Feasibility of HVDC for City Infeed

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Stockholm 2003

Licentiate Thesis
Royal Institute of Technology
Department of Electrical Engineering
Electric Power Systems
Akademisk avhandling som med tillstånd av Kungl Tekniska Högskolan framlägges till offentlig granskning för avläggande av teknisk licentiatexamen torsdag den 2 oktober 2003 kl 10.00 i sal V32, Teknikringen 72, Kungl Tekniska Högskolan, Stockholm.

TRITA-ETS-2003-11
ISSN 1650-674X
ISRN KTH/EES/R-SE

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Department of Electrical Engineering
To the memory of my father, Professor Edegard, who was my mentor and opened up my professional career.
Final objective can always be reached with perseverance and enthusiasm.
Abstract

It is well recognized that direct current and direct voltage offer special advantages for both land and sea cable systems, both with regard to power transmission capability, losses, as well as possible transmission length due to no capacitive currents. As cable systems were used very early in large cities, one of the first applications considered for HVDC was to use it for city infeed and some schemes were also built. However, it turned out that the cost for the stations was too high and that the savings on the cable part were not high enough to justify the high costs of the converter stations, even considering other possible benefits of the HVDC techniques such as fast control of active power and almost no contribution to fault currents.

During the 1990s new HVDC Voltage Source Converters, VSC, and new HVDC cables with solid insulation have been developed and the relative cost for the converters has been steadily decreasing. It was, therefore, found justifiable to reexamine the feasibility of using HVDC, especially based on the new VSC technique, for feeding electrical power to large cities. It was also decided, that the study should clarify the special requirements that had to be considered in the planning of city infeed systems as no good survey could be found. Because of this the study has been performed in close co-operation with a number of utilities responsible for the power supply of some medium sized and large cities. One such requirement, that also justified the study, was that it is expected that in the future more overhead lines in the cities or close to the cities have to be replaced by cables.

Although the transmission and distribution of electrical power will be preferably made with conventional AC technique, but HVDC transmission would offer special advantages for long transmission cable, systems with especial requirements with regard to power flow control, systems with restrictions to short circuit currents, and other relevant issues related to city center infeed. The use of HVDC transmission to feed power into city centers will also be preferable when severe restrictions exist in the system that would require significant additional measures to mitigate using conventional AC technique. In those cases, the cost of these additional measures can be significant enough to justify the use of an alternative technique. Or, the implementation of those measures will make the system too complex to operate. In these cases, HVDC transmission would have advantages over the conventional AC solution, simplifying the operation of the system or resulting in a more economical solution.
Keywords: HVDC (High Voltage Direct Current Transmission), Line Commutated Converters, Voltage Source Converters, City Center Infeed, Underground Cable Transmission.
Acknowledgements

To produce this work, there is one special person to whom I am indebted for guidance, assistance, encouragement, and tolerance. Professor Åke Ekström, Professor emeritus of the Royal Institute of Technology, was instrumental in establishing the values of the project from which this report evolved. I am deeply grateful that he has helped me with his superb knowledge and expertise in the field of power systems and power electronics. I am very privileged to have been his student.

I wish also to thank Professor Lennart Söder, head of Electric Power System department at Royal Institute of Technology, for the constructive suggestions to this work.

In order to do the thesis I have received support from my company ABB. For this I am indebted to Gunnar Asplund and Mats Hyttinen, managers at ABB, who gave me the opportunity to start this project. Besides them, I would like to express my deep gratitude to Bernt Bergdahl, Rolf Ljungqvist and Don Menzies, from ABB, for interesting discussions and constructive ideas that are reported in this work.

I also gratefully acknowledge ABB Power Systems, Elforsk and Energimyndigheten for the financial support of this project. To the members of the reference group I would like to acknowledge and give my thanks for interesting discussions and valuable suggestions: besides Åke Ekström, Lennart Söder, Gunnar Asplund and Mats Hyttinen, the steering committee consisted of Mr Olle Hansson and Kjell Gustafsson (Fortum Distribution-Region Stockholm, former Birka Energi), Ingemar Andersson and Gunilla Le Dous (Göteborg Energi). To Dr Lineu Belico dos Reis (Professor at University of São Paulo, Brazil), Mr Caius Vinicius S. Malagodi (Bandeirante, Brazil) and Dr Aty Edris (EPRI, USA), I gratefully acknowledge their valuable help in providing system data for the very interesting cases that have been studied.

Finally, I would like to thank my wife and my son, Yoshimi and Alexandre, for their continuous patience, encouragement and support on the home front throughout the two and half years during which this project was in the making.

Paulo Fischer de Toledo       Ludvika, June 2003
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Chapter 1

Introduction

1.1 General background and overall aim of the study

It is well recognized that direct current and direct voltage offer special advantages for both land and sea cable systems, both with regard to power transmission capability, losses, as well as possible transmission length due to no capacitive currents. Cable systems were used very early in large cities, and one of the first applications considered for HVDC was for city infeed. Some schemes were also built: a HVDC application was tested in Berlin (1940), without completion of the project, one scheme was built in an urban area in London (1960), the ‘Kings North’, and one scheme was studied for the city of Chicago (1970) [B14]. However, it turned out that the cost for the stations was too high and that the savings on the cable part were not high enough to justify the high costs of the converter stations, even considering other possible benefits of the HVDC techniques such as fast control of active power and almost no contribution to fault currents.

During the 1990’s, with the development of new HVDC converters using Voltage Source Converters, VSC, new HVDC cables with solid insulation and with the relative cost for the converters steadily decreasing, it was found justifiable to again study the feasibility of using HVDC, especially based on the new VSC technique, for feeding electrical power to large cities. This new HVDC-VSC technique will, for instance, make it possible to control both active and reactive power and will be more suitable for cable multi-terminal systems.

It was also decided that this study should clarify the special requirements that had to be considered for planning of city infeed systems as no good survey could be found. Because of that this study has been performed in close cooperation with a number of utilities responsible for the power supply of some medium sized and large cities. One such requirement, that also justified the study, was that it is expected in the future that more overhead lines in the cities or close to the cities have to be replaced by cables.

From the specific studies performed in close cooperation with utilities, the major driving forces and evaluating criteria used to decide whether to rebuild or expand an existing electrical power or built a complete new system, were identified. Specific criteria such as thermal security, voltage security, short circuit current security, reliability of supply, and capability for power flow control were found to be the major driving forces in the review of the existing infrastructure.
Each of these criteria was evaluated in a systematic way and a comparison was made between the existing or expected possible improved AC technique and an alternative HVDC solution. The comparison was made from both a technical and an economical point of view.

Finally a more generic study was performed in order to evaluate the expected break-even distance for a HVDC underground transmission system by comparison with an equivalent HVAC transmission. The break-even distance was in this case the distance in which the saving in capital cost and lower losses with a DC underground transmission cable may be enough to pay for the two converters, one at either end. This distance depends on several factors, and most of these factors are related to the specific characteristic of the network. Some parametric study of these factors was also made in the calculation of the break-even distance.

1.2 Contribution in the study

The present study provides the following main contributions:

- A systematic overview of evaluation criteria and values of HVDC solutions including comparison with the best HVAC alternative.
- Case studies, where different HVDC and HVAC alternatives are studied.
- Generic conclusions regarding when HVDC could be an alternative for in-feed to large cities.
- Suggestion and motivation of new Hybrid HVDC topology
- Extension of the concept of ‘break-even distance’ widely mentioned in the literature when comparing HVDC and HVAC transmission with overhead lines but now to underground cable transmission.

1.3 General overview of the thesis

Chapter 2 reviews the characteristics of conventional AC transmission. It gives an overview how the electrical system is normally built, highlighting issues like sitting a substation in the load center area, network topologies, loading of the lines, requirements in maintaining correct voltage performance, environmental aspects, etc.

Chapter 3 describes the characteristics of HVDC transmission, including existing alternatives, the classical Line Commutated Converters and the new Voltage Source Converters.

Chapter 4 discusses the different alternatives to control power flow in AC transmission system. In a meshed network the control of power flow is needed in order to achieve a good utilization of the system.
During the last years very cost effective extruded DC cables have been developed which can fit in the existing cables ducts. These cables have considerably higher power transmission capability than the corresponding AC cables. This issue is addressed in chapter 5.

In chapter 6 a number of study cases is presented, where alternative HVDC solutions to the conventional AC technique have been studied.

In chapter 7 an overview of relevant issues that have been brought up during the studied cases is presented. The break-even distances that give the same costs for HVDC as for HVAC solutions for underground cable transmission are presented.

Finally, the study is completed by giving some generic conclusions regarding the use of HVDC for city infeed. This is presented in chapter 8.
Chapter 2

General aspects related to HVAC transmission and distribution systems for City Infeed

2.1 Introduction

Today, electrical power is supplied to large cities by several circuits of alternating current sub-transmission and distribution lines. The main reason for having alternating current is because it is relatively simple to convert hierarchical voltage levels. These transformations are made with transformers that are simple and reliable devices. This is a well-established technique.

It is recognized that with the expansion of the cities, there are more demands to transmit more power into load centers that implies a higher transfer of power from the generation to the load centers. If more power is transferred through the existing lines, there is a risk that some of the lines might operate closer to their thermal capacity limit or the system as a whole will operate closer to its instability limits. If additional interconnections are introduced, then the system will become more complex to operate.

Another issue that is becoming relevant to city infeed is that there are more restrictions to the use of overhead lines. Many of the existing lines are now being replaced by cables in the cities or close to the cities.

All these issues are imposing new demands to the planning and design of the transmission and distribution system, in combination to the basic fundamental principles of operation that are: the system should present satisfactory dynamic stability of transmission; the delivery of power should be made securing adequate quality and reliability and maintaining correct voltage levels.

Some of these important issues, which are relevant to city infeed with the conventional HVAC transmission technique, are discussed in this section.

2.2 Hierarchical voltage levels in the combined transmission and distribution system

The overall concept of power delivery system is based on hierarchical voltage levels. As power is transferred from generation (large bulk sources) to the customer (small demand amounts) it is first transmitted in bulk quantity at high voltages. As power is dispersed throughout the service territory, it is gradually
distributed at lower voltage levels, along separate paths, on lower capacity circuits until it reaches the customer.

This hierarchical system structure, which has been used over the past one hundred years, has proven the most effective way to transmit and distribute power from a few large generating plants to a widely dispersed customer base.

As a consequence of this hierarchical structure, a power delivery is made with several distinct levels of equipment as illustrated in Figure 2-1. Power flows through these levels, from power production to customer. As it transferred from the generation plants (system level) to the customer, the power is transmitted through the transmission level, to the sub-transmission level, to the sub-station level, through the primary feeder level, and onto the secondary service level, where it finally reaches the customer.

![Figure 2-1: Hierarchical voltage level in a Transmission and Distribution system. Typical average cost in cents of USD (cost/kWhr) of power that depends on the effort and facilities used to deliver it [A2]](image)

The transmission system operates with voltages between 230 kV and 765 kV. The sub-transmission lines in a system take power from the transmission switching stations or generation plants and deliver it to substations along their routes. A typical sub-transmission line may feed power to three or more substa-
tions. Sub-transmission lines operate with voltage between 115 kV up to 345 kV. Here, in this study, these lines are considered the main feeders to city centers.

The substation level is the meeting point between the transmission grid and the distribution feeder system. The transmission and sub-transmission systems above the substation level usually form a network, with more than one power flow path between any two parts. From these substations on to the customer, power is delivered through the distribution systems that are normally in a radial configuration.

2.3 Location of primary substation near the city center load

A number of substations are strategically located throughout the utility service territory, as shown in Figure 2-2. Power is brought to these substations by the transmission/sub-transmission system at high transmission voltages. Then, that power is lowered in voltage to a primary distribution voltage, selected as appropriate for the service area and load density. The power is then routed between several feeders that serve the area surrounding the substations.

The substations are located near the center of the load or service area. The feeders derive from that central site in all directions, as shown for most of the substation in Figure 2-2.

Figure 2-2: Distribution of electric power – substations (squares) and feeders (lines) [A2]
2.4 Incoming transmission supply

Power is transmitted from the power sources to the distribution substations over the sub-transmission circuits. A wide variety of sub-transmission system designs are in use, varying from simple radial systems to systems similar to networks. [D6 and A4]

Several factors influence the selection of the sub-transmission arrangement. Two of the most important factors are cost and reliability of power supply to distribution substation.

2.4.1 Single Infeed topology

A simple radial arrangement of sub-transmission circuit (Figure 2-3-A) gives the lowest cost. This form of sub-transmission is not usually employed because it provides a poor reliability service. A fault on a radial sub-transmission circuit results in an interruption to all loads that are fed by it.

Figure 2-3: Single Infeed system [D6 and A4]
An improved form of radial sub-transmission is shown in Figure 2-3-B. Each radial sub-transmission circuit serves as a normal feed to certain distribution substation transformers and also serves as an emergency feed to others. This arrangement permits quick restoration of service when a radial sub-transmission circuit is faulty. This arrangement does not prevent service interruption for a short time and requires spare capacity to be built into the radial sub-transmission circuits.

With higher reliability requirement, the sub-transmission for a radial system usually takes the form of parallel or loop circuits or even a sub-transmission grid. In a parallel or loop circuit sub-transmission layout (Figure 2-3-C), no single fault on any circuit will interrupt service to a distribution substation, except for the time needed for disconnecting the faulty line. All circuits are designed so that they will not be overloaded when a single circuit is out of service. In the particular case of two parallel circuits (Figure 2-3-C) this is also considered to be a sectionalized loop, supplying one distribution substation.

Some loop circuits are designed with an open switch in the loop. Under normal operating conditions the network is operated as a number of radial feeders, and on the occurrence of a fault the sectionalizing open switch is closed to provide back-up supply after the faulted section has been isolated (Figure 2-3-D).

### 2.4.2 Multi Infeed topology

In a ring form (Figure 2-4-A), the circuit starts from a power supply point or bus, ties together a number of power supply points or busses, and returns to the starting point or bus. A ring is a loop from which substations can be supplied and into which power is fed at more than one point. In normal conditions the ring form operates with the ring closed. It can also operate with the ring open under fault condition without affecting the supply. In general, the system is also designed to accept loss of one infeed, powers source or supply substation. The ring arrangement is quite often used for sub-transmission. It is a simple form of sub-transmission network, and as the system grows it can develop into a grid.

The topology shown in Figure 2-4-B is an Open Ring Form. In this figure there are two parallel circuits between two supplier sources. Normally each circuit does not run over the same right-of-way, as otherwise a fault on one circuit may involve the other.

Figure 2-4-D shows two circuits supplied from two points. The literature usually denominates this circuit as a Link Arrangement.

The network form of sub-transmission (Figure 2-4-C) is flexible in that it can readily be extended to supply additional distribution substations in the area it covers with a relatively small amount of new circuit construction. However, it
requires a large number of circuit breakers. The network form of subtransmission provides greater service reliability to the distribution substation than the radial and loop forms of sub-transmission. This is true particularly when the distribution system is supplied from two or more power sources, because it is possible for power to flow from any power source to any distribution substation. The paralleling of power sources through the sub-transmission circuit also has the advantage of tending to equalize the load on the power sources.

In a large distribution system any, or even all of the above forms of subtransmission may be employed between the power sources and the various distribution substations, depending upon the service requirement of the different substations and economic considerations.

---

Figure 2-4: Multi Infeed system [D6 and A4]
2.5 Power quality and reliability of supply

An electric utility should provide electric power with enough quality with regard to the needs of electric consumers. If the system is built with perfect quality of supply, which means that voltages sags, transients and harmonics never occurs, the price of the electricity will become very high.

Different types of issues are relevant to qualify and quantify power quality in an electric power system: interruption of electric service, voltage variation problems (unbalanced voltage problems, voltage sags and voltage swells and voltage deviations), voltage surges and harmonics. Each of these various power quality problems has a different value to different customers. Therefore, the electric utility should be able to identify the needs that may vary with different customers, and build the system according to their needs.

In general, the service reliability (interruption of electric service) is the power quality issue that receives the most attention.

2.6 Environmental aspects

2.6.1 Aesthetic and safety aspects

A transmission-distribution substation that is located in an urban or suburban area will have a number of special requirements.

In terms of space, it might require 4000 m$^2$ (a 300 MVA underground substation sitting in a dense urban area) up 40000 m$^2$ (a 300 MVA substation sitting in an open suburban area) of land. A fence or wall around the site is required to secure it from public access. In problem areas, the fence or wall may need to be up to ten meters high. It is often required to landscape the site, with a green space including foliage to block the view of the equipment. In some cases, the substation may be enclosed in what appears to be a building to completely hide it.

In very high load density places in the core of urban areas underground design is frequently used but it is much more expensive than typical overhead construction. Cable transmission circuits must be enclosed in ducts and tunnels, in case there are many circuits that are running in parallel.

2.6.2 Electric and magnetic fields

A general perception among people is that there is an association between the incidence of disease and exposure to power frequency electric and magnetic fields. Therefore guidelines from different institutions have been recommended introducing limits for human exposure to electro-magnetic fields.
The concept of electric and magnetic fields can be described in a simple way as follows.

**Electric Fields**

An electric field is produced by:

- The potential difference between the conductor and earth;
- The space charge clouds produced by the corona effect in the conductor.

The magnitude of the conductor’s surface field intensity is dependent not only on the voltage itself, but also on the geometry of the conductor.

The highest electric field strength can be measured directly close to the conductor.

In cable transmission the cable is normally shielded, not only for mechanical reasons to withstand the mechanical stresses, but also to create some barrier to the electric field produced by the charge on the cable. That means that the electric field is cancelled (in both AC and DC cables).

**Magnetic Fields**

The strength of a magnetic field is dependent on the current flowing through the conductor and the distance from the conductor. The magnetic flux density decreases as the distance from the conductors increases.

In cable transmission the cables are usually placed close to each other. In a three-phase AC transmission system, three cables are typically used. In a DC transmission system, two cables are typically used. In a three-phase transmission the resulting magnetic field produced by any one cable will be counteracted by the other two cables, as the three cable currents will sum to zero during balanced load conditions. Similar counteraction is resulted in a DC transmission with two cables. That means that the resulting magnetic field is small.

However, it should be noted that the magnetic field produced by a DC cable is stationary (like the Earth’s natural magnetic field), while the AC cable generates an alternating magnetic field. An alternating field, but not a stationary field, can induce body current. This means that there are less restrictions.

**A sample of guide-line**

The International Commission on Non-Ionizing Radiation Protection in power System operation has established a guideline for human exposure to electric and magnetic fields (EMF) of 50/60 Hz.

According to the International Commission on Non-Ionizing Radiation Protection (Hydro-Québec), body levels of induced current density greater than 100
mA/m² bring about effects on the nervous system and heart, which may be harmful to health. To prevent these effects, they recommended that induced current in the head and trunk should not exceed a density of 10 mA/m² in workers and 2 mA/m² in the general public. These restrictions correspond to the levels of electric and magnetic fields shown in the Table 2-1.

Table 2-1: ICNIRP (International Commission on Non-Ionizing Radiation Protection) exposure limits for Magnetic and Electric Fields of 60 Hz [A6]

<table>
<thead>
<tr>
<th></th>
<th>Exposure Limits for Magnetic Fields [microtesla]</th>
<th>Exposure Limits for Electric Field [kV/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Public</td>
<td>83</td>
<td>4.2</td>
</tr>
<tr>
<td>Workers</td>
<td>420</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Note: Typical earth’s magnetic field level, which everybody is constantly exposed to, is around 50 microteslas.

2.7 Transmission and distribution substation – some considerations regarding site and cost

In general, a substation site will include the high-side equipment, the transformers and the low-side equipment. Most of the substations are built above the ground. However, there are cases in which they will be built in the basement of buildings or underground. In urban and suburban areas, the site cost and preparation of the site is a significant portion of the substation cost, which depends on the location, type of substation, size and other requirements.

Table 2-2 gives the cost for two substation sites and the cost of two representative substations. The cost of a substation will in general increase with the voltage level, the capacity and the reliability requirements.
Table 2-2: Representative Cost of Distribution Substation and Substation Site
Cost ($ x 1000) [A2]

<table>
<thead>
<tr>
<th>Substation</th>
<th>Location</th>
<th>Capital</th>
<th>Required Area</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>230kV/25kV/12.47kV</td>
<td>Suburban</td>
<td>$11 200</td>
<td>32 000 m²</td>
<td>$4200</td>
</tr>
<tr>
<td>5 incoming OH circuits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3x75MVA 230/25kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2x50MVA 230/124.47kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12x25kV and 8x12.47kV feeders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>peak load 288 MVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>230kV/25kV</td>
<td>Urban core</td>
<td>$19 200</td>
<td>4000 m²</td>
<td>$4200</td>
</tr>
<tr>
<td>3 incoming UG circuits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5x75MVA 230/25kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15x25 feeders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>peak load 225 MVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.8 HVAC transmission lines – a comparison between the electrical characteristics of overhead lines and underground cable

Overhead lines are normally used for long distances in open country and in rural areas. Cables are used for underground transmission in urban areas (and underwater crossings). For the same rating, cables are more expensive than overhead lines (10 to 20 times) and therefore they are used in special situations where overhead lines cannot be used. However, due to environmental reasons, and lack of space, the use of cables in urban and suburban areas is becoming more frequent. And due to the electrical proprieties of cables, the application of cable transmission has to be restricted to short distances.

2.8.1 Electrical parameter of typical transmission lines

A transmission line is characterized by four parameters:

- Series resistance due to conductor resistivity
- Shunt conductance due to leakage current between the phases and ground
- Series inductance due to the magnetic field surrounding the conductors
• Shunt capacitance due to the electric field between the conductors

Underground cables have the same basic parameters as overhead lines. However, values of the parameters and hence the characteristic of cables differ significantly from those of overhead lines for the following reasons:

1. The conductors in cables are much closer to each other than are the conductors of overhead lines.
2. The conductors in a cable are surrounded by metallic bodies such as shields, lead or aluminum sheets, and steel pipes.
3. The insulation material between conductors in a cable can be impregnated paper, low-viscosity oil, or an inert gas. Additionally, there is a new type of cable with extruded dielectric insulation.

Table 2-3 compares typical electrical parameters of a 230 kV overhead line with 230 kV underground cables. For the underground cables two types of cables are presented: direct-buried paper insulated lead-covered (PILC) and high-pressure pipe type (PIPE).

In the table the following constants are presented:

The constant $Z_0$ is the characteristic impedance (which is sometimes called the surge impedance) that is defined by:

$$ Z_0 = \sqrt{\frac{Z}{Y}} \tag{1} $$

A line of finite length terminated at one end by an impedance $Z_0$ is electrically equivalent to an infinite line. At this condition both voltage and current have constant amplitude along the line. The line is said to have a flat voltage profile.

A line in this condition is also said to be naturally loaded. The natural load (or surge-impedance load, SIL) is given by:

$$ P_0 = \frac{V_0^2}{Z_0} \tag{2} $$

where $V_0$ is the nominal or rated voltage of the line.

It is desirable that overhead lines operate close to their natural load because the flat voltage profile will result in uniformly stressed insulation at all points along the line. The other important characteristic of a line operating at its natural load condition is that no reactive power has to be absorbed or generated at either end. The reactive power generated in the shunt capacitance of the line is exactly absorbed by the series inductance. In other words, there is a perfect reactive power balance in a line when operating at its natural power $P_0$. 

15
Table 2-3: Typical electrical parameters for a 230 kV Overhead line and 230 kV PILC and PIPE underground cable [B2]

<table>
<thead>
<tr>
<th>Transmission Type</th>
<th>230 kV Overhead line</th>
<th>230 kV PILC Underground Cable</th>
<th>230 kV PIPE Underground Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>R [Ω/km]</td>
<td>0.050</td>
<td>0.0277</td>
<td>0.0434</td>
</tr>
<tr>
<td>$X_L = \omega L$ [Ω/km]</td>
<td>0.488</td>
<td>0.3388</td>
<td>0.2052</td>
</tr>
<tr>
<td>$B_C = \omega C$ [μS/km]</td>
<td>3.371</td>
<td>245.6</td>
<td>298.8</td>
</tr>
<tr>
<td>$\alpha$ [nepers/km]</td>
<td>0.000067</td>
<td>0.000372</td>
<td>0.000824</td>
</tr>
<tr>
<td>$\beta$ [rad/km]</td>
<td>0.00128</td>
<td>0.00913</td>
<td>0.00787</td>
</tr>
<tr>
<td>$Z_0$ [Ω]</td>
<td>380</td>
<td>37.1</td>
<td>26.2</td>
</tr>
<tr>
<td>SIL [MW]</td>
<td>140</td>
<td>1426</td>
<td>2019</td>
</tr>
<tr>
<td>Charging [MVA/km]</td>
<td>0.18</td>
<td>13.0</td>
<td>15.8</td>
</tr>
</tbody>
</table>

As shown in equation (2), the natural load of the uncompensated line increases with the square of the voltage. This explains why transmission voltages have to increase as the level of transmitted power grows.

The constant $\alpha$ is the attenuation constant and $\beta$ is the phase constant, which are the real part and imaginary part of the propagation constant $\gamma$ that is given by:

$$\gamma = \sqrt{ZY} = \alpha + j\beta$$  \hspace{1cm} (3)

The constant $\beta$ is interpreted as a wave number, that is, the number of complete waves per unit of line length. The wavelength $\lambda$ is calculated by:

$$\lambda = \frac{2\pi}{\beta}$$  \hspace{1cm} (4)

Assuming that the total length of the line is $l$, the quantity $\theta$ defined by:

$$\theta = \beta l$$  \hspace{1cm} (5)

is the electrical length of the line expressed in radians or in wavelengths. A line can be characterized entirely by its length $l$ and by the two parameters $Z_0$ and $\beta$. For overhead lines, these values are roughly comparable for all lines,
and the behavior of all lines is fundamentally the same. The differences only arise according to the length, the voltage, and the level of power transmission.

For underground cables, those values differ significantly from the overhead lines. That is why overhead lines and underground cables behave differently. This issue will be discussed in the next section.

### 2.8.2 Voltage and power characteristics

This section offers an insight into the performance characteristics of transmission lines, by comparing an overhead line and an underground cable.

As has been shown in the previous section, underground cables have very high shunt capacitance. The characteristic impedance $Z_0$ of a cable is about one-tenth to one-fifth that of an overhead line, assuming the same voltage rating (the extruded dielectric underground cable has a lower capacitance than the paper-insulated cable, and approaches the performance provided by overhead lines). The parameter $\beta$ for underground cables can be five to ten times higher than for overhead lines.

The difference in the basic parameters $Z_0$ and $\beta$ between overhead lines and underground cables makes them perform differently in terms of voltage regulation and system stability for the same length of line.

Considering an uncompensated line under load it is possible to compare the effect of load power and power factor on voltage and power stability.

Suppose that a line is energised by a generator at the sending end (designated by subscript S) and a load $P + jQ$ is connected at the receiving end. The voltage at the sending end $E_S$ is fixed and equal to 1 pu. The voltage at the receiving end $V_R$ is calculated for different values of loads.

Figure 2-5 shows a typical relationship between receiving end voltage and load for a 50 km 230 kV uncompensated overhead line. The constant $\beta$ for the line is assumed 0.00128 rad/km as indicated in Table 2-3. The load is normalized by dividing $P_R$ by $P_0$, the natural load SIL, so that the results are applicable to overhead lines of all voltages.

Figure 2-6 showns the equivalent relationship between receiving end voltage and load for a 50 km 230 kV uncompensated underground cable. The constant $\beta$ in this case corresponds to a direct-buried paper insulated lead-covered (PILC) type of cable, and equal to 0.00913 rad/km as indicated in Table 2-3. Similarly to Figure 2-5, the load is normalized by dividing $P_R$ by $P_0$.

By observing Figures 2-5 and 2-6, it is possible to identify some important properties of AC transmission lines:

- For each load power factor there is a maximum transmissible power.
• For any value of P below the maximum there are two possible solutions. Normal operation of the power system is always at the upper value, within narrow limits around 1.0 pu.

When there is no load at the receiving end it corresponds to an open-circuit condition.

• The load power factor has a strong influence on the receiving-end voltage and the maximum power that can be transmitted. Loads with lagging power factor (inductive load, $Q_R$ is positive) tend to reduce the terminal voltage $V_R$ as the load P increases. With leading power factors (capacitive load, $Q_R$ is negative) the tendency is to increase $V_R$ until P reaches a much higher value.

• Leading power factor loads generate reactive power, which supplements the line-charging reactive power and tends to support the line voltage.

Comparing Figures 2-5 and 2-6, the following observations can also be made:

• At no load condition (open circuit condition), a 50 km overhead line has its receiving-end voltage just above 1 pu. The little voltage rise is due to the low capacitive current charge of the line as compared with the underground cable. The underground cable with the same 50 km length, has a voltage rise exceeding 10% in relation to the nominal voltage. Such voltage rise could be enough to cause severe problems for insulation of the cable, which would require some means of compensation.

• In practice, a 50 km overhead line can be considered a short line. A short line can tolerate a wide range of operating conditions. This can be seen in Figure 2-5, where the influence of the load power (below 1 pu referred to its natural load SIL) and the power factor on the receiving-end voltage is small. This means that the line does not require any means of compensation.

• A 50 km underground cable is considered a very long line. It does require compensation on its terminal to reduce the effect of capacitive current charge on the terminal voltage. Shunt reactors are often placed at the terminals to limit voltage rise during light-load conditions.
Figure 2-5: Voltage-power characteristic of a 50 km, 230 kV uncompensated overhead radial line

Figure 2-6: Voltage-power characteristic of a 50 km, 230 kV uncompensated underground direct buried paper-insulated lead-covered cable
• It is possible to calculate parameters for an equivalent overhead line with behavior similar to a 50 km underground cable. Considering that the cable has an electrical length θ equal to 50km x 0.00913rad/km = 0.4565rad. The length of the overhead line to produce the equivalent θ, with β equal to 0.00128 rad/km is: \( l = 360 \text{km} \). This means that the 50 km underground cable is equivalent to a 360 km overhead line considering the relationship between receiving end voltage and load.

• In an underground cable, the inductive VARs consumed by the cable, even during heavy load condition, are not sufficient to compensate the capacitive VARs. The transmitted power is normally limited by the current capacity of the cable. Therefore a cable never approaches its natural loading SIL.

2.8.3 Transmission capability of an AC cable

![Figure 2-7: Maximum real power transfer for an impregnated-paper-insulated cable [G1]](image)

The transmission capability of AC cables is reduced by the capacitance of the cable. Figure 2-7 shows a plot of the real power that may be transferred across a 2000 kcmil (1013 mm²) copper conductor impregnated-paper-insulated cable at different system voltages. The figure shows the estimated values of maximum circuit lengths for the uncompensated cable, assuming that all reactive
charging current is supplied from one end of the cable circuit. The dashed line, where the real power transfer capability is reduced to 80 percent of the thermal capacity of the cable represents a more realistic maximum cable circuit length.

This figure clearly shows that AC cable transmission, even during heavy load conditions, will never approach the surge-impedance loading because its inductive VARs consumption is lower than the capacitive VARs generated by the cable.

2.8.4 Compensated transmission line

Shunt compensation has been primarily used in the distribution system to improve voltage profiles and reduce line loading and losses by power-factor improvement. Shunt compensation can be mechanically switched in or out according to the daily load cycle. In the transmission and sub-transmission systems, this type of reactive power compensation is also used, however, there are many cases where the compensation needs to be rapidly and continuously controlled, as for example, during disturbances.

Compensation means the modification of the electrical characteristics of a transmission line in order to increase its power transmission capacity. With this general objective, a compensation system ideally performs the following functions:

- It helps to produce a substantially flat voltage profile at all levels of power transmission;
- It improves stability by increasing the maximum transmissible power;
- It provides an economical means for meeting the reactive power requirements of the transmission system.

Compensation can be made by means of passive or active devices. Passive compensators include shunt reactors, shunt capacitors and series capacitors. These devices may be either permanently connected, or switched. They operate by modifying the line’s natural inductance and capacitance and their operation is essentially static.

Active compensators are usually shunt-connected devices, which have the property to maintain approximately constant the voltage at their terminals. They do this by generating or absorbing precisely the required amount of corrective reactive power in response to any variation of voltage at their point of connection.

In general, shunt compensation is connected at the ends of the line or at intermediate points (intermediate substations).

In case of very long lines (distances greater than 200-300 km for overhead lines or 20-40 km for underground cables), at least some shunt reactors are
permanently connected to the line in order to give maximum security against
overvoltages in the event of sudden rejection of load or open-circuit of the line.

On shorter lines, or on sections of line between un-switched reactors, the over-
voltage problem is less severe and the reactors may be switched frequently to
assist in the hour-by-hour management of reactive power as the load varies.

Shunt capacitors are usually switched. If there is a sudden load-rejection or
open-circuit of the line, it may be necessary to disconnect them very quickly, to
prevent them from increasing the voltage still further.
Chapter 3

AC Apparatus to enhance power flow in the system

3.1 Control of power flow with conventional Phase Shifting Transformers

3.1.1 General overview

The phase-shifting transformer is a special application of the power transformer concept. Contrary to a normal transformer with different voltages on the two line terminals, a phase-shifter provides a phase angle displacement between the in and outgoing terminals.

Phase Shifters are primarily used for the control of power flow in large power systems with several lines in parallel [E1 and E4]. A phase-shifting transformer comprises magnetizing and booster transformers in series with a transmission line as shown in Figure 3-1. The network operators have to adjust the phase-shifting angle depending on the actual power flow pattern. The angle variation can either cover the whole phase-shifting range or only a small portion. The phase-shifting transformer solution is used when the requirement for fast control of the power flow is not needed.

For operation of the phase-shifting transformer a balanced three-phase system is required. In a phase-shifter, power is extracted from one or two phases and injected into the third phase. A similar shift of power is carried out for all three phases.

The power extracting unit is often called the magnetizing transformer and the injection unit is called the booster transformer. Each one of the two transformers must have a rated capacity that corresponds to the maximum phase-shifting power. The unit rating of the phase-shifting equipment will therefore be twice the phase-shifting power.

The following gives an overview of the basic functioning of the phase-shifting transformer. Considering the scheme shown in Figure 3-2, the vector difference of voltages $V_S - V_L$ drives a current $I$. For the predominantly reactive (inductive) impedance of the line this current lags the voltage difference by approximately 90°.

A phase-shifter influences the phase angle as the injected voltage is approximately in quadrature to the source voltage. Therefore the active power is af-
fected. Pure voltage regulation only affects the reactive power supplied to the load side.

Hence, the phase shift controls the active power flow according to the following equation:

\[ P_s = \text{Re}\left(V_s^*L_s^*\right) = \text{Re}\left(V_s \left(\frac{V_s - V_L}{jX}\right)^*\right) \]  

(1)

Voltage regulation controls the reactive power transfer according to the following equation:

\[ Q_s = \text{Im}\left(V_s^*L_s^*\right) = \text{Im}\left(V_s \left(\frac{V_s - V_L}{jX}\right)^*\right) \]  

(2)
In a phase-shifter, active power is transferred from the adjacent phases to the third phase, by connections between windings exited by different parts of the magnetic circuit. In a pure phase-shifting transformer a voltage in quadrature to the source voltage is injected into the line, as illustrated in Figure 3-3.

As seen in the phasor diagram parts of the voltages from phases 1 and 2 are combined and added (sum of vectors) to the voltage of phase 3. Adding part of the difference between phases 1 and 2 to phase 3 acts like a rotation of phase 3.

Figure 3-2: Overview of basic functioning of the phase-shifting transformer

The added voltage does not have to be at a positive angle. It can be either a positive or negative angle. Depending on the application different fractions of phases 1 and 2, or even of only one phase could be added to phase 3. This can be accomplished by numerous physical arrangements of windings and cores.

A phase-shifting transformer, under load conditions, can be modelled according to Figure 3-4. The illustration shows a voltage phasor at the load side terminals leading the source side voltage phasor. In this case, it is said that this is an ‘advance phase angle’. The illustration also shows a voltage phasor lagging the source side voltage phasor. In this case, it is said to be a ‘retard phase angle’.

The model combines an ideal phase-shifting transformer with an ordinary 1:1 transformer with impedance $Z_T = R_T + jX_T$.

The load current $I_L$ supplies a slightly inductive load, $I_L$ that lags $V_L$ by the angle $\phi$. Adding the component $I_L X$ with $V_L$ yields $V_{LD}$, which gives the output voltage of the ideal phase-shifter needed to drive the load current $I_L$. This gives a beta angle ($\beta$) that yields the phase-shifting transformer load angle. As usual in transformers, $R_T << X_T$, which results in the resistive part of the transformer impedance having little influence on the output voltage.
Figure 3-3: A phase-shifter rotates phasor orientation

Figure 3-4: Phase-shifting transformer under load condition [E5]
In the phasor diagram the following variables are shown:

- $V_S$: voltage at source side
- $V_L$: voltage at load side under load
- $\alpha_{\text{adv}}$: advance phase angle under load (load voltage leads source voltage)
- $\alpha_{\text{ret}}$: retard phase angle under load (load voltage lags source voltage)
- $I_L R_T$: resistive voltage drop (normally a small component)
- $I_L X_T$: inductive voltage drop
- $\varphi$: angle between load current and voltage
- $\beta$: transformer load angle

The transformer load angle is calculated by:

$$\beta = \arctan\left(\frac{z \cos \varphi}{1 + z \sin \varphi}\right)$$

(3)

where $z$ is the impedance of the phase-shifting transformer and $\cos \varphi$ is the load factor.

### 3.1.2 Types of Phase Shifting Transformer

The selection of circuit layout and design concepts for magnetising and booster transformers depends on a number of factors like the size of displacement angle, requirements of angle variations, throughput power, requirements on voltage adjustments, etc.

There are two basic types of phase-shifting transformers: two cores and one core.

For a large power system with high voltage and high throughput power an arrangement shown in Figure 3-5 is often used. This is a two-core design with symmetric voltages. Source side and load side voltages differ by a certain quadrature voltage, which is inductively injected into the series unit.

The quadrature voltage $\Delta V$ is produced in the main unit ($u_{1\text{ maj}}$). The main unit is excited by the voltages taken at the mid taps of the series unit. The voltages induced in the regulating windings on the limbs excited by phases 2 and 3 are lagging phase 1 by 120° and 240°, respectively, however the difference is at 90° to the exciting voltage in phase 1 ($U_1$). This difference voltage is fed to the series unit, thus inducing the quadrature voltage symmetrically in the mid tap.
In systems with limited voltages and throughput power, the tap-changer can often be located in the main circuit. The phase-shifter can then be built as one single active part with an equivalent rating slightly higher than the power needed for the phase-shifting transformer. There is then no need for a separate magnetizing unit. It should be noted that this is only possible if transportation limits or switching capacity of the tap-changer do not require a two tank design.

Figure 3-6 shows a single core phase-shifting transformer. The exciting and magnetizing windings can be accommodated on a single core. Here the delta connected exciting windings are connected to line voltage between the source and load side, giving a symmetric design (it could also be connected at the source side, giving an asymmetric design).

The voltage picked up by the regulating windings of phase 1 is induced by the exciting winding and is fed by the voltage difference between phasors 2 and 3. This voltage difference is in quadrature to the phasor of phase 1.

In the single core design six single phase OLTCs are needed. All tap changers are at high potential. At tap positions near zero phase-shift the short circuit im-
Impedance is close to zero. Therefore, measures should be taken to limit short circuit currents, e.g., an additional reactor or the short circuit impedance of a nearby normal transformer have the task to limit short circuit currents.

![Diagram of a Phase-shifting transformer, single core and corresponding phasor diagram](image)

Figure 3-6: Phase-shifting transformer, single core and corresponding phasor diagram [E5]

3.1.3 Practical consideration regarding Phase Shifting Transformers

The power needed to reach a certain displacement in phase angle (phase-shift angle) is proportional to the throughput power and almost proportional to the phase angle.

\[
P_{\alpha} = 2P \sin \frac{\alpha}{2}
\]

(4)

where:

\( P_{\alpha} \) = phase shifting power
P = throughput power

The required KVA rating as a function of throughput KVA power can be visualized in Figure 3-7.

\[ P = \frac{2P \sin \frac{\alpha}{2}}{\alpha} \]

Figure 3-7: Equivalent KVA / Throughput KVA as a function of phase-shifting angle.

As an example, assume a power system connection with a throughput power capacity of 1000 MVA and a maximum phase-angle displacement of 30°. The magnetising and the booster transformer each need a capacity of 520 MVA, which means that for a reasonable phase displacement, fairly large unit sizes will be reached.

The short circuit impedance of the PST depends on the number of turns linked to stray flux and to the magnetic stray flux density. For single core designs with regulation at the line end there are only a few turns coupled to the stray flux at small shift angles, therefore the impedance is very low. If a minimum impedance is required for short circuit protection purposes an additional reactor may have to be integrated into the PST tank. With coarse/fine regulation the flux between these windings provides some extra impedance near zero shift.
angle. The minimum impedance of the two cores design is given by the short circuit impedance of the series unit.

### 3.1.4 Consideration regarding physical size and cost

ABB [E5] is presently manufacturing a large phase-shifter transformer with a throughput power of 1630 MVA, 400 kV, 18 degrees phase shift advance at no-load (load side leading source side phasor). This transformer is at the limit of what can be built and transported. The tap changer has 32 steps (coarse/fine), which is also close to its switching power limit. Impedance relative to the throughput power in this case is about 10% at zero degree phase shift (determined by short circuit capacity) and about 14% at full phase shift. Due to this PST impedance, the shift angle effective at the terminals at full load is reduced to about 10 degrees.

In case a larger switching range is needed, two sets of tap changers and special winding arrangements will be required.

The size is about 15 x 13 m (two tanks design), and weight 850 tons. The cost of this unit has been estimated in the range of 15-20 MUSD (9-12 $/kVA).

Table 3-1 presents other examples of phase-shifting transformers [E5]. The cost for these units in the range 5-15 $/kVA ($/rating of the transformer in kVA).

**Table 3-1: Some examples of different types of phase-shifting transformers**

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>336 MVA, 138 kV, ±30°</td>
<td>Two-cores</td>
<td>9.2 x 3.6 x 4.2 m, 392 tons</td>
</tr>
<tr>
<td>450 MVA, 138 kV, ±58°</td>
<td>Single-core with reactor</td>
<td>14.9 x 10.8 x 7.5 m, 550 tons</td>
</tr>
<tr>
<td>825 MVA, 240 kV, ±47°</td>
<td>Single-core</td>
<td>23 x 13 x 9.2 m, 825 tons</td>
</tr>
</tbody>
</table>

Note 1: specification shows throughput power rating of the transformer
3.2 Control of active and reactive power with FACTS devices

3.2.1 Background

According to the IEEE/Cigré definition, FACTS is an ‘alternative current transmission system incorporating power electronics-based and other static controllers to enhance controllability and increase power transfer capability’ [F1 and F2]. In general they are considered to be a means to benefit and improve transmission system management for a better utilization of existing transmission lines, to increase transmission system reliability and availability, to increase the dynamic and transient grid stability and to increase the quality of supply for sensitive industries.

This is accomplished by appropriate reactive compensation, where, the voltage profile along the line can be controlled by reactive shunt compensation; the series line inductance by series capacitive compensation; or the transmission angle can be varied by phase-shifting transformers.

Traditionally, reactive compensation and phase angle control have been applied by fixed or mechanically switched circuit elements (capacitors, reactors, and tap-changing transformers) to improve steady-state power transmission. The recovery from dynamic disturbances was accomplished by sufficient stability margins at the price of relatively poor system utilization.

By use of FACTS devices, which have a much faster capability for regulation compared to the conventional mechanical switched devices, it is possible to obtain an increase in the useable transmission capacity of lines and to control power flow over designated transmission routes.

3.2.2 Overview of the most common application of FACTS devices

Shunt compensator: Static Var Compensator (SVC)

The Static Var Compensation is an important FACTS device that has been used for resolving dynamic voltage problems. This type of device was developed during the 1970’s for arc furnace compensation, and then later adapted for transmission applications.

Figure 3-8 shows a typical shunt-connected static var compensator, which includes a thyristor-switched capacitors and thyristor-controlled reactor.

A proper coordination of the capacitor switching and reactor control, provides var output that can be varied continuously between the capacitive and inductive ratings of the equipment.
Figure 3-8: [F3]

Top: SVC, Static Var Compensator, employing: TCR – thyristor-controlled reactor (shown on the left side) and TSC – thyristor-switched capacitor (shown on the right side); Bottom: V-I characteristic of the SVC

The compensator is normally operated to maintain the voltage of the transmission system at a selected terminal reference voltage. The V-I characteristic of the SVC indicates that the regulation with a given slope around the nominal voltage can be achieved in the normal operating range defined by the maximum capacitive and inductive currents of the SVC. When operating outside the
regulating range, the voltage support capability of the conventional thyristor controlled static var compensator rapidly deteriorates with decreasing system voltage.

Besides the voltage support, SVCs are also employed for transient (first swing) and dynamic stability (damping) improvements. The effectiveness of the SVC for transient stability is related to its ability to maintain the transmission voltage during the major accelerating swing of the transmission angle. This is achieved when operating along the voltage regulating range. Outside the V-I characteristic of the SVC, this ability rapidly diminishes; e.g., once the maximum capacitive admittance \( B_c \) is reached, the SVC functions only as an ordinary shunt capacitor.

The capability for dynamic stability improvement (damping of power oscillations), is obtained by alternating the output of the SVC between appropriate capacitive and inductive values so as to oppose the angular acceleration and deceleration of the machines involved. The idea is to increase the transmitted electrical power by increasing the transmission line voltage (via capacitive vars) when the machines accelerate and to decrease it by decreasing the voltage (via inductive vars) when the machines decelerate.

**Series Compensator: Thyristor control series capacitor (TCSC)**

This is an extension to the conventional series capacitors and series reactor compensation with mechanical switching. Figure 3-9 shows a thyristor-controlled reactor in parallel with a series capacitor. Another possible scheme is the thyristor-switched capacitor, where the degree of series compensation is controlled by increasing or decreasing the number of capacitor banks is series.

Placing a controlled reactor in parallel with a series capacitor enables a continuous and rapidly variable series compensation system. This arrangement provides a continuously controllable reactance since the parallel thyristor reactor branch produces a current that adds to the line current through the capacitor thereby increasing its capacitive size beyond its physical reactance obtained by the line current only.

In this scheme, the degree of series compensation in the capacitive operating region is increased (or decreased) by increasing (or decreasing) the thyristor conduction period, and thereby the current in the thyristor control reactor. Minimum series compensation is reached when the thyristor control reactor is off.

The thyristor control reactor may be designed to have the capability to limit the voltage across the capacitor during faults and other system contingencies of similar effect.

The normalized power \( P \) versus transmission angle \( \delta \) is plotted in Figure 3-9 with the degree of series compensation \( k \) as a parameter. The degree of com-
Pensation is given by the effective capacitive impedance \( X_C \) (which the device is set to provide) divided by the line reactance \( X \). This is also shown in Figure 3-9.

Figure 3-9: [F3]

Top: Fixed capacitor thyristor-controlled reactor scheme; Bottom: \( P \) versus \( \delta \) plots as a function of degree of series compensation

Besides the capability to control the steady-state power flow and to balance power flow in parallel lines, the variable series capacitive compensation can also be effective for transient stability improvement, e.g. to damp power oscillations in the line.

An important characteristic of the thyristor-controlled series capacitor is that it can reduce the risk for subsynchronous resonance that might occur with series compensated lines.
Converter based FACTS controller: STATCON and Unified Power Flow Controller (UPFC)

The UPFC is considered a powerful and versatile concept for power flow control. The UPFC combines a STATCOM and a TCSC.

The STATCON is concept based on a SVC. It has been shown that a SVC provides voltage regulation and dynamic reactive power by means of thyristor-controlled reactors and thyristor-switched capacitors for var absorption and production respectively. A STATCOM accomplishes the same effect by using a Voltage Source Converter to synthesize a voltage waveform of variable magnitude with respect to the system voltage.

Connecting a STATCOM, which is a shunt connected device, with a series branch in the transmission line via its DC circuit, results in the UPFC. This device is comparable to a phase-shifting transformer plus a SVC.

As indicated in Figure 3-10, the UPFC consists of two Forced Commutated Voltage Source Converters, which are connected through a common DC link. One converter is shunt-connected and the other is connected in series with the AC transmission line. The UPFC can control both transmitted active and reactive power, as well as the AC bus voltage at the point where the shunt converter is connected.

A Forced Commutated Voltage Source Converter, including an appropriate control, can generate an AC output voltage at the converter bridge with a given variable amplitude (from zero to the maximum) and phase angle (from zero to 360°). The variable output voltage of the converter is inserted in the transmission line via a booster transformer. This changes the effective voltage drop across the transmission line impedance and thereby the current in the transmission line. The active and the reactive power flow in the transmission line can then be controlled independently by adjusting both phase angle and the amplitude of the inserted series voltage.

There is a certain active and reactive power exchange that takes place between the AC system and the series converter through the booster transformer. The active power absorbed or generated will be fed back to or will be supplied from the AC system through the shunt converter. Therefore, the shunt converter provides a direct path for the real power, which is demanded by the series converter. The reactive power absorbed or generated by the series converter corresponds to a circulating instantaneous power between the three phases.

The shunt-connected converter will provide the real power demanded by the series-connected converter. In addition to this, the shunt-connected converter can also provide an independent reactive power compensation for the AC system, to control the AC bus voltage at the point where the shunt converter is connected.
The control capability of the UPFC as a power flow controller can be analyzed assuming the equivalent model and the corresponding phase diagram shown in Figure 3-10.

The controllable current source $I_{v1}$ and the voltage source $U_{v2}$ represent the outputs of the shunt and the series converter respectively. Currents in impedances $X_1$ and $X_2$ are calculated by:

$$I_1 = \frac{U_s - U_{L1}}{jX_1} \quad \text{and} \quad I_2 = \frac{U_{L1} - U_{v2} - U_r}{jX_2}$$

\hspace{30pt} (5)
Thus the transmitted active power on the sending and receiving terminals and the reactive power absorbed by the receiving terminal are expressed by:

\[ P_s = \text{Re}(U_s \cdot I_1^*) = \frac{U_s \cdot U_{l1}}{X_1} \sin((1 - \xi)\delta) \]  \hspace{1cm} (6)

\[ P_r = \text{Re}(U_r \cdot I_2^*) = \]
\[ = \frac{U_{l1} \cdot U_r \sin(\xi \delta) + U_{l2} \cdot U_r \sin(\xi \delta - \theta)}{X_2} \] \hspace{1cm} (7)

\[ Q_r = \text{Im}(U_r \cdot I_2^*) = \]
\[ = \frac{U_r - U_{l1} \cos(\xi \delta)}{X_2} \cdot U_r - \frac{U_{l2} \cdot U_r \cos(\xi \delta - \theta)}{X_2} \] \hspace{1cm} (8)

The value \( \xi \) can be determined by the active power balance equation, making \( P_s = P_r \) (a reasonable approximation can be obtained if losses are neglected).

The required power rating of a UPFC depends on the specified control functions. In general, the power rating is derived from the product of the maximum voltage and current, since the converter has to be designed for both peak continuous operating voltage and peak continuous operating current. It is possible to see from the above equations that for a pre-designed maximum series voltage, the maximum line current is determined by the phase shift angle \( \delta \). The phase-shift angle \( \delta \) is normally in the range of 20° to 50° when the UPFC is used as a static power flow control. It may be close to 90° when used as power swing damping controller.

### 3.2.3 A comparison between Phase Shifting Transformer and UPFC

The traditional phase-shifting transformer has been the basic device to control both direction and magnitude of power flow. As mentioned in section 3.1, the phase-shifting transformer consists of a magnetizing and booster transformers, as shown in Figure 3-11.

Despite the fact that a phase-shifting transformer introduces flexibility into the system, this device has two important drawbacks: one drawback is that it introduces high series impedance; the other drawback is the slow speed for regulation due to the use of mechanical load tap changers.
The load tap-changers take several seconds per tap change and a minute or more for a major angle change. Therefore, the control of the phase-shifting transformer will be too slow to be of any value for dynamic control of the system.

The high series impedance results from the connection of the two transformers. As shown in Figure 3-11, the leakage reactance of the series winding always appears in series with the supply transmission line. The leakage reactance of the excitation winding also appears in series with the supply transmission line,
but varies with the phase-angle shift. Figure 3-11 shows a typical diagram of reactance as a function of the phase-angle shift.

From the figure it is possible to verify that the maximum reactance corresponds to the maximum phase-angle shift. Considering that the power transfer is inversely proportional to reactance, and because the transformer contributes with its maximum impedance, this might introduce special requirements to the maximum phase-angle of the transformer.

The reactance added in the transmission line because a phase-shifting transformer is included in the electric circuit can be quite significant. For example: a 230 kV line, including a 400 MVA phase-shifting transformer with a full-shift impedance of 15% on its own base may insert a series reactance equivalent to about 50 km of overhead transmission line. At no shift the transformer contributes with about 25 km. Considering that the circuits at this voltage level are typically under 150 km long, the added reactance is quite significant.

In case of cable transmission, the reactance of the phase-shifting transformer can exceed the reactance of the cable line.

The consequence of this additional impedance included in the circuit is that the phase-shifting transformer consumes significant amounts of reactive power at high power transfer levels. Normally, associated with a phase-shifting transformer there is a large reactive power source to insure adequate voltage regulation. In many cases, it requires an a controllable reactive power source like a SVC to insure stable conditions during contingencies.

Because of these two drawbacks a phase-shifting transformer deteriorates the performance of the system during disturbances, and problems with transient or dynamic stability might occur.

Using the concept of voltage insertion into a transmission line via a series transformer, a UPFC has the ability to inject a voltage with a controllable amplitude and phase angle. This makes the UPFC capable of controlling both active power and reactive power through the series transformer. As seen in Figure 3-12, the locus of the injected voltage is a circle, with its amplitude limited by the current capability of the converters. The phase-shift can be arbitrary.

When comparing the steady state performance between a phase-shifting transformer and an UPFC the following can be observed:

- A phase-shifting transformer can deliver 70-80% of the transmittable real power at maximum MVA transferred. An UPFC can essentially transfer 100% MW, since this device has the capability for load compensation. With appropriate design of the UPFC the load compensation can achieve unity power factor.

- Neglecting the device losses, considering only the line losses, with a UPFC the losses in the line are reduced due to its unit power factor, and consequently, the line is used more efficiently.
• A phase-shifting transformer requires high MVA compensation to maintain unit terminal voltage at each end. A UPFC does not require reactive power compensation.

![UPFC Diagram]

Figure 3-12: UPFC and the principal mode of operation, showing the ability to inject voltage with controlled amplitude and phase angle

3.2.4 Economic considerations regarding FACTS devices

The costs depend not only upon the installation rating but also upon special requirements of the installation. Examples of such requirements are: redundancy of the control, protection and communication system; redundancy of main components such as reactors, capacitors or transformers, etc.

For typical rating of the devices, the lower limit of the cost areas shown in Figure 3-13 indicates the equipment costs, and the upper limit indicates the total investment costs including the infrastructure costs.

Cigré reports an overview of present available information on specific investment cost for various FACTS controllers and for their conventional counterparts [F1]. This information is derived from FACTS installation commissioned prior 1996. A summary of this information is reproduced in Table 3-2.
Figure 3-13: [F5] Top: Typical investment cost for SVC / Station; Bottom: Typical investment cost for SC, TCSC and UPFC
<table>
<thead>
<tr>
<th>Device</th>
<th>Specific Cost $/kVA</th>
<th>Source Information</th>
<th>Year of publication</th>
</tr>
</thead>
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<td>45</td>
<td>Chester (550 MVar)</td>
<td>1990</td>
</tr>
<tr>
<td>SVC</td>
<td>45</td>
<td>EPRI-TR-103167</td>
<td>1993</td>
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<tr>
<td>SVC</td>
<td>40</td>
<td>EPRI-EL-6943</td>
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<td>EPRI-TR-103641</td>
<td>1993</td>
</tr>
<tr>
<td>SVC</td>
<td>35-50</td>
<td>ABB – sales estimate</td>
<td>1995</td>
</tr>
<tr>
<td>SVC</td>
<td>35</td>
<td>EPRI</td>
<td>1996</td>
</tr>
<tr>
<td>TCSC</td>
<td>40</td>
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</tr>
<tr>
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<td>STATCOM</td>
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<td>Westinghouse-sales</td>
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<tr>
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<td>80</td>
<td>EPRI</td>
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</tbody>
</table>
3.3 Current Limiting Devices

3.3.1 Background
The study made to verify the possible ways to integrate new thermal power plants into the electric network operated by Bandeirantes (see São Paulo case presented in section 6.4) shows that the solution based on HVDC transmission is too expensive. In that case, short circuit current was the only issue to be addressed, although the study also shows other benefits with the solution.

A more cost effective solution would be the use of a ‘Current Limiting Device’ that is also based on power electronics.

Today such a Current Limiting Device is not available in the market, however it is possible to manufacture this device quite easily considering that all necessary components are available, and are used in a typical HVDC converter.

3.3.2 General overview of the proposed Current Limiting Device
There are basically two concepts using standard semi-conductor components [F9]:

- Concepts based on the use of IGCT or IGBT: This concept is preferable because they have the current turn-off capability and they are fast.
- Concept based on the use of thyristor: A thyristor does not have the current turn-off capability. In order to be able to limit the first peak current after a fault without waiting for the first zero crossing of the current, an artificial current zero crossing has to be generated from a discharge of a capacitor. This concept with thyristors might result in a too complicated circuit configuration, and therefore it was not considered in this study.

In terms of using IGCT or IGBT the following considerations can be made:

- Hard-driven IGCT has the advantage over the IGBT that they have a rather low forward voltage drop. However, they have the disadvantage that a large gate current is required at turn-off, which in practice means that there is a limit at which the device can be turned off.
- Both IGCT and IGBT are designed for forward blocking voltage only. Therefore for this application they have to be connected in series with either diodes or thyristors to provide the reverse voltage capability.

It is possible to consider two different topologies for the Current Limiting Device (Figure 3-14) [F9]:

- Alternative 1: Includes series connected diodes and IGCTs or IGBTs.
• Alternative 2: Includes a diode (or thyristor) bridge connection and IGCT or IGBT in the middle of the bridge.

The alternative 2 might be preferable because it has fewer turn-off components, which are the most expensive parts.

The use of thyristors instead of diodes in Alternative 2 has the following advantage: the device will have, besides the capability to block high fault current an additional feature, that is, it will give the capability to control the current during the fault by the use an adequate firing control of the thyristors.

In the following presents results of a study made to investigate some system aspects related to the use of Current Limiting Device.

### 3.3.3 Performance of Current Limiting Device

In order to demonstrate the typical behavior of a Current Limiting Device a system study was made in a scheme according to Figure 3-15. The scheme shows a 300 MVA generator connected to a 5000 MVA system, and the topology of the Current Limiting Device is according to Alternative 1. This would give the simplest circuit design.
It is assumed that the fault detection principle used by the CLD is based on simultaneous detection of high current and low voltage. The action is simply switching, having the ability to extinguish current without waiting for the zero crossing. The time delay for acting is in the range 1-2 ms.

Figure 3-15: Simulated system to verify the performance of a Current Limiting Device

Table 3-3: Summary of results

<table>
<thead>
<tr>
<th></th>
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<td>1.0</td>
<td></td>
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<td>-</td>
<td></td>
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<td>F1-3_ph_CLD</td>
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<td>44.18</td>
<td>93.27</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Note 1: The arrester energy has been calculated assuming a fault applied at instant 0.1 sec.

Note 2: The maximum arrester energy (considering fault applied at different point of wave of the voltage) was calculated for this case and the obtained value was 2.96 MJ.

Singe-phase and three phase faults have been studied. Faults within the protective zone and outside the protective zone (faults in the system) have been studied. In addition the condition in which the CLD fails to operate has been investigated. Table 3-3 gives a summary of the results.
Faults between the transformer and CLD are the most critical in terms of maximum current through the CLD. These faults give the highest current contribution from the system network, which is greater than the contribution from the generator. The rate of rise of current in this case is in the range 15-20 kA/ms. Figure 3-16 Top shows this condition, and the case corresponds to a three-phase fault located at position F1, where the CLD failed to operate.

Figure 3-16 Bottom shows a case with normal operation of the CLD. The figure shows that during the fault, the CLD will block the current by detecting high current and low voltage until the fault is cleared. When the fault is cleared, detected by measured high system voltage, the valves are de-blocked. As soon as the valves are deblocked current is restored and the system is back into normal operation.

Figure 3-16: Top: CLD current for a fault between the transformer and CLD (CLD has not operated in this case); Bottom: Sudden current increase after fault is cleared (normal operation of the CLD)
Chapter 4

HVDC Transmission overview

4.1 HVDC transmission with Line Commutated Current Source Converters

4.1.1 Introduction

The first commercial HVDC link with converters with mercury-arc valves was commissioned 1954. This type of converter is referred to as a Line Commutated Current Source Converter (CSC). For the next generation HVDC converters, introduced during late 1960’s, the same type of converter was used but with the mercury-arc valves replaced by semiconductor thyristor valves. Thyristor valves have now become standard equipment for DC converter stations. Recent developments in conversion equipment have reduced their size and cost, and improved their reliability. These developments have resulted in a more widespread use of HVDC transmission. The following are the main applications for which HVDC transmission is used [B1 and B13]:

1. AC transmission is impractical for underwater cables longer than about 50 km distances because of the high capacitance of the cable requiring intermediate compensation stations.

2. HVDC transmission is also a competitive alternative to AC transmission of large amount of power and long distances, say 600-1000 km when using overhead lines.

3. A HVDC asynchronous link can be used to interconnect two AC systems where AC ties would not be feasible because of system stability problems or a difference in nominal frequencies of the two systems.

4.1.2 Substation configuration

Figure 4-1 shows an example of the electrical equipment required for a DC substation [B1]. In this example, two poles are represented, known as a ‘bi-pole’ configuration. Some DC cable systems only have one pole or “mono-pole” configuration and may either use the ground as a return path when permitted or use an additional cable to avoid earth currents. The main components of a converter station are summarized below:

Converter valves and converter transformers: The central equipment of a DC substation is the thyristor converter valves. Converter valves perform AC/DC
and DC/AC conversion, and consist of valve bridges and transformers with tap changers. The valve bridges consist of high-voltage valves connected in a 6-pulse or 12-pulse arrangement.

**Smoothing Reactors:** These are large reactors (inductance as high as 1.0 H) connected in series with each pole of each converter station. They serve mainly to smooth the current through the DC line, to prevent current from being discontinuous at light load and to limit the crest current in the rectifier during a short-circuit on the DC line.

![Figure 4-1. Example of a HVDC substation.](image)

**Harmonic Filters:** Converters generate harmonic voltages and currents on both the AC and DC sides. Filters are therefore used on both the AC and DC sides. AC filters are typically tuned to 11th, 13th, and higher harmonics for 12 pulse converters. AC side harmonic filters may be switched with circuit breakers or circuit switches to accommodate reactive power requirement strategies since these filters generate reactive power at fundamental frequency. DC side filters reduce harmonic current flow on DC transmission lines.

**Reactive Power Supplies:** DC converters inherently absorb reactive power. Under steady-state conditions, the reactive power consumed is about 45-50% of active power transferred. Reactive power sources are therefore provided
near the converters. The capacitors associated with the AC filters also provide part of the reactive power required.

**Electrodes:** Most DC links are designed to use earth as a neutral conductor for at least brief periods of time. The connection to the earth requires a large-surface-area conductor to minimize current densities and surface voltage gradients. If it is necessary to restrict the current flow through the earth, a metallic return conductor may be provided as part of the DC line.

**AC Circuit Breakers:** For clearing faults in the transformer and for taking the DC link out of service, circuit breakers are used on the AC side. They are not used for clearing faults on the DC line, since these faults can be cleared more rapidly by converter control.

### 4.1.3 Converter configuration

Most of the HVDC power converters with thyristor valves are assembled in a converter bridge using a 12-pulse configuration. Figure 4-2 shows the use of two three-phase converter transformers with one DC side winding as an ungrounded star connection and the other a delta configuration. Consequently the AC voltages applied to each 6-pulse valve group which make up the 12-pulse valve group have a phase difference of 30° which is utilized to cancel the AC side 5th and 7th harmonic currents and DC side 6th harmonic voltage, thus resulting in a significant saving in harmonic filters.

![Diagram](image)

**Figure 4-2.** The 12-pulse valve group configuration with two converter transformers.
4.1.4 Valve component

A thyristor or valve module is the part of a valve in a mechanical assembly of series connected thyristors and their immediate auxiliaries including heat sinks cooled by air, water or glycol, damping circuits and valve firing electronics.

The valve in an HVDC converter conducts in only one direction, the forward direction, from anode to cathode. When it is conducting, there is only a small voltage drop across it. In the reverse direction, when the voltage applied across the valve is such that the cathode is positive relative to the anode, the valve blocks the current.

Thyristor valves can carry very high currents (4 kA) and are able to block very high voltages, up to 10 kV. The thyristors are connected in series to achieve the desired system voltage (several hundred of kV). [B4 and B11]

4.1.5 HVDC converter arrangements

HVDC converter bridges and lines or cables can be arranged in a number of configurations for effective utilization. Various ways in which HVDC transmission is used are shown in a simplified form in Figure 4-3. They include the following:

![Figure 4-3: HVDC converter bridge arrangements.](image)

1. Transmission between two substations: transmission from one geographical location to another, a two-terminal or point-to-point HVDC transmission is used. Monopolar or Bipolar are the typical configurations used.
2. Back-to-Back: Back-to-back DC links are used for interconnections between power system networks of different frequencies or as interconnections between adjacent asynchronous networks.

3. Multiterminal HVDC transmission systems: They are used when three or more HVDC substations that are geographically separated with interconnecting transmission lines or cables. If all substations are connected to the same voltage then the system is a parallel multiterminal DC.

4.1.6 Converter station layout

Converter stations require more space than a conventional AC substation for the same transmission capability. The converter station layout depends on the type of valve and its design. Figure 4-4 shows a typical general arrangement for such a station rated at 600 MW, and this design uses about 90x180 m².

![Converter station layout](image)

Figure 4-4: Typical layout for a 600 MW converter station, requiring about 90x180 sq. meters.

To obtain a compact design, converter transformer and smoothing reactors are located close to the converter building with valve side bushing pointing into valve hall. The valve hall includes the quadruple valves, valve protective surge arresters, converter controls, valve cooling equipment and other auxiliaries. In the case of a Back-to-Back arrangement of the converter, the valves might be placed in containers, considering that in this case valves are operating at low voltages.
An air-insulated station layout requires a minimum ground area of some 20-30 m²/MW. Filtering requirements have an important impact on the occupied area. This area is divided between the main substation components approximately as follows:

- Valve building: 8% of the ground occupied area;
- AC filters: 35%
- AC buswork and transformers: 45%
- DC yard: 11%

### 4.1.7 Operation of a converter

In the following the basic operation of a Line Commutated Converter is presented.
Top. A 12-pulse converter consisting of two six-pulse bridges in series, one supplied by three-phase AC voltage from Y secondary and the other a D secondary of a converter transformer. The typical waveforms show a change from maximum positive DC voltage to approximately 70%, then to \(-70\)% and then to the maximum negative of about \(-90\%\). \[B13\]

Bottom. Line Commutated Current Source Six Pulse Bridge Converter and associated voltage and current wave shapes, considering the periods of firing delay and overlap angles.

The conversion of current between the AC side and the DC side is accomplished by transferring direct current in sequence from the valve, such that the DC current flows as blocks of AC current in the transforming windings. With line commutation, the AC voltage at both rectifier and inverter must be provided by the AC networks at each end and should be three phase and relatively free of harmonics.

The output DC voltage obtained from a twelve-pulse bridge by switching twelve valves is shown in Figure 4-5-top. The sequence shows the converter operating first as a rectifier at its maximum positive voltage, then at a voltage reduced by delaying the firing angle, then at a negative voltage with a delay angle exceeding 90 degrees (inverter operation), and finally, at maximum negative voltage.

In Figure 4-5-bottom, shows the influence of the transformer’s commutation reactance on the waveform, at the rectifier and inverter. The current flow through a conducting valve does not change instantaneously as it commutates to another valve because the transfer is through the transformer winding.

All the valve current contributions result in a direct current which is transferred from the DC side through the DC reactor, and is relatively flat because of the inductance of the DC reactor.

4.1.8 Abnormal operation – commutation failure

Commutation failures in Line Commutated Converters operating as inverter are sometimes fairly frequent dynamic events in HVDC systems, which disturb the connected AC systems and stress the converter valves.

Most commutation failures are caused by voltage disturbances due to AC system faults and they can never be completely avoided as the commutation of current from one valve to the next depends on the AC voltages supplied to the converter. In general, the more rigid the AC voltage to which the inverter feeds into and the fewer AC system disturbances, the less likelihood there will be commutation failures.
4.1.9 Reactive power characteristic of a HVDC converter

HVDC converters, either in rectifier or in inverter operation, absorb reactive power as part of the power conversion process. Therefore, shunt compensation is required to compensate some or all of the HVDC Var requirements (as mentioned earlier, part of the shunt compensation is made by the connected filters and shunt capacitors).

The amount of reactive power $Q_d$ absorbed is determined by the DC control strategy as follows (following different curves in Figure 4-6):

- Constant DC voltage control, curve (1)
- Constant firing (or extinction) angle control, curve (2)
- Constant DC current control, curve (3)
- Constant reactive power control, curve (4)

![Figure 4-6: Reactive power characteristic of a HVDC converter terminal with different control strategies [B6]](image)

4.1.10 Influence of the AC system strength on the AC/DC system interaction

The converter always consumes reactive power, which must be supplied by the network and by the combined shunt capacitors and filters. This is because of the requirement for a positive commutation voltage for firing the thyristor which gives that the current is always lagging behind the voltage. If the connected AC system is not sufficiently strong the interaction between the HVDC scheme and the AC system can be critical.

The nature of AC/DC system interactions and the associated problems are very much dependent on the strength of the AC system relative to the capacity of the DC link. Because of this, it is useful to have a simple means of measuring and comparing relative strengths of AC systems. The short-circuit ratio (SCR) has evolved as such a measure. It is defined as:
\[ SCR = \frac{S_{MVA}}{P_{dcN}} \]  

where \( S_{MVA} \) is the short circuit capacity of the connected AC system, and \( P_{dcN} \) is the rating of the converter terminal in MW. The effective short-circuit ratio (ESCR) includes the effects of AC side equipment associated with the DC link: filters, shunt capacitors, synchronous condensers, etc, which will reduce the short circuit capacity of the network.

Traditionally, the AC system strength has been classified as follows:

- High, if ESCR is greater than 3
- Low, if ESCR is between 2 and 3
- Very low, if ESCR is less than 2

The above classification of AC system strength provides a means for preliminary assessment of potential AC/DC interaction problems. The following are the problems associated with the operation of a DC system when connected to a weak AC system:

- High dynamic over-voltages
- Voltage instability
- Harmonic resonance
- Voltage flicker

The problems associated with weak AC system can be resolved either by strengthening the system, e.g., by a connection of synchronous compensators or by a very fast voltage control in the AC system, which will maintain a stable AC voltage. Some improvement can also be obtained by modification of the control of the HVDC converters.

**4.1.11 Economical considerations**

HVDC converter stations are more expensive than a conventional high voltage substation. About US $100 – $300/kW must be spent on both converter terminals, depending generally on size [B13]. Figure 4-7 indicates typical cost range as a function of project size. The cost of an HVDC converter station decreases with increase in size.

A cost breakdown analysis for recent DC stations is presented in Table 4-1. This analysis was made by a Cigré working group 14.20 and was published in the report number 186, Economic assessment of HVDC links, dated June 2001 [B5]. Other publications, e.g. [B7], discuss the component cost figures and factors that contributes for the total cost of a HVDC transmission system.
Table 4-1: HVDC Turnkey Cost division. Cost estimation values given in year 2000 US$/kW (both ends inclusive) for one valve group per pole

<table>
<thead>
<tr>
<th></th>
<th>Back-to-Back</th>
<th>Monopole</th>
<th>Bipole</th>
<th>Bipole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500 kV</td>
<td>±500 kV</td>
<td>±500 kV</td>
<td></td>
</tr>
<tr>
<td>Valves group</td>
<td>200 MW</td>
<td>500 MW</td>
<td>500 MW</td>
<td>1000 MW</td>
</tr>
<tr>
<td>Converter transformer</td>
<td>19</td>
<td>19</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>DC switchyard and filtering</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>AC switchyard and filtering</td>
<td>11</td>
<td>11</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Control and communication</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Civil and mechanical work</td>
<td>13</td>
<td>13</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Engineering and administration</td>
<td>21</td>
<td>21</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Total per kW USD$</td>
<td>130$</td>
<td>90$</td>
<td>180$</td>
<td>170$</td>
</tr>
</tbody>
</table>

Remarks related to the Table 4-1:

1. These costs are based on some simplifying assumptions. It is assumed that the DC bipole is made up of one valve group per pole; there are no special measures for reactive power compensation and/or voltage control to be incorporated in the case of a weak AC system.
2. If DC voltage is selected lower than $\pm$ 500 kV the station cost will be approximately 5 to 10% lower per 100 kV reduction.

3. The estimate values should be treated as having accuracy no better than $\pm$ 20%.

**4.1.12 Stages in expansion of the HVDC transmission**

HVDC transmission can be built in stages. This is made to meet the need for a gradual increase of transferred power. In many applications HVDC is chosen for a larger power transfer capability on a long-term basis. The transfer might be low in the initial stage and higher after a certain period.

The most common staging for DC transmissions is to first build a monopole and later a bipole. A new bipole can be added later or the converter stations can be upgraded in current and/or voltage by adding converters in parallel or series.
4.2 HVDC transmission with Forced Commutated Voltage Source Converters

4.2.1 Introduction

A new generation of HVDC system was developed during the 1990s based on Forced Commutated Voltage Source Converters (VSC).

The fundamental difference between the conventional Line Commutated Current Source Converter and the new Forced Commutated Voltage Source Converter technology is that the Voltage Source Converter uses components that can turn off the current, and not just turn it on. Since the current in a Voltage Source Converter can be turned off there is no need for a commutation voltage in the connected AC network.

The classical High Voltage Direct Current (HVDC) transmission systems are built up with Line Commutated Current Source Converters (CSCs) that include thyristor valves. The turn-on of the thyristor is controlled by the gate signal while the turn-off occurs at the zero crossing of the AC current which is determined by the AC network voltage (that is the line commutation).

The Forced Commutated Voltage Source Converter (VSC) is built up using turn-off devices as switching elements like IGBTs instead of thyristors. The application of high power VSCs for HVDC was made possible by the development of this type of high power turn-off device and the possibility to connect them in series. The use of a Forced Commutated VSC instead of a Line Commutated CSC in HVDC offers the following advantages [C7] and [C8]:

- Possibility to control the reactive power consumed or generated by the converter independently of the active power to or from the converter;
- No risk of commutation failures in the converter during disturbances in the connected AC network;
- Possibility to feed a weak AC network or a network without own generation (dead AC network);
- Easier to implement multiterminal schemes since the polarity on the DC side is the same in both rectifier and inverter modes.

![Diagram of two types of HVDC transmission: Line Commutated CSC and Forced Commutated VSC](image)

Figure 4-8: Two types of HVDC transmission: Line Commutated CSC and Forced Commutated VSC
As seen in section 4.1, the classical HVDC terminals can control reactive power by means of switching of filters and shunt banks and to some level by firing angle control. But this control requires additional equipment. With HVDC using Voltage Source Converters it is possible to control both active and reactive power independently, and this is done almost instantly.

The main drawback with the VSC compared to the CSC is that DC line to ground faults are critical. The DC capacitor will be short circuited and at the same time the converter bridge will act as a diode bridge and contribute to the short circuit current on the DC side. Therefore, applications where the VSC can be most suitable for HVDC include Back-to-Back stations where no DC line exists or HVDC transmission utilizing DC cable instead of overhead lines, where the risk of faults in the DC side is reduced.

### 4.2.2 Voltage Source Converter

#### General aspects

An equivalent circuit of the Forced Commutated Voltage Source Converter (VSC) connected to a three-phase AC network is shown in Figure 4-9. Here, the converter bridge is connected to the AC network via a transformer having a certain inductance (L). It is also possible to do the connection via only inductors.

The converter bridge can be represented as a variable voltage source, where the amplitude, the phase and the frequency can be controlled independently of each other. In steady state, the fundamental frequency components of the phase voltages and the phase currents are represented by the phasors according to Figure 4-9.

![Figure 4-9: (a) VSC connected to an AC network (phasor diagram). (b) Phasor diagram (fundamental) and direction of power flows [C1].](image-url)
The fundamental apparent power in the connection point of the converter is defined by:

\[ S = P + jQ = \bar{U}_{\text{L}(1)} \bar{I}_{\text{v}(1)} \ (2) \]

Considering that in high power applications the transformer or inductors losses are small, they will be neglected when calculating the active and reactive power from the converter:

\[ P = \frac{U_{\text{L}(1)} U_{\text{v}(1)}}{\omega L} \cdot \sin \delta \ (3) \]

\[ Q = \frac{U_{\text{L}(1)} (U_{\text{L}(1)} - U_{\text{v}(1)}) \cdot \cos \delta)}{\omega L} \ (4) \]

The angle \( \delta \) is the phase shift between the line voltage \( U_{\text{L}(1)} \) and the bridge voltage \( U_{\text{v}(1)} \). A positive phase shift means that the line voltage is leading the bridge voltage and the converter consumes active power. The phasor diagram in Figure 4-9b indicates how the signs of the active and reactive power depend on the phase and the amplitude of the converter bridge voltage if the line voltage phasor is assumed to be constant.

The active power consumed or generated by the VSC mainly depends on the phase shift angle \( \delta \). The reactive power consumed or generated by the VSC is mainly determined from the difference in amplitudes between the line voltage \( U_{\text{L}(1)} \) and the bridge voltage \( U_{\text{v}(1)} \).

The direction of the power is given by the sign of the direct current \( I_{\text{d,load}} \) since the polarity of the DC side voltage \( U_d \) remains unchanged for a VSC.

A key component in a Voltage Source Converter is the DC side capacitor. The size of the DC side capacitor is essential for proper operation of the converter. For example, during a disturbance in the system, such as an AC fault, DC voltage variations will occur and the ability to limit these voltage variations depends on the size of the DC side capacitor. The DC side capacitor also provides the required smoothing of the DC voltage to keep the ripple in the DC voltage within the required levels in steady state.

Two and three level-converter bridge

The two-level bridge, shown in Figure 4-10, is the most simple circuit configuration, which can be used in order to build up a three phase, Forced Commutated VSC bridge. The bridge consists of six valves and each valve consists of a turn-off semi-conductor and an anti parallel diode. In order to use the two level bridge in high power applications series connection of semi-conductors
may be necessary and then each valve will be built up of a number of series connected turn-off devices and anti parallel diodes. The number of devices required is determined by the rated power of the bridge and the power handling capability of the switching devices used.

The three-level bridge is an interesting alternative to the two level bridge in high power applications in the sense that the phase potentials can be modulated between three levels instead of two. The harmonic content in the bridge voltage in the three-level bridge is reduced for an even switching.

![Figure 4-10: [C1]. Top – The two-level Converter Bridge and corresponding switch representation; Bottom – Three-level-converter and corresponding switch](image)

**4.2.3 Pulse Width Modulation**

A way to control both the active and reactive power is the use of Pulse Width Modulation (PWM).

For a Voltage Source Converter operating at fundamental switching frequency the bridge AC voltage is determined by the magnitude of the DC voltage. Therefore, it is only possible to control the amplitude of the bridge voltage if the DC voltage is varied. This type of control is rather slow and the speed of response is partly determined by the size of the DC side capacitor.

If PWM is introduced, the switching frequency is increased. It is now possible to achieve a fast control of the bridge AC voltage and at the same time keep the DC side voltage constant. With PWM it is possible to create a source voltage, which is generated by the converters with any phase angle and amplitude (below a certain maximum voltage).
To illustrate the PWM process, Figure 4-11 shows the resulting voltage of the AC terminal for one phase, with respect to a hypothetical midpoint of the DC capacitor, assuming a switching frequency of nine times the fundamental frequency. Instead of having two square pulses per cycle, in the case of fundamental frequency switching, the waveform is made up of nine square pulse cycles of varying width per main frequency cycle. The pulses are wider in the middle of each half sine wave compared to the ends of the half sine wave.

![Figure 4-11: Operation of a PWM converter with switching frequency of nine times the fundamental. (a) a phase-leg; (b) PWM waveform [C9]](image)

### 4.2.4 Power capability

Section 4.2.2 shows that the active and reactive power flows are determined by the power transmission equations given by equations (3) and (4). The transmitted active power and the reactive power (absorption or generation) depends on required network voltages, and are functions of the maximum current capability of the converter according to the equation (5)

\[
P^2 + Q^2 = (U_{L(0)} \cdot I_{L(0)})^2
\]  

(5)
Combining equations (3) and (4), gives also the following P-Q relationship:

\[ P^2 + \left( Q - \frac{U_{(L)}}{\omega L} \right)^2 = \left( \frac{U_{(L)} \cdot U_{(V)}}{\omega L} \right)^2 \]  

(6)

Equation (5) shows the circular controllable region, which is limited by the current rating of the converter (see in Figure 4-12, the circular region at \( U = U_{(L)} = 0.9 \) pu). The controllable region is reduced when the AC system voltage is reduced, which would demand higher current capability from the converter. In general, this type of converter has no overcurrent rating capability.

The capacitive limit shown in Figure 4-12 is due to imposing a converter voltage limitation as shown by equation (6). If the system voltage is reduced, this limit increases. The reactive power control range available depends on the active power operating point.

![PQ diagram, station 1, rect](image)

Figure 4-12: Typical power capability chart of a converter station

### 4.2.5 Consideration regarding losses in Voltage Source Converter

<table>
<thead>
<tr>
<th>Type</th>
<th>Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-level VSC</td>
<td>&gt; 3 %</td>
</tr>
<tr>
<td>3-level VSC</td>
<td>Range [1% - 2%]</td>
</tr>
<tr>
<td>Classical converter</td>
<td>= 0.5 %</td>
</tr>
</tbody>
</table>

One of the main drawbacks of today’s Voltage Source Converters for bulk power transmission is the comparatively high power losses. The losses of the
VSC-based HVDC converters are higher than the traditional HVDC solution with Line Commutated Converters.

The 2-level VSC is attractive due to its simplicity, however, the switching frequency must then be chosen comparatively high in order to keep the current ripple reasonably low, and this will result in high switching losses. One way of reducing the losses is to use more advanced converter topologies at the expense of simplicity. The 3-level converter is the alternative for this purpose. It is expected that a significant loss improvement might be accomplished in the future by employing new semiconductor materials like SiC.

Table 4-2 illustrates a comparison of typical converter station losses for different type of converters operating at 1 pu power, assuming the present manufacturing technology of IGBTs and thyristor valves.

4.2.6 Converter station – some considerations regarding space and cost

An HVDC converter with VSC consists of some basic functional building blocks. They are the valve bridge, the control systems and the switchyard with AC reactors, filters and transformer.

Presently, converter stations are available for powers up 350 MW. A 500 MW up to 1000 MW converter station will be the next generation that is presently under development. However, it is expected that the valves will then be placed in a valve hall instead of enclosures considering that the operating voltages will higher than 150 kV.

A typical converter station with VSC occupies a space of 10-20 m²/MW for a small converter station with a low DC voltage. As an example, an HVDC with VSC converter station with rating of 30 MW occupies an area of 300-600 m².

A bigger converter station with a higher DC voltage (up to ±150 kV) occupies a space of 20-50 m²/MW. Examples: for a 150 MVA converter rating the expected area that is required is in the order of 1500 m²; a 350 MVA converter rating would require 40x95 m² in a compact design and up to 65x125 m² assuming a normal design.

Figure 4-13 is an example of a 350 MVA rating converter station layout. A compact layout of the same station built in a building is also shown in the figure. Although the compact layout can be more expensive it might be necessary when the demands for space are more restricted.

Compared with the conventional HVDC station with thyristor valves, the converter station with VSC is more compact. The AC circuit is considerable more simple in a station with VSC compared with a classical HVDC station. While a classical HVDC converter station rated at 600 MW occupies about 15 000 m², a 350 MW HVDC using VSC might require less than 3 500 m².
As earlier mentioned, HVDC-VSC transmission is a new generation of HVDC system. It is less economical than the conventional HVDC-LCC. A survey
made of recent HVDC-VSC projects indicated that the cost per kW could be 20% to 50% higher than the HVDC-LCC converter with the same transmission capability. As the technology matures and rating increase, it is expect that the cost relation will be reduced.
4.3 HVDC configurations for City Infeed

4.3.1 Introduction
In this section an overview of possible HVDC system configurations that can be used for city infeed is presented. The configurations are based on analogies to the existing conventional AC configurations presented in chapter 2.

4.3.2 HVDC transmission topologies
Making analogy to the conventional AC distribution network it is possible to foresee the following basic HVDC system configurations and mixed AC and DC system configurations for city infeed.

In a ‘Radial System’ (Figure 4-14-A), there is no back-up facility. However, it gives the simplest alternative solution.

Figure 4-14: Some network topologies including HVDC transmission systems
An improved radial system is shown in Figure 4-14-B. In this case the two feeders are interconnected with a HVDC link, which will increase the overall reliability of supply. Having the HVDC link with Voltage Source Converters, the voltage performance of the system is increased with the reactive power support from the HVDC converters. It should be noted that the interconnection of the feeders with the HVDC link would not increase the short circuit power since the HVDC converters do not add short circuit current.

An AC Loop network designed to operate with a normally open switch or breaker can be improved by closing the loop with an HVDC Link (Figure 4-14-C). This will produce similar benefits compared to the previous case interconnecting an existing radial system. It will reduce the downtime of the non-faulted section and improve the security of supply. It is easier to extend the system without adding short circuit power and higher utilization of the existing system is provided. Additionally, power flow can be controlled and reactive power support will be provided to the system.

In a similar way, in order to improve the reliability of supply of two systems connected in an open link arrangement, it is possible to interconnect them with an HVDC Link (Figure 4-14-D). The interconnection made with an HVDC link isolates the two systems in terms of short circuit power, power flow can be controlled and voltage control can also be obtained.

Similar to AC systems, a ‘Ring Bus’ HVDC topology has a higher degree of security of supply to the individual substations (Figure 4-14-E). In normal condition it operates with the ring closed that provides maximum security. It can also operate with open ring, under fault conditions without affecting the supply. In general the system will be designed considering the N-1 criteria, in which the arrangement can accept the loss of one infeed (power sources or supply substation) without interruption of supplies within the network. However, it should be noted that in a DC ring-bus arrangement faults on the DC side of the network might be difficult to detect.

In order to provide a good reliability of supply, the detection of the line fault in the HVDC grid has to be fast and the protection has to isolate the faulty section restoring the transmission to normal operating conditions.

An advantage of having HVDC transmission is that the power transfer between the sources is controllable.

**4.3.3 Hybrid topology combining HVDC with Line Commutated Converters and HVDC with Voltage Source Converters**

The fundamental differences between the conventional Line Commutated Current Source Converter and the Forced Commutated Voltage Source Converters were presented in sections 4.1 and 4.2.

In a Line Commutated Current Source Converter the current always lags be-
hind the line voltage due to the requirements for a positive commutation voltage at the firing of the thyristors. Thus, this type of converter needs reactive power for operation, which normally has to be provided by reactive power devices connected to the AC network. As they rely on the line voltage for commutation a minor disturbance in the AC voltage might also result in commutation failures in the converters.

However, for a Forced Commutated Voltage Source Converter the commutation process does not rely on the connected AC network. The control system for a Voltage Source Converter is primarily based on the AC quantities and it is possible to control both active and reactive power independently. The converters are significantly less sensitive to the connected AC voltages. Because of this the Voltage Source Converter is also more suitable to supply a very weak AC system.

However, the Voltage Source Converter has also some major disadvantages compared to the conventional Current Source Converter. The cost and losses are higher and it is not so easy to control the DC voltage and by that the current on the DC side as it is for the Current Source Converter.

By combining a Voltage Source Converter with a Current Source Converter in a hybrid topology it might be possible to preserve the specific advantages of each type of converter. Three different possible hybrid topologies have been studied. In the first topology Current Source Converters are used at the rectifier station and Voltage Source Converters at the inverter station, where the AC network might requires a more effective voltage support from the converters. This is not a new topology since it has been largely used in industrial drive systems for many years. The second topology is to connect a Voltage Source Converter in series with a Current Source Converter at the same station. The third studied topology is a bipolar HVDC transmission having Current Source Converters in one pole and Voltage Source Converters in the other pole. Figure 4-15 depicts the studied hybrid topologies.

The study of the cooperation between the converters made using the EMTDC/PSCAD digital simulator indicated unfavourable interaction between different types the converters for scheme I and scheme II. The need for energy storage capacitance across the VSC part and the smoothing reactor in series with the CSC creates a resonant circuit on the DC side that produces a tendency for power oscillation. This tendency of oscillatory behaviour can be mitigated with a proper tuning of the controls in either the CSC or VSC part.

The other observation is the risk of overvoltages for the scheme I, and in particular for scheme II, during inverter faults or when the inverter CSC suffers commutation failures as the rectifier does not have the capability to control the voltage build up using only its conventional current control loop. A solution that has been investigated is to retard the rectifier operation very fast to inverter operation and combining this with some additional overvoltage protection at the inverter terminal. However, further investigations are needed to solve this
problem.

Hybrid topology according to scheme III requires an additional cable for current return in case of unbalance operation of the poles. The voltage rating of this additional cable can be low since one of the cable terminals will be solid grounded.

<table>
<thead>
<tr>
<th>Scheme I</th>
<th>Scheme II</th>
<th>Scheme III</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Figure 4-15: Hybrid Topologies

The un-damped resonance problem observed for the other studied hybrid topologies and the risk of high over-voltages do not exist in the Scheme III topology.

The basic advantage of this type of hybrid topology is that, as seen from the AC system network, the Line Commutated Current Source Converter is operating in parallel with the Forced Commutated Voltage Source Converter. This results in the Voltage Source Converter supporting the operation of the Current Source Converter, providing not only part of the required reactive power but also a fast control of the AC voltage that will reduce the risk of commutation failures. Hence, the VSC converter cooperates with the CSC converter from system performance point of view, without adverse control interaction as compared with other studied schemes.

System tests performed on the digital simulator, such as steps in current or power order and severe AC system faults, showed good performance, even with a weak connected AC system at the inverter terminal (short circuit ratio equal to 1.2 and a network impedance angle of 85°).
Chapter 5

High Voltage Cable Transmission – general aspects and cable transmission capability

5.1 Introduction

Underground AC cable systems are used in densely populated urban areas and more recently also in suburban areas, mainly due to aesthetic, environmental and reliability reasons. In urban areas the underground solution is the only possible way to feed electrical power because there is not enough overhead space available for the number of feeders required to meet the very high load density. In many residential suburban applications, the underground solution is also desired because it improves reliability when compared with overhead lines.

In section 2.8 the electrical characteristics of overhead lines and underground cables are compared. It is shown that underground cables have a higher capacitive charging current component and lower characteristic impedance $Z_0$ as compared with overhead lines of the same voltage rating. The high capacitive charging current limits the utilization of cable transmission for long distances. In general distances greater than 20-30 km would require compensation to maintain the voltage profile along the cable within acceptable values. It is also indicated that with underground cables, the inductive VARs consumed by the cables, even during heavy load condition, are not sufficient to compensate the capacitive VARs. The transmitted power is normally limited by the current capacity of the cable. Therefore a cable never approaches its natural loading SIL.

In this section AC and DC cable transmissions are compared. Power transmission capability is higher in DC transmission as compared to an equivalent cable used for AC transmission. This is due to the fact that these cables can have a better utilization of insulation, have no capacitive currents and have reduced losses. DC cables have no dielectric losses, no losses in the metallic screen (armour losses), which gives a higher current capability.

5.2 Types of cable

The solid-type insulation or XLPE cable for HVAC is used extensively worldwide at voltages up to 220 kV. There are also applications at 400 kV (line-to-line voltage).

This type of cable has low dielectric losses and they are almost maintenance free. The absence of dielectric fluid in XLPE removes concerns about fluid
leaks. XLPE cables also have lower capacitance than paper-insulated cables, simplifying the requirements for reactive power compensation.

The XLPE cable, using different polymer insulation, has been used recently in DC transmission with voltages up to 150 kV (line-to-ground voltage).

High-pressure fluid-filled pipe-type cables are commonly used in USA and are installed for 230 and 345 kV applications.

The electrical insulation for the self-contained cables (or just oil-filled cable) consists of paper impregnated with low-viscosity oil for the insulation. This paper is enclosed under a watertight lead or aluminium sheath. The oil must be kept at a pressure above atmospheric pressure. This type of cable permits a higher electric service stress than the XLPE cable. It is mainly used for voltages above 130 kV (there are many applications at 525 kV operation). The oil supply system requires frequent maintenance. They are used for long submarine cable crossing.

The mass impregnated cable is only used for HVDC transmission. The cable design is similar to the oil-filled paper insulated cable. However, the paper insulation is impregnated with very high viscosity oil.

Compressed-gas insulated transmission systems are used for special applications, typically short lengths and high-power transfers.

Table 5-1: Present status of technology in terms of maximum transmission voltage, transmission capacity and maximum transmission length for some different types of cable [source: ABB High Voltage Cables]

<table>
<thead>
<tr>
<th>Type of Cable</th>
<th>Maximum Voltage</th>
<th>Power Rating</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>XLPE HVAC Cable (3 cables)</td>
<td>400 kV *</td>
<td>800 MVA</td>
<td>60-100 km</td>
</tr>
<tr>
<td>XLPE HVDC Cable (1 cable)</td>
<td>150 kV *</td>
<td>180 MW</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Oil Filled HVAC Cable (3 cables)</td>
<td>500 kV *</td>
<td>1000 MW</td>
<td>60 km</td>
</tr>
<tr>
<td>Oil Filled HVDC Cable (1 cable)</td>
<td>600 kV **</td>
<td>1000 MW</td>
<td>60 km</td>
</tr>
<tr>
<td>Mass Impregnated HVDC Cable (1 cable)</td>
<td>400 kV **</td>
<td>800 MW</td>
<td>Unlimited</td>
</tr>
</tbody>
</table>

* (line-to-line voltage)

** (line-to-ground voltage)
Table 5-1 compares the present status of technology in terms of maximum transmission voltage, transmission capacity and maximum transmission length for some different types of cable. The maximum transmission length is due to the capacitive charging current for HVAC cable or the oil feeding system for the oil filled cable.

5.3 XLPE cable

![XLPE cable Diagram]

Figure 5-1: Typical XLPE cable used for HVDC transmission

Similar to other types of high voltage cable, a XLPE cable type is built up of several layers (Figure 5-1). The following layers are typically used:

- **Conductor**: aluminium or copper. Both aluminium and copper are used for land cables, but copper is normally used for submarine cables due to the better corrosion performance.
- **Conductor screen**: it gives a smooth surface to the insulation part.
• Insulation: this part takes up the voltage between the conductor and the metallic screen.

• Insulation screen: has the same functionality of the conductor screen, and acts as an equalizing layer between the insulation and the metallic screen.

• Metallic screen or sheath: it takes care of capacitive leakage current, eventual short circuit current and protects against high electrical fields. It consists of copper wires or an extruded lead or aluminum sheath. It is connected to the earth.

• Outer serving: has the functionality to give mechanical protection and to provide corrosion protection for the cable. It will also provide electrical insulation when the metallic screen is earthed only in one point or when it is cross-bonded.

The metallic screen or sheath on the AC cable can be connected to earth in three different ways:

• Both-ends: The metallic screen is connected and earthed at both ends of the cable. In this case a current will appear in the screen for HVAC application. This will cause losses, which will reduce the cable current capacity.

• Single-point: The metallic screen is connected and earthed at in one of the end of the cable. In this case there will be induced voltage in the screen, however no current will appear. The induced voltage is proportional to the cable length and to the current. This type of bonding method is only used for short cable distances, e.g., 500-1000 meters.

• Cross-bonding: The metallic screen between phases of the cable is transposed, which means that a voltage will be induced in the screen, but no current will appear.

In a DC cable transmission, the screen is normally grounded at both ends.

5.4 Current Capacity

The current capacity of a cable is mainly dependent on the following parameters:

• Ambient temperature

• Installation conditions (air, soil, etc.)

• Installation way (close or space formation)

• Losses in the metallic screen/sheath (AC cable transmission)

When a cable is installed in the soil (ground) the thermal resistivity of the soil and the burial depth will affect the current capacity.
The continuous current capacity for AC high voltage cables is calculated according to IEC 287 standard ‘Electric cables – Calculation of the current rating’. [G3]. The calculation of the current capacity is based on the equivalent thermal resistance of the cable that for a certain current flowing in a single core AC cable, the temperature rise above the ambient temperature is determined.

The current rating for a DC cable is calculated in a similar way, except that for a DC cable there are no dielectric losses and there are no metallic screen (or armour) losses. Because of this, the current transmission capability will increase in a DC cable.

In order to evaluate the influence of dielectric losses and armour losses on the current transmission capability for a XLPE high voltage cable, current capacity was calculated for a XLPE cable to be operated in an AC transmission system, assuming a maximum power to be transmitted of 410 MVA at a 220 kV system voltage. A maximum conductor temperature of 90°C is assumed, and the cable directly buried.

The results of the calculation made according to IEC 287 standard shows that the maximum continuous conductor current is 1075 A. The following amount of losses has been determined as well:

- Conductor losses per phase 28.03 W/m
- Screen/Sheath losses per phase 12.12 W/m
- Dielectric losses per phase, $W_d$ 0.8599 W/m
- Total losses per phase 41.01 W/m

Removing dielectric losses and armour losses (as for DC transmission application) the current capacity was calculated, and the maximum continuous current was increased from 1075 A to 1560 A. The solution would give a cable having DC resistance at maximum temperature of 0.0156 Ω/km. This means that a DC application of the cable would give conductor losses of 37.9 W/m per cable.

### 5.5 Insulation stresses in cable

In AC cables, stresses created by the electric field are distributed in inverse proportion to the capacitance of the cable dielectric. It is a function of the insulation geometry, and gives the highest stresses close to the conductor.

In DC cables, the voltage distribution is determined by insulation resistance and space charges and is dependent on temperature. The electric stresses in the insulation will vary both with radius and temperature gradient in the insulation. Voltage distribution in a cold cable (with uniform dielectric temperature) is the same as in an AC cable. At a high conductor-to-sheath temperature gradient the stresses may become highest at the sheath, as shown in the Figure 5-2. Hence, the highest electrical stress is occurring at no load condition.
Figure 5-2: Stress distribution in an HVDC cable during cold and warm (load) conditions, showing that the stress on warm cable may be highest at the sheath; the highest electrical stress is occurring at no load condition [G2]

5.6 A comparison of power transmission capability between AC and DC cable

Based on the fact that DC cables have higher current transmission capability (they have lower loss dissipation) and based on its higher voltage stress capability, it is expected that a DC cable has a higher power transmission capability as compared to an equivalent AC cable.

Assume two cable transmission systems, one operated with alternating current, and the other with direct current. Assume also that AC and the DC systems have the same type of conductor and cross section. The voltage applied to the DC cable is $V_{dc}$, which is pole to ground voltage, while the voltage applied to AC cable is $V_{ac}/\sqrt{3}$, which is the rms phase-to-ground voltage.

The relation, power transmission per cable between DC and AC cable, is calculated by:

$$\frac{P_{dc}}{S_{ac}} = \frac{V_{dc}}{V_{ac}} \frac{I_{dc}}{I_{ac}} k_I$$

(1)

The constant $k_I$ is defined by the ratio between the current capability of a DC cable and current capability of an AC cable assuming similar conductor characteristics. Typically, values of $k_I$ are in the interval: $[1.1 < k_I < 1.4]$.

Regarding voltages stresses, the AC cable insulation is normally limited by the maximum voltage stress in service and by the impulse overvoltages. In the literature [G2] it is indicated that for DC cables a stress of three to five times that for an AC cable may be used. Assuming a more conservative assumption, that
a DC cable can be stressed to the same peak voltage level as for the AC cable, this means that:

\[ V_{dc} = \frac{V_{ac}\sqrt{2}}{\sqrt{3}} \]  \hspace{1cm} (2)

Introducing this assumption for \( V_{dc} \), this gives:

\[ \frac{V_{ac}\sqrt{2}}{\sqrt{3}} I_{ac} k_f \]

\[ \frac{V_{ac}}{\sqrt{3}} I_{ac} \]

This means that a DC cable can transmit 1.41 more power as compared to an equivalent AC cable, assuming that both cable are carrying the same current.

Considering now that the DC cable has a higher current capability, the relation of power transmission capability between DC and AC cable will be in the range of 1.5 to 2.0. This conclusion has a considerable impact on the cost of the cable.

5.7 Installation of cable

Underground cable is often installed inside buried duct banks. Ducts are usually made of concrete (it can also be in different forms like fibreglass, resin, and plastic) and are available with various numbers and sizes of cable positions. Occasionally metal, concrete, or pipe is used as a “single space” duct. They are quite expensive to install but provide good mechanical and electrical protection for the cables. Vaults (underground rooms for cable pulling, repairs, and terminations) are required at intervals.

In a densely populated urban area, particularly in the center of large cities direct burial of cable is preferable in order to make available room to accommodate other services like water, sewer, storm-drain, phone, steam, data-com, etc. It is also preferable in order to protect underground cable from the constant dig-ins of other utilities, stress from settling, and heat and moisture which abound in this environment.

Direct burial of cable is an option for suburban areas where the population is not so dense. Cable is buried in the soil with no duct bank or pipe protection (often a flexible plastic sheath or vinyl tube will be inserted around it). In particular, single-phase or small three-phase cables can be inserted in a streamlined operation in which a narrow trench is dug and the cable reeled in and covered.
Directly buried, single conductor

Duct, single conductor

Tunnel

Figure 5-3: Typical cable installation
The advantages of direct buried distribution cable are low cost (comparable to that of overhead construction), fast installation speed, and esthetic improvement. Direct buried cable is also immune to many causes of outages from trees falling or damage from ice and high winds. On the other hand, evidence suggests that it is susceptible to lighting strikes. Ground strikes can destroy cable.

Directly buried cables have 10-15% higher current capacity than duct cables since there is no dead air space to impede heat transfer to the earth. For an open laying in the tunnel with ventilation the cable can have higher current capacity.

Cost for the installation has an important impact on the total investment, considering that the cost of land in urban areas is very high. Typical relative costs for the installation in a medium size city are presented in Table 5-2.

Table 5-2: Typical installation cost in urban/suburban area in MUSD [Source: values suggested by Birka Energy, Stockholm cases]

<table>
<thead>
<tr>
<th></th>
<th>Cost Range (MUSD/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel (urban area)</td>
<td>5.0-6.9</td>
</tr>
<tr>
<td>Duct (urban area)</td>
<td>1.3-3.1</td>
</tr>
<tr>
<td>Direct buried (suburban area)</td>
<td>0.9-1.9</td>
</tr>
</tbody>
</table>

The cost of a cable system is in the range of 0.3-0.6 MUSD/km including joints and termination. When comparing this cost with the cost of installation it is possible to conclude that the cost of the cable itself has a small impact on the total cost of the transmission, and the installation procedure can be decisive.

5.8 Conclusions

It has been shown that a cable has higher power transmission capability if using DC transmission as compared to an equivalent cable used for AC transmission. The capability ratio has been estimated and it is in the order of 1.5 up to 2.0. The higher transmission capability has a considerable impact on the cost of the transmission system (including cable and corresponding installation).

Installation of the cable has a significant impact on the total cost of the transmission. The cost of cable itself is significantly lower than the cost of the installation when made in a tunnel.
Chapter 6

Application cases

6.1 Introduction

In order to identify the special requirements to be considered in the planning of city infeed systems a number of study cases have been performed in close co-operation with utilities responsible for the power supply of some medium sized and large cities.

From these specific studies the major driving forces and evaluating criteria, when a decision is taken to either rebuilt or expand an existing electrical power system or built a complete new system, were identified. The feasibility of using alternatives, primarily HVDC or other alternatives based on power electronics instead of conventional AC solution was also studied.

6.2 Stockholm cases: 3 cases

![Figure 6-1: Stockholm the 220 kV ring system](image)
The city of Stockholm in Sweden (population about 800 thousand people) is supplied by a number of 220 kV sub-transmission lines that receive power from the 400 kV transmission network. These 220 kV lines feeds power into a 220 kV bulk power ring around Stockholm, bounded by the following main substations: Järva, Värtan, Skanstull, Bredäng and Beckomberga substations. The lines Danderyd-Värtan and Högdalen-Skanstull are also included in the Stockholm ring complex. Figure 6-1 shows the Stockholm 220 kV ring system.

6.2.1 Definition of the cases

Case 1: Replacement of overhead lines with cables without an increase of short circuit current in the substation

The transmission lines between Järva-Värtan and Danderyd-Värtan are partly crossing a sensitive ecological area (a City Urban Park in Stockholm). The construction of new buildings along the route of those lines is also foreseen, which means that the value of the land is of significant importance. Therefore Fortum considers to replace the existing transmission lines with cables that have less environmental problems and to release the area for a new residential center. However when introducing cables the short circuit current will increase which would have impact on the rating of the installed equipment in the Värtan and other substations.

A solution is to use HVDC transmission that produces no impact in the short circuit power in the existing AC system. The study will therefore address the necessary technical and economical aspects with the implementation of the new HVDC technology solution.

For the Stockholm case the only HVDC alternative considered is HVDC with Voltage Source Converters due to its capability to feed a passive network (Cases 2) and its flexibility for multi-terminal configuration (Case 3). Because of this, a HVDC alternative with a Line Commutated Converter was not studied, even-though it is known that this type of converter would offer advantages in terms of lower initial investment costs and losses in the converters.

Case 2: Tapping from an existing transmission line

Today the areas Kyrkviken and Koltorp in Lidingö are supplied from the northern and southern part of Stockholm by old 70 kV overhead transmission lines. There is in Värtan a big transformation station from the 220 kV system. Fortum has also in Värtan a local production (380 MW). Therefore Fortum foresees advantages in feeding these areas directly from Värtan. Hence, a cable transmission system would be installed between Värtan and Kyrkviken and Koltorp. This solution will reduce power flow through the existing distribution
system, with consequent reduction of losses and unloading some existing distribution system.

The study will address the possible advantages of using HVDC as an alternative to supply Kyrkviken and Koltorp areas (Lidingö area) from Värtan as compared with the traditional AC solution with cable transmission. The rating of the transmission is 100 MW.

**Case 3: Multiterminal DC solution**

Combining Case 1 and Case 2 in an integrated DC solution would have impact on flexibility of operation of the system. The total cost of the stations is also expected to be less due to the smaller size of the converter stations.

### 6.2.2 Results of the study

#### 6.2.2.1 Case 1: Replacement of overhead lines with cables without increase of short circuit current in the substation

Today the Järva - Värtan transmission link is made in three sections:

- **Middle section already in a tunnel** containing 2 parallel 3x1x1200/150 mm² AXKJ cables;
- The rest of the link completing the other two sections is an overhead line consisting of 2 parallel 593 Curlew conductors.

The overhead line part has to be moved or made into a cable link. According to information received from Fortum, the overall solution that is under consideration consists of three separate projects as follows:

- **Järva – Brunnsviken section.** The 3 km of 2 parallel 593 CW line will be replaced by a cable system consisting of 2 parallel 3x1x1200/150 mm² AXKJ cables placed in a tunnel with an extension of 2.5 km. The cost for this project is approximately 17 MUSD.
- **Brunnsviken – Ålkistan section.** This is the section that has been moved to tunnel in a project finished in 1999. It consists of 2 parallel 3x1x1200/150 mm² AXKJ cables in a tunnel with a 1.4 km extension. The cost of this project was approximate 11 MUSD.
- **Ålkistan – Värtan section.** The 4.6 km of 2 parallel 593 CW line is considered to be replaced by a cable system consisting of 2 parallel 3x1x1200/150 mm² AXKJ cables placed in tunnel with an extension of 3.4 km. The cost of this project is approximate 22 MUSD.

The total cost of these three projects is in the range of 44 – 63 MUSD. It should be noted that this cost does not include the additional investment that might be needed to upgrade equipment in substations, due to increased short circuit power as a result of the replacement of the overhead line with cable.
Fortum has considered the tunnel solution for the all three projects due to the following reasons:

- The use of land to be exploited – the tunnel means that 100% of the existing right-of-way can be used;
- Environmental reasons – since the cable is placed several meters under the ground there is no risk of concern due to Electromagnetic Field effect on the surface;
- Easier to perform maintenance on the cable;
- The tunnel could be used for other purposes like new telephone cabling and other communication systems, and pipelines for a central heating system.

Fortum knows that tunnel solution for the cables has a high cost and there are other implications such as inconvenience to society and a negative environmental impact during the construction.

From the experience in Stockholm, the following cost figures can be considered:

- Tunnel: 5.0 – 6.9 MUSD/km
- Ducts: 1.3 – 3.1 MUSD/km
- Direct buried: 0.9 – 1.9 MUSD/km

The cost of the cable itself represents just a fraction of the whole project (less than 10% if considering the installation in tunnel). Therefore, the installation cost plays a key factor in the total cost of the project.

The HVDC Alternative: Studied HVDC topologies

Presently, the average loading of the Järva-Värtan connection is 270 MVA, and assuming a load factor of 60% this results in the required capacity of the connection being about 450 MVA. Considering some margins for expected load growth, the Järva-Värtan connection would be rated at 550 MVA.

It should be noted that today the actual rating of the Järva-Värtan link with overhead lines is 1000 MVA. The reason for having such a high rating capability is that during particular contingencies on the 400 kV transmission network, high amounts of electric power flow through the 220 kV sub-transmission system, crossing the Stockholm area.

With a HVDC link the transmission power flow can be controlled, and therefore there is no risk to over load the link during contingencies.

In this study the following two alternatives are considered in terms of rating of the link:
- Topology with a maximum transmission capacity of 760 MW (converters rated at 825 MVA to provide additional reactive power support). This corresponds approximately to the present rating of the link;

- Topology with a maximum transmission capacity of 550 MW (with converters rated to 600 MVA), which is based on the present and future load requirements.

For each transmission capacity the following topologies have been considered, as indicated in Figure 6-2.

<table>
<thead>
<tr>
<th>Topology I</th>
<th>One Bipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Järva 220 kV</td>
<td>VSC</td>
</tr>
<tr>
<td>Filter Bus</td>
<td>VSC</td>
</tr>
<tr>
<td>Järva 220 kV</td>
<td>Värtan 220 kV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topology II</th>
<th>Two poles in bipolar configuration with metallic return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Järva 220 kV</td>
<td>VSC</td>
</tr>
<tr>
<td>Filter Bus</td>
<td>VSC</td>
</tr>
<tr>
<td>Värtan 220 kV</td>
<td>Filter Bus</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Topology III</th>
<th>Two separate bipoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Järva 220 kV</td>
<td>VSC</td>
</tr>
<tr>
<td>Filter Bus</td>
<td>VSC</td>
</tr>
<tr>
<td>Värtan 220 kV</td>
<td>Filter Bus</td>
</tr>
</tbody>
</table>

Figure 6-2: Different topologies that have been considered

The following main aspects characterize each studied topology:

- The configuration referred to Topology I is a single bipole. Here an equipment failure will result in total outage of the link.
• Topology II is a bipolar configuration with two poles and metallic return cable, which allows operation of the two poles under asymmetric loading conditions. The drawback of this configuration is that the transformers have to be designed for DC voltage offset on the secondary winding.

• Topology III is the most reliable topology, which includes two HVDC poles operating completely separate from each other. However, it is expected that this is the most expensive configuration, which requires 4 cables.

Cost evaluation

The costs of the converter stations for the different alternatives were evaluated considering the assumptions listed in Addendum 1. The results are presented in Table 6-1.

Table 6-1: Total estimated cost of the two terminal converter stations for the different HVDC topology studied for the connection Järva-Värtan

<table>
<thead>
<tr>
<th>Converter Rating</th>
<th>Topology</th>
<th>Cost [percent] $^{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(300 MVA Reference)</td>
<td>Topology I</td>
<td>(100)</td>
</tr>
<tr>
<td>825 MVA</td>
<td>Topology I</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td>Topology II</td>
<td>120.3 $\times$ 2 = 241</td>
</tr>
<tr>
<td></td>
<td>Topology III</td>
<td>111.9 $\times$ 2 = 224</td>
</tr>
<tr>
<td>600 MVA</td>
<td>Topology I</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td>Topology II</td>
<td>107.6 $\times$ 2 = 215</td>
</tr>
<tr>
<td></td>
<td>Topology III</td>
<td>95.4 $\times$ 2 = 191</td>
</tr>
</tbody>
</table>

Note 1: 100 percent corresponds to approximately 60 MUSD $\approx$ 480 MSEK
The results show that the transmission according to Topology I is the most economical solution, however, it gives the lowest reliability level since a component failure implies the loss of the total transmission system.

Transmission according to Topology II is slightly more expensive than Topology III. The reason is that several components in the converter stations would have special insulation design to withstand a DC voltage offset. However, in this solution there will be some savings in the cable transmission, considering that it requires only 3 cables instead of 4 cables. Considering that the distance involved in the case of Järva-Värtan is less than 10 km, the savings in the cable transmission are not significant. Therefore, topology III can be considered more attractive than topology II since the two poles operate completely independent from each other, while in topology II one pole could be disturbed during faults in the other pole.

Cable/Installation part – cost evaluation

The involved distance in this case is 10 km. The costs of the DC cable, for either the 825 or 600 MVA alternatives are:

- Topology I – 2 cables: 2.9 MUSD
- Topology II – 3 cables: 4.2 MUSD
- Topology III – 4 cables: 5.6 MUSD

Note: The cost of the 1000 MVA AC cable has been estimated and it is in the order of 8.4 MUSD. The savings of DC cable in this case are rather small.

Installation cost: cost of installation is in the range of 50-69 MUSD for both AC and DC solution, considering that it would be installed in tunnel.

Short Circuit Current issue

An HVDC system with Voltage Source Converters has the capability to immediately control the AC current and therefore during system faults the fault current contribution from the converters can be limited by the controls. Therefore, it is possible to adopt a control strategy so that during faults close to the converter bus the converters can be temporarily blocked to reduce the short circuit current.

This strategy of control has been used during the simulation of system faults.

Table 6-2 shows a summary of the expected short circuit current resulting from different network conditions. The first column in the table refers to the present condition that still includes sections with overhead transmission line between Järva and Värtan. This is the reference condition.
The second column considers AC cable transmission all the way from Järva to Värtan. It shows an increase of short circuit current. And finally, the third column shows the configuration where the AC connection between Järva and Värtan is replaced by HVDC transmission.

Table 6-2: Short circuit current calculation, comparing AC cable and DC cable including HVDC with VSC

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>Short Circuit Current [kA]</th>
<th>AC Transmission Line</th>
<th>AC Cable</th>
<th>HVDC with VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-phase - Järva</td>
<td></td>
<td>28.8</td>
<td>31.2</td>
<td>26.2</td>
</tr>
<tr>
<td>1-phase - Järva</td>
<td></td>
<td>28.4</td>
<td>33.9</td>
<td>23.3</td>
</tr>
<tr>
<td>3-phase - Värtan</td>
<td></td>
<td>28.8</td>
<td>31.2</td>
<td>26.4</td>
</tr>
<tr>
<td>1-phase - Värtan</td>
<td></td>
<td>31.7</td>
<td>34.3</td>
<td>26.9</td>
</tr>
</tbody>
</table>

It is possible to observe that with the AC cable alternative, without including any corrective measures to reduce fault current, the fault current exceeds the maximum 31.5 kA that is the limit for some of the breakers. With the HVDC alternative lower short circuit current is obtained as expected. It should be noted that the measured fault currents are slightly below the present fault current level measured with overhead lines.

Additional studied HVDC alternative

It has been shown that it is possible to reduce the short circuit current by replacing conventional AC cable with DC cables. However, it was found that the solution was much too expensive. The main reason is that a part of the ring between Järva and Värtan requires a high transmission capacity. This would require a HVDC link with a high rating.

An alternative that has been studied is to replace another section of the ring requiring a lower transmission capacity with a HVDC link.

Fortum is investigating the consequences of having the line Bredäng-Skanstull sectionalized in ÖY substation. The new section ÖY-Skanstull will be underground, to release the land for a new residence area. The lines Bredäng-ÖY-Skanstull in this area will be a part of the 220 kV Stockholm ring, and therefore the consequences of having a HVDC transmission between ÖY and Skanstull substations have been investigated. This new section of the ring would require less than a 200 MW transmission capacity. Therefore, a HVDC transmission link between ÖY and Skanstull substations rated at 200 MVA was studied.
Short circuit current calculations have been performed assuming the new scheme in the Stockholm ring and the results are presented in Table 6-3.

Table 6-3: Short circuit current calculations, considering a 200 MVA HVDC with VSC between ÖY and Skanstull substations and an AC cable between Järva and Värtan

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>Short Circuit Current [kA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-phase - Värtan</td>
<td>26.99</td>
</tr>
<tr>
<td>1-phase - Värtan</td>
<td>30.76</td>
</tr>
<tr>
<td>3-phase - Järva</td>
<td>28.25</td>
</tr>
<tr>
<td>1-phase - Järva</td>
<td>31.57</td>
</tr>
</tbody>
</table>

In the calculation an AC cable between Järva and Värtan was assumed according to future conditions (two parallel cables) and Bredäng – Skanstull was sectionalized in ÖY, with a 200 MVA HVDC with VSC converters between ÖY and Skanstull substations.

The results show similar short circuit currents as for the existing system. The reason is that the HVDC link is placed in the southern part of the ring, but the main fault current contribution comes from the feeders located in the northern area.

Conclusions

To replace an overhead line between Järva and Värtan substations with an underground cable increases the short circuit current, which exceeds the rating of some 220 kV equipment in several substations. In addition to this high ground fault current, there is a risk of damage to the cable shield and of unsafe conditions in the substations.

Replacing Järva-Värtan with a HVDC link underground cable it is possible to obtain a sufficient fault current reduction to allow safe operation of the Stockholm ring. However, this is a very expensive solution. The link between Järva and Värtan would require a high transmission capacity.

An alternative solution has been studied with a HVDC link replacing a different section of the Stockholm ring that would require a low transmission capacity. This case did not produce a significant improvement in reducing short circuit current, considering that the main source of fault current is from the feeders outside the area where the HVDC link is located.
6.2.2.2 Case 2: Tapping from an existing transmission line – feeding Lidingö directly from Värtan

Reference conventional AC solution

Fortum is studying two different solutions to feed the areas of Kyrkviken and Koltorp in Lidingö directly from Värtan:

A. Connect the link directly to the existing 110 kV switchyard. This means that it is enough to build a new 110 kV feeder. The capacity in the existing 220/110 kV transformers can be used.

B. Install a new 220/110 kV transformation in Värtan. This will result in a new 220 kV feeder and three other 110 kV feeders. This has to be coordinated with a renewal of the station in Värtan.

Two substations are planned to be upgraded in Lidingö: Kyrkviken and Koltorp. In Kyrkviken there will be 2 x 40 MVA, 110/20 kV transformers. In Koltorp there will be 2 x 60 MVA, 110/20 kV transformers.

Figure 6-3: Proposed AC solution for the case 2 according to Stockholm Grid Company

The involved distances in this project are:

- Värtan - Kyrkviken 4.6 km
- Kyrkviken - Koltorp 1.3 km
Fortum considers that in this project the magnetic field is not a big issue at Lidingö. This is because there is plenty of space in that area. Also there are only modest development plans for the land along the cable route. Therefore it should be enough to have the cables buried under the ground.

In terms of cost for the two AC alternatives Fortum has made the following estimation:

Solution A:
- Cable: 3.9 MUSD
- Up-grading of the substations in Lidingö: 2.1 MUSD
- Upgrade Värtan substation: 0.6 MUSD

Solution B:
- Cable 3.9 MUSD
- New substations in Lidingö: 2.1 MUSD
- Upgrade Värtan substation: 2.8 MUSD

A 10% increase is added in the cost covering uncertainties, making the total cost of the project between 7.4 and 9.7 MUSD.

Alternative HVDC solution

The alternative solution for this case is to use HVDC transmission between Värtan and Lidingö. The corresponding HVDC configuration, which is equivalent to the proposed conventional AC solution in terms of reliability of transmission, is a bipolar transmission with converters placed in Kyrkviken and Koltorp area as indicated in Figure 6-4.

Figure 6-4: HVDC alternative solution feeding Lidingö area from Värtan
The expected investment just for the converter stations will be in the order of 110 MUSD, considering two independent poles, each pole rated 115 MVA. In this estimated cost value, the cost of the cable and the corresponding cost for the installation of the cable is not included.

These figures show that the DC alternative solution is far too expensive compared to the conventional AC alternative. It is obvious that the DC solution in this case can be realized only if integrated into a broader project where new concepts of sub-transmission systems are introduced.

An important issue should be considered: the short circuit current in the Lidingö network. It is expected that Kyrkviken and Koltorp networks are not interconnected due to restrictions of high short circuit current. With the HVDC solution both networks could be interconnected improving the operation of the network and increasing the reliability.

However, it should be pointed out that with the DC solution the protection system of the network has to be verified since the HVDC converters have limited capability of short circuit power.

6.2.2.3 Case 3: Combining Case 1 and Case 2 in a Multiterminal DC solution – Järva-Värtan-Lidingö

Case 3 corresponds to a DC alternative combining Case 1 and Case 2 in a multiterminal configuration.

Figure 6-5 shows the basic configuration that has been studied. This configuration attends the requirements in terms of availability and reliability, short circuit power, and power transmission.

In Järva station there will be two converters with a total capacity of 600 MVA. In Värtan there will be four converter with a total capacity of 600 MVA. In Lidingö there will be two converters, one installed in Kyrkviken and another in Koltorp. Each of these converters are rated 100 MVA. The converters are arranged to form a bipolar configuration with metallic return. Any converter can be lost without losing the whole transmission system.

The estimated cost for the whole installation is in the order of 310 MUSD. In this value some savings in the order of 38 MUSD are included because the Järva-Värtan-Lidingö links are now integrated in a multiterminal configuration.

An interesting aspect related to this multiterminal configuration is the lower losses when compared with separate and independent links, Järva-Värtan and Värtan-Lidingö.

The implementation of this solution can be made in different stages, first one pole, and later the second pole, completing the bipolar arrangement.
6.2.3 Looking at Stockholm in a long term perspective

When looking at the cases from the individual perspective from the studies reported above, it is possible to conclude that the HVDC alternative is often significantly more costly compared to the conventional AC alternative if only single lines in an AC system are considered. The HVDC solution presents technical advantages, however the involved cost is much too high. If case 1 and case 2 are integrated in a common DC solution it is possible to obtain a more economical solution, but again, it will be more costly compared to the AC solution.

Looking into the future, when all the overhead lines are assumed to be replaced by cables in the Stockholm region, then Fortum should re-evaluate the sub-transmission system, otherwise significant investment has to be made for building tunnels, upgrading substations due to high short circuit current, etc. In this case it is possible to foresee that HVDC might give significant advantages, not only technically, but also economically. Having more sections of the sub-transmission system converted to DC, resulting in an HVDC network, it is also possible to foresee that it will feed more power into Stockholm.

Assume the following long-term futuristic scenario in which the entire Stockholm ring is converted to DC, as well as all sub-transmission feeders to the ring. In this scenario, DC scheme might be considered an application alternative with better prospect basis.
This will be more evident assuming that with further development of the HVDC technology the cost of a converter station might be reduced, resulting in a more competitive solution to the conventional AC transmission.

The total length of overhead lines in the Stockholm area is about 210 km, which includes the Stockholm ring (about 30 km) and all sub-transmission feeders. Presently, there are 12 primary substations operating at 220 kV voltage level that feed the rest of the secondary substations. The present total load in these substations is about 2200 MW. Assuming a load factor of 0.6 will give a maximum peak load of 3600 MW.

Assuming the following:

- Each substation accounts with a fraction of 1/12 of the maximum peak load. This gives 300 MW per substation.
- Each substation includes 50% over-rating in order to achieve good reliability of operation. This gives 450 MVA.
- Each substation is associated with an equivalent fraction length of overhead lines: \( \frac{210}{12} = 17.5 \) km.
- 85% of the lines are replaced by cable that will be buried; 15% will be placed in tunnel.
  - Buried cables: AC cable cost and installation cost are about 2 times the cost of an equivalent DC cable;
  - Cables in tunnel: the cost of an AC cable and installation is about the same as a DC cable since the installation corresponds to the major part of the cost.

It was assumed that the present cost of a HVDC-VSC converter station, with the rating of 450 MVA, is in the order of 48 MUSD.

The average cost of 17.5 km of HVDC cable is about 35 MUSD. The average cost of 17.5 km of AC cable is in the order of: 57 MUSD.

This results in savings with HVDC cable when compared with equivalent AC cable in the order of 21 MUSD. The real cost basis of a converter station is then reduced from 48 MUSD to 27 MUSD due to the savings in the installation of the cable transmission. This also means that to get an equal investment cost, the cost of the HVDC converter stations has to be reduced by a factor of \( \frac{48}{21} = 2.3 \).

Losses Evaluation

An important issue to be considered is the losses in the transmission system. An estimation of the total losses in the substation and cable transmission sys-
tem has been made at peak load condition. The following base values are assumed:

- Losses in HVAC substation: 0.3%
- Losses in HVDC substation with Voltage Source Converters: 1.7%
- Losses in HVAC cable transmission: 0.15 MW/km
- Losses in HVDC cable transmission: 0.07 MW/km

The expected total losses in MW at peak load condition are according to Table 6-4. As can be seen HVDC transmission has significantly higher losses as compared with HVAC transmission, mainly due to the high losses of the converter valves.

Table 6-4: Expected total losses assuming HVAC transmission in Stockholm under-grounded

<table>
<thead>
<tr>
<th></th>
<th>HVAC</th>
<th>HVDC-VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 x Substations</td>
<td>16.2</td>
<td>91.8</td>
</tr>
<tr>
<td>17.5 km Cable transmission</td>
<td>2.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Total [MW]</td>
<td>18.8</td>
<td>93.0</td>
</tr>
</tbody>
</table>
6.3 Gothenburg case

6.3.1 Case definition

Presently the energy supplied to the Gothenburg network is acquired from Vattenfall and Fortum, two regional grid companies, mainly from the 130 kV system. The energy is transformed to 50 kV (at a few substations) sub-transmission level and from these levels is transformed to the distribution level (see in Figure 6-6 the major sub-transmission feeders that supply electric power to Gothenburg area).

The network system in Gothenburg is radial, and back ups are mainly made by duplicated equipment or multiple supply via breaker and switches. The system is therefore not meshed.

There is some planning to install a 300 MW Power Plant in the neighborhood of the 130 kV, K6 substation. The problem with the new power station is that it will increase the short circuit current that would require up grading the equipment in this substation. No decision has been taken so far since Gothenburg Grid Company sees that due to economical and political reasons this project should be implemented only in the long term.

Figure 6-6: General overview of the Gothenburg main feeders
There are some disturbances in the regional network (‘regionnät’) that supply the energy to the distribution utility, which may lead to unwanted consequences for the feeding of the Gothenburg area. Gothenburg Grid Company is looking for possible solutions to reinforce the internal system.

One possibility is to build a new connection between K6 and K5. The problem with this solution is that since the system is presently not meshed it would result in uncontrolled power flow from the north to the south (or vice-versa) via this route, which would require a strong AC line connection.

An alternative solution is to implement an asynchronous connection via a DC solution. The advantage with this solution is that the power flow can be controlled and short circuit power capacity will not be increased. With HVDC including Voltage Source Converters both active and reactive power interchange with the converters on both terminals can be controlled.

The study will evaluate the value of the alternative solution as compared with the conventional AC solution or possible improved AC techniques. It is assumed that the HVDC connection with VSC, between K6 and K5 will be rated 300 MW.

6.3.2 Analysis of the case – closing a ring around Gothenburg comparing different alternatives

The electrical scheme of the case is simplified according to Figure 6-7.

Figure 6-7: General overview of the studied electrical network system
The critical contingency that has been studied is the outage of the Lin feeder of the Li substation. With that contingency there is not enough capacity in the system and the As substation will be out of power. Because of this, there is a need to improve the connections in that region.

One possible alternative solution is to build a new connection between two main substations that are located in the center-load areas: the Re and As substations. This will close two rings around the city: one external ring that includes the feeders that are operated by other companies and another ring, when LA and LB busses are connected.

Since the system is not meshed, it would result in uncontrolled power flow from north to south (or vice-versa) through the new connection. This would require a strong AC cable connection. The other consequence is the risk of overloading several lines and transformers in different parts of the network.

One alternative solution is to implement a connection via an HVDC-VSC link between the two substations. The advantage with this solution is that the power flow can be controlled and that the short-circuit power capacity will not be increased. With HVDC including Voltage Source Converters, both active and reactive power interchange with the converters on both terminals can be controlled.

The other solution involves including an AC cable and an additional device to control the power flow through this new cable link connection. A possible power-flow controller might be a phase-shifting transformer or a more advanced controller like a UPFC.

In the following all these possible solutions are evaluated, indicating the corresponding advantages and disadvantages.

### 6.3.2.1 AC cable connection without power flow controller device

The first solution is to reinforce the internal system by just implementing a new AC cable connection between substations Re and As. A concern related to this simple solution is that since the system is presently not meshed it will result in uncontrolled power flow from north to south (or vice-versa) via this new route. Therefore, this is expected to require a strong AC line connection, and several components in the network will have to be upgraded.

**Short-circuit analysis**

By connecting Re to As substations with an AC cable rated to 500 MVA, the three-phase short-circuit current measured at Re and As substations will increase from 15 kA and 13 kA to 21 kA and 20 kA respectively. If bus bars LA and LB are connected by closing the breaker brkL, then the short-circuit current will increase to 22 kA and 21 kA respectively.

The usual procedure to reduce the short-circuit current in the system is to split busses in substations, and this has been investigated in the Re substation (this in indicated in Figure 6-7 by the switch splR). With such an arrangement the
short-circuit currents will then be reduced to the following levels: 15 kA in one bus section and 16 kA in the other bus section. At substation As, the measured short-circuit current is 16 kA.

System overloading

The critical studied contingency was the outage of the transformation 400 kV / 130 kV in the Li substation. As already mentioned, without the connection between the substations Re and As, there is not enough capacity in the southern region which will be out of power after the contingency. Having the new line connecting the north and south regions, the supply of As substation is maintained after the contingency. However, it has been observed that several branches in the system that feeds the Re substation became heavily overloaded (162% of the nominal rating). This also indicates the need for splitting the bus in the Re substation, which would avoid the overloading.

System voltages after contingencies

A connection between the main substations Re and As will make the system rather strong. The outage of the Lin feeder of the Li substation will result in some operating voltage drop in the system, 0.03 pu in the area of the Re substation and 0.05 pu in the area of the Li substation. However, the system is still maintained within the normal operating voltage conditions.

Loading of the main feeders

The feeders are strongly affected by the studied critical Lin feeder outage. The most affected feeders are St and His feeders.

Considering that this alternative can not control the power flow around the ring, the distribution power grid company can not balance the power flow without requesting that the generation from the different energy suppliers be re-dispatched.

Transient performance during contingency

The system was found stable for any transient disturbance in the network.

6.3.2.2 AC cable connection combined with phase-shifting transformer to control power flow around the ring

The other alternative solution that has been studied is to reinforce the internal system by combining the introduction of the new AC cable between substations Re and As with a phase-shifting transformer as a passive controller device to control the steady state power through the new link.

The main advantage of having a phase-shifting transformer in the circuit is that it is possible to control the steady state power flow through the new link and therefore obtain a proper distribution of the loads between the different feeders that supply the system. It is also possible to optimize the power flow in the network. This will minimize the transmission losses by improving the utilization of the circuit loading to their design rating.
In this studied alternative a phase-shifting transformer with 300 MVA throughput power characteristic has been assumed.

Results from the power flow analysis indicated that the required phase angle displacement is \([-20°;+15°]\). Hence, the required KVA rating of the phase-shifting transformer, which is a function of throughput KVA, can be calculated by: 

\[
300 \times 2 \times \sin\left(\frac{20°}{2}\right) = 110 \text{ MVA},
\]

for the main and series unit.

**Short-circuit analysis**

In terms of short-circuit current, the values are found to be similar to the previous studied alternative. Adding a phase-shifting transformer will not significantly change the overall impedance in the system. The obtained short-circuit currents are in the order of 21 kA and 20 kA in the Re and As substations, respectively. Due to the high short-circuit current, it is recommended to split the Re bus, which will reduce the levels to 15 kA and 16 kA, respectively.

**System overloading**

When studying the critical contingency in the Li substation, different power flow conditions were considered through the new AC link. Considering a north power flow direction as a pre-fault condition (from As to Re substation), the feeder SB will become overloaded after the contingency (140% of rated power). Since the control of power flow through the phase-shifting transformer is rather slow (between several seconds to several minutes), the high overloading is maintained for quite some time until the tap changer moves to the new positions. Due to the rather short-term overloading capability of the feeder, this case would require the increase of the rating for this feeder.

Considering another operating condition, a south power flow direction as a pre-fault condition (from Re to As substation), the feeders His and St will become overloaded after the contingency (121% of rated power). In this case, these feeders have to be upgraded.

Another observation from this studied alternative is that the lines that supply power to the Re substation tend to become overloaded after the contingency in the Li substation. As for the previous alternative, the bus bar in the Re substation needs to be split, and the load needs to be properly distributed with the new bus bar arrangement.

**System voltages after contingencies**

The system is maintained within the normal operating voltage conditions after contingencies.

**Loading of the main feeders**
The phase-shifting transformer can control the power flow through the new AC link between the Re and As substations. Therefore, it is possible to indirectly control the power through the feeders. The main feeders affected are His (that supplies the north area) and Lin (that supplies the south area). To reduce the power demand from the His feeder and consequently increase that from the Lin feeder it is necessary to set power flow to the north power direction through the new AC link (from As to Re substation). The opposite is valid, that is, to increase the demand of power from the His feeder and decrease it from the Lin feeder, the south power flow direction has to set (from Re to As substation).

With the new controllability option, the power grid company has the flexibility to control the power from the different suppliers. This creates a new opportunity for the operation of the system, which makes it flexible enough to take advantages of different levels of tariffs for the electricity.

**Transient performance during contingency**

Similar to the previous alternative, the system is also stable.

### 6.3.2.3 HVDC-VSC link

With an HVDC link between Re and As substations, there will be a connection between the two points. This solution includes a fast control of both active and reactive power in the two substations. The HVDC cable can be loaded up to its thermal capacity. The AC systems connected to the converter busses can receive reactive power support from the converters to maintain adequate operating voltage conditions.

#### Short-circuit analysis

HVDC converters do not add short-circuit current to the fault, and therefore the short-circuit current values are similar to those obtained without the HVDC link: 15 kA and 13 kA measured at the Re and As substation, respectively.

#### System overloading

The outage of the transformer in the Li substation results in losing 770 MW of infeed to that region. This will demand adjustments in the rest of the system.

The new HVDC link has the capability to rapidly control the power flow, which can reduce the impact of the contingency in the system. To support the system in such a case, an ‘Emergency Power Flow Control’ has been implemented in the controls of the HVDC converters. This control works in the following way: when there is lack of power in the southern region, e.g., after tripping the feeders in the Li substation, the HVDC link immediately moves to a new set point that corresponds to the required demand from the southern region. In addition to this, the control also includes inputs from a different supervision system that monitors the loading in some critical lines in the network. This additional feature regulates the power flow through the link in such a way that the loading in those lines does not exceed their thermal capability rating.
Two basic load flow cases were studied. One case considers the south power flow direction as a pre-fault condition (from Re to As substation). This is a favourable operating condition that produces the least impact on the system when the feeder in the Li substation is lost. In this case, the HVDC link maintains the same pre-fault operating conditions. The other case considers the north power flow direction prior to the fault (from As to Re substations). In this case, the ‘Emergency’ operating condition is used, reversing power flow through the HVDC link to support the southern region.

Similar to the previous alternatives, this alternative can also overload the AC lines that supply power to the Re substation. By splitting the Re substation the problem is solved.

System voltages after contingencies

The controllability of active and reactive power is the main feature of Voltage Source Converters. The two converters of the HVDC link can control the reactive power independently of each other. This means that the converters can control the AC bus voltages by setting the AC voltage reference in each station.

After the contingency, the voltage in the system is maintained within the normal operating condition range, which is a result of the additional reactive power support obtained from the converters to restore the pre-fault voltage.

Loading of the main feeders

Similar to a phase-shifting transformer, the HVDC link has the ability to control the steady state power though the link and therefore control the power flow from the different feeders. In the same manner, with this controllability option, the power grid company has the flexibility to control the power from the different suppliers.

Transient performance during contingency

A typical transient performance of the system during the outage of the transformer in the Li substation is shown in Figure 6-8. The case assumes pre-fault condition for the HVDC link transferring 150 MW towards the north direction (from As to Re substation). The contingency is an outage of the feeder to the Li substation. In this case, the ‘Emergency Controller’ is switched into the controllers of the HVDC link, changing the power direction immediately after the contingency, resulting in 300 MW power which is fed into the southern region of the system. As it can be seen from Figure 6-7 the system is stable.
6.3.2.4 AC cable connection including an active UPFC to control power flow

A UPFC (Unified Power Flow Controller) incorporated into the new AC transmission link gives the grid operators the flexibility to control independently both real and reactive power flow. This benefit is comparable to the HVDC transmission link previously studied. In addition to this, like an HVDC solution, the UPFC solution enables a much faster control response of the power flow if compared with the alternative that includes a phase-shifting transformer.

The implementation of a UPFC is a Back-to-Back converter arrangement, in which one converter is shunt-connected (extract power from the network) and the other is series connected (exchanges power with the line by injecting a series voltage with controllable magnitude and phase angle). These two converters are connected to each other on the DC side with a DC capacitor.

In this case study, the controllable power flow is in the range of ±300MW. To achieve this, the required rating of each of the converters can be calculated as follows:

- Required magnitude of injected series voltage: 0.3075 pu
- Required magnitude of current through the series element: 1307 Amps
- Required rating of the series and shunt element:
  - $3 \times 135kV \times 0.3075 \text{ pu} \times 1.307 \text{ kA} = 162.7 \text{ MVA}$
Additional spare capacity would be required for reactive power support that has not been included in the calculation.

**Short-circuit analysis**

Like a phase-shifting transformer, the alternative with a UPFC included in the new AC link between the Re and As substations will result high short-circuit currents: 21 and 20 kA, measured in the Re and As substations, respectively. These high short-circuit currents, will involve severe consequences for the rating of the existing equipment.

**System overloading**

Like the HVDC solution, it is possible to include in the controls of the UPFC the so-called ‘Emergency Power Control’. The results obtained in this case are similar to the HVDC alternative.

**System voltages after contingencies**

An UPFC included in the new AC cable link will give similar performance as for an HVDC link.

**Loading of the main feeders**

The controls of the UPFC can be made similar to the HVDC link solution. For this reason, similar results are obtained in this alternative solution.

### 6.3.2.5 Cost consideration for the different alternatives

Table 6-5 shows an indication of the cost of different alternatives that has been studied.

The cost of a phase-shifting transformer is about 10-20% higher than the cost of an ordinary transformer. However, as it has been shown, the solution that includes phase-shifting transformer requires additional costs, such as the replacement of circuit breakers and a rebuilt of the power station due to the increase of short-circuit current and overloading problems. These extra costs are saved in the HVDC solution.

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Phase-shifting transformer</td>
<td>180</td>
<td>10</td>
<td>1.8</td>
</tr>
<tr>
<td>HVDC-VSC</td>
<td>300</td>
<td>160</td>
<td>48</td>
</tr>
<tr>
<td>UPFC</td>
<td>190</td>
<td>160</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 6-5: Cost evaluation of different power flow control devices
When considering the alternative solution that includes a UPFC, high short-circuit current is also obtained, similar to the solution with a phase-shifting transformer. As in that case, this solution also requires upgrade of circuit breakers in several power stations.

The HVDC solution was found the most expensive solution, mainly due to the fact that the installed capacity of the converters is about 1.5 times higher than the installed capacity of the converters with the UPFC solution.

6.3.3 Conclusions

Three different alternatives to control power flow were investigated when feeding power into the city center: phase-shifting transformer, HVDC link and AC link including UPFC.

The study indicated that it is possible obtain a reasonable steady state performance with all three alternatives. By including a power flow control device in the system it is possible to control the power in the different feeders. This creates a new opportunity for the operation of the system, which makes it flexible to take advantages when there are different levels of tariffs for the electricity.

Both HVDC and UPFC solutions offer very similar control performance. The major advantage of these two alternatives as compared to the phase-shifting transformer is that they can provide a fast power flow control. This would prevent high overloading in several areas in the system during a critical contingency.

The important benefits of the HVDC transmission solution with Voltage Source Converters as compared with the other alternatives for power flow control are that there are no limits with regard to maximum phase-shift angle and more importantly, that it will isolate the two systems with regard to short-circuit current.

However, the study has indicated that the costs of the HVDC and UPFC solutions are significantly higher as compared with the solution with phase-shifting transformer.

6.3.4 Solution that the Grid Company has implemented

The actual solution that has been implemented to secure the operation of the Gothenburg network was to re-enforce the external regional network. A new high voltage 400 kV line will be built to reinforce the southern part of Gothenburg area and the Li substation will be rebuilt. With the new reinforcement the risk for severe consequences during this contingency are eliminated, without requiring additional measures in the internal network. The expected investment cost to upgrade the regional network and rebuilding of the substation is between one-forth and one-third of the cost of the HVDC alternative studied in this thesis.
6.4 Integration of new thermal power plants in the Baixada Santista area in São Paulo

6.4.1 Case definition

A study made by a working group organized by ONS (the Brazilian National Operator of the Electric System) and CCPE (Coordinator Committee for the planning of the expansion of the electric system), with participants from the other involved agents, made recommendations of possible ways to integrate the new thermal power plants in the electric network operated by Bandeirantes, a Grid company that operates the Baixada Santista network.

The scheduled installed capacity of the new thermal power plants was as follows:

- Phase 1: 160 MW, to be installed by 2003
- Phase 2: 270 MW, to be installed by 2003
- Phase 3: 510 MW, to be installed by 2005

For the phases 1 and 2 (160 + 270 = 430 MW) the study has proposed three different solutions to integrate the new thermal power plant in the Baixada Santista network as follows: the first solution is to connect the new thermal plant into the 345 kV system; the second solution is to connect it into the 230 kV system; and the third solution is to connect it into the 88 kV system.

Figure 6-9 gives an overview of the Baixada Santista network that is operated by Bandeirantes. This figure shows the selected alternative solution to integrate the new thermal power plant (solution number 3), as well as the Henry Borden and Piratininga systems.

The alternative solution that was selected is to connect the new power plant into the 88 kV. The following reasons were considered:

- This alternative gives the minimum global cost. Only an extension and sectionalizing of the busses in the substations of Henry Borden and Baixada Santista 88 kV are required.
- The new generation (160 + 270 MW) will supply most of the local load in the 88 kV system in Baixada Santista. During the year 2003 the expected load is 675 MW. When the hydraulic power plant Henry Borden is generating 404 MW there will be an excess of generation that can be exported. Without the hydraulic power plant Henry Borden the rest of load (675 – 430 MW) is supplied through the transformation 345/88 kV in the substation Baixada Santista.
• It is not necessary to replace most of the breakers in the 345 kV substations.

• There are 4 independents circuits connected to 88 kV of the substation CCBS, which means that there is a good reliability to deliver the 160 + 270 MW. In the other alternatives (Alternatives 1 and 2) the delivery is made only via the two circuits.

Figure 6-9: Overview of the Baixada Santista network that includes the Henry Borden and Piratininga systems. The new thermal power plants and corresponding selected solution (solution nr. 3) for the Baixada Santista System are shown.

The cost estimation of those three alternatives is in the range of 18-45 MUSD. The lowest cost corresponds to the selected alternative.

The studies performed by the working group in Brazil indicated, however, that the selected alternative has some drawbacks. The availability of the network will be reduced and operation of the network will be restricted due to the required changes in the network in order to avoid an increase in short circuit currents.

The study that has been proposed is to investigate if, by using an alternative to the conventional AC solution, it is possible to obtain a better result as compared to the selected alternative solution. In the following possible alternative
ways to reduce the short circuit current based on the use of power electronics are discussed.

The system data used in this study was based on the ONS Report, ‘Integration of the new thermal power plants in the areas of São Paulo and Piratininga’ (written in Portuguese), Report nr. ONS-2.1/013/2001 CCPE/CTET.021.2001, revision 0, dated 19/06/2001.

6.4.2 General description of the Baixada Santista region, including Henry Borden Hydraulic power plant and the Piratininga system

The Baixada Santista region includes a total load in the order of 900 MW. This is an area in which there is exchange of power between many companies. Bandeirante has the major amount of power – about 650 MW, and Eletropaulo and Elektro supply the rest.

During the period of peak load the Baixada Santista region receives supply from the Henry Borden Hydraulic power plant. This power plant is controlled by EMAE (Empresa Metropolitana de Águas e Energia SA). The power produced by this power plant is fed into the 88 kV and 230kV systems.

Having this energy from the Henry Borden Hydraulic power plant the transformers in the Baixada Santista substation are alleviated.

There are two lines, built in double circuit, between Baixada Santista and Henry Borden 88 kV. Bandeirante controls these lines.

The Henry Borden Hydraulic power plant has restrictions for generation due to problems related to water pumped to the Billings dam. The result is that the power plant can only generate power during a short period of time (periods in the range of 40 minutes and 1.5 hours). The generation only takes place during the peak load. However, the generators in the power plant are permanently connected to the grid to contribute with the generation of reactive power to improve the voltage level in both the 88 kV system and in the rest of the network.

Because the generators from Henry Borden Hydraulic power plant are permanently synchronized with the grid these generators contribute with high short circuit current during faults.

The Piratininga system is not integrated into the Bandeirante system. However, the Piratininga network is synchronized to the Bandeirates system through the 345 kV network. Under special conditions, it is possible connect the two systems, Piratininga and Bandeirates systems.

The following two operative characteristics isolate the substation of Henry Borden from the new Piratininga thermal generation in terms of short circuit current influence in the 88 kV:

- In the substation of Henry Borden there is a 75 MVA transformer connecting the 230 kV and 88 kV busses. This connection is normally open, and is
used only during contingencies. If connected, there should be a rigid control of the loading in this transformer.

- The two transmission lines connecting Henry Borden to Pedreira 1 and 2 are normally open. This is made in order to avoid overloading in the inter-connection made through the single circuit Piratininga – Pedreira.

### 6.4.3 Studied possible alternative configurations using power electronics

There are a number of alternative solutions to the conventional AC solution that have been investigated in this study. They are based on the use of power electronics. Several HVDC configurations were studied and one additional, Current Limiting Device, is presented.

Different types of converters have been investigated when studying HVDC transmission: Voltage Source Converters (VSC) with IGBTs and anti-parallel diodes; Line Commutated Converters (LCC) with thyristor valves; and Diode Bridge (assuming a unit connection, considering that power flow will not be controlled).

In general, the alternative that assumes Line Commutated Converters is a more economical solution in terms of investment and has lower total losses in the converters.

The alternative with Voltage Source Converters is a more expensive solution. In addition, the losses are also higher, due to the high switching frequency. However, the solution includes a number of advantages:

- Fast control of Active and Reactive power in each converter.
- AC voltage control, which means that necessary support to the 88 kV grid can be provided.

Regarding the HVDC network arrangement several configurations have been studied:

- **Configuration 1**: Multiterminal HVDC links feeding power to Henry Borden 88 kV and to Baixada Santista 88 kV. Maximum availability of the converters was considered, assuming the N-1 criteria, which means that in case of losing a converter the full transmission capability is maintained.

- **Configuration 2**: Multiterminal topology similar to Configuration 1, without considering the N-1 criteria, which means that in case of losing a converter the capability of power transmission is reduced.

- **Configuration 3**: Two independent HVDC links, one feeding power to Henry Borden 88 kV and the other to Baixada Santista 88 kV. The outage of one HVDC link will reduce the capability of power transmission to half.
• **Configuration 4**: HVDC Back-to-Back station is installed close to generators.

• **Configuration 6**: HVDC Back-to-Back, connecting the 88 kV and 345 kV busses in the ETT Baixada Santista. This will isolate the 88 kV system from the 345 kV system in terms of short circuit current. In addition, the power flow between the two systems can be controlled.

• **Configuration 7**: Similar to configuration 4, however the HVDC converters are replaced by diodes bridges, resulting in a Unit Connection of the generators.

The main conclusion from the study was that a solution with HVDC transmission is too expensive if short circuit current is the only issue to be addressed. However, the most interesting HVDC alternative seems to be the one described as Configuration 6. This solution contemplates the capability of HVDC converters to isolate systems in terms of short circuit current and also the capability to control power flow between systems. It is possible to foresee with this solution the integration of several systems: Bandeirante, Eletropaulo Metropolitana, EMAE, and EPTE.

Considering that the short circuit current is the only issue of concern, there are other possibilities that are more cost effective. Therefore, an alternative solution referred to as the ‘Current Limiting Device’ has been included in the study. This is also based on the use of power electronics. This solution is described as configuration 5. A Current Limiting Device is not a converter, but a simple fault current extinguishing device based on the use of IGBTs with anti-parallel diodes and thyristors.

In the following an overview of Configurations 5 and 6 that were considered the most attractive solutions is presented.

**6.4.4 Configuration 6: Back-to-Back HVDC connecting the 88 kV and 345 kV busses in the ETT Baixada Santista**

By including an HVDC in a Back-to-Back configuration between these systems, according to Figure 6-10, it is possible to transfer electrical power under normal conditions. However, during faults in the 88 kV system, there will be no short-circuit current contribution from the 345 kV system.

Preliminary investigation indicates that if considering only the short circuit current contribution produced by the new thermal generation to be installed in the Baixada Santista system, the 160 + 270 + 510 MW to be installed up to 2005, and the Henry Borden hydro generator connected to 88 kV grid will not exceed the current limits of the existing breakers. This means that with the HVDC isolating the short circuit current contribution from the 345 kV system, the installation of all new thermal generators in the existing 88 kV system will be possible, without any change in the network.
The estimated cost of the converter station is presented in Table 6-6. Two different types of converter have been considered: Line Commutated Converter with thyristor valves and Voltage Source Converters with IGBTs. The estimation of the cost was made considering the assumptions presented in Addendum 1 and 2.

Table 6-6 also shows the expected losses in the converter station for both alternatives of converters.

<table>
<thead>
<tr>
<th>Converter Type</th>
<th>Converter</th>
<th>Losses MW</th>
<th>Cost [MUSD]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative 1</td>
<td>LCC</td>
<td>2 x 350</td>
<td>9</td>
</tr>
<tr>
<td>Alternative 2</td>
<td>VSC</td>
<td>4 x 175</td>
<td>23</td>
</tr>
</tbody>
</table>

The following lists the main advantages that can be obtained with the proposed solution with Configuration 6:
• The solution provides the possibility to control the active power flow between the 88 kV and 345 kV in the Baixada Santista substation;

• The HVDC with Voltage Source Converters can control independently the AC voltages in the 88 kV and 345 kV busses in the Baixada Santista substation;

• The short circuit current contribution from the 345 kV system is blocked by the HVDC converters, isolating the 88 kV system;

• Since the 88 kV system receives reactive power support from the HVDC converters, it is possible to disconnect the generators from Henry Borden power plant when there is no need of power;

• The Baixada Santista system includes several agents (they were created from the de-regulation of the Brazilian electric sector): Bandeirante, EPTE and Petrobras (will be responsible for the new thermal generation). Having a good control of power flow in the system will provide flexibility of operation of the entire system;

• Having the control of power flow between the 88 kV and 345 kV systems, it is possible to foresee the connection of the 88/230 kV, 75 MVA transformer in the Baixada Santista substation. It is also possible to connect the 88kV line Piratininga – Henry Borden in Pedreira. These connections are normally maintained open to avoid overloading. A possible way of operation of the HVDC Back-to-Back converters is controlling or monitoring the power flow through these connections. As a result of all of these, there will be a significant improvement for the operation of the network, considering that several systems will be integrated: Bandeirante, Eletropaulo Metropolitana, EMAE and EPTE. Availability and reliability of the system will increase. Also, it is possible to arrange a suitable composition of power flow interchange between the systems.

It should be stressed the operative gains of the system that could be obtained with the proposed HVDC solution. This would result in the possibility to interconnect the major grid companies that supply energy to the São Paulo system. These gains that this study has indicated could be quantified in future and more detailed study.

6.4.5 Configuration 5: Use of Current Limiting Device in each generator to limit the short circuit current during faults

This solution is based in the use of power electronics to limit short circuit current during a fault in a controllable way or simply interrupt the short circuit current. Using power electronics it is possible to limit or extinguish the first current peak after the fault. With semi-conductors having the capability for turning-off the current it is possible to limit or even extinguish the current
without waiting for the first zero crossing of the current. In section 4.3 a more
detailed description of the Current Limiting Device is given.

Figure 6-11 shows a proposed scheme, indicating a single line diagram of a
typical Current Limiting Device.

![Diagram showing a single line diagram of a typical Current Limiting Device]

Figure 6-11: Application of Current Limiting Devices

There is an issue of concern related to the application of this type of Current
Limiting Device, which is the use of back-up protection. The normal protective
practice in power systems is based on primary and back-ups protections, which
normally use different operating principles. In case the Current Limiting De-
vice fails to operate, an alternative device should be considered to interrupt the
fault currents. A possible solution is to duplicate the Current Limiting Device.

The main advantage of such an application is cost. The estimated cost of a Cur-
rent Limiting Device is in the same order of the cheapest AC solution sug-
gested in the study made by ONS/COPE. The estimated cost of both devices is
in the order of 12 MUSD (24 MUSD if considering the duplication of the Cur-
rent Limiting Device).
In terms of losses, the total losses in the Current Limiting Devices (both 160 MW and 270 MW generator units), assuming symmetrical operation, is about 3 MW (0.6 % at 430 MW generation).

The conclusion is that application of Current Limiting Devices will be attractive when limiting the short circuit current is the main issue, assuming that power flow control is not important.
6.5 Supply of electrical power to and through a ‘large city’

6.5.1 General overview

The aim of the study was to identify different alternatives to control power flow through a new 345 kV network that would be established through a ‘large city’. The feasibility of using HVDC transmission as an alternative to control the power flow in this new link was studied and a comparison was made with conventional AC techniques such as a phase-shifting transformer or expected possible improved AC techniques such as a UPFC (Unified Power Flow Controller). Figure 6-12 shows the base transmission system and an indication of the future reinforcements in the 345 kV network around the city.

Capacity requirements, thermal security of the existing lines and transformers and voltage security under contingencies were considered. Estimation of the overall cost and space requirements was made.

Figure 6-12: Base transmission system and future reinforcement in the 345 kV network around a ‘large city’
6.5.2 Results of the study

**Base Case (without reinforcement)**

A summary of the load flow for the present and expected future load situations is presented in Table 6-7. The table shows that generation will increase by 20% to compensate the increase in load during the period 2003-2012.

<table>
<thead>
<tr>
<th>Network System</th>
<th>Base Config.</th>
<th>Total Generation</th>
<th>Total Load</th>
<th>Total Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>26 890 MW</td>
<td>23 769 MW</td>
<td>532 MW</td>
<td></td>
</tr>
<tr>
<td>Future</td>
<td>32 173 MW</td>
<td>28 187 MW</td>
<td>680 MW</td>
<td></td>
</tr>
</tbody>
</table>

The generation is concentrated mainly in the southern and western part of the system, while the load is concentrated primarily in the north and eastern parts. Therefore, power flows predominantly from south to north and from west to east. Some circuits in the route S9-S10-S11 are operating quite close to their thermal capacity (1200 MVA per circuit). This is an indication that the power transfer capability from south to north has to be increased to alleviate this route.

It has been considered in the study a scenario where 2000 MW generation in northern area will not be in service. These generators are currently operating as synchronous condensers, providing reactive power support to the network. Additional out of service generation in the northeast area have been also considered.

In order to reinforce the network and to bring more power into the northern region and alleviate the route S9-S10-S11, a new link connecting S1-S5-S6 through the intermediate substations of S2, S3 and S4 was considered.

**Base Case (with reinforcement)**

Having established these additional connections in the system, a closed 345 kV bulk power ring will be bounded by S1-S6/S5-S7/S8-S9-S10-S11 substations.

However, with this new arrangement it is difficult to balance the power around the ring without additional control equipment. The basic option is to install in the 345 kV system phase-shifting transformers. The other options include HVDC transmission with the converters in Back-to-Back arrangement or a Unified Power Flow Controller (UPFC).
It is assumed that the new control equipment for the power flow will be installed at the S2 substation.

Similar to the others existing 345 kV circuits, the new additional double circuit connections between S1-S6-S5 will be rated to 1200 MVA per circuit.

A preliminary load flow analysis of the new network topology including the additional connections (without adding any power flow control in the system) indicated high loading of the new lines that exceeds their nominal rating. Reactors have then been added in S4 substation to limit the loading of these lines, but still the loading was considered high, close to 1200 MVA per circuit. This is the condition that has been observed which indicated the need for additional measures to be introduced in the system to control the power flow in this part of the ring. The three different types of solutions that were considered, phase-shifting transformers, HVDC Back-to-Back and UPFC, were tested at the S2 substation, controlling power flow in the S2-S3 line.

Load flow calculations show a tendency to draw significant power from the new 345 kV system into the 138 kV system in the S2 substation.

The existing two phase shifting transformers at the S2 substation are used to control power flow in two 138 kV lines. However, the loading levels in the other 138 kV circuits in the S2 substation are also high which overloads the transformation 345/138 kV.

Attempts have been made to introduce a new controllable power flow device to limit the flow between the 345 kV and 138 kV systems. However, it was found that the simplest solution would be to include two 300 MVA step-down transformers in each circuit in the S2 substation, giving a total of 1200 MVA installed capacity.

Capacity requirement of the power flow controllable device

The designed rating of the new link was considered to be 1200 MVA for each of the two circuits. However, studies made for the future load configuration, indicated optimum power flow through S2 substation should be less than 600 MW. The power flow through S2 substation should be kept always in the north power flow direction. Power flow exceeding this level results in higher system losses and fairly high loading of many circuits in the network. For example, it has been measured that with 1000 MW power flow, to the north direction, a number of transmission lines and transformers in the network would carry loads exceeding 90% of their nominal rating. Special attention shall be given to the lines in the S8, S9 and S10 areas. High network losses have been observed as well and some phase-shifting transformers in the 138 kV system were out of their designed range of operation.

The other observation made from the analysis is that at some contingencies there is an indication of a high risk for severe overloading of a few lines and
transformers in case the power flows is in the south direction through the S2 substation.

Based on this analysis, the power flow control device, if included in the S2 substation, could be rated to control power flow in the range of \( \pm 600 \text{ MW} \), which is sufficient to fulfill the requirements of the system. Power flow higher than 600 MW in this part of the network results in overloading of several other circuits; the existing phase-shifting transformers in the 138 kV system will be out of their range of operation; and finally, a considerable increase in the internal losses in the network due to excessive circulating power around the new ring will occur.

**Required rating of the controllable device**

*Phase-shifting transformer*

Assuming that the S2 substation will include a phase-shifting transformer, the required phase-shift angle in degrees and the corresponding throughput power for the different operating ranges that have been considered are presented in Table 6-8.

Table 6-8: Required rating of the phase shifting-transformer

<table>
<thead>
<tr>
<th>Throughput power (^{\dagger}) [MVA]</th>
<th>Phase Shift Angle range [degrees]</th>
<th>Transformer Rating Capacity of the main and series unit [MVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pm 1000 )</td>
<td>[+15; -35]</td>
<td>600</td>
</tr>
<tr>
<td>( \pm 500 )</td>
<td>[+3; -22]</td>
<td>190</td>
</tr>
<tr>
<td>(+1000 / -500)</td>
<td>[+15; -22]</td>
<td>380</td>
</tr>
</tbody>
</table>

Note 1: plus corresponds to North power direction; minus corresponds to South power direction.

Table 6-8 also shows the transformer rating capacity in MVA of the main and series unit needed to reach the displacement in phase angle (phase-shift angle) to result the required throughput power. The rating is calculated based on formula (4) presented in section 3.1.3, and is reproduce as follows:

\[
P_\alpha = 2 \, P \, \sin \frac{\alpha}{2}
\]

120
where $P_\alpha$ is the phase shifting power (or transformer rating capacity of the main and series unit), $\alpha$ is the phase-shifting angle to produce the required throughput power $P$.

Especial attention shall be given in case of asymmetric requirements as per the case to control 1000 MW north and 500 MW south. The maximum throughput power ($P = 1000$ MW) will determine the current capability of the winding, while the maximum phase-shifting angle ($\alpha = 22$) will determine the voltage capability of the winding. Hence, the phase-shifting transformer has to be rated combining simultaneously those extreme-operating conditions.

**UPFC**

Assuming that a UPFC would be used, the rating of the converter is calculated considering the product of the magnitude of the injected voltage and the transmission line current. In this calculation it will be assumed that both the series and shunt unit will have the same rating. Table 6-9 gives the injected voltage and corresponding line current for the different power flow control conditions.

Table 6-9 Injected voltage and transmission line current for different power control conditions using UPFC controller

<table>
<thead>
<tr>
<th>Injected Series Voltage [pu]</th>
<th>1000 MW North</th>
<th>500 MW North</th>
<th>500 MW South</th>
<th>1000 MW South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission line current [kA]</td>
<td>0.1846</td>
<td>0.0306</td>
<td>0.3608</td>
<td>0.5467</td>
</tr>
<tr>
<td>1.607</td>
<td>0.700</td>
<td>0.817</td>
<td>1.599</td>
<td></td>
</tr>
</tbody>
</table>

To control 1000 MW power flow between the S2 and S3 substations in both power flow direction, each of the UPFC converters (the series and shunt units) has to be rated about 900 MVA.

To control only a 500 MW power flow in S2, in both direction, each of the converters has to be rated about 300 MVA.

However, to control 1000 MVA power flow north direction and 500 MVA power flow south direction would require an UPFC with voltage rating of 0.36 pu and current rating of 1.6 kA. This will give a rating of 600 MVA for the both series and shunt units.

Table 6-10 presents a summary of the calculated rating of the UPFC solution for the different studied alternatives.
Table 6-10: Required rating of the UPFC solution for each the series and shunt converter unit

<table>
<thead>
<tr>
<th>Throughput power [MVA]</th>
<th>Rating of the UPFC [MVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 1000</td>
<td>900</td>
</tr>
<tr>
<td>± 500</td>
<td>300</td>
</tr>
<tr>
<td>+1000 / -500</td>
<td>600</td>
</tr>
</tbody>
</table>

Note 1: plus corresponds to North power direction; minus corresponds to South power direction

**HVDC Back-to-Back**

In HVDC transmission, power electronics are used to perform the AC/DC and DC/AC conversion. Hence the converters should be rated for the total throughput power in the transmission. Additional rating should be considered for reactive power supply, which will support the system voltage. Usually the rating of a converter is increased by 5 to 10% of its nominal active power capability to provide additional reactive power support to the network.

Considering an HVDC-VSC type of converter, the converters could be rated at 550 MVA for 500 MW transmission in each circuit, and 1100 MVA, if assuming 1000 MW transmission.

**Contingency analysis**

Critical contingencies focusing on the area impacted by the bulk 345 kV system, which is in need of reinforcement, were studied.

Table 6-11 shows a summary of the analysis of the 54 contingencies. The table shows the number of elements where the short term rating criteria is exceeded for all studied contingencies and the number of busses outside the maximum and minimum transmission voltage criteria.

The system without the new reinforcement in the 345 kV, provides a reference for the different studied alternatives for the comparison. The system condition at the expected normal peak load and the system condition at expected high peak load for the 2012 configuration were studied.

To illustrate the benefits of the 345 kV reinforcement between S1-S6/S5, the table shows the alternative using a phase-sifting transformer located in S2. In this case it was assumed that 500 MW power flows between S2 and S3 substations, in the north power flow direction.
It is possible to observe that with the reinforcement the system becomes rather stiff, since there is no single busbar outside the transmission voltage criteria after a contingency. In terms of loading of system elements, there are quite a few components that still would require attention at the high peak load condition.

For the other studied power flow controller alternatives there has been similar conclusions. However, it is possible to add the following observation: With a HVDC Back-to-Back converter or a UPFC at S2, the results are slightly better as compared to the phase-shifting transformer. The main improvement that has been observed is in relation to the performance of the voltage, since these solutions can have a better control of the voltage due to their reactive power supply capability, which is a basic characteristic of Voltage Source Converters.

Table 6-11: Number of busses outside transmission voltage criteria and number of elements exceeding the short term rating criteria during contingencies

<table>
<thead>
<tr>
<th>Future_high peak load without reinforcement</th>
<th>Minimum/Maximum transmission voltage criteria 1</th>
<th>Short term power rating criteria 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future_normal peak load without reinforcement</td>
<td>50</td>
<td>24</td>
</tr>
<tr>
<td>PST_Future_2012_high peak load</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>PST Future_normal peak load</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

Note 1: Voltage criteria levels: normal peak load [1.03 ; 0.98 pu] for 345 kV lines and [1.03 ; 0.95 pu] for the 138 kV lines;

Note 2: Short term power rating criteria: 105% Emergency Rating for transformer and 115% Emergency rating for overhead lines

**Retirement of generation in the northern area**

A study of the consequence of the retirement of additional generation was made.

The study shows that without these generators shunt capacitors need to be installed in the region, at which generations are taken out of service, to maintain the voltage within the adopted voltage limit criteria. These capacitors have to be switchable for the load compensation.
The performance of the system during contingencies becomes more critical without the generation in that area. For example, if power flow through the new 345 kV system in S2 substation is assumed in the north-direction there are not many adverse consequences to the system. However, if the system is operating with power flow in the south-direction, contingency cases with difficult convergence have been observed, especially, if the contingencies are related to components located in the northern region of the system.

The alternative solution, which includes a HVDC Back-to-Back at S2 substation is less critical than a phase-shifting transformer, since they can reverse power flow very fast, which is not possible with phase-shifting transformers. These cases clearly show the benefit of having fast control of active power, which is characteristic of HVDC converters. Similar performance can be obtained with a UPFC.

**Short Circuit Analysis**

A brief short circuit current analysis indicated a significant increase in current in both 138 kV and 345 kV systems with the new 345 kV link between S1-S5/S6 substations. Some of the results of the calculation for a solid-three-phase fault at two different locations in the network are shown in Table 6-12.

For example, at a three-phase short fault close to S2 substation, in the 138 kV system, the measured short circuit current has increased by about 40% due to the contribution from the new 345 kV network through the step-down transformer. At faults in the 345 kV system close to S1 substation the measured increase was about 20%.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Fault Location</th>
<th>S2, in one of the 138 kV line</th>
<th>S1, in one of the 345/138 kV transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without new the 345 kV links</td>
<td>26.4</td>
<td>21.9</td>
<td></td>
</tr>
<tr>
<td>With new 345 kV links and PST</td>
<td>36.3</td>
<td>26.0</td>
<td></td>
</tr>
<tr>
<td>With new 345 kV links and VSC Back-to-Back</td>
<td>35.3</td>
<td>23.0</td>
<td></td>
</tr>
</tbody>
</table>

The study of short circuit current shows the impacts of using different types of power flow control devices. It was verified that in this electrical system, which
is rather meshed, the use HVDC converters as compared to a phase-shifting transformer (or UPFC) have little impact on the fault current, although it is known that HVDC converters do not add short-circuit current to the fault. The reason is that there are parallel paths that contribute to the current.

**Interconnection of the double-circuit**

Paralleling the 345 kV double circuits with HVDC converters: The 345kV network is duplicated, which results in two subsystems that are operating separately from each other. They are not interconnected in order to keep short circuit current levels below the design limits of the equipment. One application of HVDC in this case was to interconnect the two subsystems. Power could then be transferred between the two subsystems, without affecting the maximum short circuit current during faults.

**Cost and space requirements**

The amount of power flow to be controlled has a large impact on the capital cost of the installation and space requirements for the different alternatives that have been studied.

Controlling 500 MW in both power flow directions, which the system studies have indicated to be adequate to solve a significant number of problems in the system, will give the most simple and cheap solutions.

If a 1000 MW power control in both power flow directions is to be considered, a rather expensive solution will result with considerable demands on space requirements.

It should be noted that the alternative which consider controlling 1000 MW in north power flow direction but 500 MW in south power flow direction can give a rather economic solution.

Table 6-13 gives an estimation of the expected capital cost and space requirements for the different solutions that have been considered in the study.

Considering a line commutated HVDC, there would be a need for larger footprints.

Remarks related to Table 6-13:

- The cost of phase-shifting transformer was estimated based on the cost (cost/total transformer rating in kVA) of recent delivery of transformer by ABB company.
- Cost of HVDC Back-to-Back VSC converters were estimated based on the assumptions presented in Addendum 1 and 2.
- Cost of UPFC VSC converters are assumed to be in the same order of HVDC Back-to-Back VSC converters.

Table 6-13: Space requirement and capita cost for different studied alternatives

<table>
<thead>
<tr>
<th>Rating of the equipment</th>
<th>Capital Cost [MUSD]</th>
<th>Space Requirement</th>
<th>Throughput power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Shifting Transformer 2 x 380 MVA</td>
<td>10-15</td>
<td>2 x 50 m²</td>
<td>2x500 MVA</td>
</tr>
<tr>
<td>Phase Shifting Transformer 2 x 1200 MVA</td>
<td>30-50</td>
<td>2 x 200 m²</td>
<td>2x 1000 MVA</td>
</tr>
<tr>
<td>Phase Shifting Transformer 2 x 760 MVA</td>
<td>20-30</td>
<td>2 x 100 m²</td>
<td>+1000 / -500 MVA</td>
</tr>
<tr>
<td>HVDC BtB VSC-type 2x 1100 MVA</td>
<td>80-120</td>
<td>2 x 3600 m²</td>
<td>2x 500 MVA</td>
</tr>
<tr>
<td>HVDC BtB VSC-type 2x 2200 MVA</td>
<td>160-240</td>
<td>4 x 3600 m²</td>
<td>2x 1000 MVA</td>
</tr>
<tr>
<td>UPFC 2x 600 MVA</td>
<td>40-70</td>
<td>2 x 3600 m²</td>
<td>2x 500 MVA</td>
</tr>
<tr>
<td>UPFC 2x 1800 MVA</td>
<td>130-200</td>
<td>4 x 3600 m²</td>
<td>2x 1000 MVA</td>
</tr>
<tr>
<td>UPFC 2x 1200 MVA</td>
<td>90-130</td>
<td>2 x 3600 m²</td>
<td>+1000 / -500 MVA</td>
</tr>
</tbody>
</table>

6.5.3 Possible alternative cases that could be investigated

This study assumed only the alternative including the additional connections from S1 to S5/S6 substations.

Another alternative that can be considered is to extend the studied alternative S1-S5/S6 with HVDC Back-to-Back in S2 with a small HVDC link, from S2 up to the north, S13 substation.

6.5.4 Conclusions

Closing the 345 kV ring, by connecting S1 and S5/S6 substations will solve many problems caused by contingencies. The most economical solution is AC cable links combined with phase-shifting transformers. However, the use of HVDC-VSC would provide the following benefits:

1. Reduction of fault duty currents,
2. Possibility to balance the parallel circuits by using multi-terminal HVDC,
3. Possibility to keep better voltages in the north part of the system since HVDC-VSC can control reactive power,
4. Possibility of faster control of active as well as reactive power.
Chapter 7

Relevant issues related to City Center Infeed

7.1 Issues that have been considered relevant in transmission of electric power to City Centers

The design of transmission lines used to feed power into the city load centers is based on many different issues. Cities that are expanding need more power to be transmitted into the new load centers with limited rights-of-way. Nowadays there are new environmental concerns, which imply restrictions, especially to the use of overhead lines, usually resulting in the use of cables.

As earlier discussed, HVDC technology is generally adopted for longer distance cable based transmission, as it does not experience restrictions due to the capacitive current effect that would occur with the use of alternating current transmission. By using HVDC transmission more power can be transmitted in the same right-of-way, considering that the transmission losses in DC cable are lower than those in AC cable. HVDC transmission includes other advantages such as converters that do not contribute to fault current and that can also control power flow very quickly. However, the main drawbacks are that it requires the installation of costly converter station terminals and that these stations contribute with additional losses. These advantages and disadvantages will be qualified and quantified in this section.

List 7-1 compares the value of different types of transmission system solutions in relation to several issues that are found relevant to the transmission of electrical power into city centers. In this section a brief overview of their significance based on the findings obtained during the studies of the cases that were presented in the previous chapter will be given.

In the next section, issues related to cost and losses are treated, comparing the two types of transmission: HVDC and HVAC transmission. There, the concept of ‘break-even distance’ widely mentioned in the literature for overhead lines will be re-introduced, but now also considering underground cable transmission.
### List 7-1: List of relevant issues related to City Center Infeed

<table>
<thead>
<tr>
<th>Issue</th>
<th>Conventional Solution</th>
<th>HVDC Solution</th>
<th>Other Solutions</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Split System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upgrade rating of the system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground short circuit current</td>
<td>Isolation of the system with neutral reactor</td>
<td>HVDC limiting fault current</td>
<td>Current Limiting Devices</td>
<td>Stockholm, replacing overhead lines with low impedance cables</td>
</tr>
<tr>
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<tr>
<td>Power Flow Control (only slow requirement)</td>
<td>Phase Shift Transformer</td>
<td>HVDC transmission: intrinsic power flow control</td>
<td></td>
<td>Gothenburg, 'large city, São Paulo</td>
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<tr>
<td>Power Flow Control (fast requirement)</td>
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<td>HVDC transmission: intrinsic power flow control</td>
<td>UPFC Unified Power Flow Control</td>
<td>Gothenburg, 'large city'</td>
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<td>Reliability of supply</td>
<td>Interconnected systems</td>
<td>Multi-pole configuration</td>
<td>Interconnect HVDC systems</td>
<td>Göteborg, Lidingö, 'large city'</td>
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<td>Multi-feeders</td>
<td></td>
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<td>Discrete switchable reactive power elements</td>
<td>HVDC with VSC supporting the system with reactive power</td>
<td>SVC Static Var Compensation</td>
<td>‘large city’</td>
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<td>Adding boost transformer with wide range of tap</td>
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<td>STATCOM (ASVC)</td>
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<td>Increase Transmission Capability: existing and new cables</td>
<td>Adding new circuits</td>
<td>Replacing existing circuits with HVDC cables</td>
<td>FACTS Devices</td>
<td>New York</td>
</tr>
<tr>
<td>Mult-infeed system aspects</td>
<td>System with more than one feeder</td>
<td>HVDC with VSC multiterminal configuration</td>
<td>Stockholms, vision of the future without overhead lines</td>
<td></td>
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<tr>
<td>Power Quality</td>
<td>Strength the network with additional circuits</td>
<td>HVDC with VSC</td>
<td>STATCOM</td>
<td>(Not studied)</td>
</tr>
<tr>
<td>Environmental aspects</td>
<td>Underground installation</td>
<td>Compact HVDC station</td>
<td>Underground Cable buried</td>
<td>Stockholm</td>
</tr>
</tbody>
</table>
Short circuit current

Short circuit current has been considered an important issue in two of the cases that have been studied.

Replacing overhead lines with cable and installing new generation in distribution systems could result in circuit breaker short circuit currents exceeding their design limits.

However, it was found that, for meshed systems, the replacement of a single AC circuit by a HVDC link resulted in only a small reduction of short circuit current, since there are other parallel paths for the current. This was observed in the study of the Stockholm case where the replacement of the Järva-Värtan line by a HVDC link did not produce a significant reduction in the short circuit current.

In the São Paulo case, one alternative solution to reduce the short circuit current was to split the electrical system into two subsystems, and connect them with a HVDC link. During faults in one system, the short circuit currents are not transferred from the healthy system to the faulty system. Hence, the use of the HVDC link in this case was to separate two networks with a HVDC Back-to-Back. The Back-to-Back station connects the two systems under normal operating conditions, but they are isolated during faults.

In the ‘large city’ case, it was observed that the main part of the electrical network is fully duplicated. Each one forms a subsystem that operates separately from each other. They are not interconnected in order to keep short circuit current levels below the design limits of equipment. One application of HVDC in this case was to interconnect the two subsystems. Power could then be transferred between the two subsystems, without affecting the maximum short circuit current during faults.

The use of a Current Limiting Device made with power electronics is another alternative solution that has been investigated. One application that has been studied was the São Paulo case. In this case the problem was to limit the excess short circuit current resulting from new generation that would be installed in the network. With the use of a Current Limiting Device close to the generators, the short circuit current contribution from the generators could then be controlled or just be blocked.

An issue that has to be considered when using Current Limiting Devices is that back up based on different protection criteria should be implemented.

The most economical procedure to reduce short circuit current is to add series reactors to the lines. This solution is normally combined with splitting of busbars in substations. However, splitting busbars would affect the reliability of the system. Adding series reactors will make it more difficult to balance power flow between parallel lines in a meshed network.
Power flow control, considering slow speed requirements

In a meshed network it might be difficult to transmit power through some circuits due to the existence of parallel paths with lower impedances. Therefore controllable devices needed to be included in the network in order to balance the power flow between different circuit paths.

Another reason to include power flow control in a network is to create a new opportunity for the operation of the system, which makes it flexible and to take advantages of different levels of electrical tariffs in case there are different power grid supplier companies. This is an issue that is having increased importance in today’s open energy market environment (São Paulo and Gothenburg cases did indicate that this type of opportunity was found interesting).

Power flow control is normally made with additional series reactance that is included within lines or cables to equalize the impedance between parallel circuits. In some cases, series reactors are avoided since they might create other problems in the system. Series reactors affect the total impedance of the network, making the system more difficult to protect, and making it more difficult to transmit power from one area to another area in the network.

Another conventional technique is the use of phase-shifting transformers. This solution is particular popular in North America, and the experience has been positive when having a limited number of such devices installed in the network. When there are too many controllable devices of this type, the operation of the system becomes rather complicated since each phase-shifting transformer might affect the operation of other ones.

The ‘large city’ case was found rather complex to operate. The network includes several phase-shifting transformers and operation of one transformer affects the operation of the other transformers, requiring a good coordination between the devices.

The HVDC link is an alternative solution to the conventional phase-shifting transformer and/or series reactor. The power flow through the link is precisely equal to the set reference given by the controls. It is not affected by different network conditions or changes in the network topology. Similar performance can be obtained with the use of FACTS devices, as described in chapter 3.

Power flow control, considering high speed requirements

There are stability problems that could impose limitations in transmission capability. In one studied case, the Gothenburg case, the system might suffer severe consequences if important feeders suddenly are out of service. A typical solution to mitigate this type of problem is to reinforce the system by adding more lines and meshing the network.
An alternative solution in such a case is to introduce an intelligent control system that could immediately change power flow during special contingencies, supplying areas that are lacking in power. To be able to control quickly the power flow in the line, power electronics controllers should be used, either with HVDC transmission or with FACTS devices. They have high-speed controls for both active and reactive power.

**Power quality and reliability of supply**

An electrical utility should provide electric power with enough quality and power supply security to attend the needs of the electric power consumers. In case especially high quality, availability and reliability of supply are essential, the electrical utility must invest more in the system to reach these high levels of demand. One way is to reinforce the system by adding new feeders.

Another alternative is to supply electrical power with these high requirements using dedicated feeders with enough capability to maintain adequate quality during disturbances. One alternative is to use converters based on Voltage Source Converters. With Voltage Source Converters high power quality can be obtained since this type of converter includes reactive power capability to control the AC voltage.

There are other possible ways to improve power quality, such as the use of FACTS devices, like STATCOM or SVC.

However, the power quality issue was not found relevant in any of the cases that have been studied. On the other hand, reliability of supply was considered important in most of the cases. In general, duplication of the system is a basic solution to improve the reliability of the network.

**System voltage performance – reactive power management**

Reactive power control is an important issue in AC power systems. One primary need for reactive power control is to perform load compensation. It is basically used for power-factor correction and for improvement of voltage regulation. Reactive power compensation is usually installed together with the loads or group of loads. The other important need for reactive power control is to compensate transmission lines. By having a proper reactive power compensation for the transmission lines, maintaining voltages within an acceptable range of operation, the active power transmission capability can be increased.

The conventional control for reactive power is to use switchable capacitors and reactors. These are simple and cheap, but frequent switching might wear out the switches very quickly, requiring frequent maintenance.

Cables and lines used in HVDC transmission do not need reactive power compensation. In particular in HVDC with Voltage Source Converters, the convert-
ers do not require reactive power compensation either. In fact, the converters have the capability to provide voltage support to the connected AC system up to their current capability. This benefit might be of particular importance in case the connected AC network requires advanced reactive power compensation to maintain voltage stability. In these cases the HVDC-VSC converters can then be used as fast static VAR compensators as well.

**Transmission capability of existing and new cables links**

Cable transmission is more efficient using HVDC transmission than in conventional AC transmission. With DC transmission the cable system has a better insulation utilization and higher current capability because there are lower losses (there are no dielectric losses and no metallic screen or armour losses). This results in more power being transmitted. Since there is no capacitive current, power can be transmitted over longer distances as well. This becomes particularly important for bulk power to be transmitted over long distances, which requires a high voltage system that imposes even more distance restrictions due to high capacitance for this type of cable when using AC transmission.

As has been shown in chapter 5, the higher capability of transmission in a DC cable as compared to an equivalent cable used for AC transmission is in the order of 1.5 to 2.0. This has an impact on the cost of the transmission.

The installation of the cable is an important issue in underground transmission in urban and suburban areas. In general, the cost of installation is higher than the cost of the cable itself.

Considering that HVDC transmission has a better utilization of the cable, it is possible to obtain important savings in the installation, especially if the amount of power to be transmitted is high. In some cases, it was estimated that the cost for installation might be reduced by a factor of about two with HVDC underground cable as compared with HVAC transmission. In those cases a bipolar HVDC transmission was found equivalent to a double circuit HVAC transmission, which might require the installation in two separate circuits to reduce the operating temperature of the cable.

**Additional aspects related to the use of HVDC-VSC and HVDC-LCC transmission systems**

For HVDC-VSC (Forced Commutated Voltage Source Converter), the commutation process does not rely on the connected AC network. Its control system is primarily based on the AC quantities and it is possible to control both active and reactive power independently. The converters are significantly less sensitive to the connected AC voltages. Because of this the Voltage Source Converter is suitable to supply a very weak AC system.
With a HVDC with Voltage Source Converters it is easy to connect the converters in a multi-terminal configuration on the DC side of the converters. Therefore several AC systems can be connected with the same HVDC transmission link. The other characteristic of this type of converter is that it has a fast control of both active and reactive power through the converter.

The classical HVDC-LCC, converter with Line Commutated Current Source Converters, requires a rather stiff AC system to perform the commutation of the current between the valves. With HVDC-LCC it is only possible to have fast control of the active power. The main advantage of this type of converter in comparison with the forced-commutated Voltage Source Converter is that it is less expensive and adds lower losses into the system.

In this study the viability to combine a Voltage Source Converter with a Current Source Converter in a hybrid topology has been investigated. Several topologies have been studied, and the one, which indicated the most favourable benefits, was a bipolar HVDC transmission having Current Source Converters in one pole and Voltage Source Converters in the other pole. The basic advantage of this type of hybrid topology is that, as seen from the AC system network, the Line Commutated Current Source Converter is operating in parallel with the Forced Commutated Voltage Source Converter. This results in the Voltage Source Converter supporting the operation of the Current Source Converter providing not only part of the required reactive power but also a fast control of the AC voltage that will reduce the risk of commutation failures. Hybrid topology might be used taking advantage of both types of converters in a more economical solution.

Environmental aspects

The Electric Magnetic Field issue, EMF, and aesthetic considerations are environmental issues that are increasing the concerns of the general public.

The health aspect of electromagnetic pollution has been targeted by consumer groups, saying that communities near AC power transmission lines or cables have higher incidences of leukemia among children than those in the rest of the region. Less restriction is made for the magnetic field from a DC cable since this one is stationary (like the Earth’s natural magnetic field), while the AC cable generates an alternating magnetic field. An alternating field, but not a stationary field, can induce body current.

Another environmental issue is pollution from oil. Extruded insulation cable (fluid-less cable) exists today that is more environmentally friendly. Therefore, high voltage cable technology (either AC or DC) is characterized by a change over from the conventional lapped paper dielectric impregnated with oil under pressure to extruded synthetic dielectrics.
In large cities, large AC cables are best accommodated in tunnels. This solution provides the opportunity to maximize reliability by supplying and installing longer lengths, reducing the number of joints. However, tunnels are rather expensive and cause inconvenience to society during construction.

The installation of DC cables is less complicated compared to AC cables, because DC cables produce less EMF impact and have less losses. Therefore, it is possible to consider alternative and simpler installation such as ducts or simply buried cable in the ground or under sidewalks, instead of deep and expensive tunnels.

7.2 Break-even distance for underground transmission

The term ‘break-even distance’ has been widely presented in the HVDC literature. This is the distance in which the saving in capital cost and lowers losses with DC transmission line may be enough to pay for the two converters, one at either end.

There are different factors that influences the break-even distances, such as the amount of power to be transmitted, the geographical location of the installation and route of the lines, etc. In the literature values for overhead lines in the range of 600 to 1000 km can be found.

In chapter 5 it was seen that there are savings in cable transmission when comparing HVAC and HVDC transmission. One reason is that a maximum of two conductors is required for DC compared to three for AC; the other reason is that a DC conductor has a higher power capability for transmission as compared with an equivalent AC conductor.

Submarine cable transmission has a break-even distance is in the range of 60-100 km. However, this transmission length is due to the capacitive charging current for HVAC cable rather than the cost of the cable.

So far, long cable transmission has only been used for submarine transmission. There has been no long-distance underground transmission, mainly because overhead lines cost significantly less than underground cables.

The purpose of this section is to evaluate break-even distances when using underground cable transmission, assuming city infeed applications.

Four different basic configurations are studied, considering the amount of power to be transmitted and level of reliability (single or double circuit arrangement):

- Configuration 1: 250 MVA rating capacity in a single circuit transmission
- Configuration 2: 500 MVA rating capacity in a single circuit transmission
- Configuration 3: 500 MVA rating capacity in a double circuit transmission
• Configuration 4: 1000 MVA rating capacity in a double circuit transmission

Data used in the calculations are presented in Addendum 2.

7.2.1 Break-even distance based on the capital cost of substation and underground cable and corresponding installation

In this first analysis only the capital cost of the transmission system will be considered. Here, the calculated distances should cover the investment cost for one station terminal. The resulting break-even distances are presented in Table 7-1.

It should be noted that since a two-terminal transmission will include one terminal at the sending end and another at the receiving end, the transmission distance shown in the table should be multiplied by a factor of 2.

The following observations can be made from the analysis of Table 7-1:

• Considering that a HVDC converter station with Voltage Source Converters is more expensive than an equivalent HVDC with Line Commutated Converters, the break-even distances for HVDC-VSC are longer than for HVDC-LCC.

• A HVDC-VSC substation is more compact than an HVDC-LCC substation. Therefore, in urban areas, where the cost of land is more important, a HVDC-VSC type is more adequate as compared with an HVDC-LCC substation. This can be seen by comparing the break-even distances shown in the table.

• If the cable is installed in a tunnel, break-even distances are far too long, which means that HVDC can only compete with HVAC if cables are installed in ducts or cables are buried.

• For low power transmission the break-even distances are rather long. High power transmission gives more practical distances.

• The results of the calculation which gives the shortest break-even distances are:
  
  o HVDC-LCC-Suburban: 2x19=38km (1000 MVA in double circuit, duct installation)
  o HVDC-LCC-Urban: 2x24=48km (1000 MVA in double circuit, duct installation)
  o HVDC-VSC-Suburban: 2x20=40km (1000 MVA in double circuit, duct installation)
  o HVDC-VSC-Urban: 2x21=42km (1000 MVA in double circuit, duct installation)
Table 7-1 Part 1: HVDC-LCC – Break-Even Distance [km] considering only capital costs, substation and cable transmission

<table>
<thead>
<tr>
<th>Reference ConventionaHVAC</th>
<th>250 MVA 1 circuit</th>
<th>500 MVA 1 circuit</th>
<th>500 MVA 2 circuits</th>
<th>1000 MVA 2 circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent HVDC-LCC</td>
<td>250 MW 1 Pole 2 cables</td>
<td>500 MW 1 Pole 2 cables</td>
<td>500 MW 1 Bipole 3 cables</td>
<td>1000 MW 1 Bipole 3 cables</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substation (Suburban Area)</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
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<td>300</td>
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<td>197</td>
<td>42</td>
<td>59</td>
<td>829</td>
<td>19</td>
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<th>Duct</th>
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<th>Tun</th>
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<td>386</td>
<td>173</td>
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<td>250</td>
<td>53</td>
<td>75</td>
<td>1044</td>
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<td>34</td>
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Table 7-1 Part 2: HVDC-VSC – Break-Even Distance [km] covering only the cost of the converters and underground transmission cable

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<th>Reference ConventionaHVAC</th>
<th>250 MVA 1 circuit</th>
<th>500 MVA 1 circuit</th>
<th>500 MVA 2 circuits</th>
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<tbody>
<tr>
<td>Equivalent HVDC-VSC</td>
<td>250 MW 1 Bipole 2 cables</td>
<td>500 MW 1 Bipole 2 cables</td>
<td>500 MW 2 Bipoles 4 cables</td>
<td>1000 MW 2 Bipoles 4 cables</td>
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</tbody>
</table>

<table>
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<tr>
<th>Substation (Suburban Area)</th>
<th>Tun</th>
<th>Duct</th>
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<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
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<th>Tun</th>
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<tr>
<td>Distance [km]</td>
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<td>377</td>
<td>148</td>
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<td>37</td>
<td>251</td>
<td>53</td>
<td>75</td>
<td>900</td>
<td>20</td>
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<tbody>
<tr>
<td>Distance [km]</td>
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<td>389</td>
<td>389</td>
<td>152</td>
<td>28</td>
<td>38</td>
<td>256</td>
<td>54</td>
<td>76</td>
<td>917</td>
<td>21</td>
<td>29</td>
</tr>
</tbody>
</table>

Note 1: For a two-terminals system the break-even distances shown in the table should be ‘multiplied by a factor of 2’ considering that the values presented in the table corresponds to the investment cost for only one station terminal.
7.2.3 Break-even distance based on losses evaluation

For the same power and operating current, the DC transmission losses and consequently their capitalised cost are less than two-thirds those of AC transmission. This is due to use of 2 cables in DC transmission, while in AC transmission there are three cables. It should be noted that DC cable transmission does not have dielectric losses, and there are no metallic screen or armour losses, which reduces even further the total transmission losses in the cable.

However, the converter station, particularly the type that includes Voltage Source Converters, has higher losses than the equivalent AC substation.

Comparing the losses on the transmission cable and losses in the terminal substation, it is possible to determine the break-even distance. The results are presented in Table 7-2. It should be noted that the break-even distances based on losses criteria depends only on the equipment rating and power transmission level, and therefore they are the same for substations located in urban or suburban area.

The following observations can be made from the analysis of Table 7-2:

- HVDC with Voltage Source Converters has higher losses as compared with HVDC with Line Commutated Converter. Therefore, the break-even distances are longer.
- The assumptions made in the design of the cable result in the break-even distances not being influenced by the size of the substation and number of circuits.
- Minimum losses are obtained when designing a cable based on minimum losses criteria. This means that the selection of a high conductor cross-section and copper instead of aluminum would be the best choice. However, with such design criteria the cost of the cable would be very high.
- The results of the calculation which gives the shortest break-even distances are:
  - HVDC-LCC-Suburban/Urban: 2x12=24km (500 MVA per circuit, in duct or buried installation)
  - HVDC-VSC-Suburban/Urban: 2x32=64km (500 MVA per circuit, in duct or buried installation)
Table 7-2 Part 1: HVDC-LCC – Break-Even Distance [km] covering the losses of the substation and transmission losses in the cable ¹

<table>
<thead>
<tr>
<th>Reference</th>
<th>250 MVA 1 circuit</th>
<th>500 MVA 1 circuit</th>
<th>500 MVA 2 circuits</th>
<th>1000 MVA 2 circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent HVDC-LCC</td>
<td>250 MW 1 Pole 2 cables</td>
<td>500 MW 1 Pole 2 cables</td>
<td>500 MW 1 Bipole 3 cables</td>
<td>1000 MW 1 Bipole 3 cables</td>
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</table>

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<tbody>
<tr>
<td>Suburban or Urban Area</td>
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<td>21</td>
<td>28</td>
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<td>12</td>
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<td>21</td>
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<td>13</td>
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Table 7-2 Part 2: HVDC-VSC – Break-Even Distance [km] covering the losses of the substation and transmission losses in the cable ¹

<table>
<thead>
<tr>
<th>Reference</th>
<th>250 MVA 1 circuit</th>
<th>500 MVA 1 circuit</th>
<th>500 MVA 2 circuits</th>
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<tbody>
<tr>
<td>Equivalent HVDC-VSC</td>
<td>250 MW 1 Bipole 2 cables</td>
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<td>1000 MW 2 Bipoles 4 cables</td>
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<tr>
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<td>53</td>
<td>53</td>
<td>73</td>
<td>32</td>
<td>32</td>
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</table>

Note 1: For a two-terminals system, the break-even distances shown in the table should be ‘multiplied by a factor of 2’ considering that the values presented in the table corresponds to the investment cost for only one station terminal.

7.2.4 Break-even distance based on both capital cost of the installation and cost of the losses

Another way to calculate the break-even distance is to consider not only the total cost of the installation (substation and transmission) but also the estimation of the cost of the electrical losses.

In the following the concept of cost of the losses is introduced.

It is known that losses in the transmission and distribution have a cost, firstly because the system should include extra generation and secondly because the system should be designed with extra capacity to deliver the peak load to cover the losses in the system.
Losses occur whenever the power system is in operation. Assume that the system has a load factor 60%. The system has an amount of losses when operating at peak load. Calling these losses ‘LP’, measured in kW, and considering an annual energy cost of 3.5 cents per kWhr [base value suggested in A2], it is then possible to estimate the cost of losses per year as follows:

\[
\text{Cost of losses} = CL = LP \times 8760 \text{ hours} \times (60\% \text{ load factor})^2 \times 3.5 \text{ cents/kWhr} = \\
= $LP \times 110.376 / \text{year}
\]

These losses correspond to the demand plus energy cost per year. In order to quantify the cost during a period of 30 years, the cost for the next 30 years can be estimated.

The cost of the losses during a period of 30 years can be calculated by using the following formula [A2]:

\[
\text{Cost of Losses next 30 years} = $ LP \times 110.376 \times \sum_{t=1}^{30} 0.95^t \\
= $ LP \times 1647
\]

where LP is the losses at peak in kW and the factor 0.95 is the assumed ‘present worth factor’ (or 1/0.95 is the discount rate). Present worth factor represents the value of money a year from now on today’s term.

**Example of application:**

Case, 250 MVA, 1 circuit HVAC transmission

Substation losses = 750 kW

Losses in 25 km cable transmission installed in duct = 1875 kW

The cost of electrical losses during consecutive 30 years = (750 + 1875) x 1647

= USD 4.3 x 10^6

In this example, the capital cost of the installation is: MUSD 11.3 for the substation and MUSD 65.0 for the cable (and installation), which gives a total value of MUSD 76.3. This shows that cost of losses in the system over a period of 30 years has some significance in the analysis (in the order of 10% of the total installation cost).

The break-even distance are now calculated considering the savings obtained in the DC cable transmission in terms capital cost of the cable transmission and reduced losses to pay the additional investment for the converter stations and higher losses in these stations when comparing with the equivalent AC transmission. The results are presented in Table 7-3.
The following observations can be made from the analysis of Table 7-3:

- The break-even distances for the HVDC-LCC are in general slightly shorter when combining the capital cost of the installation and cost of the losses. This is because an HVDC-LCC converter station does not add too much losses in the system.

- The break-even distances for the HVDC-VSC are in general slightly longer when combining capital cost and cost of losses. This is because losses in the converter station are considerable higher in this type of converter station.

- The results of the calculation which gives the shortest break-even distances are:
  - HVDC-LCC-Suburban: 2x18=36km (1000 MVA in double circuit, duct installation)
  - HVDC-LCC-Urban: 2x23=46km (1000 MVA in double circuit, duct installation)
  - HVDC-VSC-Suburban: 2x22=44km (1000 MVA in double circuit, duct installation)
  - HVDC-VSC-Urban: 2x23=46km (1000 MVA in double circuit, duct installation)

Figure 7-1 illustrates the cost break-even distance (shown with and without losses consideration) for the most favourable case (1000 MVA transmission using a double circuit, and installation of the cables in ducts). Figure 7-1 Part 1 refers to HVDC-LCC transmission and Figure 7-1 Part 2 refers to HVDC-VSC transmission.

Again, it should be pointed out that for a two-terminal system the break-even distances shown in the figure have be ‘multiplied by a factor of 2’ considering that they corresponds to investment cost and losses for only one station terminal.
Table 7-3 Part 1: HVDC-LCC – Break-Even Distance [km] covering both cost of installation and cost of losses

<table>
<thead>
<tr>
<th>Reference</th>
<th>Equivalent HVDC-LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional HVAC</td>
<td>250 MVA 1 circuit</td>
</tr>
<tr>
<td></td>
<td>500 MVA 1 circuit</td>
</tr>
<tr>
<td></td>
<td>500 MVA 2 circuits</td>
</tr>
<tr>
<td></td>
<td>1000 MVA 2 circuits</td>
</tr>
<tr>
<td>Equivalent</td>
<td>250 MW 1 Pole 2 cables</td>
</tr>
<tr>
<td></td>
<td>500 MW 1 Pole 2 cables</td>
</tr>
<tr>
<td></td>
<td>500 MW 1 Bipole 3 cables</td>
</tr>
<tr>
<td></td>
<td>1000 MW 1 Bipole 3 cables</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substation (Suburban Area)</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
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<td>165</td>
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<td>127</td>
<td>40</td>
<td>53</td>
<td>244</td>
<td>18</td>
<td>24</td>
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<table>
<thead>
<tr>
<th>Substation (Urban Area)</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance [km]</td>
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<td>210</td>
<td>210</td>
<td>128</td>
<td>29</td>
<td>37</td>
<td>159</td>
<td>49</td>
<td>66</td>
<td>302</td>
<td>23</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 7-3 Part 2: HVDC-VSC – Break-Even Distance [km] covering both cost of installation and cost of losses

<table>
<thead>
<tr>
<th>Reference</th>
<th>Equivalent HVDC-VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional HVAC</td>
<td>250 MVA 1 circuit</td>
</tr>
<tr>
<td></td>
<td>500 MVA 1 circuit</td>
</tr>
<tr>
<td></td>
<td>500 MVA 2 circuits</td>
</tr>
<tr>
<td></td>
<td>1000 MVA 2 circuits</td>
</tr>
<tr>
<td>Equivalent</td>
<td>250 MW 1 Bipole 2 cables</td>
</tr>
<tr>
<td></td>
<td>500 MW 1 Bipole 2 cables</td>
</tr>
<tr>
<td></td>
<td>500 MW 2 Bipoles 4 cables</td>
</tr>
<tr>
<td></td>
<td>1000 MW 2 Bipoles 4 cables</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substation (Suburban Area)</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance [km]</td>
<td>143</td>
<td>222</td>
<td>222</td>
<td>125</td>
<td>28</td>
<td>36</td>
<td>172</td>
<td>53</td>
<td>72</td>
<td>296</td>
<td>22</td>
<td>29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substation (Urban Area)</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
<th>Tun</th>
<th>Duct</th>
<th>Bur</th>
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<tbody>
<tr>
<td>Distance [km]</td>
<td>147</td>
<td>228</td>
<td>228</td>
<td>127</td>
<td>29</td>
<td>37</td>
<td>175</td>
<td>54</td>
<td>73</td>
<td>301</td>
<td>23</td>
<td>30</td>
</tr>
</tbody>
</table>

Note 1: The break-even distances shown in the table should be ‘multiplied by a factor of 2’ considering that the values presented in the table corresponds to the investment cost for only one station terminal.
Figure 7-1 Part 1: Break-even distance for HVDC-VSC 1000 MW two circuits, installed in ducts

Line Style:
- Point ‘.’: HVAC capital cost
- Dashed ‘- -’: HVDC capital cost
- Dashdot ‘- .’: HVAC capital cost plus cost of electrical losses
- Solid ‘—’: HVDC capital cost plus cost of electrical losses
Figure 7-1 Part 2: Break-even distance for HVDC-VSC 1000 MVA, two circuits, installed in ducts

Line Style:
- Point ‘.’ HVAC capital cost
- Dashed ‘- -’ HVDC capital cost
- Dashdot ‘- .’ HVAC capital cost plus cost of electrical losses
- Solid ‘—’ HVDC capital cost plus cost of electrical losses
7.2.5 Additional discussion related to the break-even distances

In this section some other factors that influences the break-even distances will be analyzed.

Case 1: System requires slow power flow control

Assume that the system requires additional features to control power flow. Here, the HVAC with a phase-shifting transformer will be compared with the HVDC transmission.

Assume the following case: a 1000 MVA transmission system consisting of two 500 MVA circuits (that is 1000 MVA in two circuits) and cable installation in ducts. Each circuit will require a 500 MVA phase-shifting transformer. The additional investment cost is about 10 MUSD per circuit, including the infrastructure cost for the phase-shifting transformer. With the new transformers in the network there will be additional losses in the system that have been considered in the calculation.

With the HVDC solution no extra equipment is required since power flow control is inherent in the control system of the converters.

The results of the new break-even distance are shown in Table 7-4. As can be noted the distances are somewhat shorter: reduction of about 2x3 = 6 km. The lowest break-even distance is now with HVDC-LCC located in suburban area, with the distance of about 2x15 = 30 km.

Case 2: System requires fast power flow control

Assume in this case that the system needs a fast power flow control. Assume also the following situation: without a fast power flow control the system should be designed with doubled capacity rating to prevent overload. With power flow control the system is designed assuming nominal power flow conditions.

To evaluate the break-even distance in this case the following systems will be compared: a 500 MW HVDC transmission built in a double circuit configuration against an 1000 MVA HVAC transmission built in a double circuit configuration. Both systems have comparable availability and reliability of transmission since they are built with double circuits.

The results of the new break-even distance are shown in Table 7-4. As it can be noted the distances are shorter: a reduction of about 2x8 = 16 km. The lowest break-even distance is now with HVDC-LCC located in suburban area, with the distance of about 2x10 = 20 km.
Case 3: Requirements on short circuit current

Consider a system that needs to be upgraded due to an excess of short circuit current with the following assumptions.

Circuit breakers: There are five substations that would require new breakers, each including two breakers. If a breaker costs 500 KUSD, the cost of 10 new breakers is 5 MUSD.

Buswork: The high-side buswork in each of those five substations would require rebuilding, with a cost of 1 MUSD per station.

The total amount of extra capital needed for the HVAC solution would be in the order of 10 MUSD.

The results of the new break-even distances are shown in Table 7-4. As can be noted the distances are somewhat shorter: reduction of about 2x2 = 4 km. The lowest break-even distance is now with HVDC-LCC located in a suburban area, with the distance of about 2x16 = 32 km.

Case 4: Double the transmission capacity in an existing link

Assuming that an existing 500 MVA AC transmission link should double its capability of power transmission.

With a HVAC solution it would require another 500 MVA substation and installation of a new set of AC cables in another duct system.

With a HVDC solution it would require the replacement of the existing HVAC substation with a new 1000 MW HVDC converter station. The existing HVAC cables are replaced with a new set of HVDC cable in the exiting duct system.

With those assumptions, the break-even distances are given in Table 7-4. The alternative that gives the shortest distance is HVDC-LCC located in a suburban area, with the distance of about 2x26 = 52 km.

The obtained longer distances are due to the high investment cost to install the new HVDC converter terminal.

Case 5: Assuming lower losses in the HVDC converter stations

Assume that with the development of technology, it is possible to reduce the total losses in a converter station. The following reduction in losses is assumed in this case:

- 25% reduction in a HVDC-LCC type of converter
- 50% reduction in a HVDC-VSC type of converter
The 25% reduction in losses in the HVDC-LCC type is due to the fact that a significant improvement is not expected since this is already a quite mature technology. However, for the HVDC-VSC, this is still a rather new technology and therefore a significant improvement could be expected during the coming years. This explains the reduction of 50% in losses.

The results of the new break-even distances are shown in Table 7-4. As can be noted there are no significant changes in the results. The reduction is less than 2x1 = 2 km. The lowest break-even distance is now with HVDC-LCC located in a suburban area, with the distance of about 2x18 ≈ 35 km.

Case 6: HVAC with cables placed in tunnels versus HVDC with cables placed in ducts

It has been mentioned that HVDC cables have less environmental concerns due to Electric and Magnetic Field (EMF) generated by the cables as compared with HVAC cable. (This is because HVDC cable generates a stationary magnetic field, similar to the earth’s magnetic field, while HVAC cable generates alternated magnetic fields that might induce body currents.)

Because of this, assume that a HVAC cable has to be placed in tunnels to reduce the EMF impact, while HVDC cable can be placed in ducts.

Case 6 considers 1000 MVA transmission, double circuit. Results are presented in Table 7-4.

It should be noted that the installation of HVAC cable in ducts or tunnels have about the same installation cost when transmitting 1000 MVA in a double circuit.

Case 6’ considers a 500 MVA transmission, made in a double circuit. Results are also presented in Table 7-4. In this case the improved break-even distance in clearly seen in the Table. The lowest break-even distance is with HVDC-LCC located in a suburban area, with the distance of about 2x11 = 22 km.

Case 7: Cost Reduction of HVDC terminal to get break-even distance over a distance of 20 km

In this case it is assumed that a new link would be placed between two predetermined points in the network system. The necessary capital cost reduction for HVDC terminal to compete with a conventional HVAC substation, assuming that the system does not include any extra requirements, will be determined.

Table 7-4 presents the cost reduction factors. Cost reduction factor means, the required cost reduction applied to the HVDC terminals in order to balance with the cost of HVAC transmission over a distance of 20 km.
As can be observed, a HVDC-LCC converter station requires a cost reduction of about 1.5 when the station located in a suburban area and about 2.0 if located in an urban area.

HVDC-VSC converter stations would require a cost reduction of about 2.2 if located in either a suburban area or in an urban area.

Table 7-4: Summary of results obtained from the calculations made in the discussions related to the break-even distances

<table>
<thead>
<tr>
<th>Break-even distance</th>
<th>HVDC-LCC</th>
<th>HVDC-VSC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suburban</td>
<td>Urban</td>
</tr>
<tr>
<td>Reference ²</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>Case 1</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Case 2</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Case 3</td>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td>Case 4</td>
<td>26</td>
<td>33</td>
</tr>
<tr>
<td>Case 5</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>Case 6</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Case 7 (cost reduction)</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Reference ³</td>
<td>127</td>
<td>159</td>
</tr>
<tr>
<td>Case 6'</td>
<td>11</td>
<td>14</td>
</tr>
</tbody>
</table>

Note 1: For a two-terminal system the break-even distances shown in the table should be ‘multiplied by a factor of 2’ considering that the values presented in the table corresponds to the investment cost for only one station terminal.

Note 2: Cases 1-6 use Reference ²: 1000 MVA transmission, double circuit, cable placed in ducts

Note 3: Case 6’ uses Reference ³: 500 MVA transmission, double circuit
Chapter 8

Generic conclusions

Today, most of the transmission and distribution of electrical energy is made with alternating current, since it is relatively simple to convert hierarchical voltage levels using simple and reliable transformers. This is a consolidated technology and it has been used for more than a century.

Only in special applications the transmission of electric power is made using direct current instead of alternating current. Examples of such applications are connections of asynchronous systems (e.g. systems operating at different frequencies) and very long transmission lines or long transmission cables.

The important conclusion obtained in this work is that, in general, the transmission and distribution of electrical power will be preferably made with conventional AC technique. The use of HVDC transmission to feed power into a city center will only be justified when severe restrictions exist using conventional AC technique that demand significant additional measures to mitigate. In those cases, the involved cost of these additional measures must be significantly high to justify the use of an alternative technique. Or, the implementation of those measures will make the system too complex to operate. In these cases, HVDC transmission would have advantages over the conventional AC solution, simplifying the operation of the system or resulting in a more economical solution.

There are other conclusions that are listed in the following:

Underground cable and overhead line

Comparing electrical characteristic of underground cable with overhead line, underground cables have a higher capacitive charging current and a lower characteristic impedance $Z_0$ as compared with overhead lines of the same voltage rating. The high capacitive charging current limits the utilization of cable transmission for long distances. In general distances greater than 20-30 km would require compensation to maintain the voltage profile along the cable within acceptable values.

It has been shown that with underground cable, the inductive VARs consumed by the cable, even during heavy load condition, are not sufficient to compensate the capacitive VARs. The transmitted power is normally limited by the current capacity of the cable. Therefore a cable never approaches its natural loading SIL.
It has been shown that a 50 km underground uncompensated cable is equivalent to a 360 km uncompensated overhead line when looking the performance under load conditions.

**DC and AC cable transmission**

It has been shown that a cable has a higher power transmission capability if using DC transmission as compared to an equivalent cable used for AC transmission. The capability ratio has been estimated and it is in the order of 1.5 up to 2.0. This means that in the same duct, up to 2 times more power can be transmitted with HVDC transmission as compared with HVAC transmission. Hence, the higher transmission capability has a considerable impact on the cost of the transmission system (including cable and corresponding installation).

The higher power capability is due to the higher current capability of the cable and the higher operating voltage. The higher current capability is due to the fact that a DC cable does not have dielectric losses and no metallic screen or armour losses, which allow higher current flow through the cable maintaining an equivalent temperature increase. It is estimated that the higher current capability is in the range of 1.1 up to 1.4.

Assuming that a DC cable could be stressed to the same peak voltage level as an AC cable, a higher voltage utilization of the insulation results. A factor of 1.4 has been calculated.

Cable installation has a significant impact on the total cost of the transmission. Considering that HVDC transmission has a better utilization of the cable it is possible to obtain significant savings in the installation, especially if the amount of power to be transmitted is high. The saving-factor was estimated to be in the order of two, when considering transmission of bulk power.

**Short Circuit Current**

Short circuit current has been considered an important issue in most of the cases that have been studied. In those cases the short circuit current was the major concern, resulting from the need to expand the electrical system.

HVDC converters do not contribute to short circuit current, therefore HVDC transmission can be used as an alternative to reduce the short circuit levels in the system, or when needed, to expand the system without increasing the short circuit levels.

It was verified that in a meshed system, the replacement of a single AC circuit by a HVDC link resulted in a limited reduction in short circuit current, since there are other parallel paths that contribute to the current.
An alternative to reduce the short circuit current in a meshed network is to split the electrical system into two subsystems, and connect them with a HVDC Back-to-Back link. In this case, the Back-to-Back station connects the two systems under normal operating conditions, but they are isolated during faults.

An economical alternative to reduce short circuit current is to use Current Limiting Devices, made with power electronics. With the use of a Current Limiting Device close to the generators, the short circuit current contribution from the generators could then be controlled or just be blocked. A disadvantage of using Current Limiting Devices is that back up based on different protection criteria has to be arranged.

The most economical procedure to reduce short circuit current is to add series reactors to the lines. This solution in normally combined with splitting of busbars in substations. It is known, however, that splitting busbars would affect the reliability of the system. It is also known that adding series reactors would make it more difficult to balance power flow between parallel lines in a meshed network.

**Power flow control**

In a meshed network it might be difficult to transmit and control power through some circuits due to the existence of parallel paths with lower impedances. Therefore controllable devices need to be included in the network in order to balance the power flow within different circuit paths.

Another reason to include power flow control in a network is to create a new opportunity for the operation of the system, which makes it flexible and to take advantages of different levels of electricity tariffs where different power grid supplier companies are involved.

A typical solution is to use phase-shifting transformers. However, when there are too many controllable devices of this type, the operation of the system becomes rather complicated since each phase-shifting transformer might affect the operation of the other one.

The HVDC link is an alternative solution to the conventional phase-shifting transformer, since the power flow through the link is precisely equal to the set reference given by the controls. It is not affected by different network conditions or changes in the network topology. Similar performance can be obtained with the use of FACTS devices.

There are cases in which the system has some stability problems that could impose limitations in the transmission capability, such as voltage or power stability. A typical solution to mitigate this type of problem is to reinforce the system by adding more lines and meshing the network.
The alternative solution in such a case is to introduce an intelligent control system that could immediately change power flow during special contingencies, supplying areas that are lacking power or controlling the voltage with reactive power support. HVDC (or FACTS devices) could be used in those cases since they have high-speed controls for both active and reactive power.

Reliability of supply

Reliability of supply was considered an important issue in most of the cases that have been studied. In general, duplication of the system is a basic solution to improve the reliability of the network.

Environmental aspects

The Electric Magnetic Field issue, EMF, and aesthetic considerations are environmental issues that are increasing the concerns of the general public.

Since underground cables are shielded they do not produce electric fields. The magnetic field produced by DC cable is stationary (like the Earth’s natural magnetic field), while AC cables produce alternating magnetic fields. Alternating fields can induce body currents unlike stationary fields. Therefore more restrictions are applied to AC cable transmission.

In large cities, large AC cables are best accommodated in tunnels, since this solution provides a route into densely populated urban areas. This solution provides the opportunity to maximize reliability by supplying and installing longer lengths, reducing the number of joints. However, tunnels are rather expensive and cause a lot of inconvenience to society during the construction.

Break-even distances for underground transmission

The ‘break-even distance’ is the distance in which the saving in capital cost and lower losses with DC transmission line may be enough to pay for the two converters, one at either end.

There are saving in cable transmission when comparing HVAC and HVDC systems. One reason is that a maximum of two conductors is required for DC compared to three for ac. The other reason is that a DC conductor has more power capability for transmission as compared with equivalent AC conductor.

When considering only the capital cost of the transmission system, that is, the investment cost for the station terminal and cable, the break-even distance is in the order of 40-50 km.

When considering only the losses in the substation terminals and cable transmission, the break-even distance is in the order of 25 km for HVDC with Line
Commutated Converters and 65 km for HVDC with Voltage Source Converters.

When considering the savings obtained in the DC cable transmission in terms capital cost of the cable transmission and reduced losses to pay the additional investment for the converter stations and higher losses in these stations when comparing with the equivalent AC transmission, the break-even distance is in the order of 35-45 km.

Today, the maximum length of underground cable link for city infeed is less than about 20 km. Therefore, it has been shown that for a two-terminal system, the cost reduction of the HVDC terminal to get a break-even distance over 20 km, would be about 1.5, for the station to be located in a suburban area and about 2 if located in urban area. This cost reduction is for a HVDC-LCC type of converter. For the HVDC-VSC type the cost reduction is about 2.2, either for a suburban or urban location.

Intangible benefits

In this study possible applications of HVDC systems for city infeed have been qualified and quantified. It has been shown that there are several issues considered advantageous with HVDC systems. Some of them are:

- No limits in transmitted distances, especially with underground cables
- More power can be transmitted in the same right of way
- Short circuit current can be reduced with HVDC converters
- Fast control of active and reactive power
- Improved voltage performance in the system with Voltage Source Converters
- Less environmental disturbances

There are other issues in which HVDC is attractive, but in which its benefits are difficult to be quantified. For example, in a deregulated market, with open access to transmission it is possible to take advantage of regional differences in generation costs and in the increased difficulty in constructing new transmission lines. In these cases HVDC transmission is a preferable alternative to high voltage AC systems since it permits bi-directional power flow.

An example of one such application is a recent installation, in which HVDC transmission has been used (the Cross Sound Cable) to provide a directly controllable merchant interconnection between the New England and Long Island systems, in New York, bypassing the congested New York City transmission network. Besides the merchant aspect, the transmission is also used to increase the regional reliability by increasing the ability of the New England and New York networks to share generation capacity [C11].
List of References

[A] HVAC

[B] HVDC-LCC


[C] HVDC-VSC

[C1] PWM and Control of two and three level high power Voltage Source Converters. A. Lindberg. ISSN-1100.1616. TRITA-EHE 9501. Royal Institute of Technology, Stockholm, Sweden. 1995


[D] HVDC configurations for city infeed


[E] Phase Shifting Transformer


[F] FACTS devices and other AC apparatus


[G] Cable Transmission


Addendum 1: Assumptions in the evaluation of the costs of different sizes of converter stations (Voltage Source Converters and Line Commutated Converters)

1: Reference converter station

250 MVA converter rating for the Voltage Source Converter and 500 MW for the Line Commutated Converters.

2: Converter valve

The valves in a Voltage Source Converter are scaled with IGBTs rated for 500, 1000 and 1500 Arms current. The IGBT cost will change with current.

In case of both polarities, cost and size for a full phase-leg is assumed. An example is the converter where 300 kV pole to pole is assumed. In case of only one pole, cost and size of a half phase-leg is assumed. An example is the converter where 150 kV ground to pole is assumed, which requires half of the number of series connected of IGBTs compared to the 300 kV converter.

The cost of the valve is proportional to the voltage, which defines the number of units of IGBTs connected in series.

The assumed relative cost of the IGBT in the analysis is as follows: 500 Amp-rms current (80% of the cost of a 1000 Amp unit), 1500 Amp-rms current (120% of the cost of a 1000 Amp unit). All units are rated at 2.5 kV voltage.

From the valve point of view the most cost efficient solution is to have as high current as possible. In the 5 to 10 years perspective the highest current is 1500 Arms.

Thyristor valves in Line Commutated Converters can carry current up to 4 kA and withstand blocking voltages up to 10 kV. Similar to the IGBT valves, the cost is proportional to the voltage, and the cost variation is more flat with the current rating.

3: Enclosure or Valve Hall

For the configurations in which the converter valves are placed in enclosures (DC voltage limited to 150 kV) the cost of the enclosures is proportional to the size and number of enclosure units.
For the converter that requires Valve Halls (DC voltages greater than 150 kV) the cost of the Valve Hall is proportional to $\sqrt{\text{MVA}}$ of the valves.

4: Transformer

The cost is proportional to $\sqrt{S_N}$ (that is, square root of the nominal rating of the transformer).

Converter transformers rated up to 150 MVA are three-phase units. For higher transformer ratings the assumption is a bank of three single-phase transformers.

A three-phase transformers have a cost reduction of 30% compared to a bank of three single-phase units.

A transformer designed to withstand DC voltage offset has a cost increase of about 10% when compared with an ordinary transformer that is designed to operate without DC voltage offset.

5: Phase Reactor (AC side) and smoothing reactor (DC side)

Similar to the transformer, the cost is proportional to $\sqrt{(L_N \times I_N)}$ of the reactor (that is, square root of the rating of the reactor).

6: AC filter

The cost is proportional to the MVA (rating) of the filter.

Two Voltage Source Converters in a bipolar configuration have a DC component in the AC phase, and because of that the cost is increased by a factor of 10%.

Another factor of 5% is added in case of the need to adjust different AC voltage levels.

7: DC capacitor and DC filter capacitor

The cost is proportional to the stored capacitor energy.

8: Breakers and Switches

The cost is mainly affected by the voltage level rather than the breaking current.

9: Arrester and measuring devices
Arrester cost is affected by the dissipated energy, which varies from project to project. In this analysis it has been assumed proportional to the rating of the converter station. Measuring devices are assumed to have a fixed cost for all converter stations.

10: Control
A factor of 10% or 25% has been assumed to adjust to the different voltage levels.

11: Auxiliary power
The cost is proportional to the rating of the converter station.

12: Engineering
A fixed cost for a converter station has been assumed. Therefore, in a converter station that includes more than one converter, the engineering cost is split within the number of converters.
Addendum 2: Reference data used in the calculation of Break-Even Distances

1 HVAC substations

This addendum includes the reference data used in the calculation of break-even distances to compare HVAC and HVDC underground transmission systems. Four different basic configurations have been considered as follows:

- Configuration 1: 250 MVA rating capacity in a single circuit transmission
- Configuration 2: 500 MVA rating capacity in a single circuit transmission
- Configuration 3: 500 MVA rating capacity in a double circuit transmission
- Configuration 4: 1000 MVA rating capacity in a double circuit transmission

In general, a HVAC substations is built in four parts: 1) the high-side bus-work and protection that corresponds to the incoming transmission; 2) the low-side bus-work and protection that corresponds to the outgoing distribution; 3) the transformers that are the most distinguishing characteristic of a substation, which normally defines its capacity; 4) the site itself. The cost of each of these parts will increases with higher voltage, higher capacity and higher reliability.

In order to evaluate the cost of those different parts for each studied configuration, the following reference substations have been used from the literature [A2], and they are reproduced in Table A2-1.

The substations for configurations 1-4 were then scaled up or scaled down based on the following rules of thumb:

- Cost tends to increase as the square root of relative rating. For example, increasing the substation rating from 250 MVA to 500 MVA the cost increases by a factor of about 1.4.

- Cost increases in proportion to the increase of number of circuits. A substation with two 250 MVA circuits is two times more expensive as compared with a substation with just one 250 MVA circuit.

- Site tends to increase as the square root of relative rating. Increasing the substation rating from 250 MVA to 500 MVA the required site space increases by a factor of about 1.4.

- Site space tends to be proportional to increases in the substation capacity due to multiple numbers of circuits. Increasing the substation rating from one 250 MVA circuit to two 250 MVA circuits, the required site space increases by about a factor of 2.
Table A2-1: Representative HVAC Distribution Substation cost and site cost [A2]

<table>
<thead>
<tr>
<th>Reference 1 – Suburban Substation</th>
<th>Reference 2 – Urban Substation</th>
</tr>
</thead>
<tbody>
<tr>
<td>325 MVA</td>
<td>375 MVA</td>
</tr>
<tr>
<td>230kV / 25kV / 12.47kV</td>
<td>230kV / 25kV</td>
</tr>
<tr>
<td>5 incoming circuits</td>
<td>3 incoming circuits</td>
</tr>
<tr>
<td>3 x 75MVA 230/25kV</td>
<td>5 x 75 MVA 230/25kV</td>
</tr>
<tr>
<td>2 x 50MVA 230/12.47kV</td>
<td></td>
</tr>
<tr>
<td>12 x 25kV feeders</td>
<td>15 x 25kV feeders</td>
</tr>
<tr>
<td>8 x 12.47kV feeders</td>
<td></td>
</tr>
<tr>
<td>Peak load 288MVA</td>
<td>Peak load 225 MVA</td>
</tr>
<tr>
<td>Capital = 11.2 x 10^6 USD</td>
<td>Capital = 19.2 x 10^6 USD</td>
</tr>
<tr>
<td>Site – Area required = 32000 m²</td>
<td>Site – Area required = 4000 m²</td>
</tr>
<tr>
<td>Site – Estimate Cost = 1.3 x 10^6 USD</td>
<td>Site – Estimate Cost = 3.5 x 10^6 USD</td>
</tr>
</tbody>
</table>

2 HVDC-LCC and HVDC-VSC substations

Equivalent HVDC converter substations with Line Commutated Converters and Voltage Source Converters were calculated for each of the configurations, 1-4. The calculations were based on a few representative substations, which are presented in Table A2-2. Sources of information are [B5] and [B7] and some projects that have recently been put into service. The values are then scaled up or scaled up based on the assumptions presented in Addendum 1.

It should be noted that a bipolar HVDC-LCC transmission or 2 Bipoles HVDC-VSC transmission is equivalent to a double-circuit HVAC transmission, especially when availability and reliability is considered.
Table A2-2: Representative costs of a converter station with Line Commutated Converters and Voltage Source Converters and required number of transmission cables and space requirements

<table>
<thead>
<tr>
<th>HVDC-LCC 500 MW</th>
<th>HVDC-VSC 500 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 monopole</td>
<td>1 Bipole</td>
</tr>
<tr>
<td>2 cables</td>
<td>2 cables</td>
</tr>
<tr>
<td>44 MUSD</td>
<td>48 MUSD</td>
</tr>
<tr>
<td>80 x 180 = 14400 m²</td>
<td>40 x 90 = 3600 m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HVDC-LCC 500 MW</th>
<th>HVDC-VSC 500 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Bipole</td>
<td>2 Bipoles</td>
</tr>
<tr>
<td>3 cables</td>
<td>4 cables</td>
</tr>
<tr>
<td>63 MUSD</td>
<td>80 MUSD</td>
</tr>
<tr>
<td>2 x (80 x 180) = 28800 m²</td>
<td>2 x (40 x 90) = 7200 m²</td>
</tr>
</tbody>
</table>

In terms of space requirement, the following values were assumed based on existent installations:

- HVDC with VSC:
  - 250 MW: 35 x 80 = 2800 m²
  - 500 MW: 40 x 90 = 3600 m²
- HVDC-LCC:
  - 600 MW: 80 x 180 = 14400 m² (compact design substation base on active AC filter – con-tune AC filter)

3 Cable design

For HVAC cables the following assumptions have been used:

- Continuous conductor temperature: 65 degrees. This assumption maintains safe margins to keep lower losses and to avoid possible thermal instability due to drying out the surrounding soil.
• Cross-Bonding of screen, to reduce losses in the screen.
• Flat formation of the cables.
• Preference for Aluminum conductor. In case aluminum conductor can not be used, then copper conductor has been considered, with a cost increase by a factor 1.5.
• Current capability increased by a factor 1.25 to guarantee the required MW power flow due to capacitive current charge.
• Assumed cable cost: 0.44 MUSD/km for one system (three cables) including joints and terminations.
• Assumed average cost for the installation based on values considered for a middle size city:
  o Tunnel – range: 5.0-6.9 (average: 5.9 MUSD/km)
  o Ducts – range: 1.3-3.1 (average: 2.2 MUSD/km)
  o Buried – range: 0.9-1.9 (average: 1.4 MUSD/km)

Some notes regarding installation cost:
Tunnel cost tends is increase by a factor 1.25 when the number of cables is increased by a factor of 2. This assumption was based on the fact that the heat dissipation constraint in tunnels is not as severe as when the cable is installed in a duct or buried underground.

Buried installation or installation in ducts: If a single circuit includes two cables, the cost for installation in ducts or buried increases by a factor 1.5. A double circuit has a cost increased by a factor 2. This is because of the higher constraints regarding heat dissipation.

Regarding HVDC cable, the following assumptions were included:
• Both HVDC-LCC and HVDC-VSC have similar converter topologies, that is, a bipole consists of a converter and two 150 kV cables. This corresponds to a single HVAC circuit. Two bipoles consist of two converters and four cables. This corresponds to a double HVAC circuit.
• Continuous conductor temperature: 65 degrees. It should be noted that this is the same maximum cable temperature as assumed for the AC cable. This is a very conservative assumption based on the fact that with HVDC it is possible to control the power flow through the cable and therefore it would be possible to utilize the cable more effectively with lower margins.
• Both ends of the cable screen are grounded. (The grounding of the screen does not affect the design of a DC cable.)
• Flat formation of the cables.
• Preference for Aluminum conductor. In case aluminum conductor can not be used, then copper conductor has been considered, with a cost increase by a factor 1.5.
• Assumed cable cost: 0.3 MUSD/km for one system (two cables) including joints and terminations
• Cost of installation. Since DC cable has reduced demands for heat dissipation as compared with AC cable, it is possible to use the following more favorable cost figures: when the number of cables is doubled a factor 1.25 is applied for cable installed in tunnel or 1.5 for cable installed in ducts or buried cable.

4 Losses in substations
Table A2-3 shows the assumed substation losses for the different types of transmission. For HVDC transmission with Voltage Source Converters a 3-level converter is assumed that gives lower losses as compared with a 2-level converter.

Table A2-3: Theoretical loss evaluation for different types of transmission

<table>
<thead>
<tr>
<th>Substation terminal</th>
<th>Substation terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC substation</td>
<td>0.3 %</td>
</tr>
<tr>
<td>HVDC-VSC (3-level converter)</td>
<td>1.7 %</td>
</tr>
<tr>
<td>HVDC-LCC</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>
## Summary of reference data

Table A2-4 gives a summary of base data for all four different configurations that have been studied.

### Table A2-4: Base data for a HVAC Substation and Cable

<table>
<thead>
<tr>
<th></th>
<th>250 MVA</th>
<th>500 MVA</th>
<th>500 MVA</th>
<th>1000 MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 circuit</td>
<td>1 circuit</td>
<td>2 circuits</td>
<td>2 circuits</td>
</tr>
<tr>
<td><strong>Substation (Suburban Area)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Voltage Side</td>
<td>2.0</td>
<td>2.7</td>
<td>4.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Transformer Unit</td>
<td>8.0</td>
<td>11.3</td>
<td>16.0</td>
<td>22.6</td>
</tr>
<tr>
<td>Transformer</td>
<td>3.0</td>
<td>9.0</td>
<td>14.0</td>
<td>19.9</td>
</tr>
<tr>
<td>Low Voltage part</td>
<td>1.0</td>
<td>1.4</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>10.0</td>
<td>14.0</td>
<td>20.0</td>
<td>28.1</td>
</tr>
<tr>
<td><strong>Site Cost</strong></td>
<td>1.3</td>
<td>1.8</td>
<td>2.6</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Site Space</strong></td>
<td>32000</td>
<td>45000</td>
<td>64000</td>
<td>90000</td>
</tr>
<tr>
<td><strong>Losses</strong></td>
<td>0.75</td>
<td>1.3</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Substation (Urban Area)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Voltage Side</td>
<td>3.1</td>
<td>4.3</td>
<td>6.2</td>
<td>8.5</td>
</tr>
<tr>
<td>Transformer Unit</td>
<td>12.6</td>
<td>17.8</td>
<td>25.1</td>
<td>35.5</td>
</tr>
<tr>
<td>Transformer</td>
<td>11.0</td>
<td>15.6</td>
<td>22.0</td>
<td>31.1</td>
</tr>
<tr>
<td>Low Voltage part</td>
<td>1.6</td>
<td>2.2</td>
<td>3.1</td>
<td>4.4</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>15.7</td>
<td>22.1</td>
<td>31.3</td>
<td>44.0</td>
</tr>
<tr>
<td><strong>Site Cost</strong></td>
<td>3.5</td>
<td>4.9</td>
<td>7.0</td>
<td>9.9</td>
</tr>
<tr>
<td><strong>Site Space</strong></td>
<td>4000</td>
<td>5600</td>
<td>8000</td>
<td>11200</td>
</tr>
<tr>
<td><strong>Losses</strong></td>
<td>0.75</td>
<td>1.5</td>
<td>1.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Cable</strong></th>
<th><strong>Installation type</strong></th>
<th><strong>Tun</strong></th>
<th><strong>Duct</strong></th>
<th><strong>Bus</strong></th>
<th><strong>Tun</strong></th>
<th><strong>Duct</strong></th>
<th><strong>Bus</strong></th>
<th><strong>Tun</strong></th>
<th><strong>Duct</strong></th>
<th><strong>Bus</strong></th>
<th><strong>Tun</strong></th>
<th><strong>Duct</strong></th>
<th><strong>Bus</strong></th>
<th><strong>Tun</strong></th>
<th><strong>Duct</strong></th>
<th><strong>Bus</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cable Type</strong></td>
<td>A1000</td>
<td>A1200</td>
<td>A1200</td>
<td>C2000</td>
<td>A1000</td>
<td>A1200</td>
<td>A1200</td>
<td>C2000</td>
<td>A1000</td>
<td>A1200</td>
<td>C2000</td>
<td>A1000</td>
<td>A1200</td>
<td>C2000</td>
<td>A1000</td>
<td>A1200</td>
</tr>
<tr>
<td>No. cables/phase</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Cable Cost</strong></td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>1.3</td>
<td>1.3</td>
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<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Installation Cost</strong></td>
<td>9.5</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>0.4</td>
<td>2.6</td>
<td>4.6</td>
<td>6.6</td>
<td>9.2</td>
<td>13.0</td>
<td>8.3</td>
<td>13.7</td>
<td>8.3</td>
<td>13.7</td>
<td>8.3</td>
<td>13.7</td>
<td>13.7</td>
<td>13.7</td>
<td>13.7</td>
<td>13.7</td>
</tr>
<tr>
<td><strong>Losses</strong></td>
<td>0.75</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
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<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
<td>117</td>
</tr>
</tbody>
</table>

### Notes to Table A2-4:

1. Substation losses given in MW at peak load
2. Cable losses given in kW/km
3. Cost including joints, terminations
Table A2-4 Part 2: Base data for an HVDC-LCC Substation and Cable

<table>
<thead>
<tr>
<th></th>
<th>250 MW 1 Pole 2 cables</th>
<th>500 MW 1 Pole 2 cables</th>
<th>500 MW 1 Bipole 3 cables</th>
<th>1000 MW 1 Bipole 3 cables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Substation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Converter Station</td>
<td>32</td>
<td>44</td>
<td>63</td>
<td>88</td>
</tr>
<tr>
<td>Transformer Unit</td>
<td>8.0</td>
<td>11.3</td>
<td>16.0</td>
<td>22.6</td>
</tr>
<tr>
<td>Transformer</td>
<td>7.0</td>
<td>9.9</td>
<td>14.0</td>
<td>19.8</td>
</tr>
<tr>
<td>Low Voltage part</td>
<td>1.0</td>
<td>1.4</td>
<td>2.0</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>49</td>
<td>55</td>
<td>79</td>
<td>111</td>
</tr>
<tr>
<td><strong>Site Cost</strong></td>
<td>1.3</td>
<td>1.9</td>
<td>2.7</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Total Site Space</strong></td>
<td>31200</td>
<td>45000</td>
<td>66500</td>
<td>91100</td>
</tr>
<tr>
<td><strong>Concerted</strong></td>
<td>11900</td>
<td>15000</td>
<td>23800</td>
<td>31700</td>
</tr>
<tr>
<td><strong>Low Voltage</strong></td>
<td>21300</td>
<td>30000</td>
<td>42700</td>
<td>60000</td>
</tr>
<tr>
<td><strong>Losses</strong></td>
<td>1.9</td>
<td>3.8</td>
<td>3.8</td>
<td>7.6</td>
</tr>
</tbody>
</table>

|                     |                         |                        |                          |                           |
| **Substation**      |                         |                        |                          |                           |
| Converter Station   | 32                      | 44                     | 63                       | 88                        |
| Transformer Unit    | 12.6                    | 17.8                   | 25.1                     | 35.5                      |
| Transformer         | 11.0                    | 15.6                   | 22.0                     | 31.1                      |
| Low Voltage part    | 1.6                     | 2.2                    | 3.3                      | 4.4                       |
| **Total Cost**      | 45                      | 62                     | 88                       | 124                       |
| **Site Cost**       | 12.8                    | 17.1                   | 25.3                     | 34.3                      |
| **Total Site Space**| 14600                   | 19500                  | 29100                    | 39200                     |
| **Concerted**       | 11900                   | 15000                  | 23800                    | 31700                     |
| **Low Voltage**     | 2700                    | 3700                   | 5300                     | 7500                      |
| **Losses**          | 1.9                     | 3.8                    | 3.8                      | 7.6                       |

| **Cable**           |                         |                        |                          |                           |
| Installation type   | Tun                      | Duct                    | Bar                      | Tun                      |
| Cable Type          | Al950                    | Al900                   | Al800                    | Cu1400                   |
| No. cable/pole      | 1.0                      | 1.0                     | 1.0                      | 1.0                      |
| **Cable Cost**      | 0.3                      | 0.3                     | 0.4                      | 0.4                      |
| Installation Cost   | 5.9                      | 2.2                     | 1.4                      | 5.9                      |
| Total Cost          | 6.3                      | 2.5                     | 1.7                      | 6.3                      |
| **Losses**          | 78                       | 61                      | 61                       | 88                       |

Notes to Table A2-4:
1: Substation losses given in MW at peak load
2: Cable losses given in kW/km
3: Cost including joints, terminations
### Table A2-4 Part 3: Base data for an HVDC-VSC Substation and Cable

<table>
<thead>
<tr>
<th></th>
<th>250 MW 1 Bipole 2 cables</th>
<th>500 MW 1 Bipole 2 cables</th>
<th>500 MW 2 Bipoles 4 cables</th>
<th>1000 MW 2 Bipoles 4 cables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Substation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Converter Station</td>
<td>40</td>
<td>48</td>
<td>80</td>
<td>96</td>
</tr>
<tr>
<td>Transformer Unit</td>
<td>8.0</td>
<td>11.3</td>
<td>16.0</td>
<td>22.8</td>
</tr>
<tr>
<td>Transformer</td>
<td>9.9</td>
<td>14.8</td>
<td>19.8</td>
<td>25.8</td>
</tr>
<tr>
<td>Low Voltage part</td>
<td>1.0</td>
<td>1.4</td>
<td>2.0</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>48</td>
<td>59</td>
<td>96</td>
<td>119</td>
</tr>
<tr>
<td>Site Cost</td>
<td>19</td>
<td>14</td>
<td>2.5</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Total Site Space</strong></td>
<td>24400</td>
<td>34000</td>
<td>489000</td>
<td>680000</td>
</tr>
<tr>
<td>Conductor</td>
<td>3100</td>
<td>4000</td>
<td>6200</td>
<td>10000</td>
</tr>
<tr>
<td><strong>Low Voltage</strong></td>
<td>21100</td>
<td>30000</td>
<td>427000</td>
<td>600000</td>
</tr>
<tr>
<td>Losses</td>
<td>3.3</td>
<td>7.3</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td><strong>Substation</strong></td>
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Notes to Table A2-4:

1: Substation losses given in MW at peak load
2: Cable losses given in kW/km
3: Cost including joints, terminations