High Voltage DC Transmission 2

1.0 Introduction
Interconnecting HVDC within an AC system requires conversion from AC to DC and inversion from DC to AC. We refer to the circuits which provide conversion from AC to DC as *rectifiers* and the circuits which provide conversion from DC to AC as *inverters*. The term *converter* is used to generically refer to both rectifiers and inverters.

Converter technologies are based on use of switching devices collectively referred to in the HVDC community as *valves*. Valves may be non-controlled or controlled. A non-controlled valve behaves as a diode, appearing as

- a closed switch when forward-biased (voltage is positive), resulting in the device being “on”;
- an open switch when reverse-biased (voltage is negative), resulting in the device being “off.”

A controlled valve has a similar characteristic except it requires a gate pulse to turn on, i.e., it appears as

- a closed switch when forward-biased (voltage is positive) AND the gate is pulsed, resulting in the device being “on”
- an open switch when reverse-biased (voltage is negative), resulting in the device being “off.”
A controlled valve may be comprised of thyristors. Figure 1 illustrates the difference in current-voltage characteristics between a diode and a thyristor; notice the anode (A) and cathode (K). Observe that the diode is a two-terminal device whereas the thyristor is a three-terminal device.

![Diode and Thyristor Schematic](image.png)

**Fig. 1**

There have been three types of devices for implementing HVDC converter circuits: mercury-arc, thyristors, and insulated gate bipolar transistors (IGBTs).

Mercury-arc devices were developed in the early 1900’s and used for the first time within an HVDC installation in 1932. All HVDC installations built between then and about 1972 used mercury-arc devices. The last HVDC installation which used mercury-arc devices was in 1975.

We will discuss the thyristor-based converters in Section 2 and the IGBT-based converters in Section 3.
2.0 Thyristor-based converters
A so-called 6-pulse three phase rectifier is shown in Fig. 2a. It is also called a Graetz Bridge. The circuit of Fig. 2a employs a Y-connected, three-phase source \( v_i(\omega t) \), delivering dc output \( v_o \) to resistive load through a bridge consisting of six controlled switches. It performs six switching operations per period and hence is called a 6-pulse converter. Analysis is provided below (also given in [1, ch2]).

The operation of the scheme can be understood based on the following observations:

1. Exactly two thyristors are conducting at any moment, as can be seen from the bottom of Fig. 2c.
   - One thyristor is fired at \( \alpha = \omega t \) and then left on for 60°, after which a thyristor is fired every 60° thereafter.
   - We turn on the pair of thyristors that give the most positive line-to-line voltage. We can determine the thyristor pair that should be on by (a) identifying the most positive line-to-line voltage; (b) inspecting the circuit and identifying how to place the most positive line-to-line voltage (as identified in (a)) across the load.

2. Thyristors turn off when they become reversed biased. This occurs whenever the cathode voltage exceeds the anode voltage.
For the time period $\omega t=0$ to $\pi/3$,

- $v_{cb}$ is the most positive voltage relative to other line-to-line voltages;
- Th 5, 6 conduct if suitable pulses are applied, or are already applied, to their respective gates;
- At the end of the time period, at $\omega t=\pi/3$, we turn on Th 1 to apply $v_{ab}$ across the load;
- Although Th5 is on at $\omega t=\pi/3$, $v_{ca}$ goes negative at that moment (indicated in Fig. 2b by $v_{ac}$ going positive) and when Th1 is fired, Th5 is reverse biased, and it commutates (turns off). This is also seen in that at this time, $v_{ab}$ goes higher than $v_{cb}$, and so when Th1 turns on, node “a” has higher potential than node “c,” so Th5 reverse biases & turns off.

For the time period $\omega t = \pi/3$ to $2\pi/3$,

- $v_{ab}$ is the most positive voltage relative to other line-to-line voltages;
- Th 1, 6 conduct if suitable pulses are applied, or are already applied, to their respective gates;
- At the end of the time period, at $\omega t=2\pi/3$, we turn on Th2 to apply $v_{ac}$ across the load;
- Although Th6 is on at $\omega t=2\pi/3$, $v_{cb}$ goes negative at that moment and when Th2 is fired, Th6 is reverse biased, and it commutates (turns off). This is also seen in that at this time, $v_{ac}$ goes higher than $v_{ab}$ ($v_{ca}$ goes lower than $v_{ba}$), so when Th2 turns on, node “b” has higher potential than node “c,” so Th6 reverse biases and turns off.
Commutation: $v_{ab}$ goes higher than $v_{cb}$, and so when Th1 turns on, node “a” has higher potential than node “c,” so Th5 reverse biases & turns off.

Fig. 2: Three-phase, full-wave controlled rectifier scheme
A close observation of \( v_o \) shows that its fundamental frequency of variation is six times that of the input source (6 cycles of the new waveform to every one cycle of the 60Hz waveform). So the harmonic of the output voltage will be multiple orders of 6.

With the period of the output voltage being \( 2\pi/6 = \pi/3 \), the average value of \( v_o = V_{dc} \) is given by:

\[
V_{dc} = \frac{3}{\pi} \int_{\alpha+(\pi/3)}^{\alpha+(2\pi/3)} v_o(\omega t) d(\omega t) = \frac{3}{\pi} \int_{\alpha+(\pi/3)}^{\alpha+(2\pi/3)} v_{ab}(\omega t) d(\omega t)
\]

\[
= \frac{3}{\pi} \int_{\alpha+(\pi/3)}^{\alpha+(2\pi/3)} V_M \sin(\omega t) d(\omega t) = \frac{3V_M}{\pi} \cos \alpha
\]

where \( V_M \) is the maximum line-to-line voltage. Observe (a) we used the identity \( \cos(x+y)=\cos x \cos y - \sin x \sin y \) in this integration; (b) the integration is performed over the second interval of Fig. 2b (where the voltage is \( v_{ab} \)).

Similarly, the rms value of the load voltage is:

\[
V_{rms} = \left[ \frac{3}{\pi} \int_{\alpha+(\pi/3)}^{\alpha+(2\pi/3)} v_o^2(\omega t) d(\omega t) \right]^{1/2} = V_M \left[ \frac{1}{2} + \frac{3\sqrt{3}}{4\pi} \cos(2\alpha) \right]^{1/2}
\]

The DC voltage and the rms voltage are close, but not the same; for example, a \( \alpha=0 \), we obtain:

\[
V_{dc} = \frac{3V_M}{\pi} \cos 0 = \frac{3V_M}{\pi}
\]

\[
V_{rms} = V_M \left[ \frac{1}{2} + \frac{3\sqrt{3}}{4\pi} \cos(0) \right]^{1/2} = \frac{3V_M}{\pi} \left[ \frac{2\pi + 3\sqrt{3}}{12} \right] = \frac{3V_M}{\pi} (0.9563)
\]

The DC voltage is often used as a proxy to compute power; in reality, however, this gives the so-called “DC Power” which is not the same as the “average
“power” obtained from the rms values. Although DC quantities for voltages and currents are often obtained for power electronic circuits, their use for power calculations should always be seen to be approximations at best [2, pg. 40].

Fig. X illustrates the output waveform of the converter for different values of firing angle $\alpha$. 
This arrangement is realized for HVDC rectifier circuits using a transformer, illustrated in Fig. 3 [3]. It is typical that the AC voltage input would be stepped down through a transformer before applying it to the converter.

![Fig. 3](image)

The drawing at the bottom of Fig. 3 is a shorthand way of communicating the 6-pulse arrangement shown in the top of Fig. 3.

Mercury-arc converters were 6-pulse, but almost all thyristor-based converters developed recently have been 12-pulse. A 12-pulse converter, which fires a thyristor every 30°, is at left in Fig. 4. Its shorthand circuit symbol is at right. The basic building block for the 12-pulse converter is the 6-pulse converter.
We make three observations regarding Fig. 4.

- The two 6-pulse bridges are connected in series to increase the DC voltage.
- Because each thyristor is rated at only a few kV, handling the high levels of AC voltages may require stacking several thyristors in series to form a single valve.
- Packaging may be done in units of 1 valve, 2 valves or 4. A group of 4 valves (a single vertical stack in Fig. 4), assembled as one valve structure by stacking four valves in series, is referred to as a “quadrivalve.” A $\pm 500$ kV quadrivalve may have hundreds of thyristors stacked in series [3].
- The two transformers on the AC side are both fed from the same three-phase AC source; however, to obtain 12 pulses that are symmetrically phase-
displaced by 30°, one transformer (the bottom one) is connected Y-Y and the other Y-Δ, so that the
  o line to line voltages of the Δ-connected secondary (which are in-phase with the line to neutral voltages of the primary side)
  o are 30° behind the line to line voltages of the Y-connected secondary.
By taking appropriate polarities, one can obtain voltages that are phase displaced from one another by consecutive 30°, as shown in Fig. 5 (dotted lines are polarity reversals). Winding ratios can be adjusted to achieve equal amplitudes.

![Fig. 5](image-url)
Possible methods of DC voltage control can be observed from inspection of equation (1), repeated here for convenience:
\[ V_{dc} = \frac{2}{\pi} \int_{\alpha+(2\pi/3)}^{\alpha+(\pi/3)} V_o(\omega t) d(\omega t) = \frac{2}{\pi} \int_{\alpha+(2\pi/3)}^{\alpha+(\pi/3)} V_{ab}(\omega t) d(\omega t) \]

\[ = \frac{3}{\pi} \int_{\alpha+(2\pi/3)}^{\alpha+(\pi/3)} V_M \sin(\omega t) d(\omega t) = \frac{3V_M}{\pi} \cos \alpha \]

Here we see that we may control the DC voltage by controlling either the magnitude of the applied AC voltage \( V_m \) or the firing angle \( \alpha \).

For values of firing angle \( 0<\alpha<90 \), \( V_{dc} >0 \), but for \( 90<\alpha<180 \), \( V_{dc} <0 \). Therefore inversion (necessary for the negative pole) is achieved using \( 90<\alpha<180 \). To differentiate between rectifier and inverter operation, the extinction angle \( \beta=\pi-\alpha \) is defined.

Figure 6 [3] illustrates rectifier and inverter operation. Some comments about Fig. 6 follow:

- The overlap angle \( \mu \) is indicated in Fig. 6 and accounts for the finite turn-on and turn-off time of
each switching operating when there will be some overlap between thyristor on-states. We can ignore this in the ideal case.

- Commutation at the inverter side occurs as a result of the action of the three-phase AC voltage at the inverter, similar to the rectifier side.
- Due to the line commutation valve switching process, a non-sinusoidal current is taken from the A.C. system at the rectifier (I_{vr} in Fig. 6) and is delivered to the A.C. system at the inverter (I_{vi} in Fig 6). Both I_{vr} and I_{vi} are lagging to the alternating voltage and therefore both terminals absorb reactive power and usually require capacitive shunt compensation.
- Reversal of power flow is accomplished by changing the polarity of the direct voltage. Such dual operation of the converter bridges as either a rectifier or inverter is achieved through firing control of the grid pulses [3].

Some other attributes for thyristor-based HVDC are illustrated in Fig. 6.
Of particular interest, we note the following:

- **AC filters**: Converter operation results in AC current harmonics, and these must be filtered. The characteristic AC side current harmonics generated by 12 pulse converters are $12n \pm 1$ where $n$ equals all positive integers. AC filters are typically tuned to 11th, 13th, 23rd and 25th harmonics for 12 pulse converters [3].

- **High-frequency filters**: The converter operation also results in very high frequency distortion which will propagate into the AC system if not filtered.

- **DC smoothing**: The function of the smoothing reactor on the DC side is to reduce the current ripple caused by the non-smooth DC voltage.
- DC Filter: There are sinusoidal AC harmonics superimposed on the DC terminal voltage. This AC harmonic component on the DC line can link with conductors used in communication systems, inducing harmonic current flow in them.
- Surge arresters across each valve in the converter bridge, across each converter bridge and in the d.c. and a.c. switchyard are coordinated to protect the equipment from all overvoltages regardless of their source.

### 3.0 IGBT-based converters

The thyristor is a single-component device, i.e., it is comprised of a single solid-state device. The insulated gate bipolar transistor (IGBT) is different in that it is a *hybrid device* which is a device comprised of two or more solid state devices. Specifically, the IGBT combines a MOSFET with a BJT as illustrated in Fig. 7.
The symbol for the IGBT is given in Fig. 8 together with the operating characteristic.

The IGBT operates as a switch by operating between the active region and its cutoff region.

Figure 9a [] and Figure 9b [4] illustrate the difference between IGBTs and thyristors in terms of switching speed and power handling capabilities.
The IGBT (or in some cases, the GTO) is used in voltage source converter (VSC) HVDC applications, and was introduced in the late 1990’s. The major difference between VSC-based HVDC and thyristor-based HVDC is that whereas thyristor-based HVDC is line-commutated (switched off when the thyristor is reverse biased from the AC voltage), the VSC-based HVDC is forced commutated via control circuits driven by pulse-width modulation (PWM).

From [5] (italics added),

“VSC converter technology can rapidly control both active and reactive power independently of one another. Reactive power can also be controlled at each terminal independent of the HVDC transmission voltage level. *This control capability gives total flexibility to place converters anywhere in the AC network since there is no restriction on minimum network short circuit capacity.* Forced commutation with VSC even permits black start, i.e., the converter can be used to synthesize a balanced set of three phase voltages like a virtual synchronous generator. *The dynamic support of the ac voltage at each converter terminal improves the voltage stability and increases the transfer capability of the sending and receiving end AC systems.*”
The table below lists some HVDC-VSC implementations as of 2003 [6].

<table>
<thead>
<tr>
<th>VSC Project</th>
<th>Rating</th>
<th>VSC Rationale</th>
</tr>
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<tbody>
<tr>
<td>Hellefjörn</td>
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<td>Development</td>
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<td></td>
<td></td>
<td>- Voltage support</td>
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<td>- Stabilize AC lines</td>
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<td>Tjæreborg</td>
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<td></td>
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<td>- Black start</td>
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<td>- Cap bank control</td>
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<tr>
<td></td>
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<td>- Small site</td>
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Reference [7] lists examples of possible HVDC-Light applications as of 2005. Reference [8] is a more recent publication showing 20 installations, below.
Reference [6] summarizes applications of VSC, as follows:

• Point-to-point schemes—overhead lines
• Point-to-point schemes—cables
• In-feeds to city centres
• Transmission to/from weak ac systems
• Back-to-back schemes
• In parallel with an existing line-commutated converter (LCC) HVDC link, for increase of transfer capability
• Enhancement of an ac system
• As a parallel link to ac transmission lines, to reduce bottlenecks in transmission networks
• DC land cable systems
• DC transmission cables in areas where it is impossible to obtain permission to build overhead lines

• Multi-terminal systems
• Interconnections of asynchronous power systems
• Supply of loads in isolated areas
• Connection to wind farms (onshore or offshore) or wave power generation
• Supply to and from offshore loads/platforms

Reference [7] also compares and contrasts VSC to thyristor-based converters, as follows.
Advantages of VSC over thyristor-based converters:
• The VSC valves are self-commutating.
• Commutation failures due to ac system fault or ac voltage dips do not occur.
• The VSC may be operated at a very small short-circuit ratio (SCR). The least SCR which has been practically experienced by the end of year 2004 is 1.3.
• The VSC can energize a passive or dead ac system.
• VSC Transmission has no minimum dc current limits.
• The reactive power, either capacitive or inductive, can be controlled independently of the active power within the rating of the equipment.
• Reactive shunt compensation is not required.
• Only harmonic filters are needed, and they need not be switchable.
• Depending on the converter topology, if transformers are needed they do not have to be specially-designed HVDC converter transformers, but conventional ac transformers may be used.
• The voltage polarity on the dc side is always the same. DC cables are always exposed to the same voltage polarity.
• The VSC control can be designed such that the VSC stations can eliminate flicker and selected harmonics in the ac system.
• The VSC stations can be operated as STATCOMs, even if the VSC is not connected to the dc line.
• The footprint of a VSC station is considerably smaller than an LCC HVDC station.
• Inherently, VSC Transmission can operate without telecommunication between the VSC substations.

Reference [7] also lists disadvantages of VSC over thyristor-based converters:
• At the end of year 2004, practical experience with VSC Transmission was not as extensive as with LCC.
• The maximum VSC Transmission ratings are +/-150 kV and 350 MW (receiving end). For higher transmission capacities, additional parallel VSC Transmission schemes would be required, which would add costs and losses to a VSC solution.
• DC line faults require opening of the VSC ac circuit breakers at both ends of a scheme in order to clear the dc fault, unless appropriate dc breakers are provided in the scheme.
• The switching losses in the VSC valves are higher compared with similar LCC valves, primarily due to higher switching frequency, and because a VSC valve has many more semiconductor switches than an LCC valve of the same rating.
4.0 Multiterminal configurations

Some HVDC lines are configured with more than one terminal. Such a configuration is illustrated in Fig. 10 [9]. Multi-terminal lines represent a solution to the problem that HVDC suffers from no “on-ramps” between its terminals. However, additional terminals significantly increase the cost, relative to EHVAC solutions.

![Multiterminal configurations](image)

Fig. 10
Multiterminal configurations are desirable in order to provide such “on-ramps” as illustrated in Fig. 11.

![Diagram](image)
The basic reason why multiterminal configurations can be implemented with VSC is associated with bus polarity.

Thyristors cannot do a current reversal, therefore in order to change power flow direction, it must do a voltage polarity change at the terminal to which it is connected. If this terminal has other circuits connected to it, then that polarity change will also reverse the power flow in the other circuits. In contrast, VSC reverses the current in order to change power flow direction [9, Error! Bookmark not defined.]. This has no impact on other circuits connected to the terminal.

Therefore one must choose between: (a) two-terminals and no on-ramps; (b) multi-terminals with VSC and limited capacity.

There are two other issues regarding multiterminal connections.

1. Faults: DC faults are hard to interrupt because there is no natural current zero; thus, an HVDC circuit breaker must interrupt a very high current. With two-terminal HVDC, when a DC circuit is faulted, one may just interrupt the current on the AC side of the converter and still only affect the faulted circuit. With a multiterminal system,
however, interrupting the AC side connected to a
DC bus that is serving more than one circuit will
affect both of those circuits. This is unacceptable
from a reliability point of view. Thus, an HCDC
circuit breaker has to create the zero current
crossing. To do that, it injects a counter-voltage in
the circuit, high enough to counteract the sources
[10].

2. Communications: When the flow from the AC side
into a converter at one terminal changes, the other
terminals have to know this in order to continue
satisfying KCL into the DC system. This requires
communication systems to coordinate.

Research Centre, 1998.
technologies: the right fit for the right application,” Proc. of the 2003 IEEE Power
[8] “HVDC Light – The original VSC technology reference list,” an ABB publication available
Overview of High Voltage Direct Current Systems and Applications,” IEEE Power and
Delhi, India.