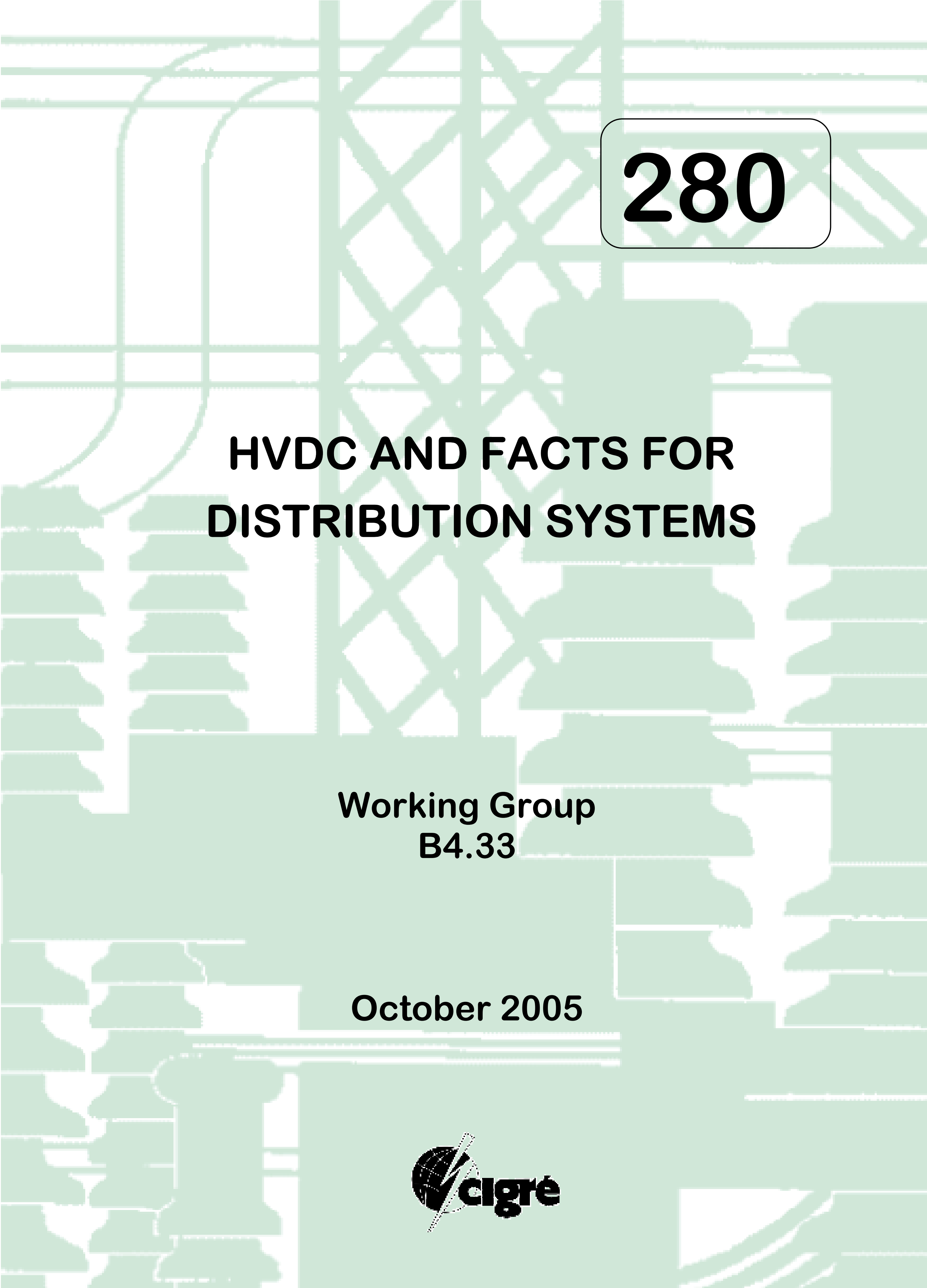

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HVDC AND FACTS FOR DISTRIBUTION SYSTEMS

Working Group
B4.33

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TABLE OF CONTENTS

1 Introduction

For a long time, power electronics applications in power systems have been synonymous with thyristor-based equipment and have been used primarily in transmission systems. Even if some applications have found their way into distribution systems there has been no major breakthrough. In the past, thyristor-based equipment was typically used for SVC applications in transmission systems and static exciters in generation systems. By the end of the nineties, with the appearance of new high-power components such as, IGBTs, GTOs and IGCTs it became possible to design Voltage Source Converters (VSC) also for usage in power systems and to introduce Pulse Width Modulation (PWM) for fast control of such power electronic devices. This new technology offers the opportunity to introduce power electronics applications in distribution systems with their lower power requirements. Since the new converters are fast acting, they can eliminate or mitigate frequently appearing power quality problems. Furthermore, using a totally static solution often facilitates the operational and maintenance activities.

The need for modernization of distribution systems has been manifested by a number of reasons:

a) The new loads are based on automated production and information systems in the industry (i.e. variable-speed drives, robots, automated production lines or machine tools, programmable logic controllers or power supplies in computers). These new loads are much more sensitive to power quality and reliability as compared with the previous electromechanical which were less sensitive to power quality and reliability.

b) The anxiety for: 1) Extensive usage of locally available energy sources including renewable sources such as windmill, small-scale hydro and solar energy plants. 2) The connection to remote power grids of loads, which are not big enough to justify the building of common transmission lines and distribution systems. 3) The feeding of small loads on islands. 4) The feeding of small rural loads from relatively distant small-scale generators.

c) The challenges originating from the deregulation processes and the new era of providing value-added services.

The scope of this CIGRE Work Group is a review of the possible usage of HVDC based on VSC (Voltage Source Converters) and FACTS (Flexible AC Transmission System) for distribution systems. The original scope of work has been slightly modified to adapt it better to distribution systems. Control of the schemes has been discussed. Included in the review are configurations of the converters possible such as two-level and three-level converters and also DC/DC converters for DC transformation. This review considers the following types of power electronic facilities:

1) HVDC transmission based on Voltage Source Converters (VSC)
2) Power electronic controllers for distribution systems, which include:
    a) Solid state switchgear equipment
    b) Shunt conditioners
    c) Dynamic Voltage Restorers (DVR)
    d) Series compensation
    e) Series/shunt combinations

Possible applications of HVDC based on VSC and FACTS for distribution systems have been investigated such as: feeding of distant rural loads, small loads on islands, feeding power from small generators such as windmills, small-scale hydro, solar energy plants etc., reactive power compensation and voltage stabilization in distribution systems. Operation and maintenance requirements are also discussed.

The possibility of building distribution systems using only dc has been investigated. As ac to dc conversion could then be made close to the generators, the frequency of the generators could be varied and an optimum frequency could be chosen in order to reduce the cost of the generator. The same applies to the consumption at the users end. Variable speed drives could be fed directly by dc.

Comparison between the use of HVDC and FACTS-applications for sub-transmission networks to supply energy and small local generation options such as diesels and small gas turbines has not been possible and thus a distinct recommendation as to when local generation, HVDC or FACTS, or conventional ac distribution is the best solution is still pending. Neither the technology nor the market has developed at a pace so that it could be justified to give such recommendations. There is still development to do before there could be consensus on some type of generality over recommendations.

Instead, the recommendations have been based on state of the art facilities that would solve or help to overcome existing problems in distribution and sub-transmission systems. It should then be of interest to study the specific facility in the specific situation to find out if it would be economic for the specific application and resolving the specific problem. Based on the above, the following state of the art power electronic facilities could be of interest:

- Solid state switchgear especially the solid state transfer switch
- HVDC transmission based on VSC
- Dynamic voltage restorer
- SVC or STATCOM

The recent advances in solid state switching technology have been investigated together with their implications, as well as the predicted future advances, which when achieved are expected to lead to a significant increase in the use of this technology.

2 Overview of Different Types of Power Electronic Facilities

2.1 Power Electronics in distribution systems

As explained in the Introduction, there is a need for a modernized distribution system and there are also means available to design and build such systems. New types of loads and generations and a new organizational structure of the electric sector drive the need for a more modernized distribution system. New high-power components give the possibility to design more sophisticated power electronics based applications, which can be used to meet the needs.

The modernized distribution system must withstand the power supply reliability problems, related to short time outage, voltage sags, overvoltages and frequency deviation and voltage quality problems such as harmonics, impulse, swell, flicker, unbalances, dc components and voltage variations. Depending on the application the new modernized distribution system to fulfil the above goals may exploit the capabilities of:

- DC transmission based on Voltage Source Converters (VSC)
- Power electronic controllers for distribution systems, which include:
  a) Solid state switchgear equipment
  b) Shunt conditioners
  c) Dynamic Voltage Restorers (DVR)
  d) Series compensation
  e) Series/shunt combinations

The following is a brief description of the above power electronic facilities. Their names are adopted by FACTS terminology but in their abbreviations there is one more letter in front, separated by a dash, specifying the type of semiconductor power devices used (T for thyristor, G for GTO thyristor, I for IGBT) and one more letter if there is rechargeable energy storage system (C for capacitor, B for battery and S for SMES) e. g. IS-STATCOM is the abbreviation of STATCOM based on an IGBT voltage source converter and using a SMES as an energy storage subsystem. As an introduction to the power electronic facilities we will give a short description of the new electronic components that have made this development possible.

2.2 Power Electronic Devices

The devices available today can be of two types: thyristors or transistors. The thyristor can be controlled on turn on (and turn off) only and would need fairly high gate currents on these occasions. The transistor can be continuously controlled and need a rather small but continuous gate current. The available devices that can be used for a VSC with PWM, i.e. IGBT, IEGT, GTO, IGCT (GCT) are presented in Table 2.1. A characteristic of this type of switching device is that it is self-commutating via a gate pulse. Also to be effective in a VSC application it is necessary that the power electronic devices be used with an inherent high switching frequency. But it must be noted that operation frequency of these devices is also determined by the losses and the design of the heat sink, which are related to the power through the component. The optimum design for the full utilization of the available power of the component specifies a practical maximum operation frequency for the component, which is specified in the following paragraphs.

Abbreviation	Type	Full Term
IGBT	Transistor	Insulated Gate Bipolar Transistor
IEGT	Transistor	Injection Enhanced Gate Transistor
GTO	Thyristor	Gate Turn-off Thyristor
IGCT	Thyristor	Integrated Gate Commutated Thyristor
GCT	Thyristor	Gate Commutated tern-off Thyristor

Table 2.1 Available Switching Devices for VSC.

2.2.1 Insulated-gate bipolar transistor (IGBT, IEGT)

The IGBT is a fast power-switching device capable of working in the kHz range. It is a MOS-device with a high impedance gate, which requires low energy to switch the device and maintain power flow. This makes series connection of devices possible with good voltage distribution even at switching frequencies in the kHz range. The gate power for the series connected semiconductors can be economically provided via the voltage dividing circuits across the individual IGBT’s.

There is a fast development of IGBT's taking place and the voltage rating of the components has recently reached 6.5 kV and higher voltages are expected. The market for IGBTs is also increasing rapidly which adds to the knowledge base of the technology itself and makes it a very attractive component for HVDC and other applications, in which many series-connected elements are needed especially in small-scale transmission and distribution links. Figure 2.1 shows a 4-module parallel-connected IGBT for 2.5 kV.

Figure 2.1 IGBT with 4 parallel-connected sub-modules for 2.5 kV.

The IEGT is a variation of the IGBT. It achieves a low forward voltage drop during conduction similar to thyristor devices, by the effect of electron injection from emitter. The maximum ratings today are: voltage 4.5kV and current 2.1kA.

2.2.2 Gate-turnoff thyristor (GTO)

The GTO has a self-turn off capability, unlike a conventional thyristor, and can turn on and turn off by gate current action. The GTO is one device of the thyristor family that has a very low on-state voltage and high current and voltage capabilities. Presently, a 6kA, 6kV GTO is commercially available. Its operation frequency is up to 500 Hz and a snubber circuit is necessary to control the rate of rise of voltage (dv/dt) during turn-off. The GTO is controlled by gate current and turn-off gain is between 3 and 5. Series connection of devices is possible by matching the turn-off storage time of the devices. At present the GTO is widely used in high power applications such as traction, steel mills and can be used for SVG and BTB etc.

2.2.3 Integrated-gate commutated thyristor (IGCT or GCT)

The IGCT (GCT) has a self-commutated turn-off operation and all of the main current is commutated to the gate during turn-off. As a result, there is no current concentration during turn-off, which is different from a GTO commutation. Consequently, turn-off capability is drastically improved and snubberless turn-off becomes possible. Turn-off storage time is decreased to about one tenth when compared with a GTO and operation frequency is improved to about 1000 Hz. Series connection is easier because of the small storage time. Gain is 1, but gate charge becomes a half compared with GTO and gate power can be decreased. Furthermore, the rate of rise of current (di/dt) can be increased more than 2 to 3 times than a GTO and anode reactor size can be decreased to a low value. IGCT (GCT) also has high current and high voltage capability like a GTO and now a 6kA/6kV IGCT (GCT) is commercially available. A 6.5kV IGCT (GCT) is also commercially available and there are possibilities for higher voltage capability in the future. IGCT (GCT) has low on-state voltage and low total power loss compared with other devices. They are suitable for applications which need high power and high voltage capability i.e. HVDC, SVG, BTB and Medium Voltage Drive etc.

A view of the GTO and IGCT (GCT) is shown in Figure 2.2 together with their equivalent circuits. Figure 2.3 shows a comparison of system losses for a converter using either a GTO or IGCT (GCT). Losses with an IGCT (GCT) converter are reduced to half of a conventional GTO converter.

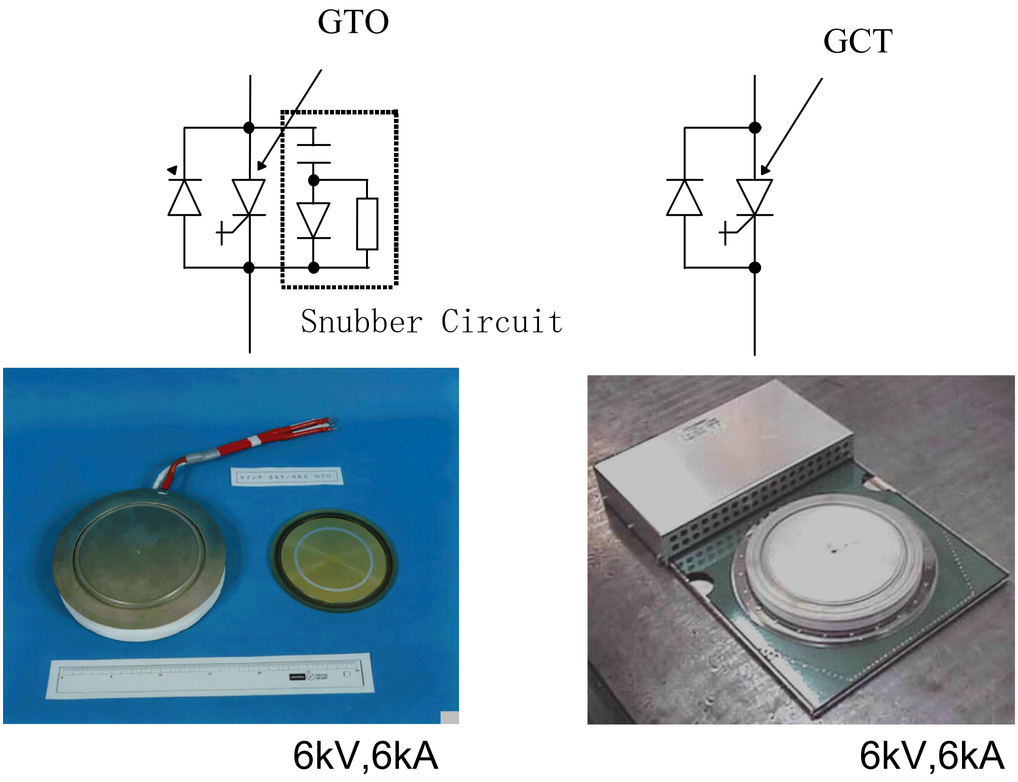


Figure 2.2. Equivalent circuits and outlook for GTO and IGCT (GCT) respectively.

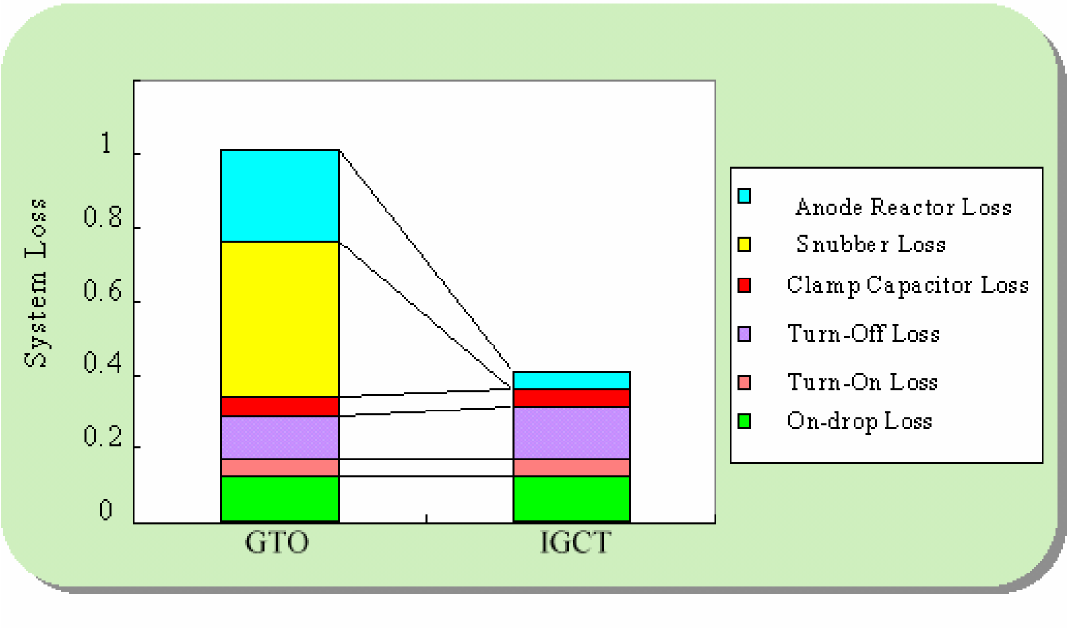


Figure 2.3. Comparison of system loss for a converter using GTO or IGCT (GCT).

2.3 Voltage Source Converters (VSC)

The commercial availability of high-power and high-voltage GTO and IGBT valves in the 1990's offered the viable operation of VSCs in HVDC schemes.

VSCs utilize self-commutating switches (e.g. GTOs, IGBTs) which can be turned-on or off at will. This is in contrast to the conventional converters, which operate with line-commutated thyristors. Commutation in a force-commutated VSC valve can occur many times per cycle, whereas in a line-commutated CSC it can happen only once per cycle. This feature allows the voltage/current in a VSC to be modulated to produce a nearly sinusoidal output and control the power factor as well. Furthermore, power reversal in a VSC can be made with either current or voltage reversal at the dc side. Pulse Width Modulation (PWM) techniques can be employed to operate the VSC in inverter mode to provide a sinusoidal output to the ac system.

VSC can be classified into two-level or multi-level converters. The traditional two-level converter is shown in Figure 2.4.

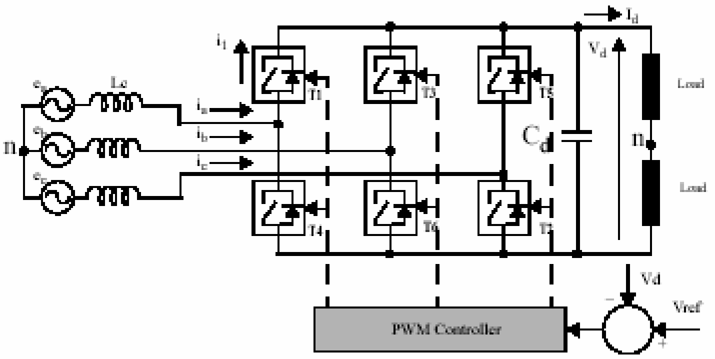


Figure 2.4 Two-level converter.

In Figure 2.4, the operating principles of a VSC are shown. The dc side capacitor Cd and ac side inductor Lc are necessary elements of the VSC. The dc voltage Vd is monitored and compared to a reference value Vref to generate an error signal, which controls the PWM controller. When the dc current Id is positive, the VSC acts as a rectifier; the dc capacitor is discharged as it feeds the dc load, and the control system will modify the firing angle to import power from the ac system. When the dc current Id is negative, the VSC acts as an inverter; the dc capacitor is charged from the dc source, and the control system will modify the firing angle to export power to the ac system.

The PWM controller can generate a voltage Vgen with the same frequency as the ac system voltage Vs. By altering the amplitude of Vgen and its phasor relationship with Vs, the converter can be made to operate in all four quadrants i.e. rectifier/inverter operation with lagging/leading power factor. Thus the VSC can also modulate the firing of the valves to control the reactive power so that a wanted power factor can be obtained.

There are two control strategies possible with the traditional two-level converter configuration.

PWM with Bipolar Voltage Switching (two-level switching)

In this PWM scheme, diagonally opposite switches from two legs of the converter are switched together as switch pairs 1 and 2, respectively. With this type of PWM switching, the output voltage waveform of the leg is identical to the output of the basic one-leg inverter, which is determined by comparison of a sine wave and a triangular wave. The output voltage switches between +Vd and -Vd voltage levels. That is the reason why this type of switching is called PWM with bipolar voltage switching.

PWM with Unipolar Voltage Switching (three-level switching)

In the PWM scheme with unipolar voltage switching, the switches in the two legs of the full-bridge inverter are not switched simultaneously, as in the previous PWM scheme. Here, the legs of the full-bridge inverter are controlled separately by comparing the triangular wave with a sine and cosine wave respectively. The comparison of Vcontrol with the triangular waveform results in the logic signals to control the switches T1 and T3. In this type of PWM scheme, when a switching occurs, the output voltage changes between zero and +Vd or between zero and -Vd voltage levels. For this reason, this type of PWM scheme is called PWM with a unipolar voltage switching, as opposed to the PWM with bipolar (between +Vd and -Vd) voltage-switching scheme described earlier. This scheme has the advantage of “effectively” doubling the switching frequency as far as the output harmonics are concerned, compared to the bipolar voltage-switching scheme. Also, the voltage jumps in the output voltage at each switching are reduced to Vd, as compared to 2Vd in the previous scheme.

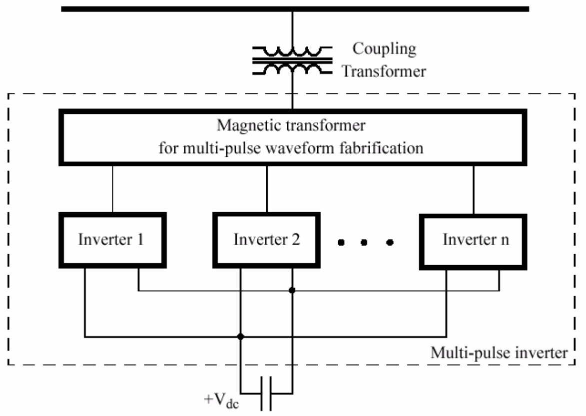


Figure 2.5 Magnetic structure arrangement for a multi-pulse inverter.

Due to limitations in the size and rating of GTOs and IGBTs, the capacity of a single element valve VSC has been limited. In order to increase the rating of the terminal, users have had to rely on the parallel operation of converters with the assistance of special transformer arrangements for example as shown in Figure 2.5 or go to valves with series-connected elements. Four converters in parallel can provide terminal ratings of 250 MW with a high quality multi-stepped output waveform. However, transformer arrangements can be very costly, and the trend is that their cost will not diminish substantially with time. Valves with up to 200 series-connected IGBTs have been used to form a high voltage valve in commercial installations.

Voltage source converters used in wind turbines of doubly fed induction generators to provide a feedback between rotor and stator circuits are very sensitive to the grid conditions. A disturbance in ac network may result in a significant increase in generator stator and rotor currents and this in term could cause overvoltages in the dc circuit. Simplicity of the design of LV installations calls for very fast protection and disconnection of the generator from the ac source. Unfortunately with the large penetration of wind generation, a fault in the grid may affect performance of a number of wind farms causing wide spread disconnections. Such performance is not acceptable. Wind turbines should be capable of remaining connected to the grid, typically for up to three seconds, if voltage dips occur due to grid problems. The turbine may also need to support voltage at the weak grid connection point.

Wind turbines can run through a disturbance and feed reactive power to the electric grid during a disturbance. The ride-thru capability enables wind turbines to meet transmission reliability standards and offer dynamic performance similar to conventional synchronous generators. The fault ride through is achieved with an aid from power electronics. The solutions used include application of a series impedance controlled by a thyristor bridge to achieve fast switching times or the use of a chopper circuit in series with a discharge resistor installed in parallel with a dc capacitor within the dc link. Injecting short circuit current during a disturbance provides voltage support during the disturbance. Active and reactive currents are modulated by a rotor side VSC converter to achieve desired outcome.

The requirement to ride through disturbances has resulted in significant design changes to VSC installed at wind turbines. However, such low voltage applications of VSC appear to suffer from high internal currents leading to damage of IGBTs. A review of protection philosophy of LV IGBT bridges may need to be considered to avoid this.

2.4 DC Transmission Based On Voltage Source Converters (VSC)

2.4.1 VSC Technology with Pulse Width Modulation (PWM)

A VSC is based on valves that can be switched on and off by a control signal. By choice of the switching instants it will be possible to generate any desired wave shape from an inverter and there is no need for a network to commutate against. In this way a dc transmission system can supply even «dead» networks, that is, areas which lack rotating machines or does not have enough power in the rotating machines (too low short circuit power).

In the case where the available valves can only switch at low frequency, Fundamental Frequency Commutation (FFC) (or line commutation) will probably be the right technology. Then, in order to reduce harmonics, the converters have to be divided into several smaller converters operating with a phase shift. Thereby 12, 24 or 48 pulse operation can be achieved and the generation of harmonics can be reduced in proportion to the pulse number. In such a case the transformers have to be relatively complicated in order to connect all these small converters.

If higher switching frequency components are available it is possible to use Pulse Width Modulation (PWM) Technology. Then only one converter is needed and very fast switching between two fixed voltage levels creates the ac-voltage. After low pass filtering, the desired fundamental frequency voltage is created. In this case the transformer arrangement is very simple. In some applications it may not even be necessary to have a transformer for the functioning of the converter (see Figs 2.6 and 2.7).

With PWM it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern, which can be rapidly achieved compared to network frequency. Thus PWM offers the possibility to control both active and reactive power independently.

This makes the PWM VSC a nearly ideal component in the transmission network. From a system point of view, it acts as a motor or generator without inertia that can control active and reactive power almost instantaneously. Furthermore, it does not contribute to the short circuit power as the ac current can be controlled.

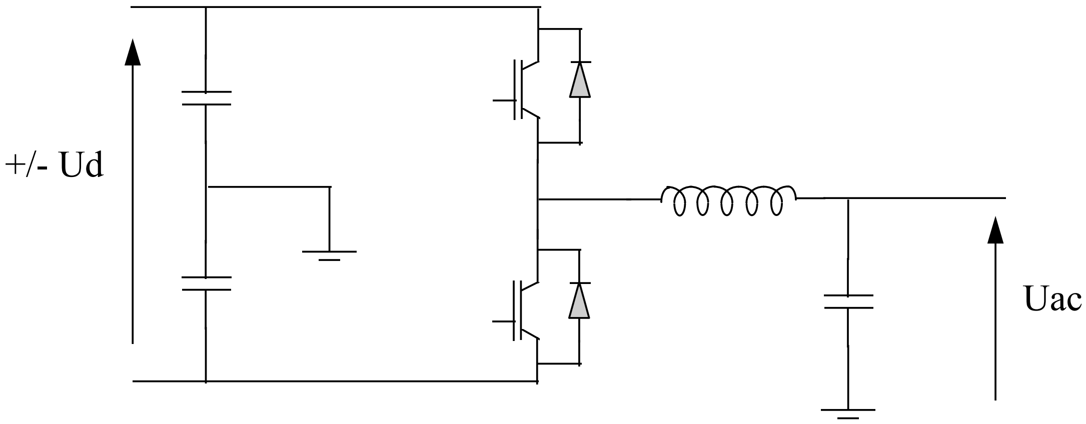


Figure 2.6 One phase of a VSC using PWM.

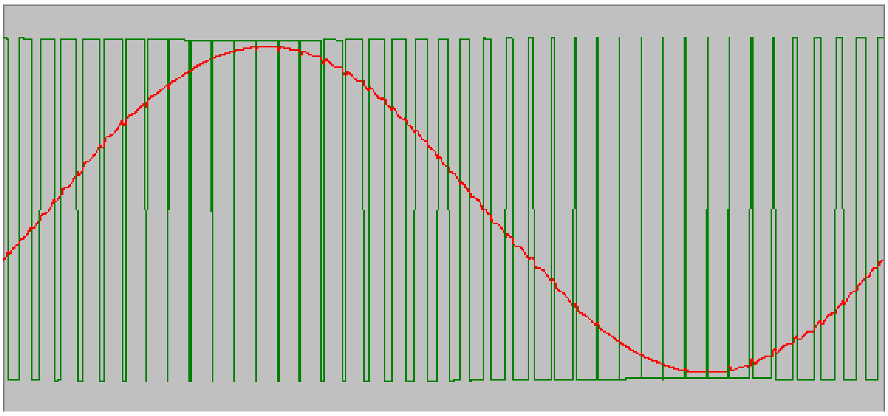


Figure 2.7 PWM pattern and the fundamental frequency voltage in a VSC.

2.4.2 The VSC

The converter consists of a bridge, a reactor, dc capacitor and an ac-filter, which is a simple and straightforward circuit solution, compared to conventional thyristor converters. These simplifications of the converter circuit, such as a small filter, none or simplified transformers, less switching equipment and simple civil works contribute to a small footprint and easy handling.

The bridge, in its simplest form, consists of a two-level converter, which for a three-phase system comprises six valves with series connected IGBT's in each valve. Each IGBT is provided with an anti-parallel diode. Valves, dc busses and dc capacitors have a low inductive design to reduce the voltage overshoot across the valve at turn-off. The objective for the dc capacitor is primarily to provide a low inductive path for the turned-off current and energy storage to be able to control the power flow. The capacitor also reduces the harmonics on the dc side. The semiconductors are preferably cooled with water to utilise their full power capability. Turn on/off of each single IGBT is ordered via an optical link from the control equipment on ground potential.

The converter generates characteristic harmonics related to the switching frequency. The converter reactors block the harmonic currents and a high-pass filter reduces the harmonic content on the ac bus voltage**.** The fundamental frequency voltage across the reactor defines the power flow between the ac and dc sides.

Two VSCs, which are interconnected by an overhead line or cable, constitute a low power HVDC transmission system and its general configuration is shown in Figure 2.8.

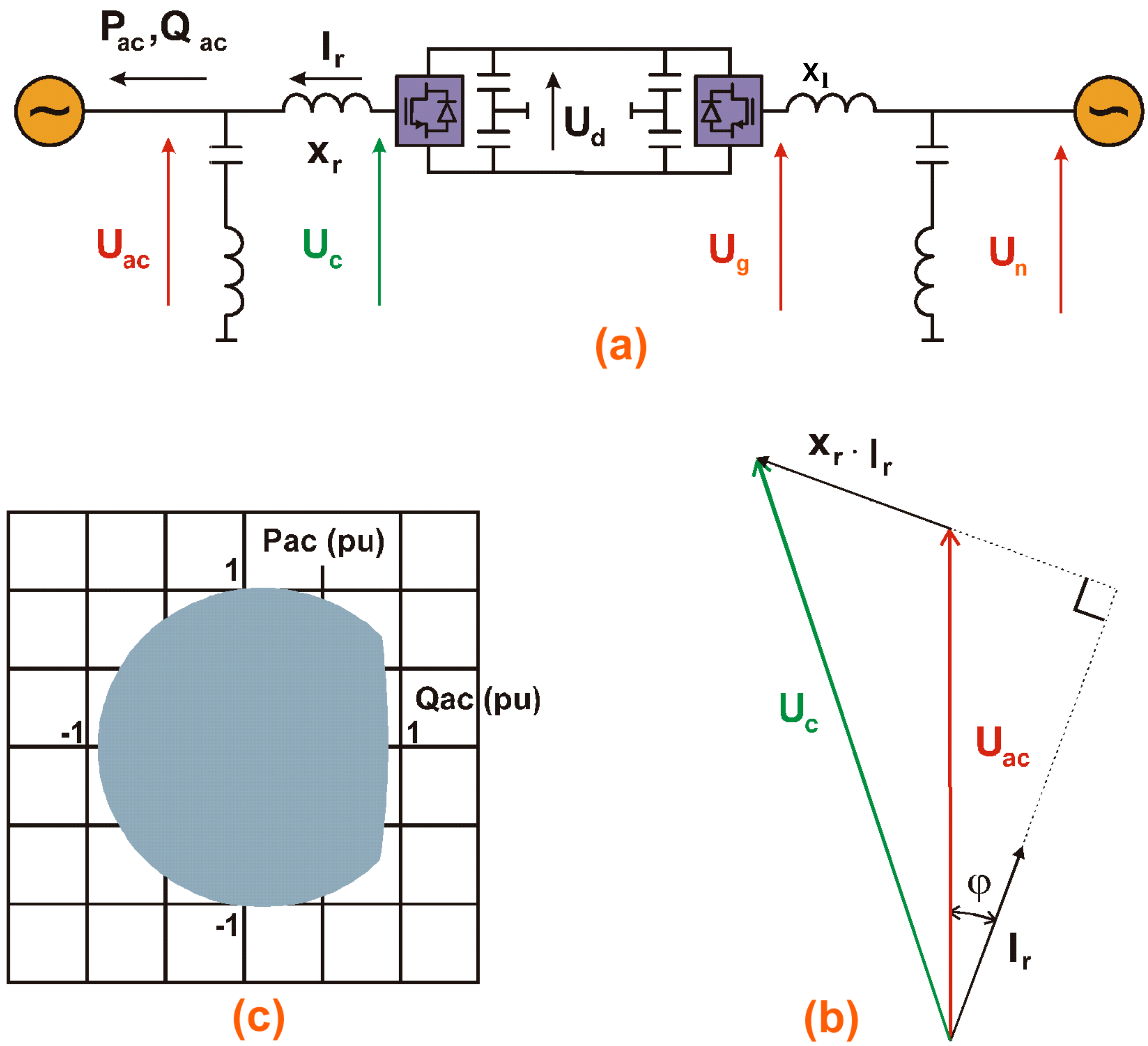


Figure 2.8 a) General configuration of a HVDC light transmission system.

b) Phasor diagram.

c) Combined active/reactive power capabilities of the HVDC light transmission system.

2.4.3 Control

2.4.3.1 General description

The converter firing control calculates a voltage time area across the converter reactor, which is required to change the current through the reactor from its present value to the reference value. The current order to the controller is calculated from the set power/current order or the dc voltage control. A reference voltage, equal in phase and amplitude to the fundamental frequency component of the output voltage from the bridge Ug, is calculated. The pulse pattern is generated by the pulse width modulation (PWM) where the reference voltage is compared with a triangular carrier wave. If the reference voltage is higher than the carrier wave then the phase terminal is connected to the positive dc terminal and if it is lower, the phase terminal is connected to the negative dc terminal.

The active power flow between the converter and the ac network is controlled by changing the phase angle (δ) between the fundamental frequency voltage Ug generated by the converter and the ac voltage Un on the ac bus. The power is calculated according to the following formula, assuming a reactor without losses:

$$P = \frac{Ug * Un * \sin\delta}{Xl}$$

The amplitude of Ug is controlled by the width of the pulses from the converter bridge. The reactive power flow is determined by the amplitude of Ug, according to the formula:

$$Q = \frac{Ug * (Ug - Un * \cos\delta)}{Xl}$$

The maximum fundamental voltage out from the converter depends on the dc voltage.

Reactive power generation and consumption of a PWM VSC can be used for compensating the needs of the connected network within the rating of a converter. As the rating of the converter is based on maximum currents and voltages, the reactive power capabilities of a converter can be traded against the active power capability. The combined active /reactive power capabilities can most easily be seen in a P-Q diagram, Figure 2.9 (positive Q is fed to the ac network).

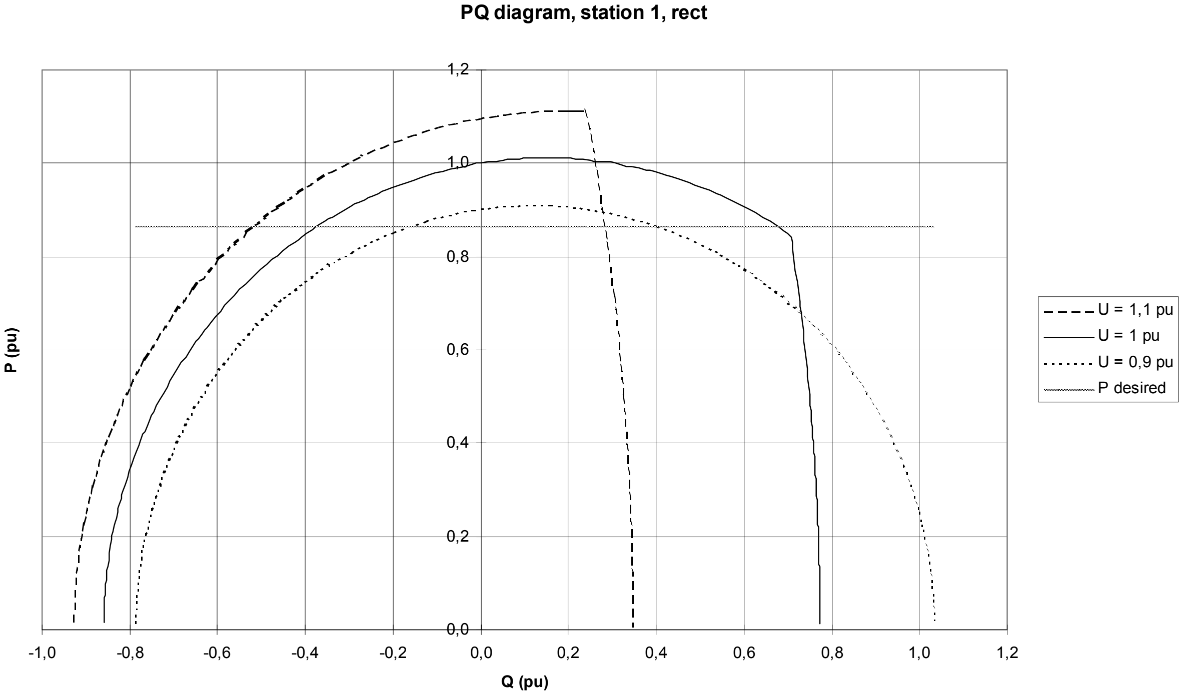


Figure 2.9 Combined active/reactive power capabilities of a converter.

Normal operation modes mean that each station controls its reactive power flow independent of the other station. However, the active power flow into the dc network must be balanced which means that active power out from the network must equal the active power into the network minus the losses in the system. Any difference means that the dc voltage in the system will increase or decrease. To achieve this power balance one of the stations is made to control the dc voltage. This means that the other station can set any active power order within the limits for the system. The voltage controlling station will adjust its power order to ensure power balance, meaning constant dc voltage. This will be based on measurement of the dc voltage without the need of any telecommunication link between the stations.

In connection with transients unbalances may occur. Assume that a converter, which supplies power to its ac side, taking it from the dc network is momentarily blocked, blocking its current. The energy stored in inductances in the dc circuit will charge the dc capacitors and the dc voltage will increase. The increase of dc voltage will be fed back to the dc voltage controlling station, which will counteract by decreasing and even reversing the active power flow to maintain the dc voltage. The converter in operation (the dc voltage controlling one) can continue to operate and act as a STATCOM and control the required reactive power flow to its connected ac system.

In the opposite case assume that the dc voltage-controlling converter is blocked, then the dc voltage will drop, as no power is input to the dc system to balance the output. The decrease of the dc voltage will be fed back to the remaining converter, which will then start to control the dc voltage and restore it to the set value. The remaining converter can continue to operate and act as a STATCOM and control the required reactive power flow to its connected ac-system.

2.4.3.2 HVDC based on VSC control functions

The control system design is modular and flexible to allow future adaptation of additional control functions. The control functions are implemented as programmed systems in different processes operating in a multi-tasking environment. The control system is primarily implemented in one computer.

In an integrated power transmission system, the control of active power in the converter stations should be co-ordinated. The co-ordination of active power control between the stations is realised by designating one converter controlling the dc voltage whereas the other converter controls the active power. A constant dc voltage control will result in an automatic balance of active power flow between the stations.

The control of reactive power is completely independent for the two stations. The desired reactive power order can be generated by the AC voltage control or set manually.

Due to the limited power rating of the converters, the independent control of the active and reactive power within a station may be limited to a certain operation range.

The control system is designed such that no telecommunication link between the two stations is required.

The control structure is hierarchical with one Basic control level and a Master control with one or possibly two levels.

The Basic Control of the converter generates the reference of the converter ac output voltage, according to the ac current references given by the Master Control. The Basic Control mainly consists of the Phase-Locked Loop (PLL) and the ac current control.

- **Phase-Locked Loop**

The Phase Locked Loop (PLL) is used to synchronise the converter control with the line voltage. The input of the PLL is the three-phase voltages measured at the filter bus. The output of the PLL is a time dependent phase angle, which should be equal to the phase angle of the filter bus voltage vector in steady state, and a phase angle error.

- **AC current control**

The ac current control results in the three-phase voltage reference for the converter.

The ac current control consists of the feed-forward of ac bus voltage, the feed-forward of current order depending voltage drops on the reactor and the feedback control of ac current.

1. Pulse-Width-Modulation (PWM)

The purpose of PWM is, from a constant dc voltage, to be able to construct an arbitrary ac voltage. A triangle waveform is compared to a sine waveform and by detecting the intersections the resulting modulation waveform is being achieved. This waveform provides the firing pulses to the valve control.

2. Master control

The Master control consists of active power control, dc voltage control, ac voltage control, Current order calculation and Current order limiter.

3. Active power control

The active power control generates a contribution to the dc voltage reference depending on the active power reference. The active power reference is entered by the operator in the power controlling station. A feedback control keeps the power at the desired value.

The operator can change the power level by entering a power reference and a ramp speed from the Operator Work Station (OWS). The power is then ramped to the desired value.

The operator is free to choose any power level within the permitted range. The power can easily be reversed, and there are no minimum current restrictions as for line-commutated converters.

4. DC voltage control

In the station that is designated to control the dc voltage, the reference will be constant. In the station designated to active power control, the dc voltage reference will be dependant on the active power order in order to compensate for the voltage drop in the dc link.

5. AC voltage control

The AC voltage control generates the reactive power order for the converter, which is independent for the two stations. This feature gives the possibility to control the filter bus voltage or the ac voltage at the network side of the transformer.

The HVDC Light converter can either generate or consume reactive power. The operator enters an ac voltage reference value, which is kept constant by a feedback controller.

The converter can vary the reactive power very rapidly. Thus a very powerful ac voltage controller can be designed to meet requirements on fast response in the ac voltage regulation.

6. Current order limiter

The function of the current order limiter is to limit the amplitude of the phase current. If the amplitude of the current order is lower than the rated current, the outputs of the current order limitation will be the same as the corresponding inputs. That means that the executed current orders in the current control will be the same as resulted from the ac voltage control and dc voltage control/active power control. If the amplitude of the current order is higher than the rated current, the outputs of current order limitation may be different from the corresponding inputs. In order to optimise the system performance, higher priority is given to the dc side voltage control.

2.4.4 Extruded HVDC cables

The new Extruded HVDC cables have insulation of extruded polymer. The insulation is triple extruded together with the conductor screen and the insulation screen. This offers a very robust cable design. The robustness opens the possibility for new cable applications i.e. land cables can be installed with ploughing technique, use of aerial cables and submarine cables for severe conditions.

The cables are operated in pairs in bipolar mode, one cable with positive polarity and other cable with negative polarity. Extruded HVDC single core cables are installed close to each other in bipolar pairs with anti-parallel currents and thus cancelling the resultant magnetic fields. Extruded HVDC cables are particularly well suited for long distance power transmissions. They have no technical limitations for distance as opposed to ac cables, which are limited by the capacitive charging current and the impedance.

Extruded HVDC polymeric cables have significant advantages over paper-oil-insulated HVDC cables. Polymeric insulation eliminates the risk of oil spillage. Their strength and flexibility make the Extruded HVDC cables well suited for severe installation conditions.

2.5 SOLID STATE SWITCHGEAR EQUIPMENT

To provide premium-quality electricity to customers with sensitive loads to distribution system disturbances, such as short time outage, voltage sags and swells, utilities may now use solid state switches based on conventional thyristors or GTO thyristors. Fault current limiters may be employed to reduce fault currents and consequently reduce the voltage sags on the healthy segments. Fast isolation of line faults can be achieved by the solid state breakers and uninterrupted power to a load can be provided by quickly transferring the load from the faulted feeder to an independent healthy feeder by the solid state transfer switch [3-9].

2.5.1 Solid State Current Limiter using GTO switch (G – SSCL)

Mechanical reclosers, which require three to six cycles to react to a distribution feeder fault, are not fast enough to provide the virtually instantaneous switching needed to keep sensitive equipment operating properly. However, the breaker should not be allowed to operate before a consumer’s circuit breaker operates, when a fault occurs at the consumer’s end. To overcome these conflicting requirements a very fast fault current limiter can be used. This action protects other feeders upstream of the distribution system, while protection devices downstream attempt to clear the fault and prevent the distribution system from voltage decrease. In another application, the use of G-SSCL prevents the replacement of installed devices (i.e. circuit breakers and power transformers) when the increase of fault current due to electric power systems grow and expand exceeds their ratings.

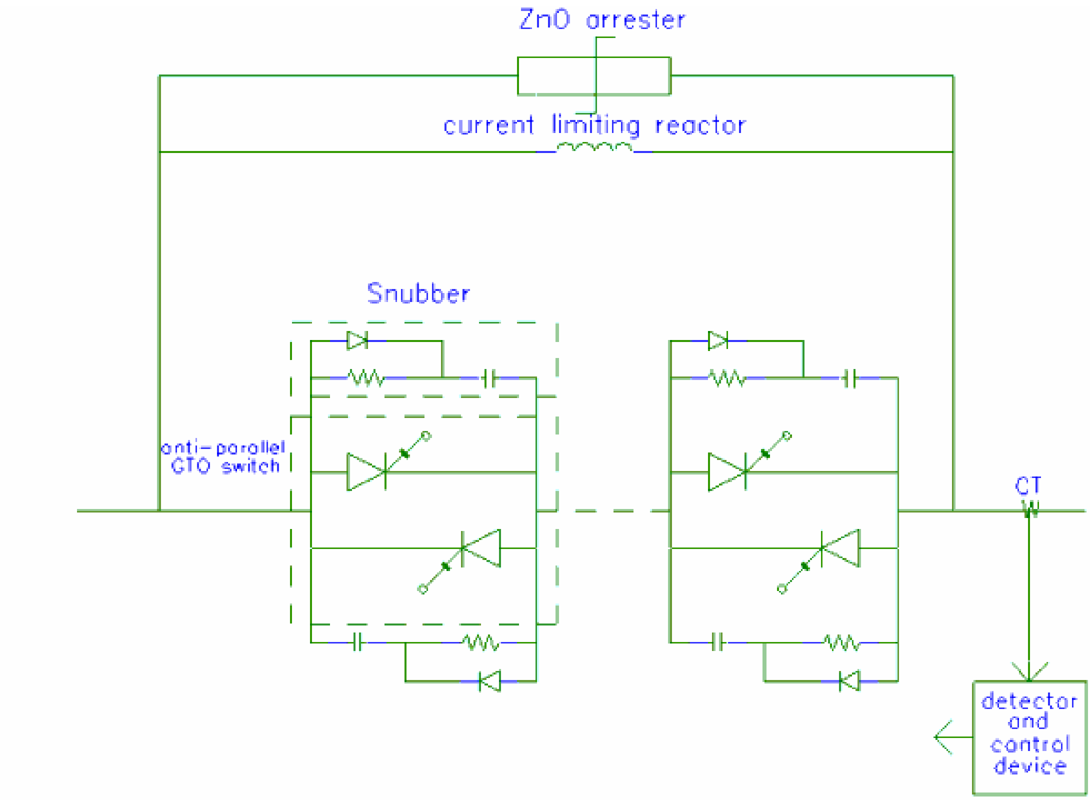


Figure 2.10 Simplified G – SSCL configuration.

A simplified G–SSCL configuration is shown in Figure2.10. It consists of series connected, anti-parallel GTO switches with their snubbers, a current limiting reactor, a zinc oxide arrester and the detector and control device. The GTOs are maintained in full conduction under normal load conditions. A fault on the load side of the G – SSCL is detected by the detector, which monitors the instantaneous magnitude and/or rate-of-rise of current. A fault current has to be detected promptly before it reaches a large value and must be discriminated from inrush current. After detection of the fault current, the control device initiates a turn-off for the GTOs, which interrupts the fault current in less than 0.1 ms and before it reaches a destructive level. The fault current must be commutated to the current limiting reactor under finite reactive impedance of the distribution system. This may cause a steep voltage build-up across the GTOs but its rate of rise is limited by the snubber capacitor, which receives the current immediately after the GTOs turn off. This voltage is also applied across the current limiting reactor and the zinc oxide arrester limits its maximum value. After the establishment of the clamping voltage level of the zinc oxide arrester the reactor current rises linearly until it reaches the instantaneous value of the fault current flowing in the line. While the current is building up in the reactor, it is decreasing in the zinc oxide arrester, which absorbs energy during this time. The final fault current is specified by the source impedance of the distribution system, the current limiting reactor and the line impedance of the fault and must be large enough to leave unaffected the overcurrent protection of the consumer. If the fault was in a consumer and has been cleared the line current drops back to normal and the control device turns back on the GTOs when the voltage across them is near to zero to avoid high magnitude discharge currents from the snubber capacitor. The current in the current limiting reactor is transiently trapped but decays rapidly.

2.5.2 Solid State Current Limiting Breaker using GTO switch (G-SSCLB)

A G-SSCLB combines the characteristics of a very fast current limiting device and a circuit breaker. It results from a G-SSCL added in series with a mechanical circuit breaker, as shown in Figure2.11. In case of a fault on the load side of the G-SSCLB, first the fault current is limited by the action of the G-SSCL. If the fault remains after a specific period of time (i.e. for a feeder line fault) the control device will activate the series mechanical switch to isolate the faulted line within a few tenths of a second.

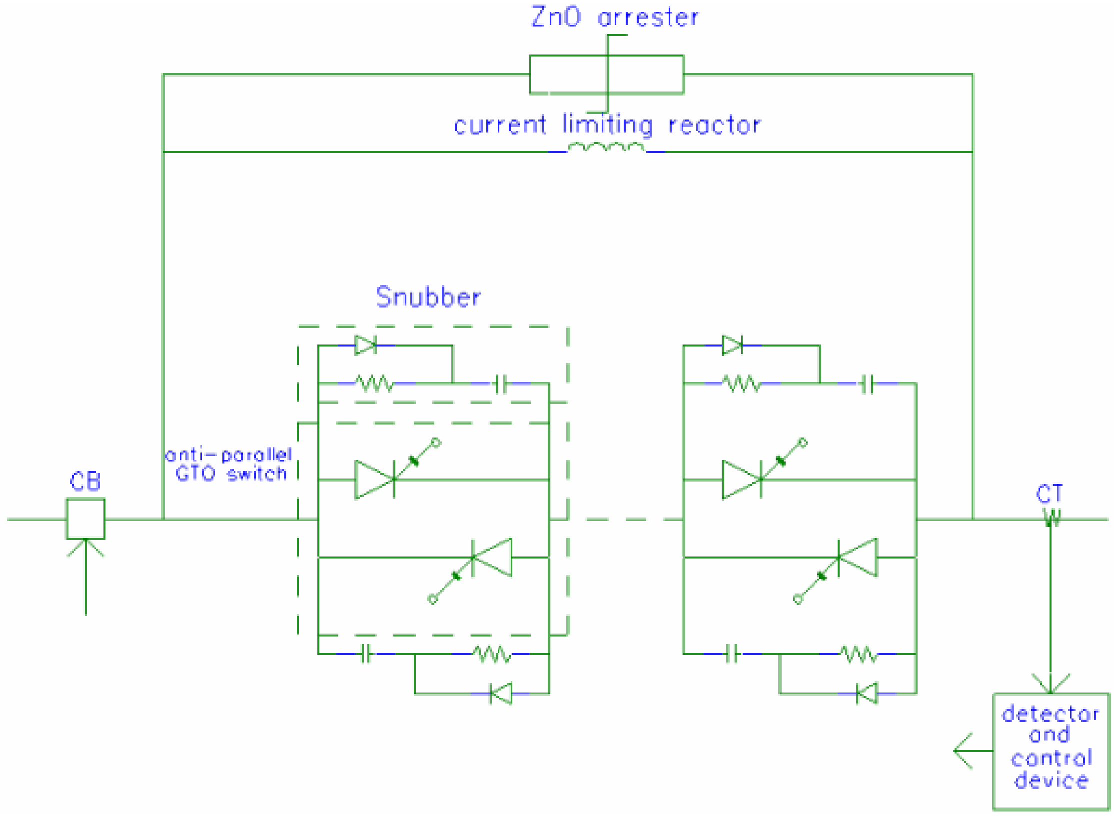


Figure 2.11 Simplified G-SSCLB.

In another design, a high-speed vacuum circuit breaker is used in parallel with the GTO switch to lower the breaking capacity of the switches and to suppress instantaneous voltage drops. The vacuum switch carries the normal load current and the fault current is commutated to and interrupted by the GTO switch by opening the vacuum switch.

The G-SSCL or G-SSCLB can be used for transformer main protection and for feeder protection where coordination with downstream conventional protection is required.

2.5.3 Solid State Breaker using GTO switch (G-SSB)

Without the current limiting reactor, the device of Figure 2.10 represents a very fast solid-state breaker (G-SSB), as shown in Figure2.12. When a fault occurs on the load side of the G-SSB, the controller initiates the turn-off of the GTOs and the current is diverted into the snubber capacitor, which limits the rate of rise of voltage across the valve until it reaches the clamping voltage level of the ZnO arrester. The current of the ZnO arrester is stopped when the voltage across the valve falls below the clamping voltage of the arrester. At this moment the G-SSB completely interrupts the fault current. When the fault is cleared, the controller turns back on the GTOs when the voltage across them is near zero to avoid high magnitude discharge currents from the snubber capacitor. The G-SSB is protected from voltage surges by ZnO arresters on both sides of the G-SSB.

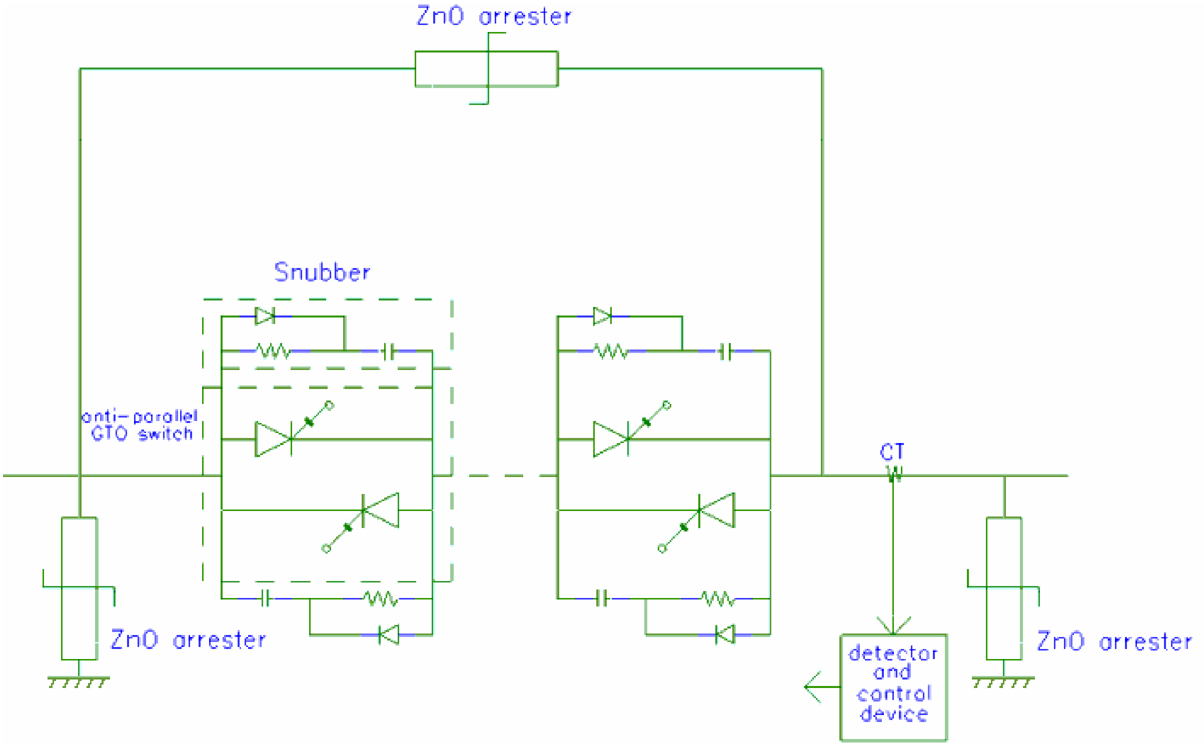


Figure 2.12 Simplified G-SSB.

The application of G-SSB is limited to locations in the distribution system where rapid fault current interruption is required without the need of coordination with existing downstream devices (e.g. isolation of a faulty load from the feeder). The most acceptable rated values (but not only) for a G-SSCL, G-SSCLB or a G-SSB are:

Rated voltage: 7.2 kV or 15 kV

Rated load current: 300 A, 600 A or 1200 A

Short circuit current: 12.5 kA, 23 kA or 45 kA (Symmetrical)

To satisfy the expectations and needs of utilities, this equipment must operate at least 50 times before requiring replacement or repair, have losses no greater than 0.25% of throughput power and a target cost of $50,000 for a 15588 kVA rated equipment, including loss evaluation based on $1,000/kW. Also another important characteristic is the automatic reclosing, since the lightning is the predominant cause of faults on overhead distribution systems. This reclosing action requires that the equipment must be able to carry its short circuit current several times in quick succession affecting its thermal mass requirement.

2.5.4 Solid State Transfer Switch (T-SSTS)

In some applications, two independent (i.e. with high degree of electrical isolation at the voltage level) power infeeds have been provided to sensitive loads to minimize disturbances caused by planned or forced outage. The T - SSTS is designed to replace the mechanical auto-transfer gear currently used to switch from one feeder to another. This process takes 2 to 10 seconds and is not fast enough to prevent disturbing the sensitive load. The T-SSTS makes the transfer in a fraction of a cycle (5 to 20 ms). Note that operation within power acceptability curves IEEE 446 or CBEMA (Computer Business Equipment Manufacturers Association) or its successor ITIC (Information Technology Industry Council) is not necessary in a medium voltage system since motor loads in the user facilities normally provide sufficient inertia and re-generation, which reduces the impact of a short disturbance on the high voltage system. The operating characteristics of a T-SSTS allow sensitive equipment such as computers and motor drives to ride through an interruption or disturbance in the power without losing the ability to perform critical functions.

In its simplest configuration, T-SSTS consists of two SCR thyristor switches connected back-to-back, Figure 2.13, which direct power flow from two feeders to a load.

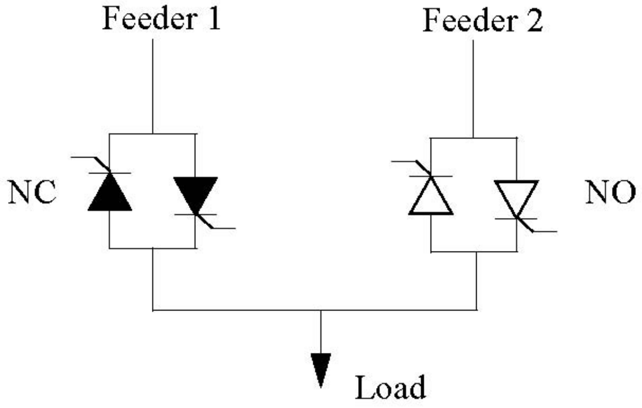


Figure 2.13 Simplified T-SSTS configuration.

In normal operation, the switch connected to the feeder 1 is kept closed and the switch on the feeder 2 is kept open. The T-SSTS senses voltage sag or outage on the feeder 1 before they affect the load and turns on the switch of the feeder 2, which immediately forces the switch of feeder 1 to shut off and transfer the load within a quarter of cycle. In the event of a voltage swell or surge, the transfer takes about half a cycle, because the switch of feeder 1 shuts off at the first current zero point.

Rated values for T-SSTS are:

Rated voltage: 660 V to 38 kV

Rated load current: 200 A to 6 kA

Short circuit current: 6 kA to 100 kA (symmetrical)

2.6 Shunt Compensation

2.6.1 Introduction

An inherent characteristic of alternating current transmission is that real power is invariably associated with reactive power. Because a transmission system itself is primarily inductive in nature, reactive current flowing through it causes variations in the magnitude of the receiving end ac voltage. Typical loads, for example induction motors are also inductive and therefore absorb reactive power causing the voltage on the system to drop as the load increases. Conversely, other system components, i.e. cables and lightly loaded overhead lines, are capacitive in nature and generate reactive power, thereby causing the voltage to rise.

The need to control reactive power in a transmission or distribution system has been recognised since the very beginnings of alternating current power systems. Conventionally, reactive power compensation in transmission systems has been achieved with synchronous compensators, which are basically synchronous motors, but without a mechanical load. Control of the machines field excitation allows it to generate or absorb reactive power from the ac system. Alternatively, capacitor and/or reactor banks can be switched to generate or absorb reactive power from the ac system.

This report highlights two different types of equipment, which have replaced the more traditional methods of reactive power compensation; these being the Static VAr Compensator (SVC) and the STATic Synchronous COMpensator (STATCOM).

2.6.2 The Static VAr Compensator (T - SVC)

Advances in high power semiconductors and sophisticated control techniques allowed the development of the Static VAr Compensator (SVC). These were originally developed for electric arc furnace compensation in the early 1970s and applied to transmission system compensation a few years later.

In a conventional SVC, reactive current and hence reactive power is varied by switching shunt capacitor banks and/or by controlling the current flowing in shunt reactors. Depending on the particular compensator requirements, a number of different configurations of SVC are possible but are generally built up from a combination of Thyristor Switched Reactors (TSRs), Thyristor Switched Capacitors (TSCs) and Thyristor Controlled Reactors (TCRs). The first two are only capable of switching on and off but the TCR may be phase controlled to provide continuously variable reactive impedance. A brief description of the TCR and TSC is given below.

2.6.2.1 Thyristor Controlled Reactor (TCR)

The Thyristor Controlled Reactor (TCR) consists of a linear reactor connected in series with a bi-directional switch made up of a number of series connected thyristors to obtain the necessary voltage rating. A simplified single line diagram is shown in Figure 2.14.

Variation of the current is obtained by control of the thyristor conduction duration in each half cycle, from a 90° firing angle delay as measured from the applied voltage zero for full conduction to 180° delay for no conduction. The simplest design of TCR uses three single-phase bi-directional thyristor switches (commonly referred to as thyristor valves) connected in delta giving a 6 pulse unit; hence it produces substantial 5th and 7th order harmonic currents and in most cases will require the use of harmonic filters.

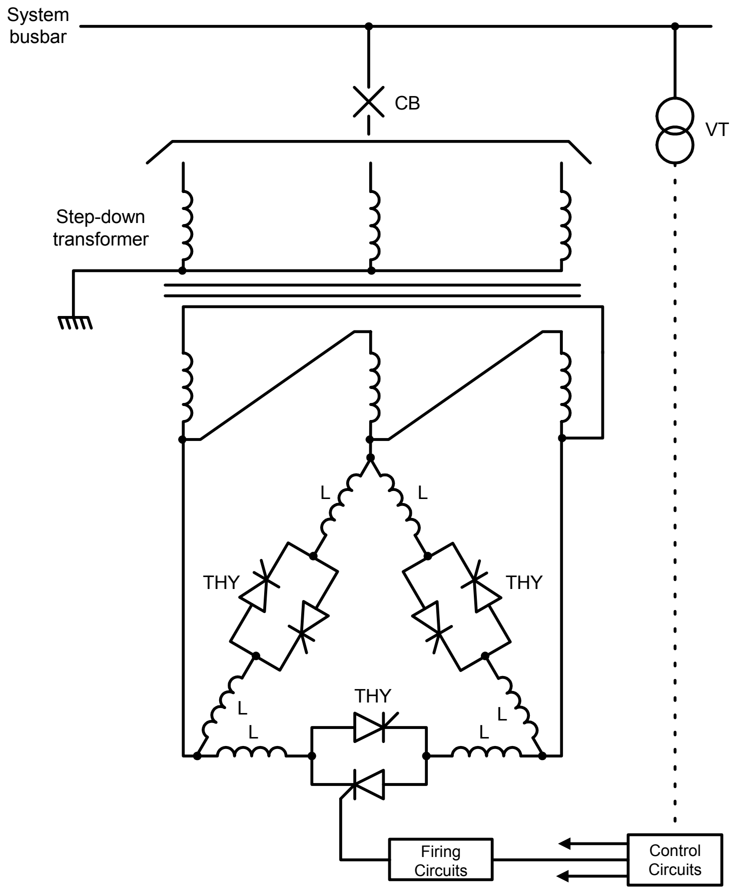


Figure 2.14 Simplified Diagram of a Thyristor Controlled Reactor.

2.6.2.2 Thyristor Switched Capacitor (TSC)

The thyristor switched capacitor consists of a capacitor, a thyristor valve and a small current limiting reactor. A simplified single line diagram is shown in Figure 2.15. The reactor is required to limit the surge current in the thyristor valve during fault conditions, for example due to the failure of the control system to fire the thyristors at the correct point on wave. It can also be used to prevent resonance with the ac system at particular frequencies.

The thyristor valve in a TSC is operated as a switch, which is either on or off. Control of the TSC by phase angle control is not possible since the thyristor valve must be turned on when the voltage across it is nearly zero otherwise there would be an extremely high discharge current from the TSC capacitors.

After the capacitor current through the thyristor ceases at current zero and unless the thyristor is re-gated the capacitor remains charged at peak voltage whilst the supply voltage peaks in the opposite direction half a cycle later. This imposes a double voltage stress on the non-conducting thyristor valves so that it is necessary to increase the number of series connected thyristors in a TSC valve compared with a TCR valve of equivalent voltage rating.

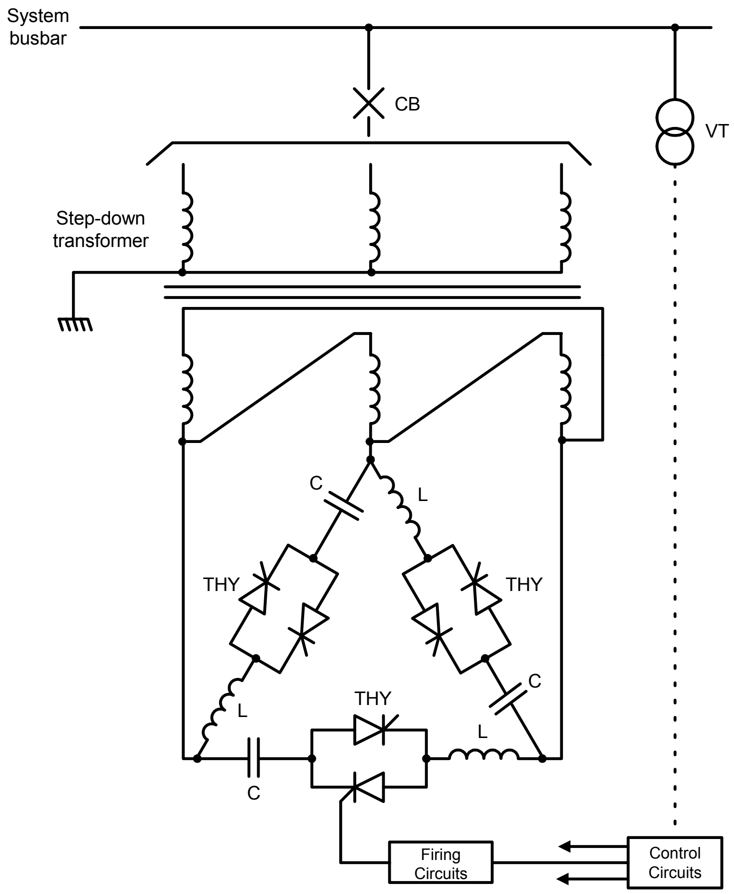


Figure 2.15 Simplified Diagram of a Thyristor Switched Capacitor.

2.6.2.3 SVC Configuration

A TSC or TCR may be directly connected to the ac system for voltages up to about 20kV; higher connection voltages need an interconnecting transformer. Depending on the size of thyristor, SVC ratings may range from +6 to –12MVAr for small industrial SVCs to +150 to –75MVAr or larger for transmission system SVCs (+ve is capacitive reactive power, -ve is inductive reactive power). The thyristor valves are generally rated to fully utilise the current carrying capability of the thyristor devices with ratings up to 4000A often being used.

The configuration of a typical low voltage industrial type SVC is shown in Figure 2.16. The active control range of –6Mvars to +12Mvars is provided by the continuously variable absorption of an 18MVAr TCR combined with 12Mvars of fixed capacitors. The fixed capacitance is configured as harmonic filters to attenuate the harmonics generated by the TCR. 5th, 7th and 11th 1.5MVAr tuned harmonic filters are predominantly associated with the TCR harmonics and are connected in parallel with the TCR from one circuit breaker.

This arrangement is suitable if the SVC is required to operate at or near its full capacitive output, i.e. if the TCR current and thus loss is low. If the SVC is required to operate around zero output the loss evaluation may dictate that the fixed capacitors are sub-divided into smaller TSCs. This then allows a smaller TCR to be used and the overall losses of the SVC are reduced. To summarise, the actual configuration of a SVC depends on its rating, reactive power range, operating strategy and loss evaluation.

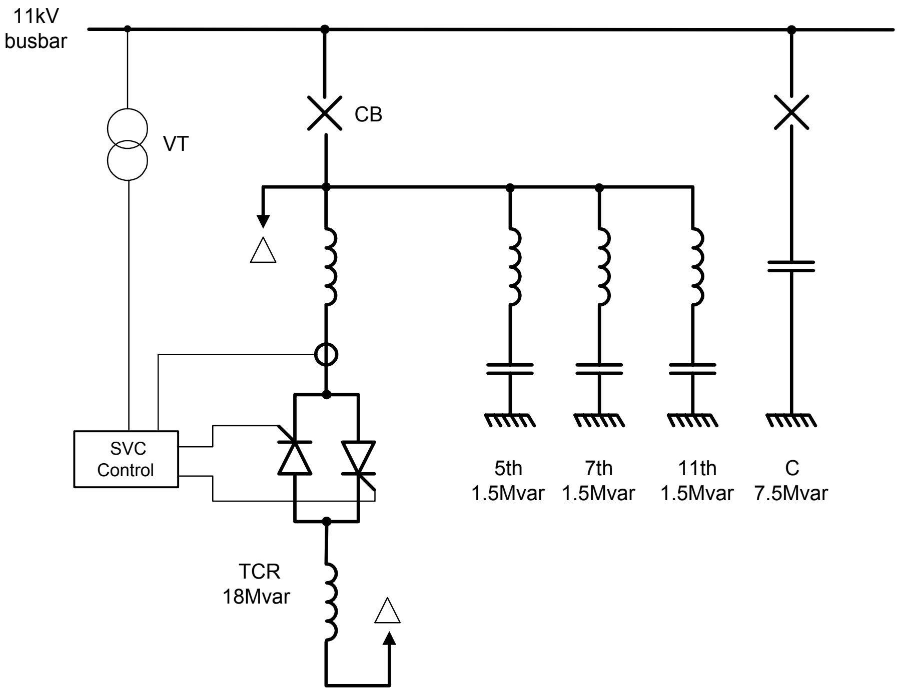


Figure 2.16 Single Line Diagram of a Typical Industrial SVC.

2.6.3 The Static Synchronous Compensator (STATCOM)

The conventional SVC is basically a thyristor controlled reactive impedance with the thyristor valves controlling the current drawn by the capacitor and reactor banks. Consequently, the capacitor banks are rated for the full capacitive output, the reactor banks for the full inductive output and the thyristor valves for the total controlled reactive output. For this reason, conventional SVCs are large systems involving a number of major components which are expensive and which require a significant site area.

The possibilities of generating controllable reactive power by various power electronic switching converters has long been realised but in order to produce leading as well as lagging VArs the converter must have an intrinsic turn-off capability. Semiconductor devices capable of self-commutation and with a large enough power handling capability have only recently become economically available and a small number of experimental schemes are now in operation. These converters are generally voltage sourced (VSC) and produce reactive power without the need of capacitors or reactors.

The Static Synchronous Compensator or STATCOM is a shunt connected device and is the true electronic equivalent of the rotating synchronous compensator. It produces a set of three phase output voltages, each of which is nominally in phase with, and coupled to the corresponding ac system voltage via a small reactance (which may be provided by an interconnecting transformer). By varying the output voltage of the STATCOM, the reactive power exchange between the STATCOM and the ac system may be controlled. That is, if the voltage generated by the STATCOM is greater than the ac system voltage, the STATCOM generates reactive power (is capacitive) and conversely if the output voltage generated by the STATCOM is less than the ac system voltage, the STATCOM absorbs reactive power (is inductive). If the output from the STATCOM is equal to the ac system voltage then no reactive power is exchanged. In comparison with a conventional SVC, a STATCOM provides potential savings of site area and several system performance benefits e.g. its inherent tendency to compensate system voltages (even without control action), its speed of response, improved harmonic performance and enhanced MVAr output capability at low system voltages.

The output voltage of a STATCOM is generated by a VSC operated from a dc energy storage capacitor. A number of different circuit topologies may be used for the STATCOM; the most commonly used being the 6-pulse Graetz bridge. A new idea, the Chain Circuit STATCOM is an alternative design and an example of this is being installed at a substation in the UK [Reference]. Different examples of VSC are discussed below.

2.6.3.1 VSC based on Graetz Bridge

The circuit layout of this inverter is identical to the Graetz bridge arrangement used in the majority of power electronic applications. In its simplest form it consists of six self commutated semiconductor switches, each of which has a reverse parallel diode connected across it with the bridge connected across a dc capacitor as shown in Figure 2.17. With a charged capacitor the inverter can produce a set of three quasi-square wave voltages of the appropriate frequency by connecting the capacitor sequentially to the three output terminals via the appropriate semi-conductor switches. Although the converter only exchanges reactive power with the ac system, the dc capacitor is required to supply the real power consumed by the circuit losses and is charged by operating the STATCOM such that its output voltage lags the system voltage by a small angle.

In practice, the quasi-square waveform generated by the inverter would produce unacceptable harmonic current when connected to an ac system. Consequently, in practice a STATCOM of this type would consist of a number of inverters suitably phase shifted with their outputs combined magnetically to produce a better approximation to a sine wave. The pulse number of such an arrangement is generally quoted as six times the number of inverters used and provides the level of harmonic neutralization required. For transmission or distribution applications, a pulse number of 24 or higher is required.

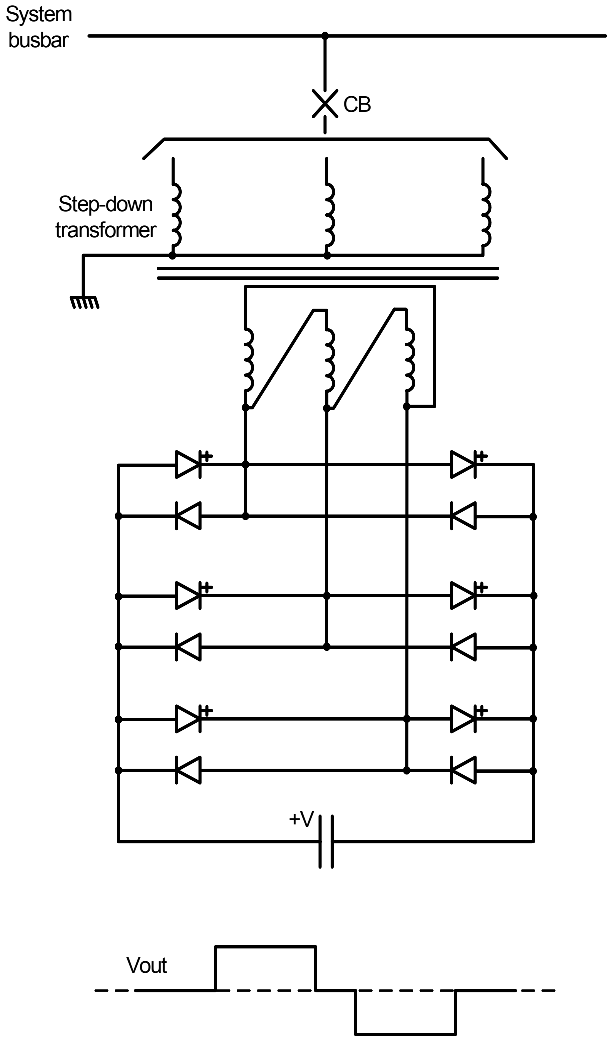


Figure 2.17 Circuit Layout of a Graetz Bridge STATCOM.

The magnetic circuit used to integrate the output voltages of the inverters is provided in the form of a transformer with multiple secondary windings in order to provide the necessary phase shifts. The magnetic circuits also isolate the STATCOM from the ac system and allow the secondary voltage to be selected in order to give the optimum valve design.

2.6.3.2 VSC based on Graetz Bridge utilising PWM switching techniques

As described above, a number of phase-shifted 6-pulse inverters can be used to provide acceptable harmonic performance. Unfortunately, this method results in a complicated transformer design with multiple windings required to provide the necessary phase shifts or magnetic components to interconnect the individual 6 pulse inverters.

PWM switching techniques are commonplace in motor drives for industrial and traction applications. The advantages include excellent control dynamics and reduced filtering for harmonic cancellation. These advantages would be naturally attractive in the STATCOM application as well.

With increased switching frequency and PWM, the STATCOM converter system can, in principle, be made of fewer bridges as the low order harmonics from each bridge can be cancelled. In addition, utilising high frequency PWM techniques to move the harmonics to higher frequencies would enable more cost effective filters to be employed instead of transformer magnetics to reduce harmonic levels.

Increased switching frequency results in increased switching losses and more difficult series connection of converters. The realisation of higher switching frequencies requires the use of IGBTs and the converter thus utilised is similar to that used for dc transmission based on voltage source converters, see section 2.3.

2.6.3.3 VSC based on Chain Circuit

An alternative method of minimizing harmonics is to develop the near-sinusoidal wave shape directly in the power electronic converters. This requires the use of a multi-level converter approach in this case using a number of series connected «chain» circuits as shown in Figure 2.18.

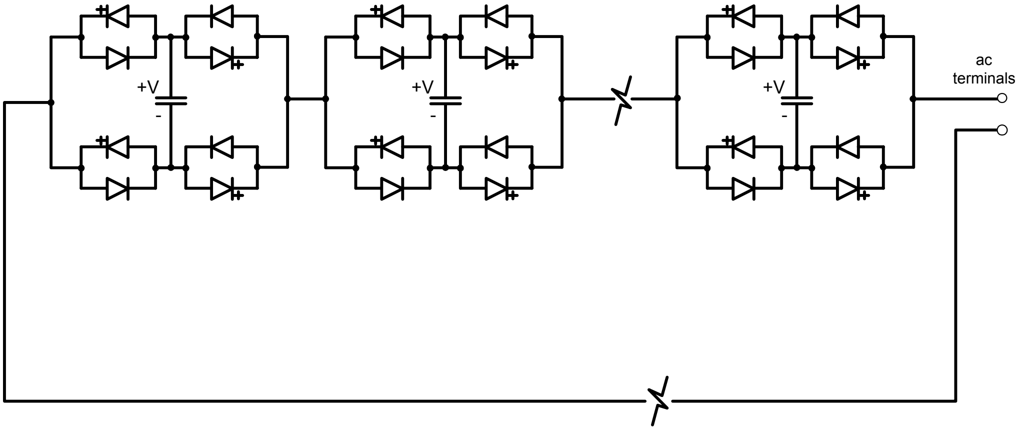


Figure 2.18 Chain Circuit Schematic (shown for one phase).

Each chain circuit is identical and consists of a single-phase bridge arrangement of GTOs (or IGBTs) and freewheel diodes, together with its own dc capacitor as a voltage source. Each link is able to generate three voltage levels to give a positive, negative or zero voltage contribution to the overall generated wave shape. In a similar way to the Graetz bridge based STATCOM, the dc capacitor is required to supply the losses incurred in the converter circuit and charged by operating the STATCOM such that its output waveform lags the system voltage by a small angle.

A number of links (n) are combined in series to give a multi-level converter with 2n+1 levels. With three links connected in series, seven voltage levels can be produced between the output terminals. By suitable choice of the instants at which these voltage levels are produced, the stepped waveform shown in Figure 2.19 can be synthesized.

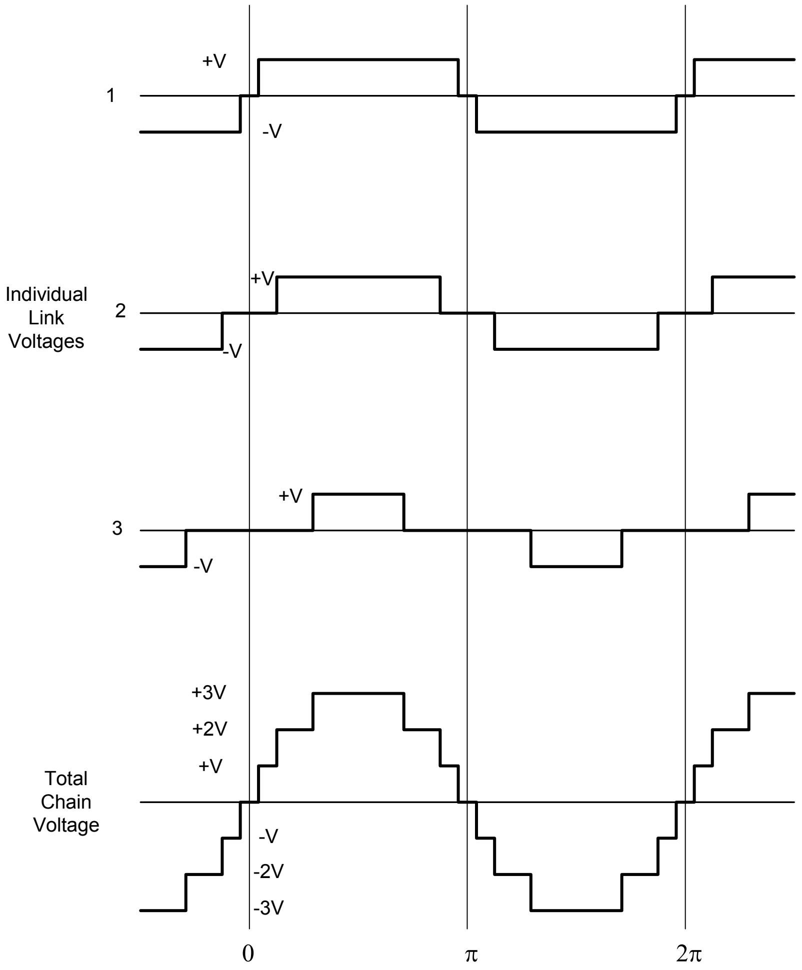


Figure 2.19 Voltage Waveforms for a Three link (7 level) Chain Converter [ref].

The Chain Circuit STATCOM [ref] in its simplest form is connected to the ac system via a small impedance provided by three air-cored reactors. For higher voltage applications, it would be normal to include a step down transformer to provide a more optimal voltage to the Chain Circuits. The step down transformer in this case would be a conventional two winding design and maybe a tertiary winding of an existing grid transformer. As with the Graetz Bridge inverter, the transformer isolates the STATCOM from the ac system.

The chain circuit STATCOM has a number of advantages over the Graetz bridge circuit, for example it eliminates the need for the complicated and expensive (in both capital cost and loss) magnetic interface circuits required to provide acceptable harmonic performance. Since it comprises of three independent single-phase inverters, an important advantage of the chain circuit is its ability of operating in unbalanced conditions when it is most needed to provide assistance to the ac network.

2.7 Dynamic Voltage Restorer (DVR)

2.7.1 General nature of problems to solve with a Dynamic Voltage Restorer (DVR)

Voltage swells or sags / dips are a serious problem for power quality. Dips are rapid drops in voltage, typically within 10 ms, down to a level below the stipulated voltage tolerance of the equipment. These events, random in character, are mainly caused by lightning strikes on the transmission / distribution network, which in turn, affect industrial distribution systems. Other causes include ground faults, for example trees falling onto / touching transmission and distribution lines – and last but not least scheduled switching of line breakers and capacitor banks in the transmission system. Despite the localised nature of the cause, voltage dips and sags can be felt hundreds of kilometres away. Even a modest reduction in voltage, for example down to 70 percent in one phase, may trip paper machines. Other industries affected include textile, pulp, chemical and critical hydraulic plants. Automatic manufacturing lines (semiconductors!), industrial robots etc. could be affected as well. Industrial cogeneration plants or embedded local generation based on synchronous generators might drop off line.

The control objective for restoring the disturbed system to normal is to maximize the positive sequence system and minimize the negative and zero sequence systems. If the step down transformer used for connection between the distribution line and the loads blocks the zero sequence voltages then the DVR does not have to block the zero sequence system. However, if there are single-phase loads connected between phase and a neutral, then the zero sequence voltages will be transferred to the loads. In order to avoid overvoltages resulting from a ground potential rise caused by the fault to impact the load voltage, the zero sequence voltage must also be blocked by the DVR. Note also that for a three-phase voltage dip, energy storage may be needed to restore the positive voltage to the nominal level.

2.7.2 The basic function of a DVR

A single line diagram with the basic function of a DVR is illustrated in Figure 2.20. In the event of a voltage swell or sag / dip, the power electronic injects the appropriate voltage, possibly also including a zero sequence voltage, required into the supply bus to compensate for the swell or sag / dip. For many voltage sags and swells, the DVR effectively acts as a buffer to the load and prevents unacceptable disturbances. However, for symmetrical three-phase disturbances, an energy storage system may be required to provide the needed ride-through capacity. The rapid control cycles and millisecond switching speed of the converter afford fast and accurate control of the voltage experienced by the load.

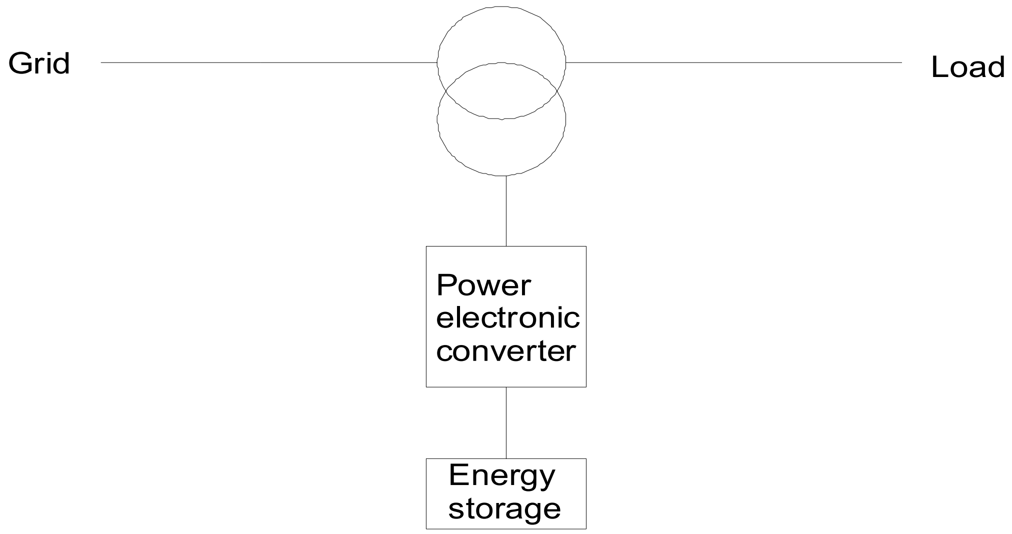


Figure 2.20 Series connected DVR.

2.7.3 The energy storage system of a DVR

Three practical energy storage systems have been identified. Though all of these energy-storing systems are under fast development (increasing energy density, high energy output, expected lifetime and decreasing storage space, weight, maintenance needed and price) three main fields of use for each energy storage system can be identified as well.

2.7.3.1 Capacitor as an energy storage system

A DVR can restore the positive voltage system to nominal voltage by stealing power from one phase and injecting into the phase or phases with below normal voltage. Energy storage would be required in DVR's, which are required to compensate for three-phase voltage sags / dips. It may be feasible to use capacitors for such storage to compensate for voltage dips down to about 50% of nominal voltage for up to 200 milliseconds. The MVA range could be between 3 and 50 MVA.

2.7.3.2 An inductor as an energy storage system

Magnetic energy storage is an alternative storage medium. These have been used in smaller DVRs, which need sufficient energy storage capacity to compensate a 50 to 100 per cent three-phase voltage sag / dip for up to 2 seconds. So far practical energy storage capacity is around 2 MWs - that is for a 2 MVA unit a 100 per cent three-phase voltage dip can be compensated for up to 1 second and a 50 per cent three-phase voltage dip can be compensated for up to 2 seconds etc. The inductor used is a so-called SMES (Super-conducting Magnetic Energy Storage). (However, for deep voltage sag correction, a distribution level unified power flow controller (UPFC), which uses a shunt connected rectifier to feed the series connected inverter (DVR section) might be more economical.) Note that for compensation of 100% voltage dips, energy storage cannot be avoided.

2.7.3.3 A battery as an energy storage system

Mainly used in DVR's which need sufficient energy storage capacity to compensate a 50 to 100 per cent three-phase voltage sag / dip for up to 10 seconds. So far only one size - a 2 MVA unit has been identified. Actually practical energy storage is unlimited if the growing footprint of the battery unit can be accepted. The battery is containerised in units that are dimensioned at 0.25 MW for 10 seconds. That is for sags / dips of 10 / 20 / 30 ... seconds dimensioning is straightforward - one just orders the number required of battery containers. For sags / dips of less that 10 seconds special calculations will be needed as the battery's energy output is decreased when the energy is needed in a shorter time.

2.7.4 Series versus shunt connected DVR's

So far it has been assumed that all DVR's are series connected. This is true but for DVR's that are dimensioned to compensate 100 per cent one- or three-phase voltage sag this is not practical. Compensating a 100 per cent one- or three-phase voltage sag actually means not only supplying the load 100 per cent (on one or three phases) but feeding into the weak or open circuited grid as well. A breaker must be inserted between the grid and the DVR and the DVR must be able to fully supply the load - that is in shunt. A single line diagram with the basic function of such a DVR is illustrated in Figure 2.21. Note however, that a shunt connected system is not suitable for injection of active power into the system since the injected power will probably flow towards the source more easily that towards the load. If reactive power is not sufficient for keeping the load in operation, the source side must be disconnected and the shunt connected DVR must then supply the active as well as reactive power for the load. (Some manufacturers like to stress that this should be regarded as a distribution voltage UPS (Uninterruptible Power Supply) - and try to name it accordingly.

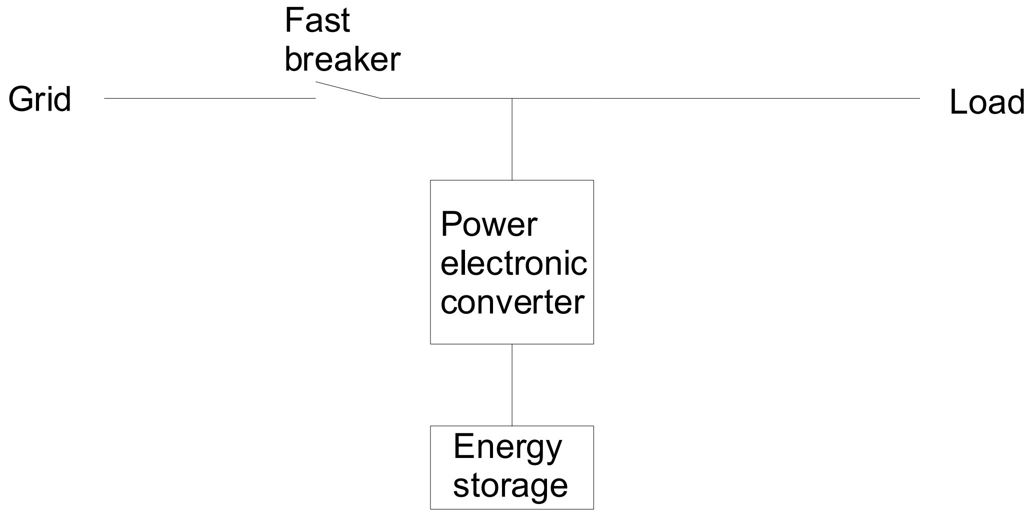


Figure 2.21 Shunt connected DVR.

2.8 Series/Shunt Combinations

2.8.1 Unified Power Flow Controller using IGBT's (IC-UPFC)

The Unified Power Flow Controller (UPFC) concept was proposed as the cornerstone of a family of power electronic equipment, capable of inserting controlled synchronous voltage sources either in shunt or in series in electric power transmission lines to optimise power flow in transmission systems. The first UPFC was dedicated 26 June 1998 at American Electric Power's Inez station in eastern Kentucky. It comprises two GTO-thyristor based back-to-back voltage source inverters; each rated at ± 160 MVA and coupled to a DC link capacitor. Each inverter output is a three-phase voltage set of 48-pulse that is coupled to the transmission line by a conventional mains coupling transformer. One transformer is connected in shunt and the other in series. This arrangement functions as an ideal ac-to-ac power converter in which active power can freely flow in either direction between the two inverters. The series inverter is controlled to inject a synchronous voltage V_{ser} in series with the transmission line. The magnitude and phase angle of the injected voltage are fully controllable in real time and therefore control of all three parameters of AC transmission systems is possible, i.e. voltage magnitude, transmission impedance and transmission phase angle. The parameters can be controlled sequentially or simultaneously. The shunt inverter has the basic function of supplying or absorbing the active power demanded by the series inverter and can also act as a STATCOM, i.e. it provides independent reactive power compensation to the bus connected. While there is a closed direct path for the active power through the two inverters back to the transmission line, the corresponding reactive power is exchanged locally by the inverters.

The smaller power rating for a UPFC applied to a distribution system makes technically feasible the use of two-level VSCs with IGBT switching elements and the application of PWM technique, Figure 2.22. The IC-UPFC incorporates not only the multiple compensation functions at the fundamental frequency but also provides improvement of the distribution system power quality, i.e. mitigation of voltage fluctuation, flicker, voltage asymmetry and active harmonic filtering. Short interruptions of the supply can be overcome if an energy storage system is used. Even with the previous great capabilities and reduced price, since IC-UPFC is based on series produced IGBT converters for drive systems; it is very difficult to find an economically feasible application of IC-UPFC in distribution system.

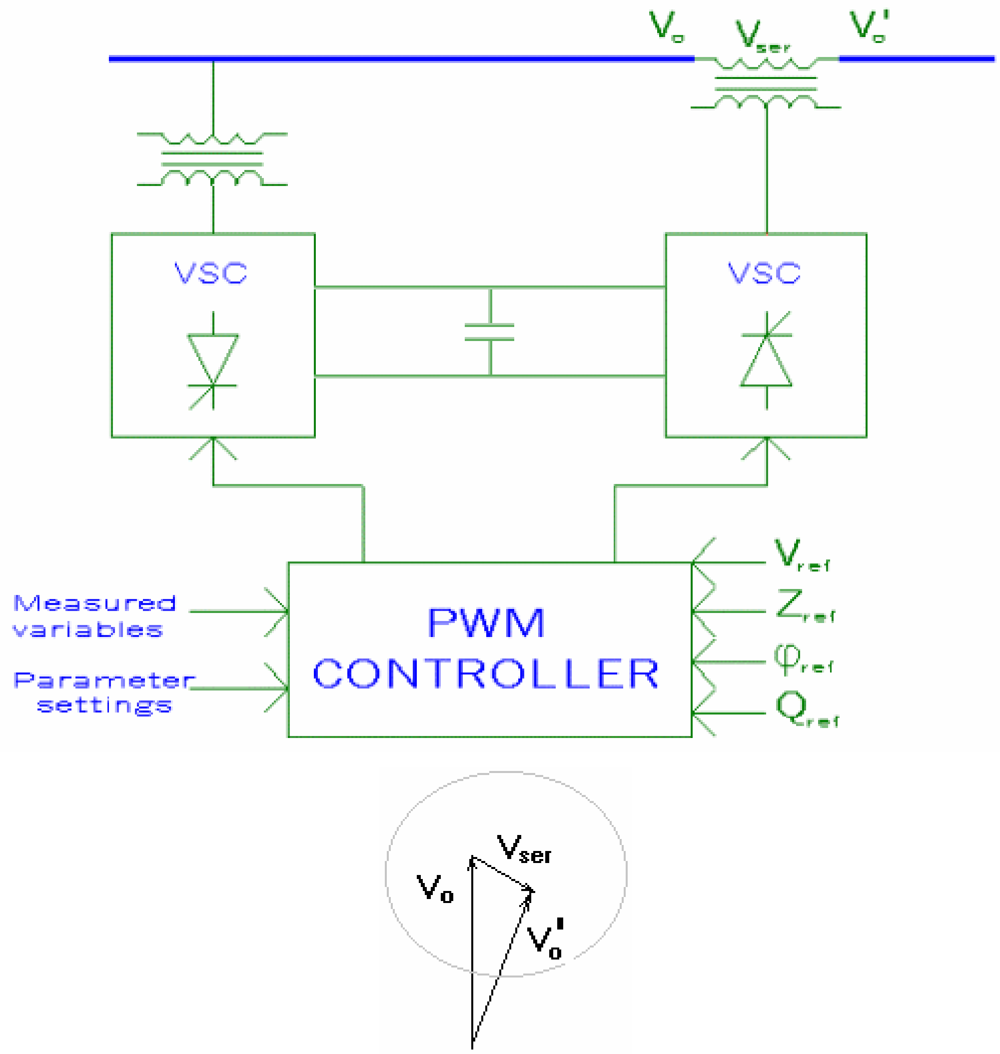
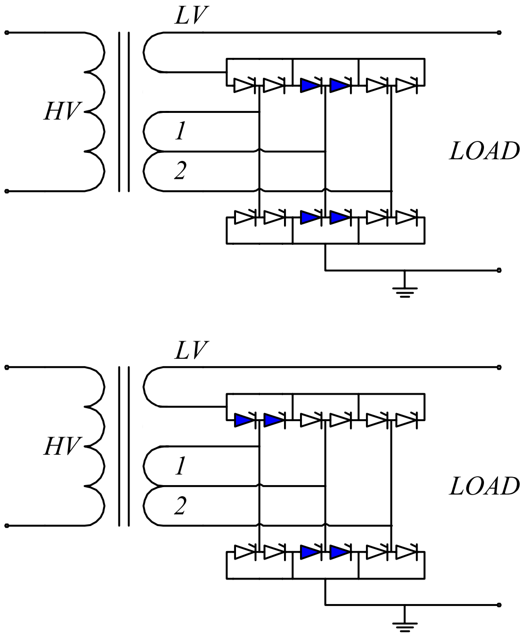


Figure 2.22 Simplified representation of UPFC.

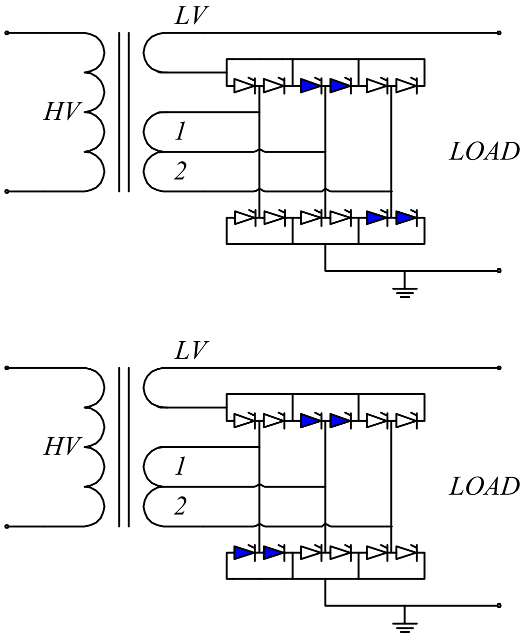
2.9 Solid State On-Load Tap-Changer (T-SSLTC)

The T-SSLTC is a transformer where the winding ratio may be varied individually for each phase by means of thyristors. It generates almost no harmonics and thus no additional filtering is required. The use of thyristors in the tap-changer has the advantages of low losses and elimination of moving parts. It has high reliability and a long service life minimizing required maintenance. The lifetime depends on maintenance and operation conditions such as frequent overloads but is usually more than 30 years.

Figure 2.23 shows schematically the principles of operation of a T-SSLTC with ± three steps in the low voltage side of the transformer. The connection of the desired part of the secondary winding is achieved by firing the appropriate anti-parallel thyristors, which are protected by snubber circuits. Figure 2.23 shows which of the thyristors are conducting for some tap positions. All commutations are carried out when crossing current zero and the operation time is less than half a cycle.



(a) No regulation **(b) +1 step**



(c) +2 step **(d) -1 step**

Figure 2.23 Principles of operation of a T-SSLTC.

The maximum allowable step voltage is limited by the thyristors and therefore is a function of rated through current. Normal losses are between 0.05 and 0.5% of the rated load power.

The very fast acting T-SSLTC can be used to protect critical loads from voltage dips or sags caused by faults in the feeding network. In this function the T-SSLTC regulates the phase voltage in a fast, controlled manner by monitoring the system voltage. Even though the T-

SSLTC acts by regulating the voltage amplitude, experience has shown that appropriate earthing conditions and transformer connection enable it to maintain both amplitude and angle of the voltage at the critical load. Since the phases are controlled individually, unbalances can also be compensated for.

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3 Overview of applications for which power electronic devices would be beneficial

3.1 Objective

The primary objective of this chapter is to provide a qualitative overview of the applications where it is considered advantageous to use Power Electronics. Typical power system situations where it may be advantageous to consider the use of power electronics are:

1. Limited access to easements1 and site space in heavily built up areas.
2. Low fault level, leading to poor power quality, e.g. voltage fluctuations.
3. High/rising fault level, which is exceeding or is expected to exceed the ratings of existing plant.

The selection of the most cost effective distribution system technology is dependent on the specific application and local factors. However, the main advantages of Power electronics are its ability to provide:

1. Rapid control of both active and reactive power giving a high level of power quality.
2. Ease of control in market applications.
3. An economical solution to the installation of plant in environmentally sensitive or congested areas.

This overview paper includes discussion, by way of examples, of:

1. Typical power system problems for which it may be advantageous to consider the use of Power Electronics.
2. The control, operation and maintenance requirements of the proposed power electronic devices.
3. The appropriate, cost-effective distribution technology.
4. The system interactions that have to be taken into consideration when those new applications are introduced.

3.2 Terminology

The very fast employment of power electronic devices in the creation of Flexible Alternating Current Transmission Systems (FACTS) did not give enough time for the establishment of standardized acronyms and terminology related to this subject. The confusion is even bigger for the distribution systems where acronyms and terminology developed for FACTS applications have been applied without much justification.

Within the WG B4.33, we have considered acronyms and terminology for distribution systems to describe distribution systems:

One suggestion is Flexible Distribution System (FDS), which would be defined as a distribution system that employs power electronic controllers to make the distribution of electricity more reliable, controllable and efficient. To fulfil its obligations, the FDS may exploit the capabilities of:

1. Power electronic controllers (e.g. SSTS, SVC, STATCOM, and DVR etc.) included in the ac distribution system.
2. HVDC link based on Voltage Source Converter (VSC).

3. A distribution system using only dc .

The advantages with the FDS are 1) its simplicity and 2) may include both ac and HVDC solutions.

Another suggestion is to use FACTS-D for ac systems and continue to use HVDC for dc systems within distribution.

As it was hard to get consensus on the use of FDS we have refrained from using it. The conventional terminology of FACTS or HVDC will be used where applicable and we will use Power Electronics for general purposes.

3.3 Advantages of Power Electronics

Switching and control of active and reactive power in conventional distribution systems is based on mechanical devices. These limit the speed with which control operations can be performed.

Power electronics incorporate solid-state power electronic controllers, which are capable of much faster action than mechanical switches. The advantages of FACTS have been presented in [1]. Some of these advantages, such as the removal of transient stability limits etc., are normally not applicable to distribution networks, when it refers to radial feeders. However, the following advantages of using Power Electronics have been identified:

1. Rapid control of both active and reactive power giving a high level of power quality.
2. Good control of active and reactive power flow, facilitating operation in a market environment, i.e. as a Market Distribution Service Provider.
3. Ability to connect to weak networks without impacting adversely on power supply quality.
4. Pre-assembled enclosures, which reduce civil work, installation and commissioning time.
5. Modular construction, allowing relocation if circumstances change and thus minimising the risk of stranded assets at a time of rapid change.
6. Reduction of environmental impact and reduced planning approvals time.
7. Reduced overall project cost compared with conventional technology or the “do nothing” scenario.

Some of the above are also applicable to conventional ac technology. For example, the use of pre-assembled enclosures is possible. Similarly, with the exception of the replacement of the ac magnetic field with a dc field, the environmental impact of an indoor, underground, cable-based distribution system is similar to that of an HVDC system.

The cost advantages of power electronic controller’s technology are extremely dependent on the nature of the distribution problem and the particular application. Where significant distribution network upgrading can be avoided or deferred, then there will be a net economic gain in using it. Similarly, in some quality of power supply applications, the ac alternatives may be so costly as to become infeasible.

3.4 Typical distribution system problems

The main need for the use of Power Electronics is to provide feasible solutions to previously intractable problems or more economic solutions to problems, which are currently solved by other means.

Although the range of problems for which this technology provides an appropriate design solution is wide, most of the issues are related directly to the four key areas in the first column of Table 3.1 below:

Problem/Issue	Use of Power Electronics	Competing Technology/Solution
Limited easements/space **Severe environmental or planning restrictions**	VSC with extruded dc-cable technology.	Conventional MV AC distribution based on XLPE cables.
Low fault level: Voltage fluctuations Poor power quality	Thyristor Switched Series Compensation. [2] STATCOM. [3] HVDC based on VSC [4]	Local soft-starters or UPS systems. Raise fault level by embedded generation or augmented distribution.
High/rising fault level: Existing plant limitations, Reduced security with open-breaker operation	HVDC based on VSC [4] Solid State Transfer Switch	Operation with split bus sections. Air cored or saturable reactors, splitting network, increased transformer impedance, switchgear/cable replacement.
Variable frequency or DC embedded generation. Photovoltaic or variable speed wind turbines	VSC with cable or back-to-back connection	Difficult to accommodate in conventional AC system.

Table 3.1 Opportunities for Use of Technologies based on Power Electronics.

As the technology becomes more mature, acceptance grows and the economies of scale start to be realised, its solutions will become more economically feasible for a variety of applications that are outside the range of conventional HVDC power transmission.

3.4.1 Limited easements/space or planning restrictions

As the size of the concentrated load increases due to on-going urbanisation, the metropolitan power networks need to be continuously upgraded to meet the demand. In heavily developed inner city areas the availability of new easements to develop parallel distribution feeder routes may be limited land space often being scarce and expensive. Similarly, the high cost associated with making available additional site space may encourage the use of compact solutions for terminating equipment. The use of underground cable supplies may be mandatory.

In some regions of recognised natural beauty, such as wildlife parks or wilderness areas, the construction of conventional overhead distribution circuits may not be permitted. Such regions are increasingly being targeted for development for their often-significant wind or small hydro energy resources.

Consequently, new power infeed solutions are required. The HVDC based on VSC meets both the space and environmental demands: The cables are economically installed underground often in existing ducts and the converter stations are compact. From an environmental perspective, a dc grid connected supply is much more desirable and also it eliminates the requirement for the operational and maintenance support over the lifetime of the project.

In these circumstances, the Power Electronics solutions may provide a cost-effective alternative to conventional ac distribution. The additional cost of the converter equipment may be offset by the provision of additional features such as improved quality of supply or freedom from fault level constraints since, by virtue of their control, they do not contribute to short-circuit levels. Thus, with the use of modern extruded dc cables, underground transmission would be in the same order of overall project cost as overhead AC line transmission.

Since the output from a VSC always has the same polarity, it is theoretically possible to connect any number of VSCs to a dc bus and build a multi-terminal system. Thus the configuration of a meshed dc system similar to an ac system can be envisaged.

The HVDC based on VSC links so far in operation or under construction have a common basic control and then each one of them has its specific control features to act in its specific network environment. Thereby each one of them can give ample support to the connected ac networks.

3.4.2 Low Fault Level

The issue of low fault level, weak grid system at the connection point, is discussed from three points of view:

- Power quality,
- Isolated loads and generation,
- Protection and control.

3.4.2.1 Power Quality

In situations where the network connection point is weak, the quality of power supply will be poor due to voltage fluctuations at the point of common coupling.

Typical scenarios where poor power quality arises are at the point of connection of significant wind generation into weak networks, the operation of large motor loads in areas remote from the main grid and the operation of sensitive industries such as paper manufacture. Typical installations are:

- Distant rural loads, particularly those with demanding duty cycles, such as sawmills or log chippers.
- Small loads on islands.
- Power from small generators such as wind turbines, small-scale hydro or solar energy plants.

In these distribution systems, the Power Electronics facilities can provide fast reactive power compensation with consequential good voltage stabilisation. Examples of this would be the use of HVDC Light technology with connection via a VSC. Similarly, for wind turbine applications, some manufacturers have adopted synchronous generators with embedded ac/dc/ac conversion based on VSCs to enhance the ability to operate in weak grid situations.

For instance in Australia SVCs (thyristor switched capacitors) are used to provide voltage support and regulation on some wind farms using induction generation technology. These SVCs are low voltage and are connected through a step up transformer to 22kV board distribution board.

The use of shunt conditioners, e.g. STATCOM, would be another way of solving the poor power quality problem. Alternatively, DVR or DVR with energy storage are other examples of ways to achieve good power supply quality in weak grid scenarios.

3.4.2.2 Isolated Loads and Generation

Many isolated communities (i.e. a town, mine or an island) are not connected to the main electrical grid and are dependant on either expensive or polluting local generation for their needs. The need for supply redundancy may lead to the provision of additional generation plant or the operation of diesel plant at inefficient low loads. The HVDC light transmission concept makes it feasible, in many cases, to connect these communities to the main grid. By doing so, the local generation can be either replaced or avoided altogether.

3.4.2.3 Protection and Control

Since the VSC is self-commutated, for operational purposes, there is no requirement for short circuit capacity in the receiving network. Furthermore, for protection relay discrimination purposes, the converter normally gives sufficient short circuit current in relation to load current at locations far from the feeding point. However, for the lines connected to the converter bus, another type of protection will be needed. This new protection scheme relies on an impedance-based protection system that is implemented together with the converter control.

3.4.3 High/Rising Fault Level

As system fault levels rise with time, due to the increase in the number or capacity of parallel infeeds, the short circuit fault rating of existing plant can be exceeded. Therefore, with increasing power levels, the risk of exceeding the short-circuit capability of switchgear equipment and other network components becomes a real obstacle to further expansion. Operation with an open bus circuit breaker may comply with the fault level restriction at the price of reduced distribution network reliability. This is unlikely to be acceptable in a CBD area.

When the rate of growth is low, it may be more cost effective to replace the older underrated plant, which may be close to the end of its economic life. However, when the growth rate is high, with a consequent rapid increase in fault level at the connection point, the replacement of the existing switchgear is not an attractive option.

Another possible reason for a rapid increase in fault level may be a decision to install embedded generation in order to benefit from a new de-regulated electricity supply environment.

Under these circumstances the conventional options are to:

1) Replace existing plant with new plant at a higher fault rating.
2) Replace existing supply transformers with higher reactance units.
3) Install air-cored reactors to increase the effective source impedance.
4) Install saturable reactors to decouple the fault level requirement from the normal voltage regulation performance.
5) Use fault-current limiters in the superconducting or impedance insertion mode.

The alternatives to these are to use:

- A Solid-State Breaker or Solid-State Transfer Switch, (SSTS) with fast (sub-cycle) operating time.
- A DC connection between the high fault level connection point and the existing plant so that the rapid control of the converter can be used to interrupt the fault current.

An additional advantage of the use of the Power Electronics technology is that the parallel infeed of city loads through a VSC transmission system can contribute to the stability of the AC distribution system exploiting the flexibility of the controller and thus enhancing the exploitation of the existing AC distribution system.

3.4.4 Asynchronous grid connection

This refers to a connection between two networks with either different frequencies, or different control programs of frequencies and/or voltages. It can also apply to a sensitive load that needs an asynchronous connection to safeguard the power quality of the bus.

In the case of a market distribution service provider, (unregulated or entrepreneurial connection), where it is important that contracted power and energy can be continuously achieved and monitored, an asynchronous connection offers an interesting business alternative. The high availability of the HVDC Light option together with the improvements it gives to both networks makes it especially suitable for such applications.

As described under 3.5.2 above, remote small scale generating capacity (i.e. small hydro generators, wind turbine and solar farms) will be economical to develop and permit connection to either the main grid or to remote loads by the use of the Power Electronics technology. By use of a unit connection of a small hydro generator together with the VSC converter, it would be possible to take advantage of the converter characteristics and design the generator for a higher frequency operation and thus optimise the weight and cost of the generator. This would be especially important when connecting to a variable speed wind turbine. The variable speed operation scheme can boost the energy delivery of some large, modern wind power plants by some 2.5 to 5 %, thus improving the economy of the installation.

3.5 Additional requirements of the Power Electronics facilities

The following issues have been identified.

3.5.1 Training and Operator Acceptance

The control, operation and maintenance requirements of the proposed Power Electronics facilities will require some increased operator training. On the contrary the possibility of more automatic supervision than in a conventional distribution system will probably facilitate decision-making and reduce stress on the operators. This is one important experience from operation of HVDC based on VSC links.

3.5.2 Control and Protection Requirements

Power utility-sponsored research for the optimal operation strategies of Power Electronics would be an interesting contribution to the development of the field.

Integration of many VSC devices in the same distribution network requires some consideration of their overall impact. There is a need for the coordination of controls to ensure that the common dc voltage is well controlled by one of the converter stations in a multiterminal aggregate.

One typical solution would be a configuration with a single source controlling the voltage with the current controlled by each individual consumer.

3.5.3 Operation and Maintenance Requirements

It is recommended that a data base of distribution systems with VSC devices be set up to start to develop a picture of the issues concerning Operation and Maintenance, reliability etc.

3.5.4 Converter Configurations

The use of different converter configurations has not been extensively investigated at this stage. However, the selection of multiple-level converters for situations where the three-phase distribution load is significantly unbalanced has been noted, presumably in order to provide a better waveform or higher voltage operation.

3.6 Applications of HVDC based on VSC

3.6.1 Hellsjön

The Hellsjön transmission was implemented to demonstrate the feasibility of the technology to operate in a network. It was not provided with any sophisticated controls but used control settings for active and reactive currents. Nevertheless, it showed quite interesting characteristics for network support. Basic tests were made with the link to show its operational possibilities with varying frequencies, start against black networks and operation with networks without generation.

3.6.2 Gotland

In operation since November 1999, the Gotland scheme transports 50 MW over a distance of 70 km. The control for network support is more developed than the Hellsjön transmission system and the basic controls are changed to control active and reactive powers. The reactive power capabilities are used to control the ac voltages of the networks connected to the converter stations. The voltage control of a station constitutes an outer feedback loop, and it gives the reactive current order in such a way that the set voltage on the network bus will be maintained.

On the Gotland network, the introduction of a dc link permits the active power flow in the network to be controlled. The goal is for the active and reactive power controls to minimise the over all losses in the system. The optimum power flow is continuously calculated in a special module of the SCADA system and orders the preferred amount of active power through the dc link resulting in minimal over all losses. The calculation considers both reactive power compensation and active power flow and the optimisation is made for the losses in the entire Gotland system. The ability to control both active power transfer and reactive compensation at both ends makes the HVDC based on VSC transmission a very powerful tool for power flow control for the Gotland scheme.

3.6.3 Direct Link

Direct link is a 180 MVA HVDC based on VSC project that links the regional electricity markets of New South Wales and Queensland in Australia. Direct Link is a non-regulated project, operating as a generator by delivering energy to the highest value regional market. Direct Link employs dc transmission to define the power flow over the link precisely for fully commercial service. The Voltage Source Converter terminals can act independently of each other to provide ancillary services (such as VAr support) in the weak networks to which Direct Link connects.

3.6.4 Tjaereborg

A dc feeder, using an 8 MVA HVDC link with Voltage Source Converters was installed at Tjaereborg in Denmark to demonstrate how a dc feeder can be used to transmit power from wind farms to a receiving AC grid. Since it can operate as a rectifier or an inverter at any frequency and at the same time either absorb from or supply reactive power to the AC network, it is therefore suitable for connection of wind farms with induction generators.

The normal operation of such a link is to use frequency and voltage control in the converter connected to the wind farm. The VSC's ability to change the stator frequency of the induction generator gives the possibility to optimize the power output from the wind turbine by adjusting the frequency in relation to the wind velocity in order to operate at the maximum power. Also, since VSC's can be operated with variable frequency, it is possible to control the rotational speed of the wind turbines and by that the power production. With increasing amounts of wind power coming on line, any introduced instabilities can be damped by dc transmission with VSCs.

3.6.5 Eagle Pass

The control scheme of the Eagle Pass 36 MW HVDC based on VSC Back-to-back controls the reactive power at each converter independently. In Voltage Control Mode, the AC voltage control uses the full capability of the VSC regardless of the power order set point. One of the converters may be connected to a passive network, i.e., where no synchronous machine is connected to the network. In this case, the magnitude of the ac voltage may be controlled, as long as the converter valve current is below the permissible value. Furthermore, the VSC has black start capabilities.

3.6.6 Troll A

The Troll A is a platform in the North Sea for pumping gas to the shore. The Pre-compression Project will use two HVDC based on VSC transmissions, each 45 MW, +/-60 kV as feeders from mainland to the platform. This HVDC will feed directly a high voltage variable-speed synchronous machine for compressor drive with variable frequency and variable voltage, from zero to max speed (0-63 Hz) and from zero to max voltage (0-56 kV). Converters are designed for installation in housings that will be lifted on to the platform. The platform-based converters in their housings were lifted on to the platform in May 2004 and are expected to enter into operation in the beginning of 2005.

The inverter control software is adapted to perform motor speed and torque control - while the control hardware is identical for rectifier and motor converters. Over the entire motor operating range, unity power factor and low harmonics are assured, while sufficiently high dynamic response always is maintained. There is no telecommunication for control between the rectifier control on land and the inverter motor control on the platform - the only quantity that can be detected in both ends of the transmission is the dc-link voltage. The control is however prepared so that together with a telecommunication it could provide for land based operation, fault finding and maintenance of the platform station.

On a platform for an offshore installation the equipment has to meet requirements on space and weight to be kept at a minimum. Therefore the HVDC based on VSC concept offers important advantages and thanks to smaller filters than classic HVDC and no need for additional reactive power generation equipment it can be made compact and lightweight. Another challenge is the environment - the high voltage equipment must be protected against the salt laden, humid air at sea.

3.6.7 Siemens Switchgear Factory and Flender-Werft, Germany

These two HVDC installations, based on VSC back-to-back, are used to feed 60-Hz-LV-networks in the test field of a Siemens switchgear factory in Frankfurt, Germany, and of a shipyard installation with Flender-Werft in Lübeck, Germany. The power is transferred from 50-Hz-LV-networks. The installations consist of a single circuit VSC with a rated maximum power of 1.2 MVA.

3.6.8 Stadtwerke Karlsruhe and Stadtwerke Ulm/ Neu-Ulm

An HVDC, based on VSC back-to-back connection, is used to connect two stations in a 20 kV network in Karlsruhe, Germany. A galvanic connection is not easily possible due to problems with the residual currents in the neutral point compensation. In this case, the 2-MVA-HVDC-connection is even more economic than a conventional AC solution. The HVDC connection was able to improve both voltage quality and supply reliability significantly for the customers in the affected network area.

A similar installation is in operation to connect the 10 kV networks of Ulm and Neu-Ulm. This technology allows power to be transferred between the separate networks supplying the municipalities of Ulm and Neu-Ulm at times of peak demand. It will reduce the amount of costly regulating energy that has to be bought in and will further optimize grid utilization when either network has spare capacity.

3.6.9 Industrial factory, Saudi Arabia

A multi-parallel HVDC based on VSC back-to-back, scheme is designed to connect a 33 kV, 60 Hz network and a 10 kV, 50 Hz network. The maximum power is 30 MVA.

3.7 Installed solid state switchgear equipment

3.7.1 Baltimore Gas and Electric

A solid-state transfer switch (SSTS) was installed indoor by BGE at an office in downtown Baltimore in September 1995. The SSTS is rated at 15 kV, 600 A, and it has operated successfully since its installation.

A similar SSTS was also installed in September 1996 by BGE at a customer's chemical manufacturing plant in the Baltimore metropolitan area. Between the time of installation and January 1998, this switch has successfully prevented over twenty service interruptions due to power quality events.
In December 1998, a 15kV 1200A split-bus SSTS was installed by BGE at a customer's chemical manufacturing plant in the Baltimore metropolitan area. Since installation, this unit has prevented over ten power interruptions from the customer.

3.7.2 Chubu Electric Corporation

In 1991, Chubu Electric Corporation of Japan installed three 7.2 kV, 300 A SSTSs in a loop line configuration. These devices are reported to have a high reliability rate since installation and require a maintenance check once a year.

3.7.3 Commonwealth Edison Company

On August 14, 1996, ComEd installed a static transfer switch rated at 12.47kV, 600 A at a plastic film manufacturer. Between January 1 and October 15, 1997, there were 50 events with 40 successful transfers with no loss of production and 10 events that resulted in production interruption. Of these 10 events, 5 events can be explained because voltage sags were present on both feeders.

The data indicated that some of the events where the customer lost production in 1997 could have been prevented if the switch response was a little faster. The data also indicated that there is little effect on the alternate feeder when the switch transfers the load over to it. Due to a change in the control settings, there were 95 transfer events in 1998. The customer seems quite satisfied with the performance of the switch.

3.7.4 Detroit Edison Company

In November 10, 1996, Detroit Edison installed a SSTS at the Ford Motor Company, Sheldon Road Plant. This plant is fed from a 40 kV sub-transmission system and has a load of 9 MVA. The switch is installed on the 13.8 kV side of the transformers and has avoided costly downtime.

3.7.5 Kyushu Electric Corporation

Between 1990 and 1997, Kyushu Electric of Japan installed eleven static transfer switches for the purposes of high-speed line transfer. Each unit is rated at 7.2 kV, and for operation between 200 A and 300 A. The units use a hybrid-switching device made up of a thyristor switch and a high-speed parallel switch. The high-speed parallel switch can open and close in less than one millisecond using an electromagnetic repulsion scheme. Thus, through the use of the parallel switch, the thyristor elements are bypassed during steady-state operation, and only conduct during a transfer or other such operation. This eliminates the need for any type of cooling equipment.

3.7.6 PG&E Energy Services

In September 1996, PG&E Energy Services installed two static transfer switches. Both switches are rated at 25 kV, 300 A, and are presently in commercial operation.

3.7.7 Texas Utilities

TU has demonstrated an outdoor 15 kV, 600 A SSTS at an electric operations building in Fort Worth, Texas. The switch was placed in service in October 1996 and has operated successfully since that time.

3.7.8 Toyo Oil Industry Company

In 1997, The Toyo Oil Industry Company of Japan installed a SSTS for a generating unit transfers application.

3.8 Installed devices of shunt conditioners

Since the conventional thyristor based SVC is established technology and many examples exist around the world, the following list contains examples of STATCOM based applications only:

3.8.1 American Electric Power

AEP has installed a STATCOM (Graetz bridges connected through magnetics) based static shunt voltage compensator at a rock crushing facility to control voltage flicker. The rating of the device is ± 2 MVA at 12.47 kV. It was placed online in January 1998 and commissioned on February 12, 1998. The unit utilizes two 1 MVAr capacitor banks that allow operation with output from 0 to 4 MVAr capacitive. This mode allows the customer's load to grow and provide increased capacity at lower cost. The unit is considered successful by AEP and has allowed the customer to grow its business and operate all three stone crushing operations at the same time with minimal impact of voltage flicker to other customers on the circuit.

3.8.2 British Columbia Hydro and Power Authority

This STATCOM (Graetz bridges connected through magnetics) provides voltage regulation and voltage flicker mitigation caused by a large, whole-log chipping operation. This device is capable of adjusting the line voltage by ± 4.2%. Field experience has shown that overall flicker was reduced from 5-8% to 2.5-4%. The ± 2 MVA inverter-based trailer unit is now being readied by BC Hydro for relocation to another site where voltage flicker is creating major problems for customers on the 25 kV distribution system.

3.8.3 Chubu Electric Corporation

A STATCOM (Graetz bridges connected through magnetics) was implemented in October 1990 using a 20 MVAr GTO inverter for arc furnace flicker compensation on a 22 kV feeder. The successful operation and experience of this first installation encouraged the steel manufacturer to further increase arc furnace operation, and was followed by another static shunt compensation device installation using a 21 MVAr GTO inverter for the same purpose in May 1995. The GTO inverter cubicles of the second static shunt compensation device were specifically designed to be more compact in size in order to provide benefits for industrial application use

3.8.4 Hagfors, Sweden

In 1999 a STATCOM, utilising PWM switching was installed at Uddeholm Tooling at Hagfors, Sweden to provide voltage flicker correction for two arc furnaces. The STATCOM has a rating of 10.5 kV, 22 MVAr and is combined with two harmonic filter banks to give a total rating of 0 – 44 MVAr. The reactive power compensation system is based on the VSC technique, as conventional SVC equipment does not meet the requirements on flicker compensation.

3.8.5 Kansai Electric Power Co.

The first experimental prototype of a STATCOM (Graetz bridges connected through magnetics) was installed on the 77 kV sub-transmission line at the North Osaka substation of the Kansai Electric Power Co. in Japan in August 1979. The application’s voltage source inverter was comprised of conventional thyristors with force-commutated circuits. The objective of this project was to prove the operational characteristics (i.e. generation and control of capacitive/reactive power) of a 20 MVAr class voltage source inverter at the sub-transmission level for the first time in the world. The experience from this experimental static VAr compensator resulted in the successful installation of an 80 MVAr, 154 kV unit connected at Inuyama switching station in Japan in May 1991.

3.8.6 Rejsby Hede Wind farm

In 1997, trial operation of a +/- 8MVAr STATCOM began to provide reactive power to the Rejsby Hede Wind farm of the Danish utility ELSAM. The STATCOM provides power factor correction for the induction generators of the wind turbines and is connected to the 15kV wind farm system.

3.8.7 RWE Energie

A 20kV, 38MVArs STATCOM, utilizing PWM switching is installed at RWE Energie, Germany. It is used mainly to mitigate flicker problems caused by a steel plant.

3.8.8 Sumitomo Steel Co.

One static MVAr compensator using an 8 MVAr GTO inverter for arc furnace flicker compensation was installed on the Sumitomo Steel Co. 22 kV feeder in July 1995. This installation successfully provided a reduction in flicker level, and enabled an increase in steel productivity from the arc furnace.

3.8.9 Avestapolarit STATCOM, Torneå, Finland

A large EAF for stainless steel has been installed in northern Finland. Studies performed before the installation indicated a requirement for flicker mitigation. The chosen solution was a STATCOM based on VSC with IGBTs and with ratings 33 kV, 0-164 MVAr. The usefulness of this solution has been demonstrated in field measurements for e.g. the Hagfors installation, showing a flicker improvement ratio in the order of 4-5 times. Such a STATCOM has shown outstanding performance in respect of safeguarding the power quality in the feeding grid in conjunction with the steel mills and similar installations.

3.9 Dynamic voltage restorer installations

3.9.1 Duke Power Company

A series compensation device was installed carrying critical customer plant load in 1996 on the Duke Power Company system in Anderson, South Carolina. The device is now in service at Orian Rug Company where the unit is protecting the automated yarn manufacturing and weaving plant from voltage sags and disturbances coming from the Duke Power distribution system that serves the plant. The unit is rated at 2 MVA, can store 0.66 MWs and operates at 12.47 kV. No further technical data. Pricing unknown.

3.9.2 Florida Power Corporation (FPC)

A series compensating device was installed in 1997 at the FPC 230/12.5 kV, 100 MVA Econ substation in Orlando where it protects one of the six 12.5 kV feeders. The project is designed to demonstrate the ability of the series device to provide improved feeder power quality in a high isokeraunic environment. Power quality measurements of the Econ feeder data will be compared with the unprotected feeders. No further technical data. Pricing unknown.

3.9.3 Oglethorpe Power Corporation

A series compensation device was installed carrying critical customer plant load in 1996 on the Slash Pine Electric Membership Corporation, South Georgia. The device is now in service and protecting a highly automated, high-tech lithograph plant from voltage sags and disturbances coming from the distribution system that serves the plant. The unit is rated at 2 MVA and protects a 2 MVA load. Energy stored in batteries is 20 MWs, which means that a 100 per cent three-phase voltage sag can be compensated up to 10 seconds. Operating voltage is 12 kV. No further technical data. Pricing all in all approximately US$ 2 million.

3.9.4 Powercor Australia, Ltd.

A 50 Hz series compensation device was installed at the Bonlac Foods plant at Stanhope, Victoria, in Australia where it will protect the sensitive dairy food process plant load from disturbances originating on the Powercor Australia overhead rural distribution system. The Bonlac plant produces powdered milk and other related dairy products from milk supplied by nearly 800 dairy farms in the area. The unit is rated at 2 MVA, can store 0.66 MWs, and operates at 22 kV. No further technical data is available. Pricing details are also unknown.

3.9.5 Public Service Electric and Gas

A series compensation device was installed around 1996. This device might not be a DVR but probably is, as no other type of series compensating device for distribution level was available at that time. No further technical data is available. Pricing details are also unknown.

3.9.6 Scottish Power

A 4 MVA, 11 kV, 50 Hz series compensation device was installed around 1997 at the Caledonian Paper Mill at Irvine, Scotland to protect the paper machine from voltage sags originating on the 132 kV system feeding the mill. Installation involved segregating the critical load bus protected by the series device from the rest of the plant load. The unit protects an 8 MVA load. Energy stored in capacitors is 0.8 MWs, which means that a 50% three-phase voltage sag can be compensated in up to 200 ms. No further technical data is available. Pricing details are also unknown.

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4 Selection of recommended state of the art devices and applications

4.1 Introduction

At the start of this Working Group (WG) a rapid growth of the technology and its application was anticipated. The various electronic facilities and possible usage described in the foregoing chapters did not make the expected break-through, and so far its usage has been limited to specific applications. There are several contributing factors: a general decline in the business climate, the deregulation-reregulation scenario that stopped halfway through without clear rules for transmission and distribution ancillary services and the technology development that could not keep up with the expected growth rate.

There are installations of various types of facilities and to pick up available information as a background for the WG, it was decided to send out Questionnaires to users and suppliers, but the response from the market players was meagre. It seems that the technology and/or the market have not yet matured.

With this background, a selection of the state of the art devices for distribution systems will be somewhat arbitrary. Therefore, the suggestions in the following paragraphs have to be evaluated with the above in mind.

4.2 Suggested state of the art power electronic facilities

The following state of the art facilities are suggested because they have been used at least in some application. They would also solve or help to overcome existing problems in distribution and sub-transmission systems. Common to all of these systems is the fact that the world economy has not progressed as expected and that modern power electronic facilities would be economic for many specific applications and resolving specific problems. As the economy could rebound rapidly it may be of interest to investigate new applications.

Based on the above, the following state of the art power electronic facilities could be of interest:

- Solid state switchgear especially the solid state transfer switch
- DC transmission based on VSC
- Dynamic voltage restorer
- SVC or Statcom

The above-mentioned power electronic facilities will be further discussed below.

4.3 Solid State Transfer Switch

The Solid State Transfer Switch is a typical facility for a distribution system in the voltage range from 6 kV to 36 kV, as indicated by the majority of installations so far. Operating experiences have been good and the expected functions work well. No specific problems have been encountered and only minor component failures in the electronic parts have occurred.

The experience when making installations in existing systems is that the changes to the system may raise the cost to an inconvenient level. For new systems, or expansions to existing systems, it may be easier to plan it in from the beginning and thus keep costs to a lower level.

4.4 DC transmission based on VSC

DC transmission based on VSC is a facility that is applicable for both transmission and distribution systems. It can be used for interconnection between networks, power supply to distant loads such as isolated areas, islands and platforms, in-feed to cities, etc. All of these systems are installed and the HVDC option was chosen to address specific requirements.

Of the HVDC VSC transmissions, which have been contracted and put into operation or are under construction some would be of specific interest to distribution systems and reference is made to the following three applications:

- On the island of Gotland to bring power from a set of wind mills to a consumer area The Gotland system was chosen to provide reactive power control close to the windmills, and for ac voltage and flicker control at the connection points to the ac system. It is rated 50 MW at +/-80 kV. AC connection is 70 kV at the two ends.
- In Australia to supply power to an unconnected region. The Direct Link provides power to a small part of the NSW state that was earlier not connected to the main part of the state but had its supply from Queensland. At the same time it is an interconnection between NSW and Queensland. It consists of three parallel links each rated 60 MW at +/-84 kV.
- Troll A in the North Sea to distribute power from a network on shore to a platform. The Troll A will provide power to a high voltage motor, which will drive a compressor. It is rated 45 MW at +/-60 kV and ac connection on the mainland is 130 kV. On the platform it will operate within a voltage and frequency range (0-56 kV; 0-63 Hz;).

The experience from the HVDC VSC links in operation is good and it fulfils various functional tasks in a good manner. Its flexibility makes it easy to recommend whenever there is a specific task or a difficult problem to resolve in a system. At the present time, Cost-wise it is on the high side for simple transmission tasks.

4.5 Dynamic Voltage Restorer

A Dynamic Voltage Restorer is a facility that can help a sensitive load to survive in a weak and electrically vulnerable (weak) environment with frequent voltage dips and swells. The DVR will then protect and decouple the load from the voltage transients, which are originating from the system. This facility is in service at the moment for railway use by a number of transport authorities using flywheel energy storage system of up to 100 kW, and is also under evaluation for distributed power and UPS applications.

Presently, storage units based on a number of energy storage technologies of up to a few MWs are possible at 15-24 kV. This could correspond to protecting the load of 15-20 MVA against a voltage dip of 30-40% up to some hundred milliseconds.

4.6 STATCOM

The most important task of a STATCOM in a distribution system is for improving the power quality. This is especially important both to protect industrial plants from voltage variations in an ac network and to protect the network from voltage variations originating from the industrial plant. Especially this refers to rapid variations such as flicker.

There is no specific voltage level as a STATCOM can be connected via a transformer. Ratings exist from 1 MW level up to a few 100 MW.

4.7 Some comments on commercial aspects

The above facilities can be designed with various types of semiconductors, but basically distinction can be made between two main types: those based on thyristor technology (e.g.

GTO) and those based on transistor technology (e.g. IGBT). Designs based on transistors give a higher operational flexibility and controllability. Designs based on thyristors give lower losses at designs that operate with low switching frequencies. Presently, thyristor elements can be manufactured with higher ratings than transistors as the thyristor is now considered a mature product while the power transistor is a fairly new product.

Equipment losses are dependent on application, but very roughly they can be given as a percentage of the rating of the equipment or facility. Today thyristor-based facilities should have losses in the range 0.5-1.0% and transistor based facilities in the range 1.5-2.0%.

The operational experiences for power electronic based installations shows that it is possible to achieve a reasonably high availability irrespective of whether the design is based on thyristors or transistors. Today a statistical experience value for operational availability is in the range of 98-99.5%, if availability is considered in the design.

For the installation of a Solid State Transfer Switch or a Dynamic Voltage Restorer the total costs including changes to the system, assuming a system voltage of 12-36 kV would be in the range of MUSD 1 and above.

The cost for SVC, STATCOM and HVDC by VSC per station could be estimated to be in the range USD 100-400/kVA.

5 New Opportunities and Future Trends

5.1 Future expectations

When considering future trends, we have to identify within which areas development is important for the future Power Electronics. Here we have concluded that the following areas are basic to such development:

- **Device technology.** It is fundamental for development of the future facilities that cost effective and low-loss devices are available for the functions that need to be created.
- **Converter topologies, especially for VSCs**. Development of topologies will be complementary to the development of devices and also contribute to the more effective use of existing and developed devices.
- **Application development.** This will be based on the need of new applications that will, in many cases, be opportunities waiting for newer and better devices. We know that many of these applications would materialize, when cost effective components are available.

The above-mentioned three areas are further described below.

5.2 Device Technology

One aspect that will lead another revolution in the FACTS technology and its applications is the development of efficient, high-power, high-current power electronic switching devices. In the forefront of today's technology leading to state-of-the-art applications are the developments in GTO and IGBT technologies.

The impact of the developments will occur on two fronts: on one front will be the development of high power devices and, on the other front, will be the packaging of the switches into functional blocks, developing a power electronic equivalent of the integrated circuit. There are still some practical problems to be overcome to achieve this.

At present the power semiconductor devices available for high power FACTS applications are all based on Silicon technology. For example, the devices just being released to the market are “MOS Turn-Off Thyristor” (MOT), Emitter Turn-Off Thyristor (ETO), “Integrated Gate Commutated Thyristor” (GCT or IGCT) and “MOS Controlled Thyristor” (MCT). All of these devices have fast turn-off capability and low turn-off switching losses. They will eliminate some of the present day limitations of the widely used devices for FACTS applications, i.e. GTOs and IGBTs, and could make FACTS devices of the future more efficient and economically attractive [8,11]. Increasing the voltage capability is a clear trend in the development of silicon based IGBTs, and this will also apply to non-silicon based devices. This is because increasing the voltage capability of the device reduces the number of series connected components required overall, which in turn gives possibilities to reduce the overall cost of the function. The rated voltage of the silicon-based turn-off IGBTs today has reached about 6.5 kV at 400A [15]. However silicon based devices have clear limitations, and so new materials are being investigated in order to obtain benefits, which are not possible with silicon.

In the future, new wide-band gap semiconductor materials such as Silicon Carbide (SiC), Gallium Nitride (GaN) and thin-film diamond could increase the power handling capacity and the switching speed of the devices leading to a significant reduction of the cost of FACTS devices. High switching speeds will dramatically reduce the switching losses associated with the FACTS devices and will enable the use of more versatile VSC topologies, as well as allowing a further increase in the operating frequency, which in turn would lead to a reduction is size of the associated harmonic filters, [12]. Such devices could also increase the peak junction temperature at which full control of the device can be maintained to over 200º C with a consequential reduction in the cost and complexity of associated cooling systems. Also this increase in peak junction temperature translates into a significant improvement in surge capability.

The first GaN based MOSFET devices were fabricated in a laboratory in 1999. Presently the fastest inverters are based on silicon-based MOSFETs. MOSFETs based on GaN promise to handle higher power levels and operating temperatures, resulting in wider applicability and better performance [1]. The demonstration of a fast turnoff thyristor based on wide-band gap semiconductors took place in 2001 [2].

The best candidate at the moment however is still SiC for a new practical material. This is because when compared with silicon, SiC has the potential for producing semiconductor switching devices with 5 to 10 times greater voltage handling capability, a several hundred degrees higher working temperature and less than a few tenths of the loss. High voltage, high power, SiC based diodes with a rating of 3500 V/ 200 A have been developed under laboratory conditions [3, 9], and in the short to medium term this material looks very promising, although there are still fabrication issues to be resolved and time to market is uncertain. However producing SiC material capable of blocking the higher voltages needed for practical ratings such as 20 to 40 kV will in any case be technically very difficult, as there is no neutron transmutation doping technique as there is in silicon to help produce very uniform high resistivity layers needed to make high voltage devices. Individual SiC devices > 20 kV will probably not be introduced for more than 15 years hence. In addition, it is clear that for the future SiC GTO and Thyristor chips will be very difficult to connect in parallel to make them share current although this will become more practical at the higher voltage ratings.

In the future, high-voltage, high-power switches will be packaged into different functional configurations. Each package will also include features such as gate drive circuits; protection and control circuits with built in heat sinks for cooling purposes. Such pre-packaged, standardised and modular blocks will drastically reduce development time, design and maintenance costs of new inverters. Such modules are already being developed for ratings of 2.8 kV dc link voltages and 1 MW. Devices are already available with six or seven IGBT in one package, which can also include a brake circuit for motor control integrated within the package [14].

Another technological advance expected to change the design and applications of the FACTS devices is the development of capacitors with high energy and power storage densities. Already such "super capacitors" that contain power and energy densities in excess of 30 kW/litre and 600 J/litre have been fabricated under laboratory conditions [3].

The developments described will lead overall to simpler, more compact, installations, which in turn will be more reliable and cheaper to maintain due to the fact that there would be very many fewer series components required for a given FACTS installation.

5.3 VSC Topologies

In recent years, multi-level converters have been considered to obtain high voltage operation without the need for converter transformers. There are two versions possible of five-level converters:

- Diode clamp arrangement (Figure 5.1), and
- Flying capacitor arrangement (Figure 5.3).

The switching arrangement is shown in Table 5.1, and an example of the voltage waveform possible is shown in Figure 5.2.

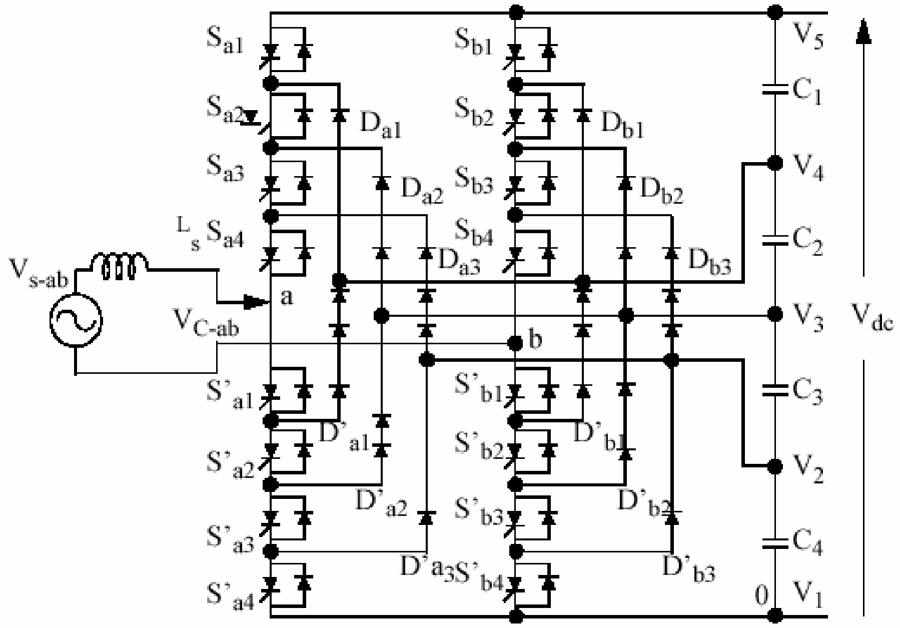
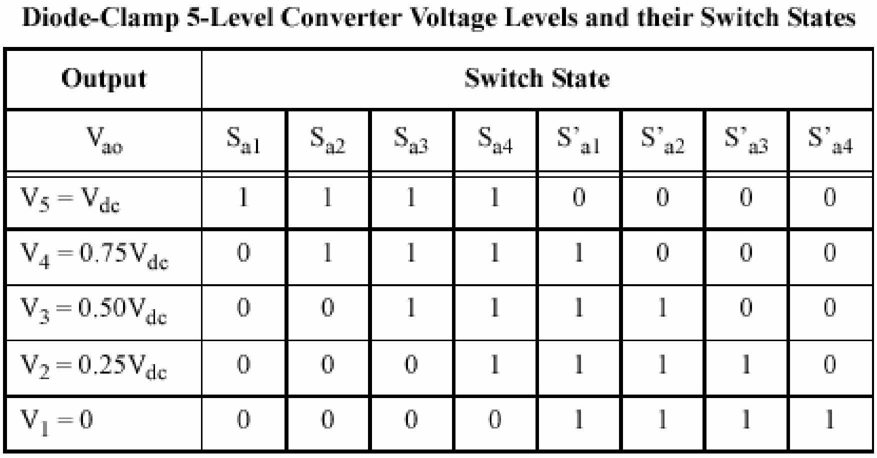


Figure 5.1 A diode-clamp 5 level converter circuit diagram.



Diode-Clamp 5-Level Converter Voltage Levels and their Switch States

Output	Switch State							
V_{ao}	S_{a1}	S_{a2}	S_{a3}	S_{a4}	S'_{a1}	S'_{a2}	S'_{a3}	S'_{a4}
$V_5 = V_{dc}$	1	1	1	1	0	0	0	0
$V_4 = 0.75V_{dc}$	0	1	1	1	1	0	0	0
$V_3 = 0.50V_{dc}$	0	0	1	1	1	1	0	0
$V_2 = 0.25V_{dc}$	0	0	0	1	1	1	1	0
$V_1 = 0$	0	0	0	0	1	1	1	1

Table 5.1 5-level diode-clamp converter switch states.

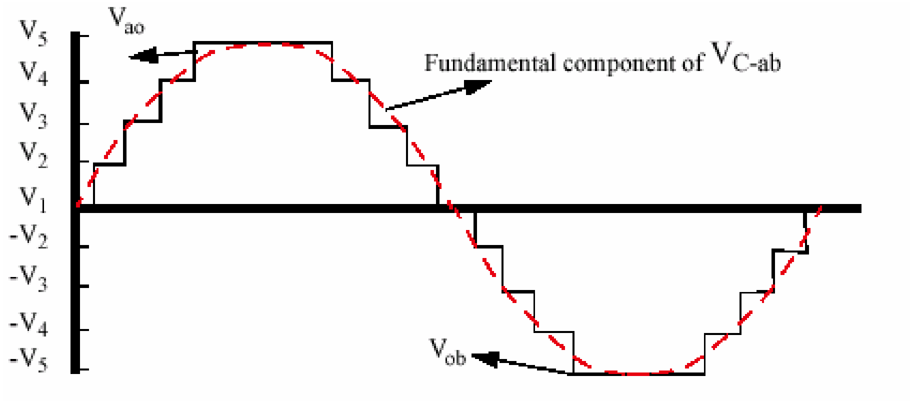


Figure 5.2 diode-clamp 5-level converter voltage waveforms.

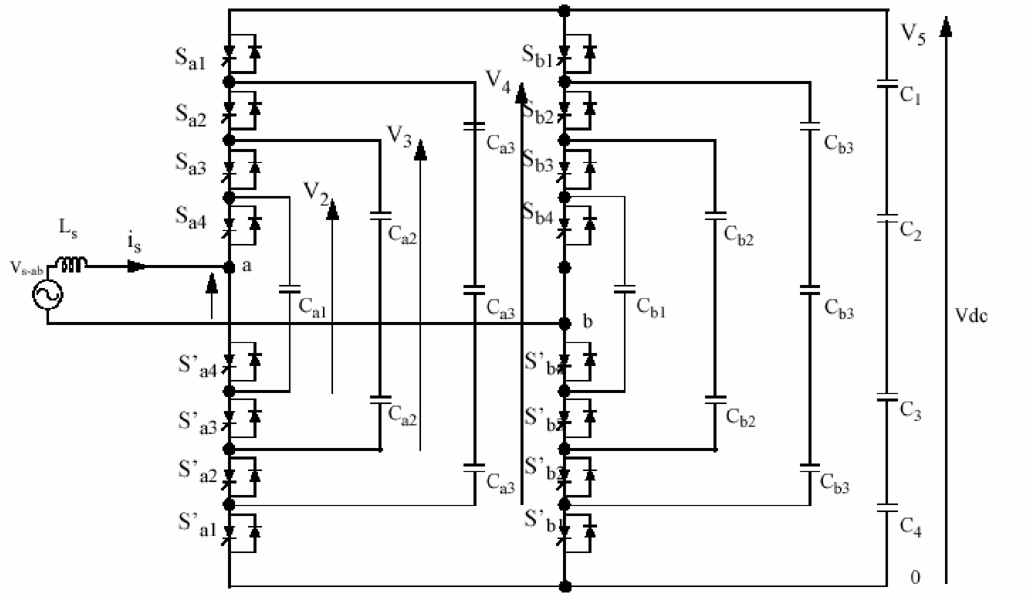


Figure 5.3 flying capacitor 5-level converter circuit diagram.

5.4 Future Applications

5.4.1 Integrated power quality solutions

With the projected reduction in cost, complexity and size of the VSCs, it is highly probable that:

(a) A FACTS device could be used for providing solutions to a number of power distribution problems,

(b) Multiple FACTS devices could be used in one location for mitigating a series of problems associated with distribution system operation.

One application of the first type is using FACTS devices for cancelling power system harmonics by appropriately controlling the turn on/off instances of the switches. Therefore, when a FACTS device is used for providing the primary functionality of a STATCOM, DVR or similar application, it can also be used for cancelling the harmonics injected into the system from the point of connection by incorporating appropriate measurement points and control techniques [4].

An application of the second type is the combination of more than one FACTS device into forming a "near-universal", power system quality solution provider. Considering the fact that all the VSC based FACTS devices operate from a dc bus, one advantage of such approach is that a common dc bus or energy storage source can be used for supporting all the FACTS devices. Figure 5.4 shows one such application. In this application, the battery storage system required for providing the power required for the DVR is supplied from a shunt VSC based rectifier. This shunt VSC also functions as a D-STATCOM for providing the reactive power necessary for correcting the load power factor to unity. The same dc bus is also used for supplying the active filter, whose function is cancellation of the harmonics produced by the non-linear load. The combination of the devices, DVR and D-STATCOM can be used for providing additional functions such as load unbalance compensation etc. Another functionality of the arrangement shown is that shunt VSC1, battery storage and shunt VSC-2 can also perform as an uninterruptible power supply.

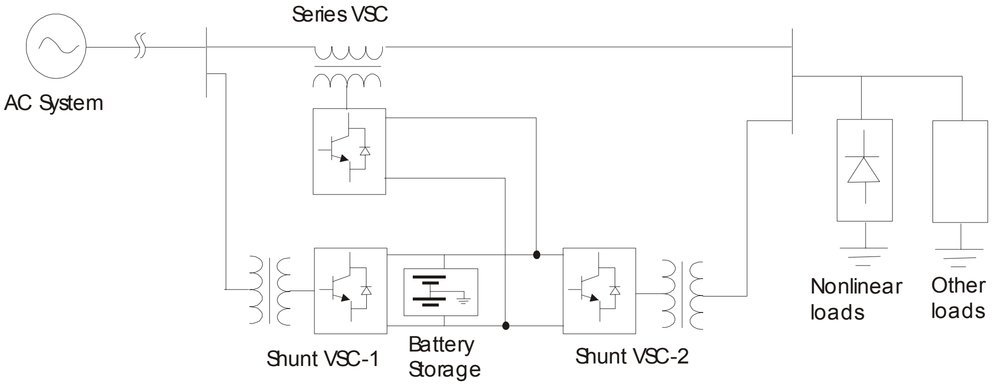


Figure 5.4 Universal Power Conditioner.

5.4.2 DC Transformers

Industrial, commercial and domestic dc distribution systems may be an inevitable result of the low-cost power electronic devices and the versatility that they offer in conditioning power to match the requirements of various applications. Examples of the dc distribution systems expected to be implemented in the future are described in sections 5.4.3 – 5.4.5.

In order to effectively use dc distribution networks, the loads must be supplied at the most optimum supply voltage. This implies transforming the dc voltage from one voltage level to a different voltage level. In the past, using the traditional electro-magnetic voltage transformation concepts, the transformation of dc voltage levels was very difficult and inefficient. This has been the primary reason for the popularity of ac distribution over the dc distribution and the beginning of the ac distribution systems utilised today. However, with the availability of low-cost VSCs, voltage transformation can be efficiently carried out.

Figure 5.5 shows a concept for a dc transformer.

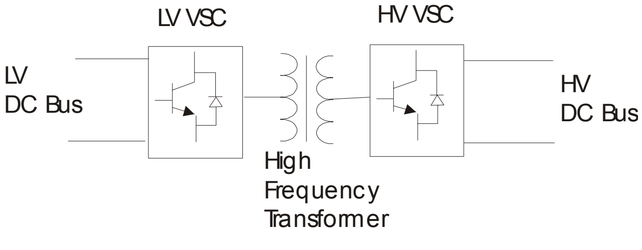


Figure 5.5 DC voltage transformer (bi-directional).

In the dc transformer (Figure 5.5), the dc voltage is converted to high frequency ac by using a VSC based inverter. The high frequency ac is then transformed to the required high or low voltage level using a high frequency ac transformer. The ac waveform is then rectified back to dc at the required voltage level. Voltage transformation at high frequency will have the advantage that the magnitude of flux in the transformer core is proportionately reduced, reducing the volume of core material required and therefore the transformer size and cost. Further, since the conversion to ac is only done as an intermediate stage and isolated from the dc distribution networks, the intermediate ac need not to have a pure sinusoidal waveform. Therefore the filtering required in the ac side of the transformer would be very minimal.

The configuration shown in Figure 5.5 can be used for bi-directional power transfer through the transformer. Since VSCs are used for both rectification and inversion, their roles can be interchanged depending on the direction of power transfer. On the other hand, when only unidirectional power transformation is required, one VSC can be replaced by a high frequency diode rectifier, as shown in Figure 5.6. In this instance, the VSC will provide the reactive power requirement of the diode rectifier and perform the required voltage and power control functions. In the example shown, the power flow will be in the direction LV to HV.

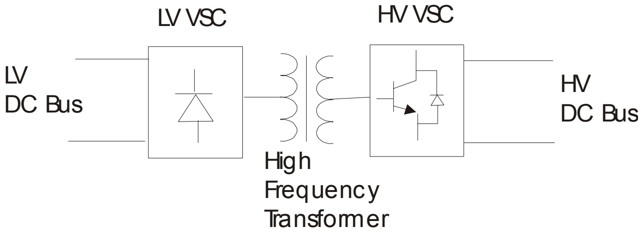


Figure 5.6 Dc transformer (unidirectional).

5.4.3 DC sub-transmission systems

In power distribution systems, reverting back to dc transmission, at least in the sub-transmission voltage networks could result in significant advantages. The increase in quantity of power transmission for the same conductor size, low cost of dc cables compared to that of ac cables, and low voltage drop (compared to overhead ac lines) are some of these advantages. In addition where transmission structures are considered unacceptable due to environmental and electro-magnetic field concerns, underground dc cables become a viable and more attractive alternative.

Because of continuing urbanisation, metropolitan power networks have to be continuously upgraded to meet the increasing demand. Moreover, since land is scarce and expensive, substantial difficulties arise whenever new right-of-ways are to be acquired for new lines. Therefore, at present the drive is to maximize the utilisation of existing assets and possibly deferring the expenditure on new capital investments. Furthermore, with the deregulation of distribution line business, it is inevitable that distribution services will be subjected to intense competition, especially the connections to large consumers. Competing line companies could provide new line connections to large consumers, encroaching the “franchise boundaries” and bypassing the assets of the incumbent distribution service provider. As a result the line companies face the risk of getting parts of their networks being under utilized or stranded.

Presently, there is no direct mechanism for controlling the power flow along desired routes in distribution networks. Although, to some extent, the power flow in the network is partly controlled by the sectionalising switches connecting different feeders, it is otherwise largely uncontrolled and follows the laws of physics. During certain equipment outages, although there may be extra capacity available in the other parts of the network for re-routing the power flow, such action can usually not be effectively implemented due to the unavailability of interconnecting transmission links and/or suitable equipment for controlling the direction of power flow.

In the future, by creating a dc sub-transmission "backbone" for urban distribution networks the above mentioned problems can be solved and the existing distribution networks can be better utilized [2]. An example of such a low power HVDC (LP-HVDC) sub-transmission concept can be explained with the help of Figure 5.7. In summary, one can expect to have a dc transmission ring, routed through the main parts of the distribution network and use it as a "controlled" highway exchanging power flow between these zones. The LP-HVDC converters will act as real/reactive power sources and sinks, extracting power from certain parts of the network and delivering it to the other zones.

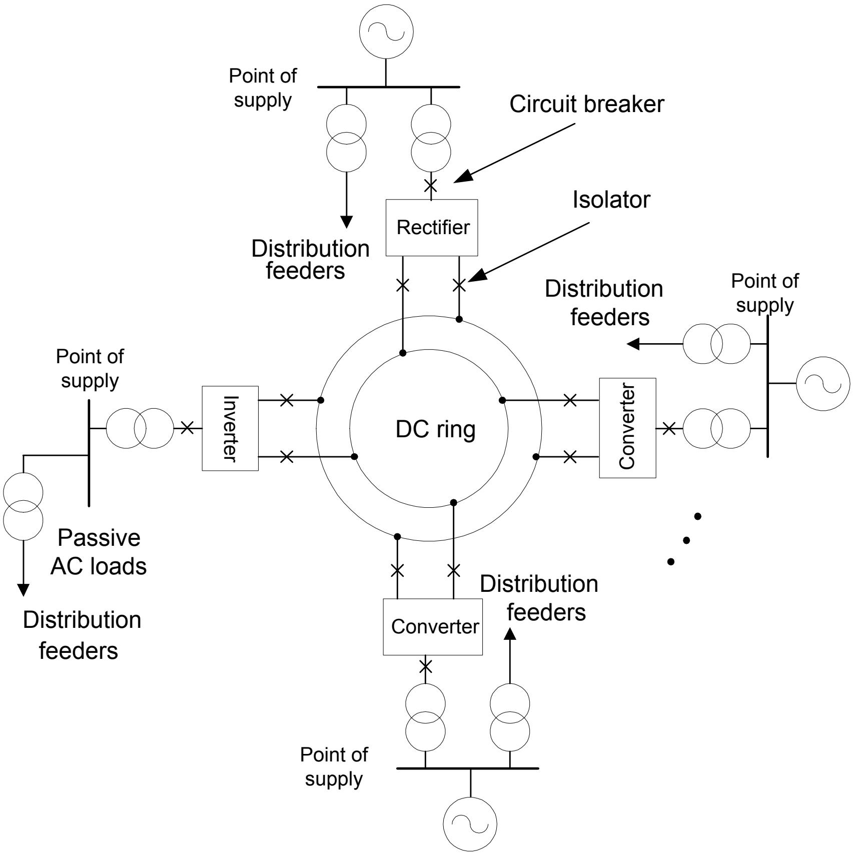


Figure 5.7 LP-HVDC sub-transmission concept.

In the Figure 5.7, a number of VSC converters are connected to the dc ring through isolators that could be used for the isolation of each converter from the dc transmission system. Depending on the requirements, converters can be operated as either rectifiers or inverters, either feeding energy into the dc link (as rectifiers) or transferring energy back to ac system from the dc link (as inverters). The mode of operation of the converters could also be rapidly changed from one mode to the other as the situation demands. The ac side of each converter is connected to an ac supply network through a transformer as shown in Figure 5.7. The different distribution zones may be connected to one or more high voltage ac points of supplies as well as to one or more LP-HVDC converters. Further, the distribution zones connected to the converters may be inter-linked either through the distribution network or the transmission network.

The next stage of evolution of the above concept would be the use of high temperature super conducting dc loop for the above sub-transmission backbone. Such dc loops are expected to become a common feature in distribution systems by 2010 [6].

5.4.4 Industrial and commercial dc power distribution

DC distribution within industrial and commercial premises promises significant technological advantages and cost savings. The technology appears to be economical even at present in some situations and with the reduction in cost of distribution FACTS may become more attractive and viable.

Figure 5.8 shows an example of an industrial dc distribution system.

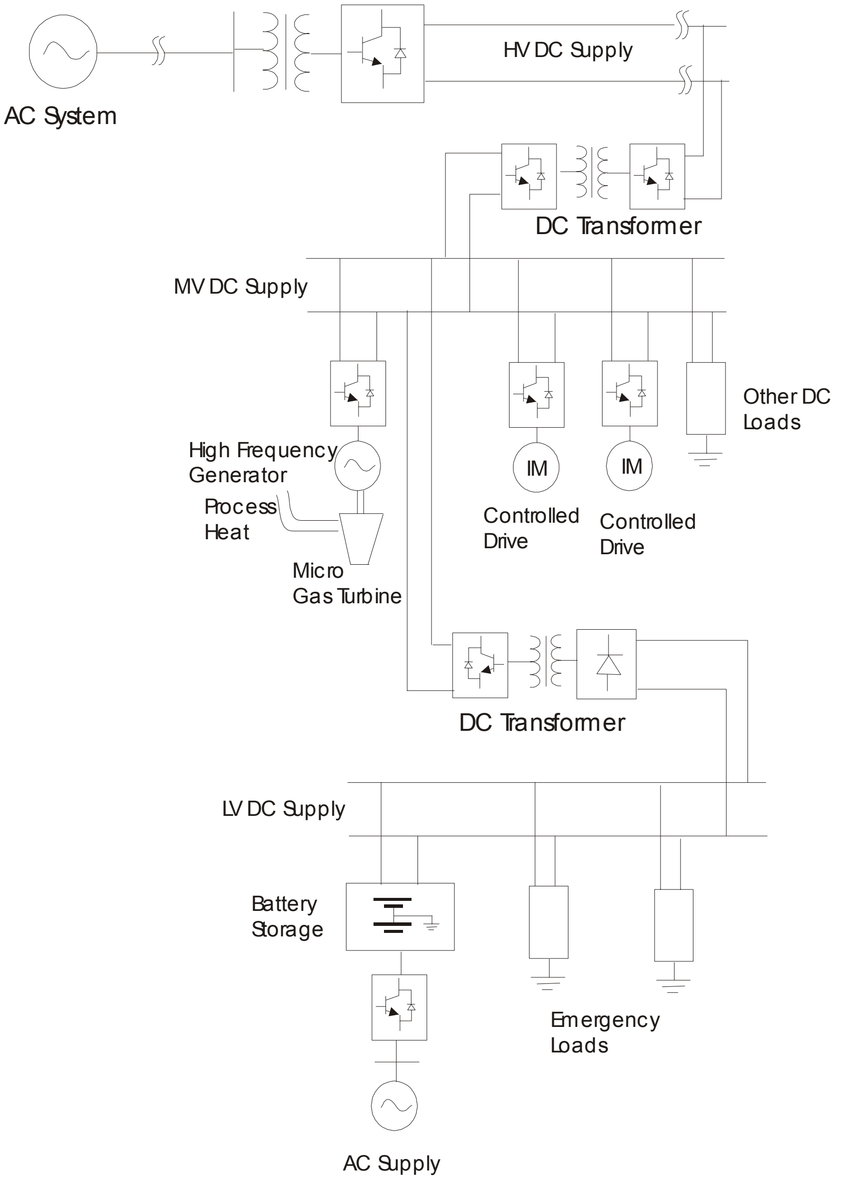


Figure 5.8 An industrial dc power distribution network.

The dc distribution network may consist of several distribution voltage levels, for example a high voltage distribution ring feeding into several medium voltage feeders and these in turn feeding into low voltage feeders. The key for having a number of distribution levels is the dc voltage transformer.

The MV distribution network can be used for receiving power from mini-gas turbines that are being produced for co-generation and distributed generation applications. Such gas turbines drive a synchronous machine at very high speed, producing high-frequency ac power. The output of the synchronous machine is rectified and fed into the dc network. The power available in the dc network can be used for supplying the controlled motor drives and other dc loads. Using such a dc distribution scheme for supplying the motor drive controllers eliminates the requirement for an ac rectification front end and therefore reduces the associated costs and losses. Use of power electronics drives provides the advantages such as soft starting of the motors, flexibility in controlling torque and speed. Above all, by enabling the processes to be operated at the optimum speed, significant gains can be obtained in the process efficiency and therefore reducing the operating costs.

The low voltage dc distribution networks can be easily incorporated with battery storage uninterruptible power supplies and therefore can be used to supply emergency services. They could also be used for directly supplying other equipment, which could be powered from a dc supply.

Figure 5.9 shows an example of a power distribution network suitable for a commercial installation. In this example, the utilisation of the HV, MV and LV dc networks are similar to the case described above for an industrial installation.

5.4.5 Domestic dc power distribution

As discussed earlier, a majority of home appliances use dc electricity. Often the ac to dc rectification is done within the power supply unit of the appliance. Examples of such appliances are television receivers, stereos, personal computers and energy efficient fluorescent light bulbs. Therefore, by supplying these appliances directly from a low voltage dc distribution network, the need of an ac to dc rectification stage, and the associated costs and losses can be avoided.

However, the major concern in using dc for domestic use is its safe handling, as the dc fibrillation current level happens to be significantly less than its ac counterpart. In the future it is likely that the safety of dc electricity handling can be avoided by using intelligent solid-state switches.

A conceptual, “intelligent solid-state switch”, shown in Figure 5.10 will consist of interlocking arrangements to make sure that

1. A safe connection is made through the plug-in socket
2. No earth leakage paths are present (by incorporating current differential protection)
3. The supply to the device is switched on manually

With the cost of power electronic and low power electronic devices continuously being reduced, in the future, such intelligent switches would become economical and viable. Therefore it is not unrealistic to expect dc distribution to domestic premises in the near future.

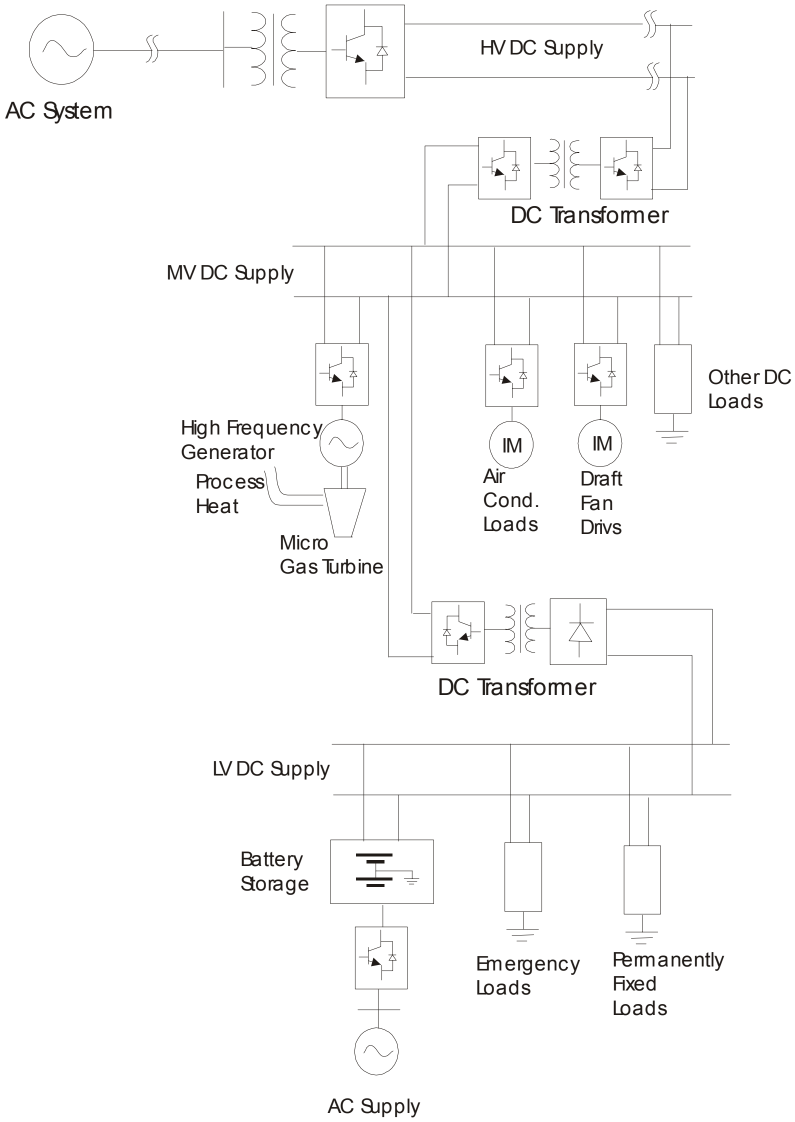


Figure 5.9 An example of a dc distribution network for commercial premises.

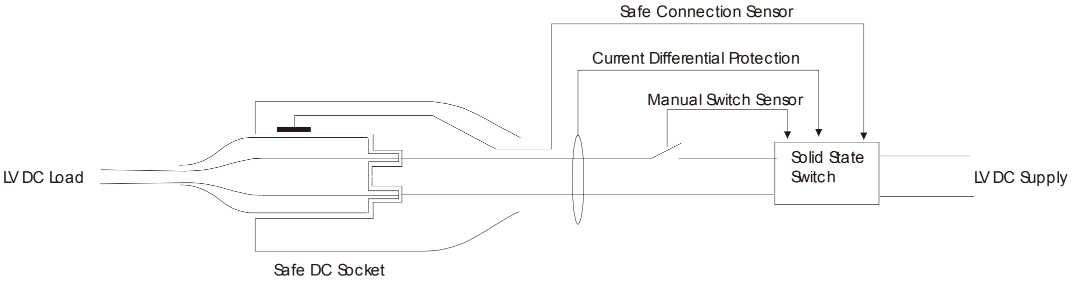


Figure 5.10 An intelligent dc connection with a solid-state switch.

5.5 Future Distribution System Planning

In the past, power systems were planned to provide all consumers an almost equal level of power quality and security, irrespective of their individual needs. At present, the power system planning approach is being changed to provide an increased level of power quality to quality-sensitive consumers by utilising appropriate distribution system FACTS devices. Following these concepts, the first of "premium power quality industrial parks" is being developed at present in Ohio, USA by American Electric Power [7]. In the future, such industrial parks would be more common, providing increased power quality, wherever necessary, using distribution FACTS devices.

The majority of common household appliances such as television receivers, stereos, personal computers and energy efficient fluorescent light bulbs have their own built-in power conditioning stage and therefore do not require a high quality power supply for their reliable operation. Therefore, another aspect of being able to provide power quality wherever necessary is that the quality of power distributed through the common distribution systems could be significantly reduced in the future. This will significantly reduce the capital investment required for maintaining high level of quality through out the whole distribution system.

5.6 References

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