation design (Table 6-3)
- Further remarks

Table 6-4: Basic system changes

Impact Index	***Impact***	***Important Notice***
Fault level	minor	Introduction of series transformer reduces fault current
Power flow	minor	Increased impedance has minor effect on power flow
Frequency	none	
Voltage	high	The device is capable of injecting up to 50% voltage during faults to prevent the voltage supplied to the load from dipping.
Thermal rating	minor	The series transformer must be rated for the full throughput of the circuit
Unbalance	none	
Harmonics	minor	As the device uses power electronic components there is some increase in harmonics. This depends on the type of inverter.
Impedance	minor	Series transformer increases the impedance in the circuit
Resonances	none	
Losses	minor	The transformer and the power electronic components add losses.

Table 6-5: Singe line diagram impact

Impact Index	*Impact*	*Important Notice*
Short circuit rating	none	
Operational switching	minor	The DVR is in series with one circuit and usually has a bypass, so switching in and out of service required.
Filtering	minor	Depends upon the acceptable level of harmonics and the exact type of inverter.
Compensation	high	The DVR is a form of voltage compensating device.
Installation	high	The DVR requires to be housed in containers. The type provided to Caledonian Paper is modular with one container per 2MVA injection. Also construction of the bypass circuit is required.
Maintenance	high	The DVR adds new components which will require maintenance
Bypass	high	A bypass is required to facilitate maintenance without losing the use of the circuit.
Commissioning	high	Commissioning of the DVR is longer than for a normal transformer and requires specialist skilled engineers
Insulation coordination	minor	May need protecting by surge arresters if connected in an overhead line circuit

Table 6-6: Detailed substation design

Impact Index	*Impact*	*Important Notice*
Protection (external)	minor	No significant change required to existing circuit protection
Protection (internal)	high	The DVR itself needs to be protected. Much of this is built into the control circuitry for the device.
Control	minor	The only impact on the S/S control is the operation of the bypass and additional alarms and indications required. Internal control of the device is complex.

Impact Index	***Impact***	***Important Notice***
Communications	minor	
Land & layout	high	Requires space for the containers
Visual impact	minor	Depends on the site.
External pollution	none	
Audible noise	minor	Additional noise from the series transformer and the cooling for the electronics.
EMC	minor	
Electrical clearances	none	
Safety clearances	none	
EM fields	minor	
Civils	high	Requires space for the containers and the transformer. Bunding required for transformer
Containment	none	
Auxiliaries	high	Requires auxiliary power to cool the electronics
Equipment ratings	minor	
Busbar layout	none	
Earthing	minor	Equipment requires earthing
Monitoring	minor	In built monitoring with device
Testing	high	Commissioning of the DVR is longer than for a normal transformer and requires specialist skilled engineers
Relocatability	high	Should be relatively easy to relocate
Spares requirement	minor	Spares required for electronic components
Hazards	none	

Fault Level

The inclusion of a series transformer adds additional impedance which will slightly reduce the fault level although this is not the main purpose of the device.

Power Flow Control

The increased impedance may have a small effect upon the power flow in certain circumstances.

Voltage

Under normal condition the device will not have any effect upon the voltage. However, in the event of a voltage dip on the network the DVR will attempt to restore the voltage to the full value by injecting an additional voltage into the circuit to replace the missing voltage. This injection will happen very quickly in less than one cycle and can enable the load to ride through the disturbance on the network.

Thermal Rating

The primary winding of the series transformer must be rated for the full load throughput current of the circuit and not just based upon the rating of the DVR.

Impact upon harmonics

As the DVR is a power electronics device it will inherently generate harmonics. Using higher order bridges and multilevel converters can mean that the harmonics occurring at the lower orders is minimal.

Impedance

The inclusion of the series transformer will change the impedance in the network although this is not the prime reason for installing it.

Losses

The DVR is a power electronics device and there are losses inherent in these devices. Furthermore, there may be fans required or water cooling pumps and these will also increase the losses. Finally the series transformer which is required to connect the power electronics will also add to the losses.

Operational Switching

It is usual when connecting a DVR to fit a bypass circuit. This bypass enables the circuit to be put into service if it is necessary to carry out some essential maintenance or repair work on the DVR. Switching is required to put the bypass into action before commencing any work and also to replace it after completion of the work.

Filtering

Usually the level of harmonics created by a DVR are of a significantly lower magnitude than those from conventional power electronic devices using thyristors and it is not normally necessary to have filter circuits to deal with these. The acceptable level of harmonics and the pre-existing harmonics will need to be considered and the levels predicted after the connection of the DVR discussed and agreed with the network operator.

Compensation

The DVR is a form of voltage compensation device. It will not require any compensation to allow for its connection to the network.

Installation

The power electronics will be accommodated in a building or a container. It may have been designed in a modular format so that higher power levels can be created by connecting modules in series or parallel. The transformer is required to couple the voltage into the circuit and this will also need to be installed.

Maintenance

Maintenance will be required in accordance with the manufacturer’s instructions. The frequency of maintenance may be reduced if there is redundancy built into the design of the power electronics. Co-ordination of the maintenance periods for the DVR with those for the circuit which it is associated with should be considered.

Bypass

In common with most other series connected devices it is usual to connect a bypass to allow usage of the circuit in the event that the device is out of service for maintenance or repair.

Commissioning

Commissioning tests in accordance with the manufacturer's instructions will be required. A full factory acceptance test (FAT) should have been completed before the device is shipped to site and this will help to reduce the amount of tests required during commissioning. The tests will usually include a functional test to prove that the device is responding correctly to changes in the system voltage.

Insulation Co-ordination

The insulation levels of the components should be chosen according to the network conditions in the usual way. If the device is to be connected to an overhead line network susceptible to lightning strikes it will probably require the use of surge arresters to protect it.

External Protection

The DVR has no effect upon the external protection other than the location of the protection current transformers.

Internal Protection

The series transformer will require protection in the normal way. The power electronics devices are usually protected by the control equipment. Protection is provided to prevent the devices from experiencing excessive voltage or excessive current.

Control

The impact on the substation control is limited to the control status indication and alarms arising from the device. The DVR will have its own control system which will take in system parameters such as voltage, current, real and reactive power.

Land and Layout

Space needs to be allocated for the containers for the power electronics and for the series transformer.

Visual Impact

The measures necessary to be adopted will depend upon the particular site. Although containers may be the cheapest housing for the power electronics it may be necessary to consider a building to blend into the surroundings in certain locations. Alternatively the colour of the containers may be carefully chosen for the same reason.

Audible Noise

There is likely to be additional noise from the cooling equipment associated with the power electronics. The series transformer will also contribute significantly to additional noise.

EMC

Screening of the control circuits to the power electronic components may be required to protect them from interference.

Civils

Allowance needs to be made for the foundations for the transformer. If the power electronics are in a container rather than a building then compacted hardcore may suffice as the base for the container. Cable trenches may be required between the transformer and the container.

Containment

If an oil filled transformer is used then oil containment will need to be provided. It may be necessary to consider a fire barrier between the transformer and adjacent equipment on other circuits to prevent a fire on the transformer from damaging equipment on the other circuits.

Auxiliaries

The DVR will require auxiliary ac supplies to feed the cooling equipment for the power electronics. Additional dc supplies will also be required for the control and protection.

Earthing

Earthing of all of the metalwork associated with the device such as containers, panels etc. will require to be earthed. It may be necessary to consider instrumentation earthing in association with the control circuitry.

Monitoring

Usually the control associated with the DVR will have its own monitoring equipment to ensure the safe and continuous operation of the device.

Testing

In addition to the commissioning testing the device and particularly its control system should undergo a thorough factory acceptance test to ensure that it is functioning as intended before dispatch to site.

Relocatability

Since privatization it is becoming an increasingly common request that the equipment should be relocatable. As this device lends itself to a modular construction then it should be a relatively simple exercise to relocate it.

Spares requirements

As the power electronics will be different from any other components already existing on the site it will be necessary to hold additional spare parts. Advice should be sought from the supplier on the quantities of spares to be held.

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