# NEAR EAST UNIVERSITY

## Faculty of Engineering

## Department of Electrical and Electronics Engineering

# High Voltage Direct Current Transmission (HVDC)

Graduation Project
EE- 400

Student: Walied Ahmed Hussein (970894)

Supervisor: Mr. Özgür Cemal Özerdem

Nicosia - 2002

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# ACKNOWLEDGEMENT

First of all, I would like to thank all of those who made it possible for this thesis to see the light. Special thanks for Mr. Ozgur Ozerdim, who was the thesis's supervisor and who also supported me through my research for the right source materials and helped me in the process of searching and preparing, for him goes my special thanks. I would also like to thank all of my friends who by anyhow have helped me getting this job done.

Finally, I am proud to thank may family for their continuous support and passion that have guided me through all of my academic life as well as in my real life and for being there whenever needed, for them all my love.

# ABSTRACT

High-voltage DC transmission installations are being built all over the world as a useful alternative to AC transmission systems or extra-high voltage transmission systems.

From the very beginnings of HVDC technology with mercury-vapor tubes to the microprocessor-controlled semiconductor systems of today, HVDC technology is being continually developed. Depending on the power-system conditions in each case, HVDC transmission systems are being installed for long-distance transmission of high voltages by overhead lines and by sea-cables as back-to-back links, e.g., for connecting two independently operated power systems.

As we can see, HVDC technology is becoming a very important factor in the industry of high voltage transmission in the world. From here, comes the reason why I chose HVDC to be the subject of my thesis.

I have tried to gather as much of information concerning this topic as I can and introduce them in a simple understanding manner, which would help understanding the concept of HVDC system as well as for its importance for high voltage transmission applications.

Names, classifications, standards, types and definitions of HVDC system components differ from a manufacturer to another. But in general the main concept is the same. In this thesis, ABB's (ABB is the leading organization in HVDC systems) standards are considered as a reference for the naming, classifying and defining of the HVDC system components.

## Table of Contents

# INTRODUCTION

High-voltage direct-current (HVDC) transmission is used for the bulk transfer of electricity over large distances at high voltage and in direct-current mode. The first HVDC project was built in Sweden in 1954 with a power rating of 20 MW and 100 kV over a distance of 96 km. The largest HVDC project is in Brazil and was built in 1987, with a power rating of 6.3 GW and 600 kV over a distance of 800 km.

High-voltage DC systems are specially designed to fulfill specific tasks, of which there are fundamentally three different types:

1. HVDC for long distance point-to-point transmissions, where there are no limitations to the length of cable because there are no stability problems in HVDC installations. The load flow remains stable over the entire power range, greatly reducing investment costs.
2. HVDC with back-to-back ties, used to connect two power networks that function independently from one another. Using cable only a few yards in length, both rectifiers and inverters are operated in a single station.
3. HVDC installations with multi-terminal transmissions.

This advanced power transmission technology in addition to the Flexible AC Transmission Systems are very promising technologies that are making a revolutionary development in the high voltage transmission systems industry. New methods of power generation, such as thermoelectric, magnetohydrodynamic and fuel cells (which generate direct current), will make HVDC more attractive.

In this thesis I have tried to simplify the concept of High Voltage Direct Current transmission in an understandable interesting sequence of topics. Towards that, this thesis is divided into four chapters.

The first chapter is presenting the High Voltage AC Transmission systems and Flexible AC Transmission systems and their applications. A quick comparison between AC transmission systems and DC transmission systems is also made in this chapter.

In the following chapter, the concept of HVDC system is explained with its different types being briefly explained. A historical overview of the development of the technology of HVDC is also mentioned in this chapter. Finally, an interesting argument explaining the advantages of HVDC systems.

As for the third chapter, the HVDC technology is discussed with a sufficient explanation for the corresponding components that the HVDC technology is built upon. A new concept is introduced in this chapter, which is the HVDC 2000 (an advanced HVDC system) discussing its applications and the technology involved in its development. At the end of this chapter, a section discussing the control of HVDC systems is provided.

The forth chapter introduces HVDC Light technology, explains it, discuss the technology involved in the development of this technology, explain the different applications in which such technology is of greater priority and provides a powerful comparison between the HVDC systems and HVDC Light at the en of this chapter.

Finally, A conclusion is derived upon all what have been discussed in this thesis offering possible solutions or suggestions that would be of a great benefit if were taken in consideration for TRNC.

# CHAPTER 1

# ALTERNATING CURRENT AND FLEXIBLE TRANSMISSION

## 1.1 High Voltage Alternating Current (HVAC) Transmission Systems

There are two basic types of power lines: Transmission Lines and Distribution Lines. **Transmission lines** are high-voltage power lines. The high voltage allows electric power to be carried efficiently over long distances from electrical generation facilities to substations near urban areas. Most transmission lines use alternating current (AC) and operate at voltages between 50 and 765 kV (lkV or kilovolt = 1000 V).

Utilities use lower-voltage **Distribution Lines** to bring power from sub-stations to businesses and homes. Distribution lines operate at voltages below 50 kV. For residential customers, these levels are further reduced to 120/240 V once the power reaches its destination. Each transmission system is of course composed of these two types of power lines one of these systems is High Voltage Alternating Current Transmission System.

HVAC transmission systems are commonly used to transport energy from power plants to main consumption centers. Systems up to 800 kV are presently in commercial operations. The following variables need to be taken into account when designing optimized HVAC transmission systems:

1. Power to be transmitted and transmission line length
2. Required system reliability and availability levels (these influence the redundancy-related design criteria)
3. Power loss levels, impacting on the total system cost
4. Local standards and environmental conditions, affecting component design and selection
5. Acceptable environmental impact

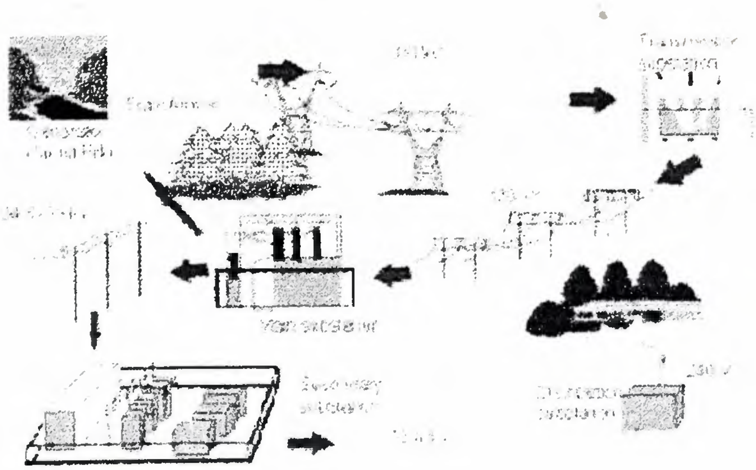

**Figure 1.1** HVAC transmission system

In broad terms, HVAC systems are a combination of engineered solutions, comprising:

1.Overhead transmission lines

2.Substations

3.Power flow control and compensation devices

4.Underground and submarine cables

Combining the above variables to construct an optimized transmission system ensures that every one is a tailor made solution.

## 1.2 DC Versus AC Transmissions

Power stations generate alternating current, AC, and the power delivered to the consumers is in the form of AC. Why then is it sometimes more suitable to use direct current for transmitting electric power?

The reasons behind a choice of DC instead of AC to transmit power in a specific case are often numerous and complex. Each individual transmission project will display its own set of reasons, but the most common reasons that cause to choose DC transmissions can be divided into three groups, these are:

1. Technical
2. Economical
3. Environmintal

In many cases, projects are justified on a combination of benefits from the three groups. Today the environmental aspects are also becoming more important. DC transmission is in that respect favorable in many cases, as the environmental impact is less than with AC. This is due to the fact that an DC transmission line is much smaller and needs less space than AC lines for the same power capacity.

The system characteristics of a DC link differ a lot from AC transmissions. One of the most important differences is related to the possibility to accurately control the active power transmitted on a DC transmission line. This is in contrast to AC lines, where the power flow cannot be controlled in the same direct way. The controllability of the DC power is often used to improve the operating conditions of the AC networks where the converter stations are located.

Another important property of a DC transmission is that it is asynchronous. This allows the interconnection of non-synchronous networks. In other words we can summarize the advantages of DC transmissions in the following:

1. More power can be transmitted per conductor per circuit.

2. Use of Ground Return Possible:

In the case of DC transmission, ground return (especially submarine crossing) may be used, as in the case of a Monopolar DC link. Also the single circuit bipolar DC link is more reliable, than the corresponding AC link as in the event of a fault on one conductor, the other conductor can continue to operate at reduced power with ground return. For the same length of transmission, the impedance of the ground path is much less for DC than for the corresponding AC because DC spreads over a much larger width and depth.

3. Smaller Tower Size: The DC insulation level for the same power transmission is likely to be lower than the corresponding AC level. Also the DC line will only need two conductors whereas three conductors (if not six to obtain the same reliability) are required for AC. Thus both electrical and mechanical considerations dictate a smaller tower.

4. Higher Capacity available for cables:

In contrast to the overhead line, in the cable breakdown occurs by puncture and not by external flashover. Mainly due to the absence of ionic motion, the working stress of the

DC cable insulation may be 3 to 4 times higher than under AC. Also, the absence of continuous charging current in a DC cable permits higher active power transfer, especially over long lengths.

5. No skin effect:

Under AC conditions, the current is not uniformly distributed over the cross section of the conductor. The current density is higher in the outer region (skin effect) and result in under utilization of the conductor cross section. Skin effect under conditions of smooth DC is completely absent and hence there is a uniform current in the conductor, and the conductor metal is better utilized.

6. Less corona and radio interference:

Since corona loss increases with frequency (in fact it is known to be proportional to f+25), for a given conductor diameter and applied voltage, there is much lower corona loss and hence more importantly less radio interference with DC Due to this bundle conductors become unnecessary and hence give a substantial saving in line costs.

7. No Stability Problem:

The DC link is an asynchronous link and hence any AC supplied through converters or DC generations do not have to be synchronized with the link. Hence the length of DC link is not governed by stability.

8. Asynchronous interconnection possible:

With AC links, interconnections between power systems must be synchronous. Thus different frequency systems cannot be interconnected. Such systems can be easily interconnected through DC transmission links.

9. Lower short circuit fault levels:

When an AC transmission system is extended, the fault level of the whole system goes up, sometimes necessitating the expensive replacement of circuit breakers with those of higher fault levels. This problem can be overcome with DC, as it does not contribute current to the AC short circuit beyond its rated current. In fact it is possible to operate a DC link in "parallel" with an AC link to limit the fault level on an expansion.

10. Tie line power is easily controlled:

In the case of an AC tie line, the power cannot be easily controlled between the two systems. With DC tie lines, the control is easily accomplished through grid control. In fact even the reversal of the power flow is just as easy.

### 1.2.1 Areas of Application

The question is often asked as to when should a DC transmission system be chosen over an AC system. In answering this question, we can say that DC transmission systems are to be chosen when the case is one of the following:

1. Large amounts of power (>500 MW) needed to be transmitted over long distances (>500 km)
2. Transmitting power under water
3. Interconnecting two AC networks in an asynchronous manner.

### 1.2.2 Decision Making

So how should power system planners, investors in power infrastructure (both public and private), and financiers of such infrastructure be guided with respect to choosing between a high voltage DC transmission system and a high voltage AC system? The answer is to let the "market" decide. In other words:

1. The planners, investors and financiers should issue functional specifications for the transmission system to qualified contractors, as opposed to the practice of issuing technical specifications (which are often inflexible, and many times include older technologies and techniques) while inviting bids for a transmission system.
2. The functional specifications could lay down the power capacity, distance, availability and reliability requirements; and last but not least, the environmental conditions.
3. The bidders should be allowed to bid either a DC solution or an AC solution and the best option chosen.

It is quite conceivable that with changed circumstances in the electricity industry, the technological developments, and environmental considerations, high voltage DC transmission systems would be the preferred alternative in many more transmission projects.

## 1.3 Flexible AC Transmission Systems-FACTS

With the ongoing deregulation of the electricity supply industry, the demands for flexibility in power transmission are growing continuously. This gives added momentum to established solutions for flexibility in power transmission, as well as openings up opportunities for quite new technologies in the field.

The collective acronym FACTS has been adopted in recent years to describe a wide range of controllers, many of them incorporating large power electronics converters, which may be used to increase the flexibility of power systems and thus make them more controllable.

The two main reasons for incorporating FACTS devices in transmission systems are:

1.Extend power transfer limits

2.Provide better power flow control

FACTS devices are used for the dynamic control of voltage, impedance and phase angle of high voltage AC transmission lines. Below the different main types of FACTS devices are described:

### 1.3.1 Static Var Compensation

Optimum power transmission and distribution entails the reduction of transfer losses and provision of adequate power supply quality and availability at the receiving end. In other words, what matters is how much power gets through, not how much is generated.

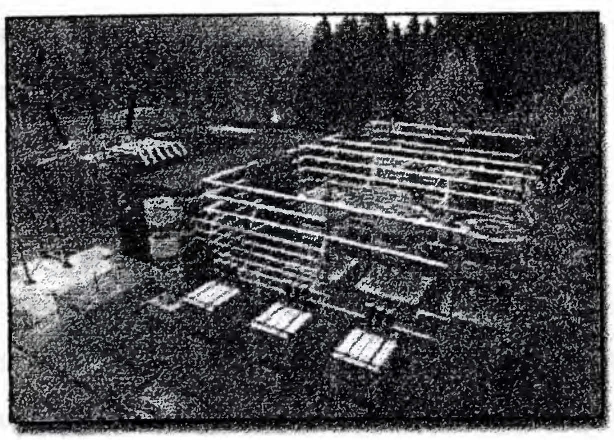

**Figure 1.2** Static Var Compensation

Transmission lines both generate and absorb reactive power. Since the transmitted load varies considerably from one hour to another, the reactive power balance of the line varies as well. A rapidly operating Static Var Compensator (SVC) can continuously control dynamic power swings under various system conditions. The main reasons for incorporating SVC in transmission systems are:

1. To stabilize voltage in weak systems
2. To reduce transmission losses
3. To increase the transmission capacity
4. To increase the transient stability limit
5. To increase damping of small disturbances
6. To improve voltage control and stability
7. To damp power swings

The characteristics of Static Var Compensators are their flexibility, dependability and their exceptional controllability. SVC can be used for symmetrical three-phase control or phase-by phase control.

#### 1.3.1.1 STATCOM

With the commercial breakthrough of high power Gate Turn-Off (GTO) and Insulated Gate Bipolar Transistors (IGBT), the road is paved for an additional step forward in flexibility of AC transmission and distribution systems: STATCOM - Static Synchronous Compensator.

STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs.

#### 1.3.1.2 SVC Light - STATCOM

SVC Light is a device of the STATCOM type, based on voltage source converter technology equipped with IGBT. With the advent of SVC Light, still better performance can be reached in areas such as:

1.Dynamic and steady-state voltage control in transmission and distribution systems
2.Transient stability improvements
3.Power oscillation damping in power transmission systems
4.Ability to control both active and reactive power

SVC Light can be seen as a voltage source behind a reactance. It provides reactive power generation as well as absorption purely by means of electronic processing of voltage and current waveforms in a voltage source converter. This means that capacitor banks and shunt reactors are not needed for generation and absorption of reactive power, giving a compact design, a small footprint, as well as low noise and low magnetic impact.

The voltage source converter has the same rated current capability when operating with capacitive or inductive reactive current. Therefore a converter having a certain MVA rating gives SVC Light twice the dynamic range in Mvar. This also contributes to a compact design. A DC capacitor bank is utilized to support, stabilize, the controlled DC voltage needed for the operation of the converter.

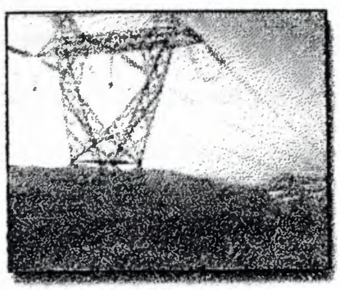

**Figure 1.3** HVDC line

Depending on the desired rating and application, three main circuit configurations of SVC Light are valid. Each has specific advantages:
1.typically tens of Mvar up to hundreds Mvar
2.Dual Converter Scheme - Suitable for large dynamic ranges, typically above 100 Single Converter Scheme - Suitable for medium size dynamic ranges, Mvar
3.Dual Purpose Scheme - Offers active power transfer and dynamic reactive power compensation to each connected AC system simultaneously and independently.

### 1.3.2 Series Compensation

In today's power market, concessions for new transmission lines can be subject to long and exhaustive discussions. Squeezing more active power out of existing lines by means of series compensation can be than a more immediate and compelling alternative.

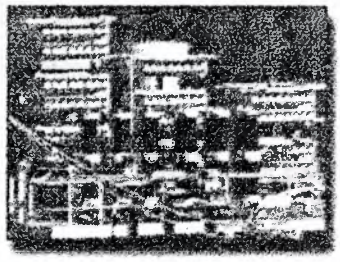

**Figure 1.4** Series Capacitor

The use of series capacitors for compensating the inductive reactance of long distance lines is the most effective and economic method of improving power transfer. The two main reasons for incorporating series capacitors in transmission systems are:

1.To increase power transfer capability as a result of raising the transient stability limit.

2.To reduce transmission system losses by optimizing the sharing of active power between parallel lines. Optimization of the active power transfer process is not only key to reliability, cost efficiency and competitiveness, but also creating an environmental friendly image.

### 1.3.3 Thyristor Controlled Series Capacitors

Thyristor Controlled Series Capacitors (TCSC), Thyristor Switched Series Capacitors (TSSC) and Mechanically Switched Series Capacitors (MSSC) provide a proven technology that can address the different needs of the transmission system.All installations of series compensation presently in operation use passive capacitor banks as the main component to provide reactive power. Adding control means to the fixed capacitor permits a variation of the inserted capacitor reactance, physically or virtually, so that the degree of compensation can be controlled. Such means may be based on mechanical switching equipment or on semiconductor technology in the form of power thyristors.

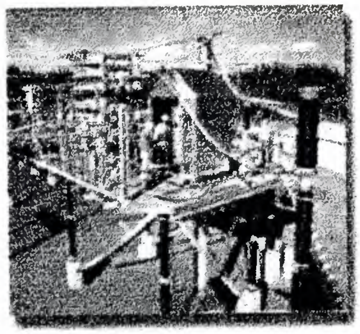

**Figure 1.5** Thyristor Controlled Series Capacitor

Controlling power flow on specific lines allows the following achievements:

1.Minimum system losses

2.Power oscillation damping

3.Avoiding of subsynchronous resonance

4.Adapted power transfer to actual conditions

5.Improved post-contingency stability.

### 1.3.3.1 Controllable Series Capacitors Patent

In recent years, progress in the field of high power electronics, has made it possible to build converters placed on high potential. This technology can be used to perform different tasks such as Thyristor Controlled Series Capacitors (TCSCs). The development of direct light triggered thyristors has made it possible to design reliable converters using minimum of components on potential. Several demonstration projects have shown that the uses of semiconductors on high potential are a reliable and today feasible technology. The patent is a result of recent work describing control algorithms for controllable series capacitor, changing its impedance in the sub-harmonic frequency range. Using the synchronous voltage reversal (SVR) control algorithm eliminates the problems associated with sub-synchronous resonance problems, when series compensation at high levels are introduced in networks close to thermal generating units equipped with long shafts.

Further improvements has been made in the field of computation tools for network studies that together with the powerful hardware development, makes it possible to perform fast studies of networks and relate the results to the development of the associated TCSC control algorithms.

The concept of TCSC can be used for a wide range of objectives in the power system control technology. Recent studies shows that thyristor controlled series capacitors enables higher compensation degrees without any increased risk for sub-synchronous resonance phenomena and offers an economic solution in power oscillation damping field.

### 1.3.3.2 The Characteristics of a CSC System

Characterstics of a CSC system are:

1.Control of power flow on specific lines

2.Minimum system losses

3.Power oscillation damping

4.Avoiding of subsynchronous resonance

5.Adapted power transfer to actual conditions

6. Improved post contingency stability

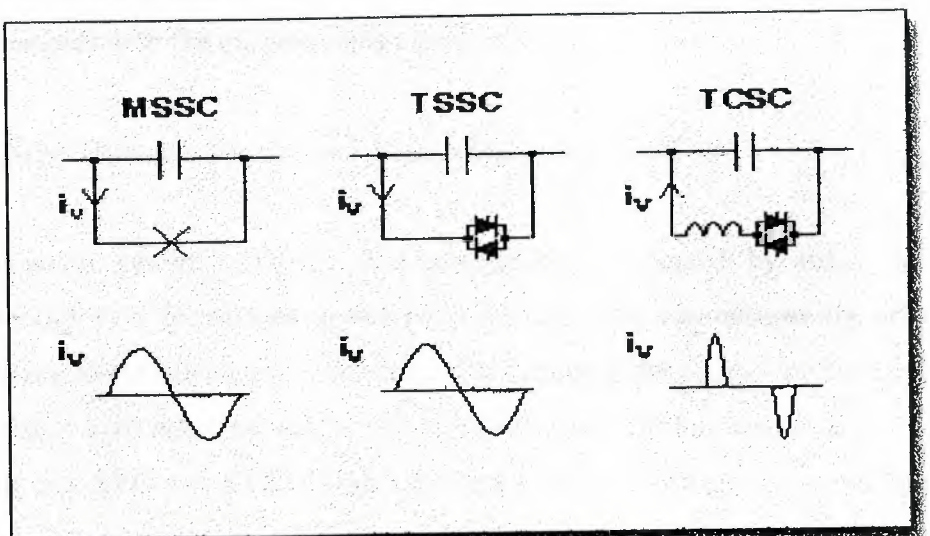


**Figure 1.6** Thyristor Controlled Series Capacitor

## 1.4 Benefits of Utilizing FACTS Devices

The benefits of utilizing FACTS devices in electrical transmission systems can be summarized as follows:

1.Better utilization of existing transmission system assets

2. Increased transmission system reliability and availability

3. Increased dynamic and transient grid stability

4. Increased quality of supply for sensitive industries

5. Environmental benefits

### 1.4.1 Better Utilization of Existing Transmission System Assets

In many countries, increasing the energy transfer capacity and controlling the load flow of transmission lines are of vital importance, especially in de-regulated markets, where the locations of generation and the bulk load centers can change rapidly. Frequently, adding new transmission lines to meet increasing electricity demand is limited by economical and environmental constraints. FACTS devices help to meet these requirements with the existing transmission systems.

### 1.4.2 Increased Transmission System Reliability and Availability

Transmission system reliability and availability is affected by many different factors. Although FACTS devices cannot prevent faults, they can mitigate the effects of faults and make electricity supply more secure by reducing the number of line trips. For example, a major load rejection results in an over voltage of the line which can lead to a line trip. SVC's or STATCOMs counteract the over voltage and avoid line tripping.

### 1.4.3 Increased Dynamic and Transient Grid Stability

Long transmission lines, interconnected grids, impacts of changing loads and line faults can create instabilities in transmission systems. These can lead to reduced line power flow, loop flows or even to line trips. FACTS devices stabilize transmission systems with resulting higher energy transfer capability and reduced risk of line trips.

### 1.4.4 Increased Quality of Supply for Sensitive Industries

Modern industries depend upon high quality electricity supply including constant voltage, and frequency and no supply interruptions. Voltage dips, frequency variations or the loss of supply can lead to interruptions in manufacturing processes with high resulting economic losses. FACTS devices can help provide the required quality of supply.

### 1.4.5 Environmental Benefits

FACTS devices are environmentally friendly. They contain no hazardous materials and produce no waste or pollutanse. FACTS help distribute the electrical energy more economically through better utilization of existing installations thereby reducing the need for additional transmission lines.

## 1.5 Future Developments in FACTS

Future developments will include the combination of existing devices, e.g. combining a STATCOM with a TSC (thyristor switched capacitor) to extend the operational range. In addition, more sophisticated control systems will improve the operation of FACTS devices. Improvements in semiconductor technology (e.g. higher current carrying capability, higher blocking voltages) could reduce the costs of FACTS devices and extend their operation ranges. Finally, developments in superconductor technology open the door to new devices like SCCL (Super Conducting Current Limiter) and SMES (Super Conducting Magnetic Energy

Storage). There is a vision for a high voltage transmission system around the world – to generate electrical energy economically and environmentally friendly and provide electrical energy where it's needed. FACTS are the key to make this vision live.

### 1.6 How the World Bank Can Facilitate Increased Usage of FACTS Devices

Since **FACTS** devices facilitate economy and efficiency in power transmission systems in an environmentally optimal manner, they can make a very attractive addition to the World Bank's portfolio of power projects. In spite of its attractive features, FACTS technology does not seem to be very well known in the World Bank. The following is a proposed action plan for giving FACTS technology increased exposure in the World Bank:

1. Informing Bank staff and its stakeholders on FACTS technology, including case studies through publishing relevant papers on its "Home Page" and as part of its **Energy Issues** series
2. Organizing presentations/workshops/training activities in connection with high profile events (such as Energy Week) on FACTS technology as well as in the field to provide information to Borrowers. This has now occurred for the Greater Mekong Sub-region (GMS) Workshop on Energy Trade in Bangkok February 2000
3. Conducting a review of its power sector portfolio over the last twenty years to quantify the level of usage of FACTS devices in Bank projects and identifying lessons learned
4. Reviewing its lending pipeline to identify opportunities for increased usage of FACTS technology.

### 1.7 Design, Implementation, Operation and Training Needs of FACTS Devices

Network studies are very important for the implementation of a FACTS device to determine the requirements for the relevant installation. Experienced network planning engineers have to evaluate the system including future developments. Right device – right size – right place – right cost. Reliable operation of FACTS devices require regular maintenance in addition to using equipment of the highest quality standards. Maintenance requirements are minimal but important.

Optimal use of FACTS devices depend upon well-trained operators. Since most utility operators are unfamiliar with FACTS devices (compared with for example switched reactors or capacitors), training on the operation of FACTS devices is therefore very important. What is important for the operators to know is are the appropriate settings of FACTS devices, especially the speed of response to changing phase angle and voltage conditions as well as operating modes.

# CHAPTER TWO

# HIGH VOLTAGE DIRECT CURRENT (HVDC)

## 2.1 What is HVDC?

HVDC stands for High Voltage Direct Current and is today a well-proven technology employed for power transmission all over the world. In total about 60,000 MW HVDC transmission capacities are installed in more than 80 projects.

The HVDC technology is used to transmit electricity over long distances by overhead transmission lines or submarine cables. It is also used to interconnect separate power systems, where traditional alternating current (AC) connections cannot be used.

The development of the HVDC technology started in the late 1920s, and only after some 25 years of extensive development and pioneering work the first commercially operating scheme was commissioned in 1954. This was a link between the Swedish mainland and the island of Gotland in the Baltic Sea. The power rating was 20 MW and the transmission voltage 100 kV. At that time mercury arc valves were used for the conversion between AC and DC, and the control equipment was using vacuum tubes.

A significant improvement of the HVDC technology came around 1970 when thyristor valves were introduced in place of the mercury arc valves. This reduced the size and complexity of HVDC converter stations substantially. The use of microcomputers in the control equipment in today's transmissions has also contributed to making HVDC the powerful alternative in power transmission that it is today.

In 1995 a new generation of HVDC converter stations was out, HVDC 2000, that further improves the performance of HVDC transmissions. And in 1997 a completely new converter and DC cable technology called HVDC Light was introduced.

## 2. 2 HVDC Transmissions Categories

There are three different categories for HVDC transmissions:

1. Point to point transmissions
2. Back-to-back stations
3. Multi-terminal systems

### 2.2.1 The HVDC Point-to-Point Transmission (Monopolar and Bipolar HVDC Transmissions)

Most HVDC transmissions are point-to-point transmissions using overhead lines or submarine cables or a combination of lines and cables.Many of the cable transmissions are monopolar with only one metallic conductor between the converter stations and using the ground as the return path for the current.

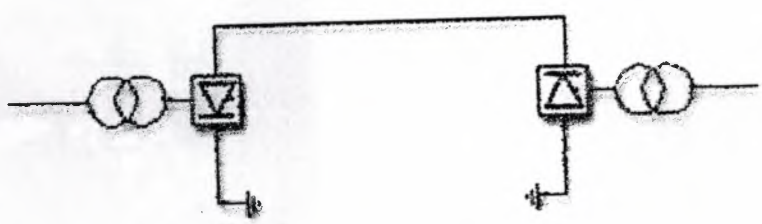

**Figure 2.1** Monopolar cable transmission

Most overhead line transmissions are bipolar, i.e. they use two conductors of opposite polarity (one positive and one negative). A bipolar transmission is in fact a double circuit transmission, since one pole can continue to transmit power when the other pole is out of service.

**Figure 2.2** Bipolar cable transmission

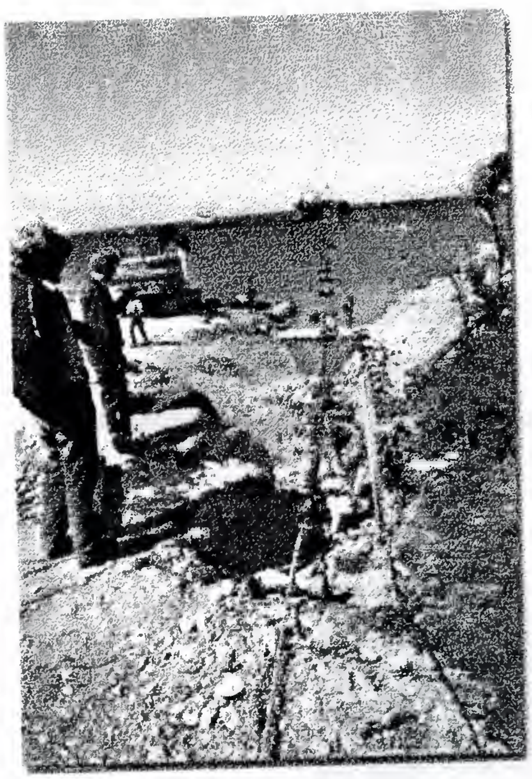

**Figure 2.3** HVDC cable link

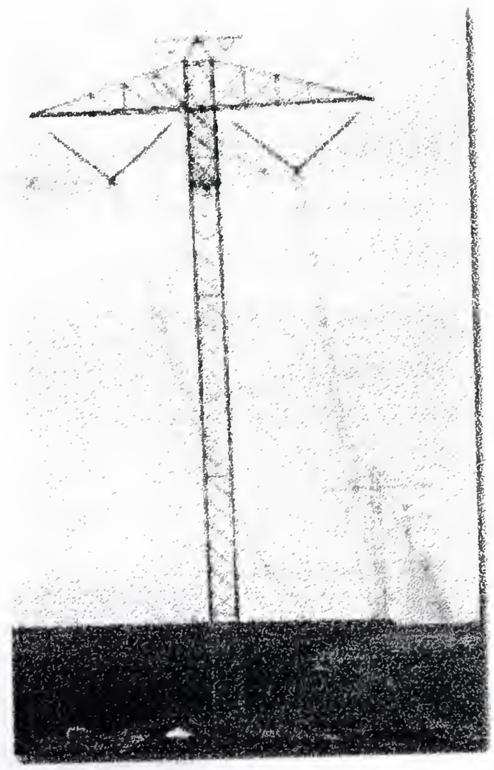

**Figure 2.4** Overhead HVDC lines

### 2.2.2 The HVDC Back-to-Back Station

A HVDC back-to-back station is normally used to create an asynchronous interconnection between two AC networks. There are several back-to-back stations in operation in the world. In these installations both the rectifier and the inverter are located in the same station and are normally used in order to create an asynchronous interconnection between two AC networks, which could have the same or different frequencies.

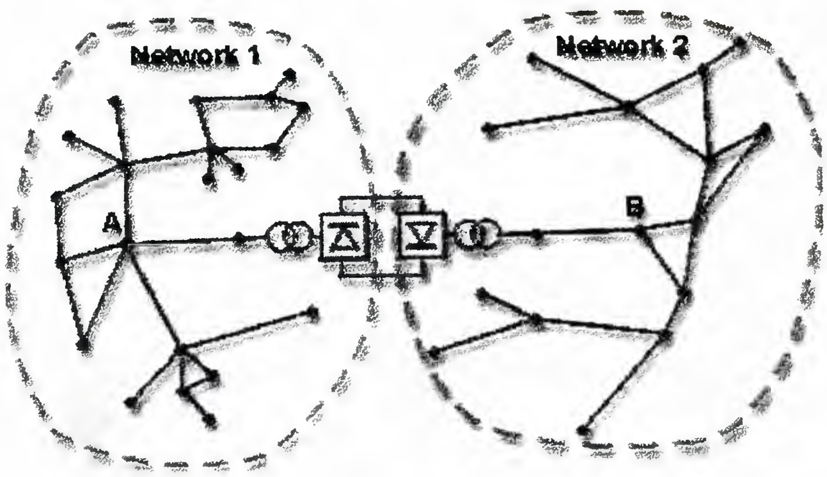


**Figure 2.5** HVDC back-to-back station

A back-to-back station is normally somewhat simpler than a converter station for a transmission project. The direct voltage level can be selected without consideration to the optimum values for an overhead line and a cable, and is therefore normally quite low, 150 kV or lower. The only major equipment on the DC-side is a smoothing reactor. The control equipment can also be simplified, as there is no need for a telecommunication link between the two converters.

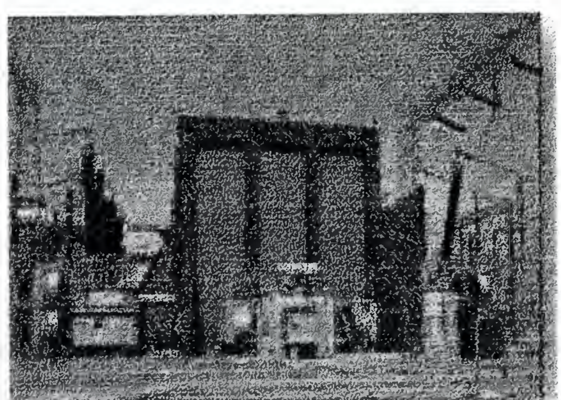

**Figure 2.6** back-to-back station, India

### 2.2.3 The HVDC Multi-Terminal System

A multi-terminal HVDC transmission is an HVDC system with more than two converter stations.

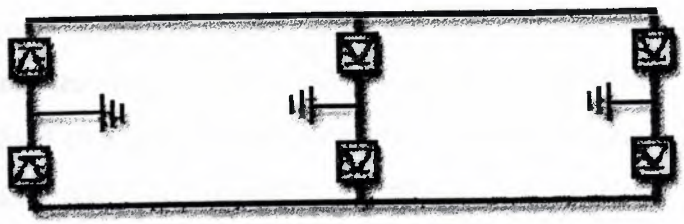

**Figure 2.7** HVDC multiterminal system

A multi-terminal HVDC transmission is more complex than an ordinary point-to-point transmission. In particular, the control system is more elaborate and the telecommunication requirements between the stations become larger.

There is only one large-scale multi-terminal HVDC system in operation in the world today. It is the 2000 MW Hydro Québec - New England transmission. The operating experience of this transmission is very good and has proved that from a technical point of view there are no problems to connect several converter stations to the same HVDC transmission line.

## 2.3 HVDC Development

The key problem in the HVDC technique was the development of reliable and economic valves which could convert high-voltage alternating current into high-voltage direct current and vice versa. Experiments performed in different parts of the world on mechanical moving contact devices did not prove successful. On the other hand, the mercury-arc valve offered one possible line of development. From the end of 1920's, when ASEA (now ABB) embarked on the development and manufacture of static converters and mercury-arc valves for voltages up to about 1000 V, the possibilities of developing valves also for higher voltages were investigated.

This necessitated the study of completely unknown fields, where earlier technical experience could only be applied to a limited degree. For a number of years it was indeed an open question whether there existed any solution at all to the problems. When the HVDC system finally proved to be a technical reality, there still remained uncertainty as to whether it could compete in practice and be economical. By then the already established power transmission systems had also made significant progress.

While electrical machines, transformers, etc., can be designed with great precision with the aid of mathematically formulated physical laws, the design of the mercury-arc valve must be based to a large degree on empirically acquired knowledge. When trying out higher voltages, one is confronted by specific physical problems. In a power line or high-voltage apparatus raising the voltage is met by increasing the insulation clearances. In the mercury vapour atmosphere of the mercury-arc valves it does not help at all to increase the spacing between the electrodes.

This problem was solved in 1929 by a proposal, which was subsequently patented and which in some ways can be considered as forming the cornerstone of the development work on the high-voltage mercury-arc valve. An experimental valve, tried out in 1933, confirmed the validity of this principle during its brief life. At the same time it was found there still remained major material problems to be solved. However, after continued development work it proved possible, in 1944, to operate a rectifier and an inverter in the laboratory at Ludvika with a DC. load of 2000 kW at a voltage up to 60 kV. The development work was lead by Dr. Uno Lamm, who has been named "The father of HVDC".

During the 1940s the Swedish State Power Board (now Vattenfall AB]) was planning the long transmission system from the new Harsprånget hydroelectric power plant in the far north to the load centers in the southern part of the country. High-voltage direct current (HVDC) was considered for the Harsprånget transmission, but the system and component development work that was being made by ASEA had not yet advanced sufficiently for a practical application of the technique. Therefore it was decided to build a 400 kV AC transmission system. The first part of this system was energized in 1952 and it was then the highest voltage used anywhere in the world.

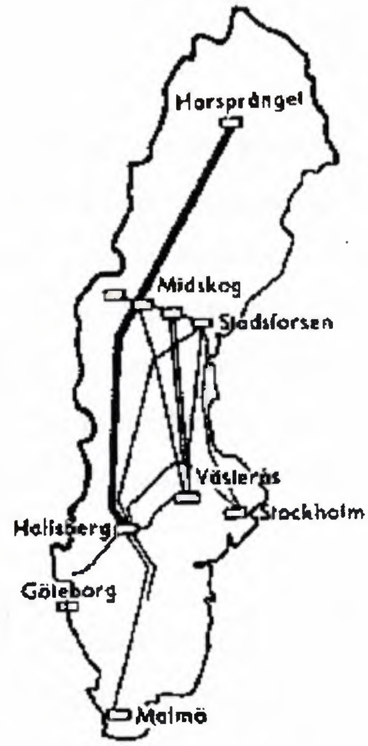


**Figure 2.8** The first 400 kV line and the 220 kV network,Sweden

### 2.3.1 The Gotland Link

The time was now ripe for service trials with larger powers than permitted by the resources at Ludvika. A test station at Trollhättan, run jointly by the Swedish State Power Board and ASEA, was established in 1945, and a 50-km power line was made available for service trials. In 1950 the State Power Board placed an order with ASEA for equipment for the first HVDC transmission, between the island of Gotland and the Swedish mainland. In the following year a larger test station was taken into service at Trollhättan, possessing adequate resources for the empirical development of large high-voltage mercury-arc valves. Accelerated development work resulted in the solving of the final problems in 1953, and the design of the most critical component, the mercury-arc valve, was fixed. The Gotland transmission with a rating of 20 MW, 200 A, 100 kV came into service in 1954. The accelerated work during the latter stages of the development project involved the tackling and solving of a series of problems at the same time as new problems and obstacles were discovered. Over one hundred modifications were systematically tried out. The number of possible development lines, which at the beginning appeared to be very large, gradually shrank. Finally, there remained only a few alternatives, and among these was found the way which led to the final solution.

Design work on other components in the converter stations and transmission such as transformers, reactors, switchgear and protective and control equipment took place in parallel with the development work on mercury-arc valves. AC system technology, which had been built up over half a century by power specialists the world over, could only be partly applied to a DC system. This meant that a completely new system technique became necessary. However, this did not require empirical work as in the case of the mercury-arc valves. Advanced mathematical methods and network models (TNA) could be applied.

With these aids, ASEA's specialists in Ludvika led by Dr. Erich Uhlmann tackled the comprehensive complex of problems and developed a system concept, that was applied in the Gotland transmission. This concept proved to be very successful, and has remained basically unchanged until today.

### 2.3.2 The Mercury-Arc Valve Era (The English Channel)

At the beginning of the 1950's, the British and French power administrations planned a power transmission across the English Channel. A few weeks after the commissioning of the Gotland transmission, the study committee appointed for this purpose published its report, which recommended AC cables. The distance was sufficiently short for this to be possible. After lengthy deliberations and studies of the experiences from the Gotland transmission, the HVDC alternative was chosen instead and ASEA received their second order for transmission equipment. It was an extremely favourable circumstance for developments that a transmission project of such a moderate scope as the Gotland link happened to take place just at the time it did. No power administration would dare to embark on a completely unproven system for bulk power transmission. However, the foundation stones were laid with the Gotland project, even if there remained much work to do in the development of converters for twice the voltage and 10 to 20 times higher power required by the subsequent installations.

Following the English Channel project, several HVDC transmissions using mercury arc valves were built during the 1960s. These were Konti-Skan (Sweden - Denmark), Sakuma (50/60 Hz frequency converter in Japan), the New Zealand transmission (linking the South and the North Islands) and the Italy - Sardinia link.

The largest mercury arc valve transmission built by ASEA was the Pacific HVDC Intertie. The early challenges in Sweden. built by ASEA was the Pacific HVDC Intertie. This is a 1440 MW (later re-rated to 1600 MW) ±400 kV transmission from The Dalles, Oregon to Los Angeles, California. This project was undertaken by a joint venture formed by ASEA and the General Electric Co. The Pacific Intertie started operating in 1970. The southern converter station at Sylmar was however badly damaged in the 1971 Los Angeles earthquake. The station was rebuilt and the Intertie could resume operation in 1972. The Pacific HVDC Intertie has twice been further extended with modern technology during the 1980s. It now has a capacity of 3100 MW and a voltage of ±500 kV.

### 2.3.3 The Thyristor Takes Over

In view of ASEA's extensive activities in the semiconductor field, it was natural that the company also worked on the development of high-voltage thyristor valves as an alternative to mercury-arc valves. In the spring of 1967 one of the mercury-arc valves in the Gotland transmission was replaced by a thyristor valve, the first in the world to be taken into commercial operation for HVDC transmission. After about one year of trial operation, the Swedish State Power Board ordered a complete valve group for each converter station in order to increase the transmission capacity by 50 %. The new valve group was connected in series with the two existing mercury-arc valve groups, thus increasing the transmission voltage from 100 to 150 kV. This enlarged transmission was taken into service in the spring of 1970 - the Gotland transmission had once more become a world pioneer.

Thyristor valves made it possible to simplify the converter stations, and they have been used in all subsequent HVDC transmissions. A number of large HVDC transmissions were built by ASEA and BBC (the predecessors of ABB) during the 1970s. These were the Cahora Bassa (Mozambique - South Africa), Skagerrak (Norway

- Denmark), Inga-Shaba (Zaire), CU Project (USA) and Nelson River 2 (Canada).

The contract for the largest of all HVDC transmissions in the world, the 6300 MW Itaipu HVDC transmission in Brazil, was awarded to the ASEA-PROMON consortium in 1979. It went into operation in several stages between 1984 and 1987 and is an important element in the Brazilian power supply delivering a large portion of the electricity needs of the city of Sao Paulo.

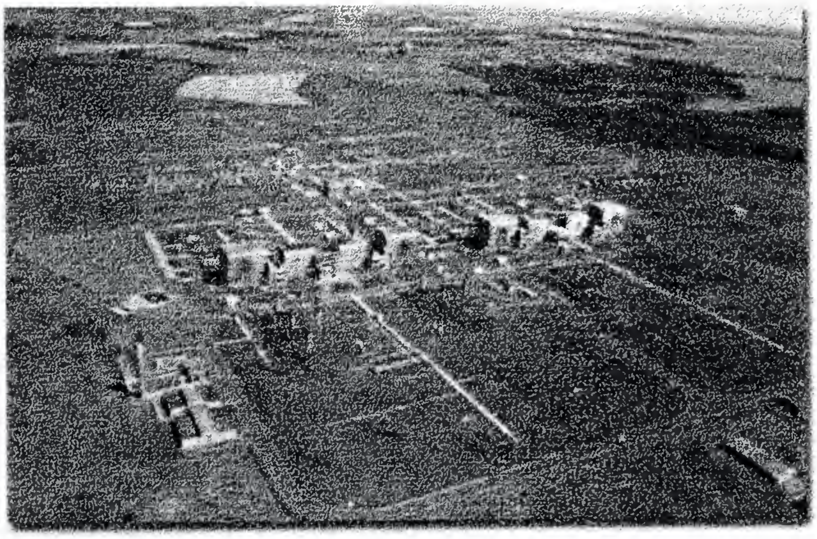

**Figure 2.9** Converter station in the Itaipu 6300 MW transmission

### 2.3.4 Historical Mile Stones

It has been widely documented in the history of the electricity industry, that the first commercial electricity generated (by Thomas Alva Edison) was direct current (DC) electrical power. The first electricity transmission systems were also direct current systems. However, DC power at low voltage could not be transmitted over long distances, thus giving rise to high voltage alternating current (AC) electrical systems.

Nevertheless, with the development of high voltage valves, it was possible to once again transmit DC power at high voltages and over long distances, giving rise to HVDC transmission systems. Some important milestones in the development of the DC transmission technology are presented as follows:

1. Hewitt's mercury-vapour rectifier, which appeared in 1901.

2. Experiments with thyratrons in America and mercury arc valves in Europe before 1940.

3. First commercial HVDC transmission, Gotland 1 in Sweden in 1954.

4. First solid state semiconductor valves in 1970.

5. First microcomputer based control equipment for HVDC in 1979.

6. Highest DC transmission voltage (+/- 600 kV) in Itaipú, Brazil, 1984.

7. First active DC filters for outstanding filtering performance in 1994.

8. First Capacitor Commutated Converter (CCC) in Argentina-Brazil interconnection, 1998

9. First Voltage Source Converter for transmission in Gotland, Sweden, 1999

## 2.4 Why HVDC?

Power stations generate alternating current, AC, and the power delivered to the consumers is in the form of AC. Why then is it sometimes more suitable to use direct current, HVDC, for transmitting electric power?

The vast majority of electric power transmissions use three-phase alternating current. The reasons behind a choice of HVDC instead of AC to transmit power in a specific case are often numerous and complex. Each individual transmission project will display its own set of reasons justifying the choice of HVDC, but the most common arguments favoring HVDC are:

1. Lower investment cost

2. Long distance water crossing

3. Lower losses

4. Asynchronous connection

5. Controllability

6. Low short circuit currents

7. Environment

In general terms the different reasons for using HVDC can be divided in two main groups, namely:

1. HVDC is necessary or desirable from the technical point of view (i.e. controllability).
2. HVDC results in a lower total investment (including lower losses) and/or is environmentally superior.

In many cases, projects are justified on a combination of benefits from the two groups. Today the environmental aspects are also becoming more important. HVDC is in that respect favorable in many cases, as the environmental impact is less than with AC. This is due to the fact that an HVDC transmission line is much smaller and needs less space than AC lines for the same power capacity.

The system characteristics of an HVDC link differ a lot from AC transmissions. One of the most important differences is related to the possibility to accurately control the active power transmitted on a HVDC line. This is in contrast to AC lines, where the power flow cannot be controlled in the same direct way. The controllability of the HVDC power is often used to improve the operating conditions of the AC networks where the converter stations are located.

Another important property of an HVDC transmission is that it is asynchronous. This allows the interconnection of non-synchronous networks.

### 2.4.1 The HVDC Transmission for Lower Investment Cost

A HVDC transmission line costs less than an AC line for the same transmission capacity. However, the terminal stations are more expensive in the HVDC case due to the fact that they must perform the conversion from AC to DC and vice versa. But above a certain distance, the so-called "break-even distance", the HVDC alternative will always give the lowest cost.

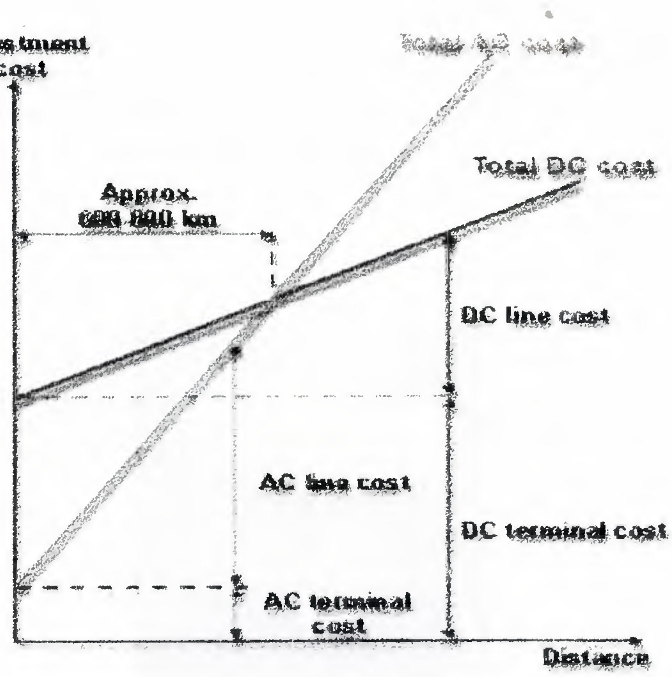


**Figure 2.10** Typical investment costs for an overhead line transmission with AC and HVDC.

The break-even-distance is much smaller for submarine cables (typically about 50 km) than for an overhead line transmission. The distance depends on several factors (both for lines and cables) and an analysis must be made for each individual case.

The importance of the break-even-distance concept should not be over-stressed, since several other factors, such as controllability, are important in the selection between AC or HVDC.

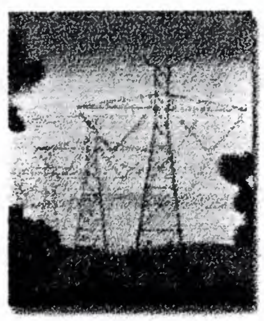

**Figure 2.11** An overhead DC transmission line

### 2.4.2 The HVDC Cable Transmissions for Long Distance Water Crossing

In a long AC cable transmission, the reactive power flow due to the large cable capacitance will limit the maximum possible transmission distance. With HVDC there is no such limitation, why, for long cable links, HVDC is the only viable technical alternative. The longest HVDC submarine cable presently in operation is the 250 km Baltic Cable transmission between Sweden and Germany. Several HVDC submarine cables of 500 km or more are currently being planned in Europe and elsewhere.

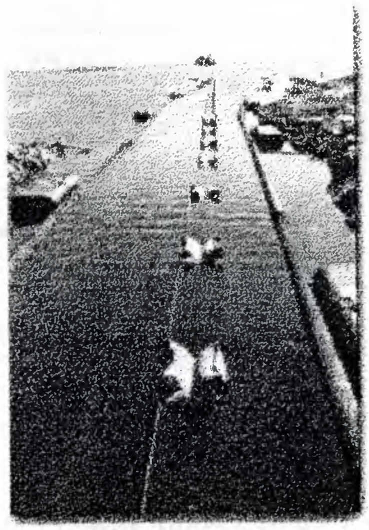

**Figure 2.12** HVDC submarine cable

### 2.4.3 The HVDC Transmission has Lower Losses

HVDC transmission losses come out lower than the AC losses in practically all cases. An optimized HVDC transmission line has lower losses than AC lines for the same power capacity. The losses in the converter stations have of course to be added, but since they are only about 0.6 % of the transmitted power in each station, the total HVDC transmission losses come out lower than the AC losses in practically all cases. HVDC cables also have lower losses than AC cables. The diagram below shows a comparison of the losses for overhead line transmissions of 1200 MW with AC and HVDC.

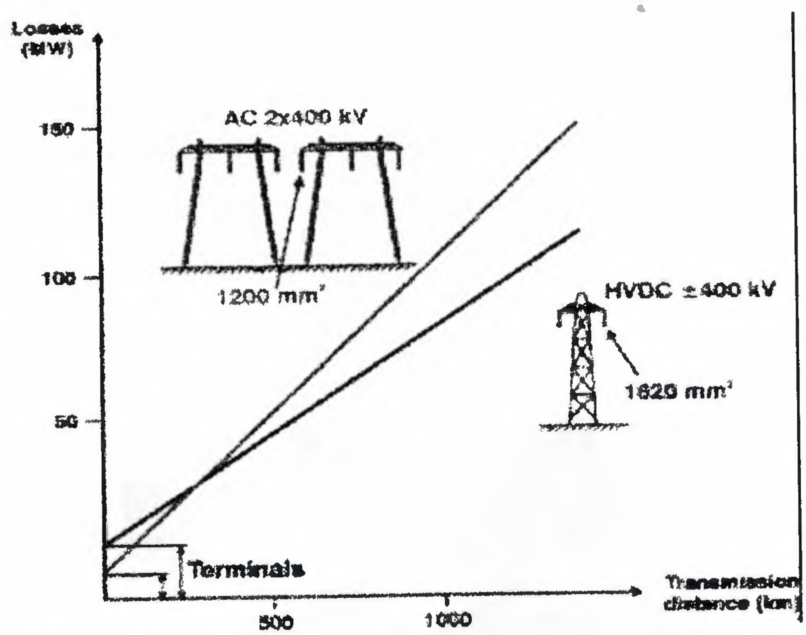

**Figure 2.13** An optimized DC line has lower losses than an AC line

### 2.4.4 An HVDC Transmission Limits Short Circuit Currents

An HVDC transmission does not contribute to the short circuit current of the interconnected AC system. When a high power AC transmission is constructed from a power plant to a major load center, the short circuit current level will increase in the receiving system. High short circuit currents is becoming an increasingly difficult problem of many large cities. They may result in a need to replace existing circuit breakers and other equipment if their rating is too low.

If, however, new generating plants are connected to the load center via a DC link, the situation will be quite different. The reason is that an HVDC transmission does not contribute to the short circuit current of the interconnected AC system.

### 2.4.5 The HVDC Transmission for Asynchronous Connection

Many HVDC links interconnect incompatible AC systems. Several HVDC links interconnect AC system that are not running in synchronism with each other. For example the Nordel power system in Scandinavia is not synchronous with the UCTE grid in western continental Europe even though the nominal frequencies are the same. And the power system of eastern USA is not synchronous with that of western USA.

The reason for this is that it is sometimes difficult or impossible to connect two AC networks due to stability reasons. In such cases HVDC is the only way to make an exchange of power between the two networks possible. There are also HVDC links between networks with different nominal frequencies (50 and 60 Hz) in Japan and South America.

**Figure 2.14** HVDC systems

### 2.4.6 Environmental Benefits

Many power transmissions have been built to interconnect different power systems by overhead lines or cables. These links serves to utilize the existing generating plants in the networks more effectively so that the building of new power stations can be deferred. This makes economic sense, but it is also good for the environment. There is an obvious environmental benefit by not having to build a new power station, but there are even greater environmental gains in the operation of the interconnected power system. The greatest environmental benefit is obtained by linking a system, which has much hydro generation to a system with predominantly thermal generation.

With the ongoing deregulation of the electricity supply industry, the demands for flexibility in power transmission are growing continuously. This gives added momentum to established solutions for flexibility in power transmission, as well as openings up opportunities for quite new technologies in the field.

Optimum power transmission and distribution entails the reduction of transfer losses and provision of adequate power supply quality and availability at the receiving end.

### 2.5 Inherent Problems Associated with HVDC

1. Expensive converters:

   Expensive converter stations are required at each end of a DC transmission link, whereas only transformer stations are required in an AC link.

2. Reactive power requirement:

   Converters require much reactive power, both in rectification as well as in inversion. At each converter the reactive power consumed may be as much at 50% of the active power rating of the DC link. The reactive power requirement is partly supplied by the filter capacitance, and partly by synchronous or static capacitors that need to be installed for the purpose.

3. Generation of harmonics:

   Converters generate a lot of harmonics both on the DC side and on the AC side. Filters are used on the AC side to reduce the amount of harmonics transferred to the AC system. On the DC system, smoothing reactors are used. These components add to the cost of the converter.

4. Difficulty of circuit breaking:

   Due to the absence of a natural current zero with DC circuit breaking is difficult. This is not a major problem in single HVDC link systems, as circuit breaking can be accomplished by a very rapid absorbing of the energy back into the AC system. (The blocking action of thyristors is faster than the operation of mechanical circuit breakers). However the lack of HVDC circuit breakers hampers multi-terminal operati

5. Difficulty of voltage transformation:

Power is generally used at low voltage, but for reasons of efficiency must be transmitted at high voltage. The absence of the equivalent of DC transformers makes it necessary for voltage transformation to carried out on the AC side of the system and prevents a purely DC system being used.

6. Difficulty of high power generation:

Due to the problems of commutation with DC machines, voltage, speed and size are limited. Thus comparatively lower power can be generated with DC.

7. Absence of overload capacity:

Converters have very little overload capacity unlike transformers.

# CHAPTER THREE

# HVDC TECHNOLOGY

## 3.1 The HVDC Technology

The conceptual design of the classic HVDC converter stations of today dates back from the mid 1970's, when thyristor valves were taking over in place of the mercury arc valves. But there has been a dramatic development in the performance of HVDC equipment and systems.

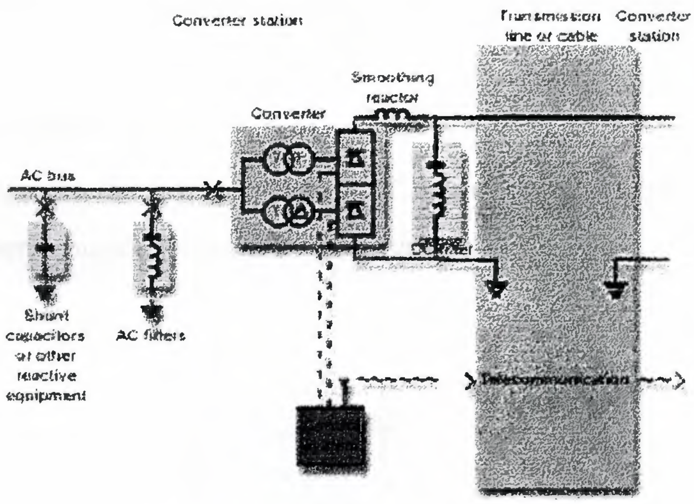


**Figure 3.1** HVDC converter station

An HVDC converter station uses thyristor valves to perform the conversion from AC to DC and vice versa. The 12-pulse converter valve bridge is connected to the AC system by means of converter transformers. The valves are normally placed in a building and the converter transformers are located just outside.

The HVDC converter produces current harmonics (11th, 13th, 23rd, 25th, 35th, 37th etc.) on the AC side. These harmonics are prevented from entering into the connected AC network by AC filters, i.e. resonant circuits comprising capacitors, inductances (reactors) and resistors. The filters also produce a part of the reactive power consumed by the converter.The HVDC converter also produces voltage harmonics on the DC side (12th, 24th, 36th etc.). A large inductance (smoothing reactor) is always installed on the DC side to reduce the ripple in the direct current. In addition, a DC filter is also normally needed to reduce the level of harmonic currents in the DC overhead line. The harmonics may otherwise cause interference to telephone circuits in the vicinity of the DC line.

The power transmitted over the HVDC transmission is controlled by means of a control system. It adjusts the triggering instants of the thyristor valves to obtain the desired combination of voltage and current in the DC system.Several other apparatus are needed in a converter station, such as circuit breakers, current and voltage transducers, surge arresters, etc.

The conceptual design of the classic HVDC converter stations remained unchanged until 1995, when ABB introduced HVDC 2000, a significant step forward.

### 3.1.1 Thyristor Valves for HVDC

Thyristor valves are the heart of the HVDC conversion process. Modern valves have an excellent performance record and very small losses.

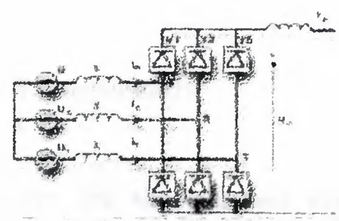

Figure 3.2 6-pulse Graetz bridge

The thyristor valves do the actual conversion from AC to DC or vice versa. The basic circuit used is the Graetz bridge consisting of six valve functions, but in order to eliminate the largest harmonics, two such bridges are connected in series forming a 12-pulse converter.The valves are normally located in a valve building and arranged as three structures suspended from the ceiling of the valve hall. Each valve consists of a number of series connected thyristors with their auxiliary components. The HVDC valves are water cooled by a closed loop with de-ionised water. The thyristors are arranged in a number of modules. The ABB design has six thyristors per module.

The thyristors are triggered by electrical gate pulses generated in a small electronic thyristor control unit (TCU) located near each thyristor. These units receive triggering impulses 50 or 60 times per second from the HVDC control system by means of light guides, that can transmit the triggering order from ground potential to each thyristor position in a valve in spite of the fact that a thyristor may have a voltage of 500 kV to ground!


**Figure 3.3** 500 kV HVDC valve

### 3.1.2 The HVDC Converter Transformers

The converter transformers are the heaviest equipment in a HVDC converter station. Single units can often have a total weight of 200 - 400 tons.The converter transformer is an integral part of an HVDC system. High AC and DC voltages put specific requirements on the dielectric insulation. Non sinusoidal currents give rise to additional losses which are to be considered. Converter transformers connect the AC network to the thyristor valve bridge, and adjust the voltage on the valve side to a suitable level based on the DC voltage used for the transmission. The transformers can be of different design depending on the power to be transmitted, and possible transport limitations. The most common type is a single-phase-three-winding design. Three identical transformers are then needed per converter.

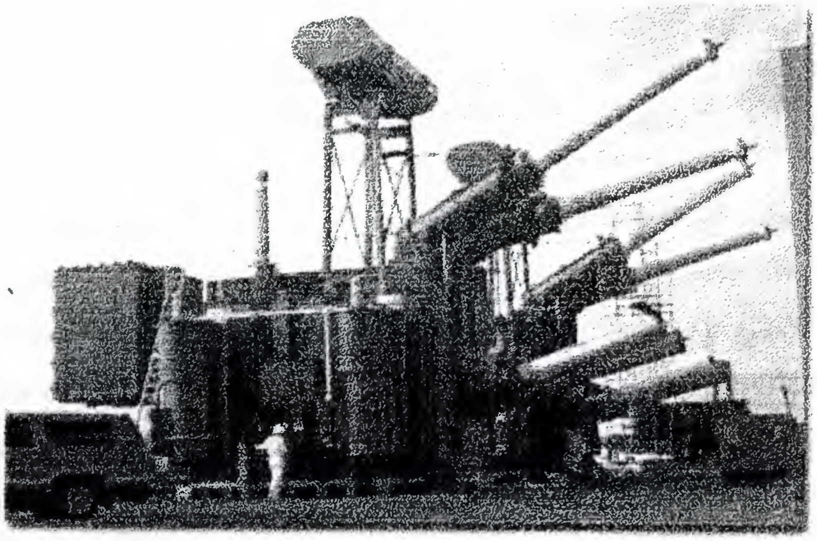

**Figure 3.4** Two single-phase-three-winding HVDC converter transformers during final assembly at the site.

The converter transformer serves several functions:

1. Supply of AC voltages in two separate circuits with a relative phase shift of 30 electrical degrees for reduction of low order harmonics, especially the 5th and 7th harmonics.
2. Act as a galvanic barrier between the AC and DC systems to prevent the DC potential to enter the AC system.
3. Reactive impedance in the AC supply to reduce short circuit currents and to control the rate of rise in valve current during commutation.
4. Voltage transformation between the AC supply and the HVDC system.
5. A fairly large tap range with small steps to give necessary adjustments in supply voltage.

HVDC transformers are often placed near the valve building and the valve side bushings protrude into the valve hall.

### 3.1.3 Reactive Power and AC Filters

How to make things right on the AC-side...conventional HVDC converters always have a demand for reactive power. At normal operation, a converter consumes reactive power in an amount that corresponds to approximately 50 % of the transmitted active power. The least costly way to generate reactive power is in shunt connected capacitor banks. Some of these capacitor banks can then be combined with reactors and resistors to form filters providing low impedance paths for the harmonics in order to limit them from entering into the connected AC network.

A series resonance filter branch will give a very low impedance and thereby efficient filtering in a narrow frequency band around the tuning frequency. Such branches are therefore normally used for the largest harmonics, i.e. the 11th and 13th. For the higher order harmonics, the current levels are lower, but these frequencies have the largest impact on telephone interference. Therefore they must also be attenuated, but the filter impedance can be larger than for the 11th and 13th harmonics. Thus, broadband filters, normally of high-pass type, are used to take care of all harmonics from the 23rd and upwards.

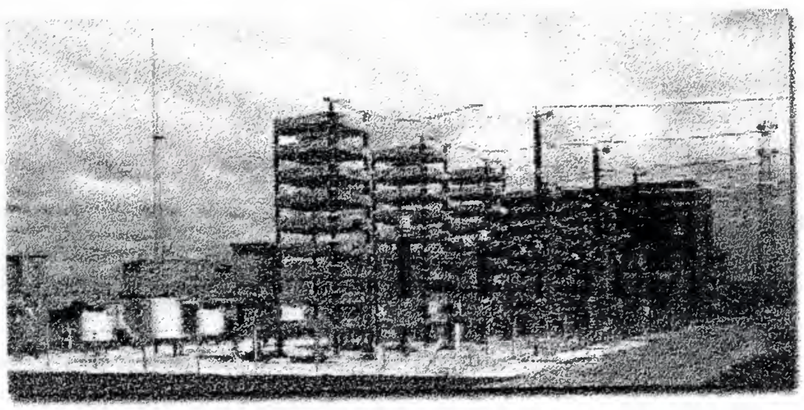

**Figure 3.5** Two three-phase AC filter banks for 400 kV at the Tjele HVDC converter station, Denmark.

Automaticly tuned AC filters (Cone Tune) was developed (By ABB) as part of the HVDC 2000 concept. The ConTune filters, which replace the traditional series resonance filter branches, can be built to generate small quantities of reactive power but still provide good filtering.

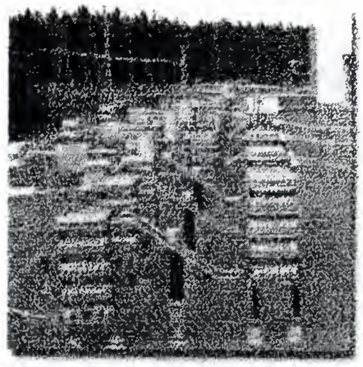

**Figure 3.6** One 400kV shunt capacitor (foreground) and one AC-filter (background)

### 3.1.4 The HVDC Smoothing Reactor

HVDC smoothing reactors can be of air-core design as well as and oil-insulated units. A DC reactor is normally connected in series with the converter. The main objectives of the reactor are:

1. To reduce the harmonic currents on the DC side of the converter.
2. To reduce the risk of commutation failures by limiting the rate of rise of the DC line current at transient disturbances in the AC or DC systems.

By reducing the ripple, the DC reactor also contributes to reduce the potential for telephone disturbances from the DC line. Most smoothing reactors are air-core and air-insulated but reactors for the largest HVDC projects are often built as iron-core, oil-insulated units.

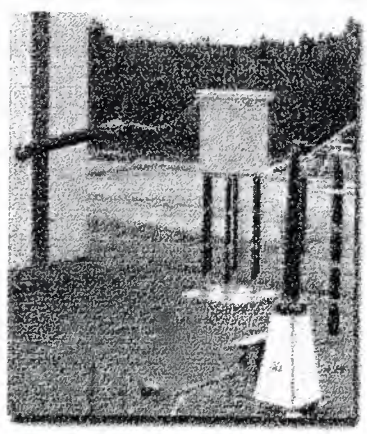

**Figure 3.7** Air-core smoothing reactor in the FennoSkan HVDC transmission

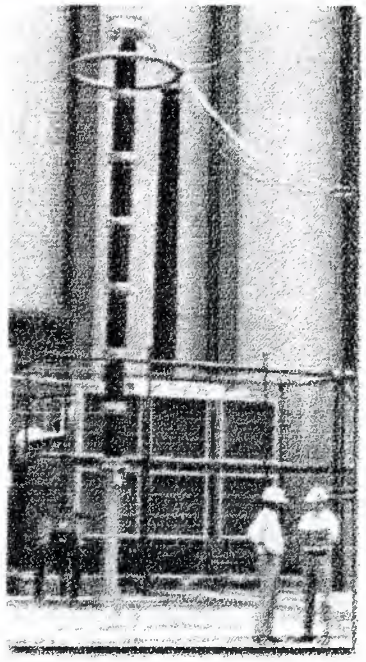

**Figure 3.8** Oil-insulated smoothing reactor in the Rihand - Dehli HVDC transmission

### 3.1.5 DC Filter

For overhead line HVDC transmissions the DC filter takes care of telephone interference. The smoothing reactor, which is installed also for other reasons, is an important element in the filtering of DC side harmonics. For overhead line transmissions, it is normally necessary to install additional filter circuits between the pole bus (outside the smoothing reactor) and the neutral bus. Capacitors or filter circuits may also have to be installed between the neutral bus and ground. The filter types used on the DC side are essentially the same as those used on the AC side, i.e. series resonance filters and high pass filters. The largest item of a DC filter, the capacitor, is often suspended in most HVDC projects, especially in seismic areas.

An active DC filter was developed (By ABB) DC filter as part of the HVDC 2000 concept that enables efficient filtering using a small-size filter

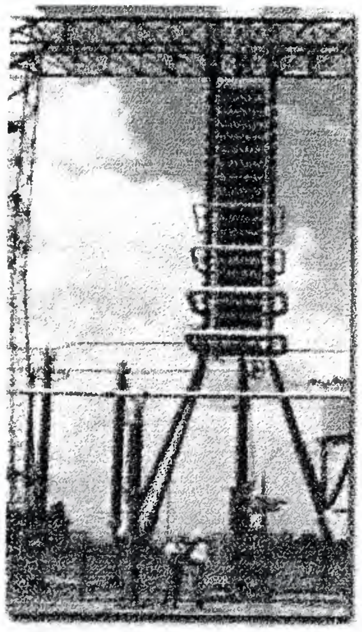

**Figure 3.9** 500 kV DC-filter with suspended capacitor

### 3.2 Transmission medium

For bulk power transmission over land, the most frequent transmission medium used is the overhead line. This overhead line is normally bipolar, i.e. two conductors with different polarity.

HVDC cables are normally used for submarine transmission. The most common types of cables are the solid and the oil-filled ones. The solid type is in many cases the most economic one. Its insulation consists of paper tapes impregnated with a high viscosity oil. No length limitation exists for this type and designs are today available for depths of about 1000 m. The self –contained oil-filled cable is completely filled with a low viscosity oil and always works under pressure. The maximum length for this cable type seems to be around 60 km.

The development of new power cable technologies has accelerated in recent years and today a new HVDC cable is available for HVDC underground or submarine power transmissions. This new HVDC cable is made of extruded polyethylene, and is used in VSC based HVDC systems.

### 3.3 HVDC 2000

A decisive lead has been taken (By ABB) in the HVDC field by introducing HVDC 2000, a new generation of thyristor based converter stations for HVDC. The first HVDC 2000 station, the Garabi 1000 MW station, is already in full operation since June 1999.HVDC 2000 offers the following advantages:

1. Improved dynamic performance
2. Significantly better stability, in particular when connected to AC networks with low short circuit capacity and in transmissions with long DC cables
3. Dependable performance in the event of AC system disturbances, with reduced risk of commutation failures
4. Lower load rejection over voltages
5. Improved AC and DC filtering with smaller filters
6. No need to switch AC filters or shunt capacitor banks to compensate for converter reactive power consumption.

Reduced area requirements and construction time:

1. Less equipment in the converter station
2. No need for large and complex valve buildings
3. Reduced area requirements
4. Reduced visual impact
5. Less specialised engineering for each project
6. Simplified interface between high voltage equipment and civil works
7. Reduced delivery time

The key feature of HVDC 2000 is the utilisation of Capacitor Commutated Converters (CCC), a well known circuit concept. The CCC is now an interesting solution in conjunction with the development of continuously tuned AC filters (ConTune). These filters can be built to generate small quantities of reactive power but still provide good filtering. These properties match the characteristics of the CCC, which has a much reduced need for reactive power.

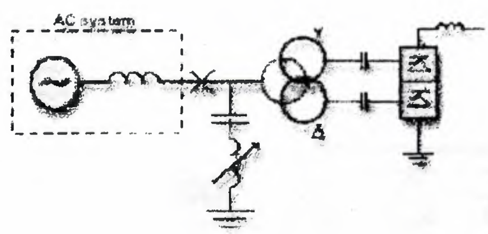


**Figure 3.10** A monopolar converter with CCC and Con Tune AC

The above diagram shows a of monopolar converter with CCC and ConTune AC filters. The CCC concept and ConTune provide the basis for HVDC 2000. But other recent ABB developments such as the items listed below are also important in exploiting the full range of advantages offered by HVDC 2000:

1. Outdoor HVDC valves

2. Active DC filters

3. Optical direct current transducers

4. The fully digital MACH 2™ control system

**Availability, reliability and life cycle cost...**Several of the newly developed features will improve availability and reliability. The same factors will also reduce costs for operation and maintenance. In short, smaller stations with less equipment, fewer outages and less need for maintenance will lead to reduced life cycle costs for the HVDC 2000 plants.

### 3.3.1 CCC - Capacitor Commutated Converte

The use of capacitor commutated converters has made possible a significant improvement of the traditional HVDC converter circuit. In HVDC 2000 concept, commutation capacitors are connected between the valve bridge and the converter transformers. This location has been found to be advantageous for several reasons. The capacitor stresses are much lower in this position than outside the converter transformer, as both the operating current and overcurrents are controlled by the valve bridge.

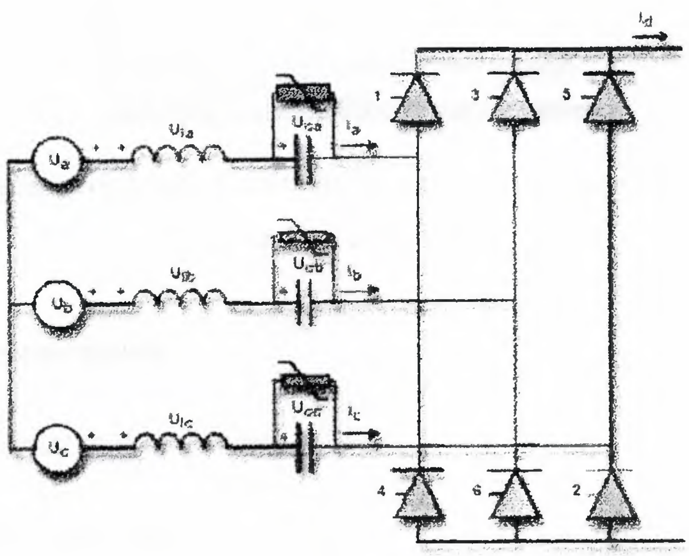

**Figure 3.11** The CCC main circuit configuration

The capacitor overvoltage protection can thus be handled by a varistor of reasonable size. With a CCC there is no need to switch filter banks or shunt capacitors banks in and out to follow the reactive consumption when the active power is changed. This is the case for a conventional converter where it is normally necessary to subdivide the var supply in several breaker-switched banks.

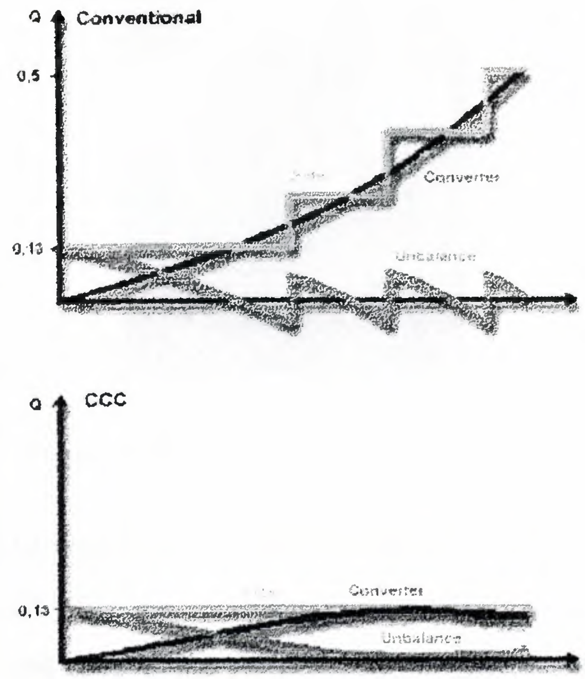


**Figure 3.12** The reactive power conditions for a typical conventional converter station and for a CCC.

**Performance Improvements**

1. Robust and resistant to disturbances

2. Dynamic stability improved

3. Reduced load rejection overvoltage

**Equipment considerations**

1. The commutation capacitor

2. Influence on other equipment

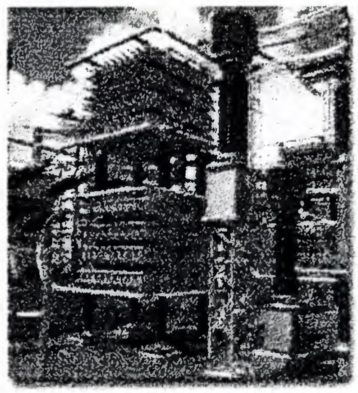

**Figure 3.13** Commutation capacitors in Garabi

### 3.3.2 ConTune - Continuously Tuned AC Filter

The ConTune AC filter has electromagnetic tuning that adjusts to the inherent frequency variations and temperature variations of the filter components.The ConTune AC filter has a high quality factor for the best filtering performance in HVDC converter stations and the lowest possible losses. The tuning frequency is automatically adjusted to provide prefect tuning irrespective of network frequency excursions and filter component variations. The ConTune filter offers:

1. Maximum filter performance even at large frequency excursions

2. Lower losses

3.Less space

4. No moving parts.

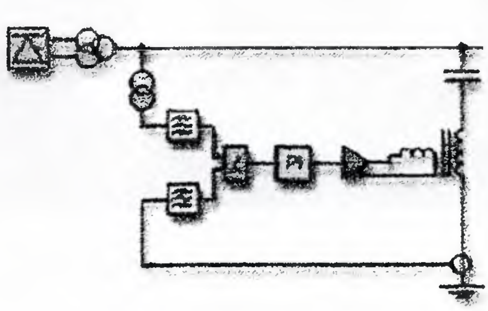

**Figure 3.14** Principle of continuos tuning

The high performance of the ConTune filter is achieved by using a filter reactor with variable inductance. The variable inductance is achieved with an iron core which is placed inside the reactor. Around the iron core there is a control winding. By feeding a corrective direct current into the control winding, the total magnetic flux in the reactor is influenced, thereby changing the inductance, which tunes the filter to the correct frequency of the harmonic. Control of the inductance is characterised by its high linearity.

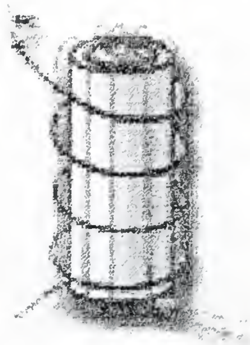

**Figure 3.15** Tuned reactor

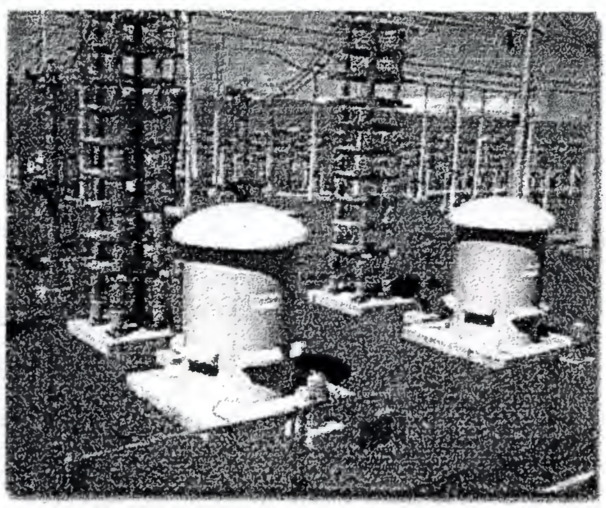

**Figure 3.16** ConTune filter installed in the Celilo station of the Pacific Intertie HVDC transmission

### 3.3.3 Outdoor HVDC Valves

The outdoor HVDC valves come in modular housings, factory assembled and tested and shipped to site ready for operation.

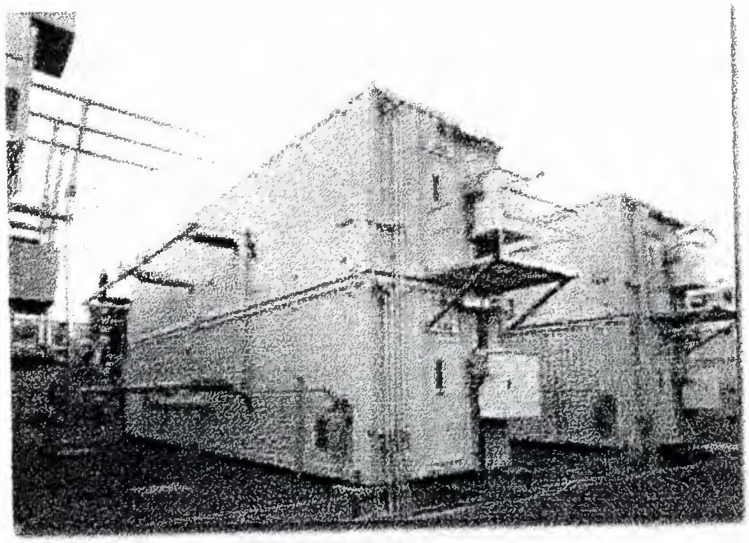

**Figure 3.17** The outdoor HVDC valves at Garabi are placed on top of each other to save space.

HVDC outdoor valves makes large customs made valve buildings unnecessary with a saving in cost and time. The outdoor valves come in modular housings, factory assembled and tested and shipped to site ready for operation. They give full flexibility in station layout and reduce delivery time.

The outdoor valve unit contains a single valve function. Consequently, 12 units are needed for a 12-pulse HVDC converter. Inside the outdoor valve unit, the electrical configuration is of traditional design with thyristor modules and reactor modules. Therefore, valve maintenance is as easy to perform.

### 3.3.4 Active DC Filters

With the active DC-filter, the toughest HVDC interference level requirements can be fulfilled with a minimum of equipment. Demands on the HVDC converter stations regarding permitted interference levels from DC lines have become increasingly stringent in recent years. Therefore an active DC filter was developed to enable efficient filtering using a small-size filter.

### 3.3.4.1 Operating Principles

The principle of the active DC filter is to inject a current generated by a power amplifier into the DC circuit cancelling the DC side harmonics coming from the HVDC converter. The amplifier is controlled by a high speed digital signal processor controller.

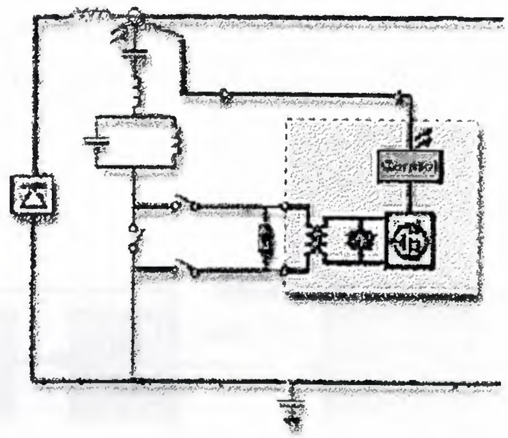

**Figure 3.18** Circuit diagram of active DC filter

### Performance

These measurements were taken in a prototype active DC filter that was installed in 1991 in the Konti-Skan 2 HVDC transmission:

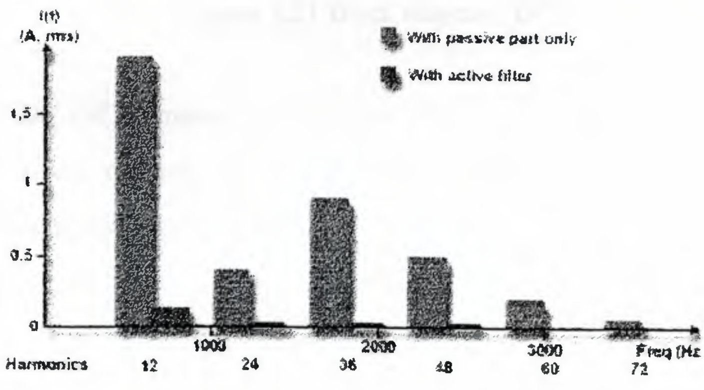


**Figure 3.19** Harmonic current content on the DC line

### 3.3.5 Optical Direct Current Transducer – OCT

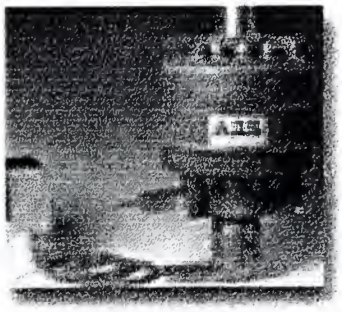

**Figure 3.20** Optical current transducer

The measuring principle is based on a high precision shunt. The electronic A/D converter on high potential is powered by light sent to the device in a separate fiber.

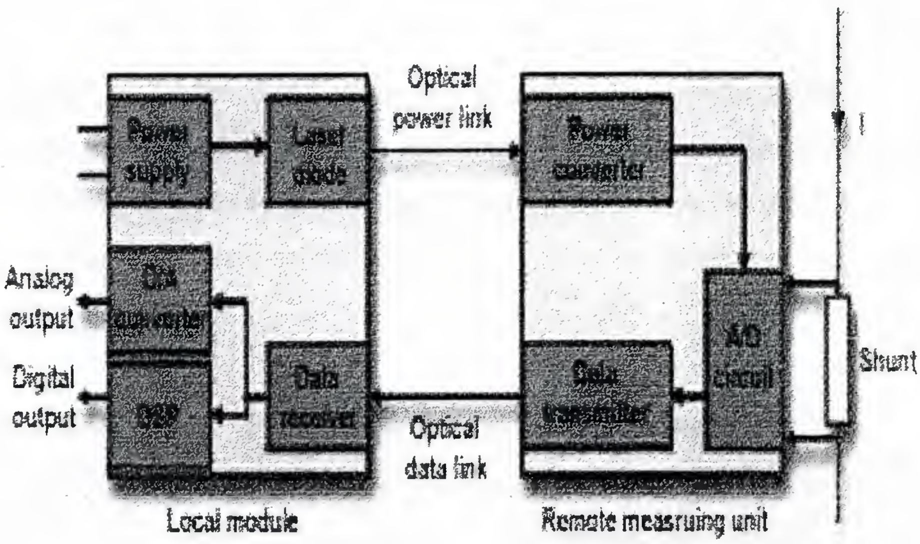


**Figure 3.21** Block diagram, OCT

The new DC-OCT meets or exceeds the performance requirements normally prescribed for direct current transducers. The accuracy is better than 0.5% in the frequency range from DC up to 7kHz.

### 3.4 The HVDC Control System

The control system is the brain in an HVDC transmission system. One major advantage of a HVDC transmission is its controllability. A modern HVDC station is equipped with a well integrated microprocessor based control and protection system. The basic power control is achieved trough a system where one of the converters controls its DC voltage and the other converter controls the current through the DC circuit. The control system acts through firing angle adjustments of the thyristor valves and through tap changer adjustments on the converter transformers. Each pole in a bipolar HVDC link has its own control system and each control system is duplicated. In the normal mode, the control systems of the two stations of a two-terminal HVDC system communicate with each other trough a telecommunication link between the stations. Most of the HVDC transmissions are remotely controlled from a dispatch center for the grid.

The MACH 2 control and protection system (developed by ABB) is fully digital. All functions for control, supervision and protection of the stations are implemented in software running in a family of microprocessor circuit boards. In the following sections we will give an over view on the MACH 2 as an example of one of the control and protection systems.

#### 3.4.1 MACH 2 - The HVDC Control System for Excellence

Highest performance and specifically developed for HVDC...MACH 2, is designed specifically for converters in power applications, meaning that many compromises have been avoided and that both drastic volume reductions and substantial performance improvement have been achieved.

The MACH 2 system is the highest performance HVDC control and protection system on the market. It has gradually evolved from an unequalled installed base of HVDC control systems around the world. MACH 2 is today also used in conventional SVC, HVDC and SVC Light and a number of other applications. Integrated with the MACH 2 control and protection equipment is the Station Control and Monitoring (SCM) system. Work stations (PCs) are interconnected by a local area network.The distributed system for remote I/O, for control as well as for process interfacing with the SCM system, is built up by a field bus network.



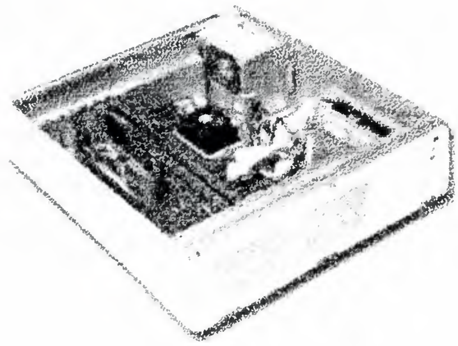

**Figure 3.22** Main computer in MACH2

The most important part of the control system, the converter firing control, is built around a host 700 MHz Pentium III dual-processor system and six high performance digital signal processors (SHARC). This gives an unequalled calculation capacity (above 1 GFlops) that is used to fine-tune the performance of the converter firing control system during various system disturbances.

### 3.4.2 MACH 2 - Open Systems Strategy and Redundant System for Maximum Security

#### 3.4.2.1 Open Systems Strategy

The development in the field of electronics is extremely fast and the best way to make sure that the designs can follow and benefit from this development is to build all systems based on open interfaces. This can be done by using international and industry standards wherever possible as these types of standards have a long life and assures that spare parts and enhancements are readily available. The open systems strategy in MACH 2 is reflected both in the use of industrial standard serial and parallel communication buses, as well as in the use of standard formats for all collected data (such as events, alarms and disturbance data).

#### 3.4.2.2 Redundant System for Maximum Security

All critical parts of the system are designed with inherent parallel redundancy in accordance with the principles used by ABB for HVDC since the early 80's. The redundant systems are designed as duplicated systems acting as active or hot standby. At any time only one of the two systems is active, controlling the converter and associated equipment. The other system, the standby system, is running, but the outputs from that system are disabled. If a fault is detected in the active system, the standby system will take over the control, with no disturbance to the transmission.

### 3.4.3 Application Software and Debugging Facilities

Most application software for the MACH 2™ system are produced using a fully graphical code generating tool called HiDraw. This facilitates the programming enormously and improves the quality of the software.

HiDraw can be run on any industry standard Windows compatible computer and is very easy to use, as it is based on the easiest possible pick, drag, place method. It is designed to produce code either in a high level language (ANSI standard C) or in assembly language. For functions not available in the comprehensive library (one for each type of processor board) it is very easy to design a new block and link to the schematic with a simple name reference.

For debugging, a fully graphical debugger, called HiBug, operating under Windows is used. HiBug allows the operator to view several HiDraw pages at the same time and look at any internal software "signal" in real time by just double clicking on the line that represents the signal. Parameters can easily be changed by double clicking on their value.

### 3.4.4 Human Machine Interface (HMI)

Efficient tools for control, monitoring and analysis of HVDC transmission systems is of great importance. The relevance of a well-designed and flexible Human Machine Interface (HMI) is obvious when it comes to more demanding application areas such as HVDC power transmission. These systems must also in all parts be easy to use in order to avoid human errors. It must be able to announce alarms and perform operator controls in a safe and reliable way. Wrong operator actions due to a bad HMI is not acceptable and could be very costly.

The requirements on these types of tools are therefore high. It is for example necessary to handle several thousands of measured values, indications and alarms of different types. All changes of state of these signals must be recorded with high time resolution for accurate real time and post fault analysis. Time resolution down to one millisecond between the stations is often required.

The new generation of integrated HMI adopted in MACH 2, the Station Control and Monitoring (SCM) System, employs the most advanced software concepts with regard to system openness and flexibility as well as ergonomic aspects. A number of different power companies have given valuable contributions to this work. Distributed over an Ethernet LAN, the SCM system comprises several operator workstations (OWS) and SQL servers. The Windows NT based OWSes are characterized by high performance and an open software architecture based on the latest trends in data engineering supporting TCP/IP, SQL and OPC.

The SCM system integrates a large number of features such as:

1. Control of the HVDC from process images

2. Sequence of Event Recorder (SCR)

3. Archiving of events

4. Powerful alarm handling via list windows

5. Effective user defined data filtering

6. Flexible handling of both on-line and historical trends

7. On-line help functions and direct access to plant documentation

8. TFR analysis

9. Remote control

10. Instant access to standard applications such as e-mail, word processing, spreadsheet, Internet

11. Automatic performance report generation developed with the most versatile graphical package

**3.4.5 Quality and Testing**

Quality is of paramount importance in MACH 2... To achieve high reliability in MACH 2, quality is built into every detail from the beginning. This is secured by careful component selection, strict design rules and finally by extensive testing of all systems. The tests are finalized by an extensive factory system test where the function and performance of the complete control and protection system is tested during normal and disturbed operation. The factory system test is performed using a real time HVDC simulator, meaning that the complete system can be tested in a very realistic way. The extensive factory system test is a guarantor for fast and trouble free field commissioning of the HVDC system.

**Figure 3.23** Factory system test of Bipole 1 of the Three Gorges - Changzhou 500 kV DC transmission project

**Figure 3.24** Partial overview of factory system test room at ABB Power Systems with control systems for three bipolar HVDC projects with a total capacity of more than 5.000 MW.

# CHAPTER FOUR

# HVDAC LIGHT

## 4.1 HVDC Light

HVDC Light is the most interesting power transmission system developed for several decades. It has the potential of changing the way transmissions are built in the future.

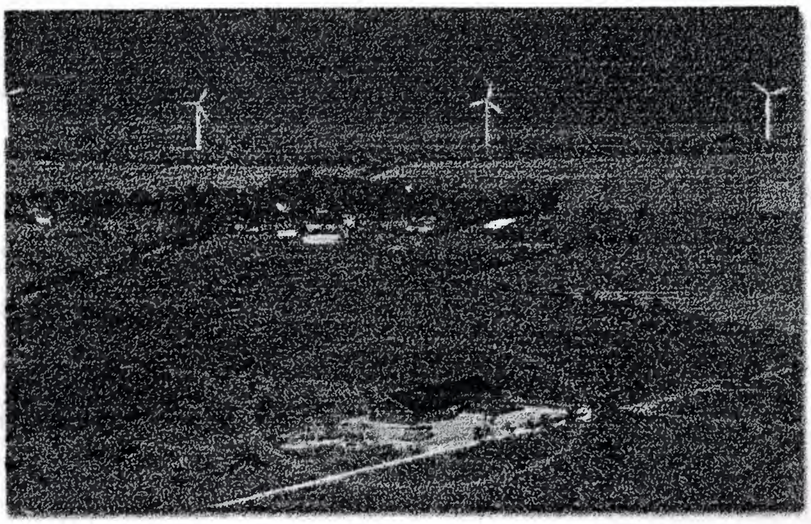

**Figure 4.1** HVDC Light

HVDC Light is a fundamentally new power transmission technology. It is particularly suitable for small-scale power generation/transmission applications and extends the economical power range of HVDC transmission down to just a few Megawatts (MW). The HVDC Light system comprises two (or more) converter stations at the ends of the transmission, and a link between them. Although conventional DC overhead lines could be used for the link, maximum benefits would be derived from the system when underground cable is used as the link between the two converter stations. In many cases the evaluated cable cost is lower than for a line and environmental and other permissions for a HVDC Light cable is much easier to obtain!

Besides being a cost competitive alternative to conventional AC and local generation, HVDC Light also opens up new possibilities for improving the quality of supply in AC power networks. HVDC Light was introduced in 1997. A number of transmissions are in commercial operation and schemes up to 300 MW are being built.

### 4.2 What is HVDC Light?

HVDC Light is an alternative to conventional AC transmission or local generation in many situations. Possible applications include:

1. Supply of isolated loads
2. Asynchronous grid connection
3. Infeed of small-scale generation
4. Infeed to city centers
5. DC grids ... etc.

HVDC Light unit sizes range from a few MW to presently 300 MW and for DC voltages up to ±150 kV and units can be connected in parallel. HVDC Light consists of two elements: **converter stations** and a **pair of cables**. The converter stations are Voltage Source Converters (VSCs) employing state of the art turn on/turn off IGBT power semiconductors. (IGBT = Insulated Gate Bipolar Transistor)

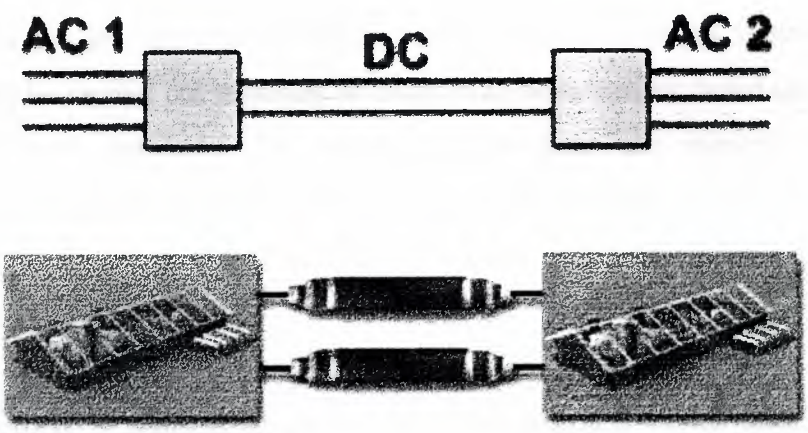


**Figure 4.2** HVDC Lihgt's elements

Unlike conventional HVDC, HVDC Light does not rely on the AC network's ability to keep the voltage and frequency stable. This gives additional flexibility regarding the location of the converters in the AC system. The HVDC Light design is based on a modular concept with a number of standardised sizes. Most of the equipment is installed in enclosures at the factory, which makes the field installation and commissioning short and efficient. The standardised design allows for delivery times as short as 12 months. The stations are compact and need little space (a 65 MVA station occupies an area of approx. 800 sq. meters). The appearance can easily be adapted to local environmental requirements.

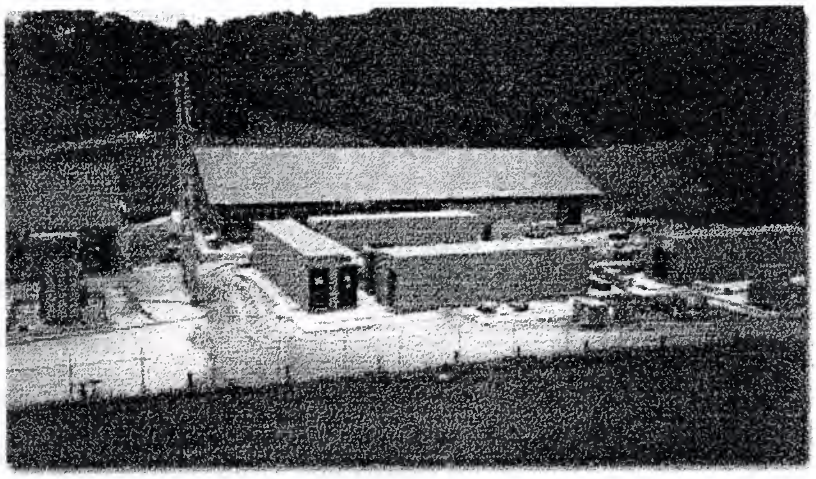

**Figure 4.3** Installation of an HVDC Light station

The stations are designed to be unmanned and are virtually maintenance free. Operation can be carried out remotely or could even be automatic based on needs of the interconnected AC networks. No communications links are required between the converter stations. Maintenance requirements are determined by the few pieces of conventional equipment such as e.g. the AC breakers and the pumps and fans in the cooling system.

Since power is transmitted via a pair of underground cables there is no visual impact, no ground current and the electromagnetic fields from the cables cancel each other. The HVDC Light cable is extruded. The selected material gives cables with high mechanical strength, high flexibility and low weight. The cables are small, yet robust and can be installed by ploughing, making the installation fast and economical.

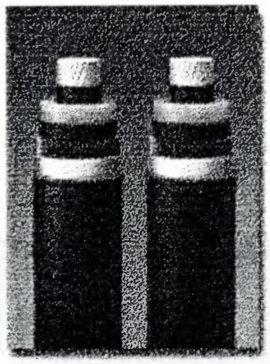

**Figure 4.4** A pair of HVDC Light cables

The role of network services has changed as a result of the introduction of competitive power markets. HVDC Light is a new DC transmission technology that has important advantages for application in competitive markets. These advantages include: modularity, standardised design, short delivery times, compact stations, cables reducing environment impacts and controllability of power and voltages.

### 4.3 Aplications of HVDC Light

1. Small scale generation
2. Feed small local loads, Island supply
3. City center infeed
4. Multiterminal DC grids
5. Interconnecting networks
6. Oil and gas offshore platforms
7. AC transmission line conversion

### 4.3.1 Small Scale Generation

"HVDC Light could make it easier to develop environmentally friendly generation sources."

**Figure 4.5** Small scale generation

Sometimes a possible small-scale generation resource remains undeveloped due to, technical or economical transmission difficulties. For example when an AC transmission needs to be oversized so that it becomes uneconomical or when it is not possible to get permission for an overhead line. An HVDC Light transmission may now improve the conditions so that it becomes economical or feasible to develop. Examples of such generation are small hydraulic generators, windmill farms and solar power. A typical example of this application is Gotland HVDC Light.

By use of a block connection from a small hydraulic generator to the HVDC Light converter it would be possible to take advantage of the converter characteristics and design the generator for a higher frequency and thus decrease weight and cost of the generator. Another possibility is to use an asynchronous generator .

To take advantage of the frequency independence of the transmission would be still more important when connecting an HVDC Light station to a windmill. Thereby a variable frequency can be used in the windmill by which it can operate always at the speed that gives maximum power.

### 4.3.2 Feed Small Local Loads and Islands

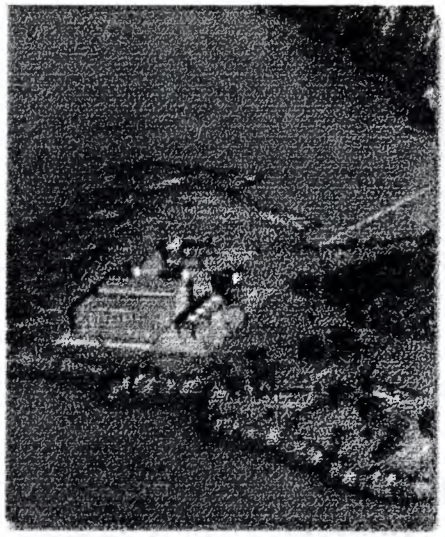

**Figure 4.6** Small local loads

In the past, for loads in the range below 100 MW, local generation was necessary if the distance between the existing electric grid and the load was beyond what is possible to achieve economically using traditional AC technology. The HVDC Light system makes it possible to cost effectively bridge across large distances with a minimum of losses. This is because the relatively high operating costs associated with the transportation of diesel fuel to remote generators as well as the low energy conversion efficiency of small diesel-generator units, are effectively eliminated by deploying the HVDC Light system and transmitting electricity from a larger grid. Such application of HVDC Light is foreseen in small cities, mining towns, villages and other places located far from any electrical network. In this way, the advantages afforded by large electricity grids are brought basically to any place on land or even offshore (e.g. islands).

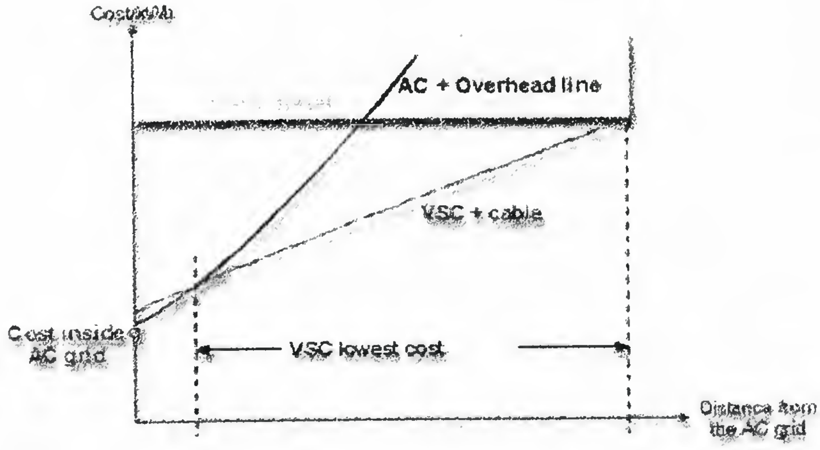


**Figure 4.7** Cost versus distance of AC with overhead lines and VSC with cables

Cost versus distance for supplying remote loads Island supply was the in fact the first application of classic HVDC already in 1954 with the link from the Swedish mainland to Gotland. But classic HVDC had a drawback in that it required synchronous compensators if the link was to be a dominant feeder of the isolated grid. With HVDC Light, no synchronous compensator is needed, and the power range has been reduced down to a few MW. Therefore HVDC Light can replace polluting, inefficient and expensive local generation and replace it with power from the main grid. Several such applications are being studied

### 4.3.3 City Center Infeed

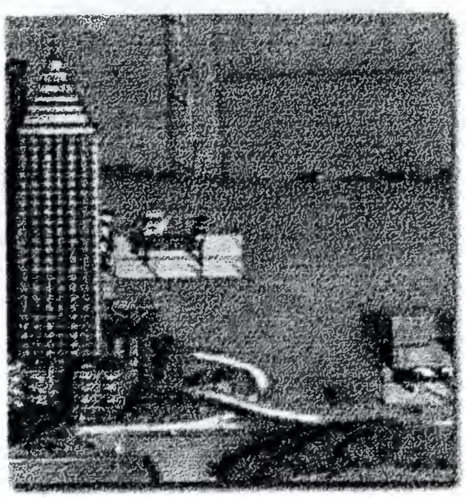

**Figure 4.8** City center infeed

As the size of a concentrated load increases due to the on-going urbanization, metropolitan power networks have to be continuously upgraded to meet the demand. Land space being scarce and expensive, substantial difficulties arise whenever new right-of-way is to be secured for the feeding of additional power. Furthermore, with increasing power levels, the risk of exceeding the short-circuit capability of switchgear equipment and other network components becomes a real threat to further expansion.HVDC Light system meets both demands - the cables are easily installed underground using existing right of ways. The capacity can thus be increased on existing power corridors. The HVDC Light converter stations are compact and by virtue of their control, they do not contribute to the short-circuit levels. The controls can furthermore balance power flow on multiple urban infeeds.

### 4.3.4 Multiterminal DC Grid

"HVDC Light makes it a lot easier to build multiterminal grids than with classic HVDC."

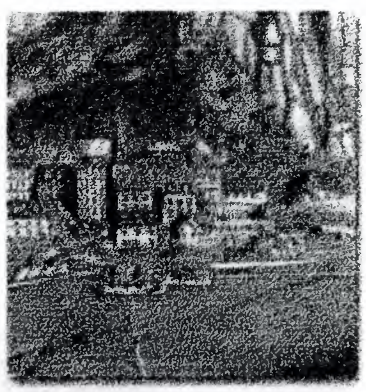

**Figure 4.9** Multiterminal DC grid

With HVDC Light three or more converter stations can make up a HVDC grid a lot easier than with classic HVDC. Because the HVDC Light converters are voltage controlled there is no need to balance the currents like in "conventional multiterminal" HVDC.

The HVDC Light terminals can be connected to different points in the AC grid or to different AC grids. These DC grids can be radial, meshed or a combination of both, that these can be changed and expanded. In fact multi-terminal configurations and grid alterations can be done in a "plug and operate" fashion, with continued robust performance.

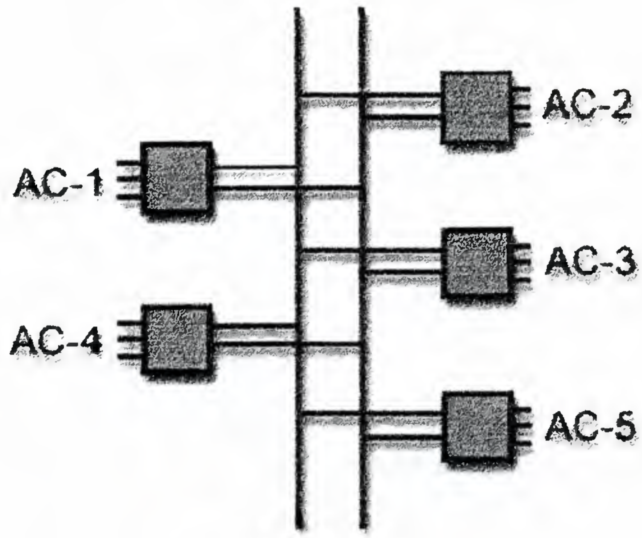


**Figure 4.9** HVDC Light termenals

### 4.3.5 Interconnecting Networks

**Figure 4.10** Interconnecting networks

As with classic HVDC, HVDC Light is ideal for asynchronous network interconnection.The interconnection can be built either with a DC cable or overhead line, or if AC-lines are brought to the same station, as a back-to-back station. The HVDC Light interconnections Directlink in Australia employ DC cables, while Eagle Pass linking Mexico with Texas is a back-to-back station.

### 4.3.6 Oil and Gas Offshore Platforms

HVDC Light can be used to deliver power both to and from offshore platforms.

#### 4.3.6.1 Power to Platform

Traditionally, all auxiliary power used on oil and gas production platforms has been generated locally. A large number of investigations have been made over the years to feed power from land using classic HVDC. But none of these has materialized because of the weight and size of the converter equipment, and in particular the synchronous compensators that would have been necessary.

But with HVDC Light these difficulties are overcome: the converter is smaller and weighs much less, there is no need for a synchronous compensator, and the power range is better adapted to the needs of the platform. And the HVDC Light extruded cable is much less expensive than a traditional mass impregnated submarine HVDC cable.

For a group of platforms the converter station can be located on one and power can be distributed to the others via AC cables, or DC power can be distributed to several platforms in a multi-terminal arrangement.

#### 4.3.6.2 Offshore Power Plants

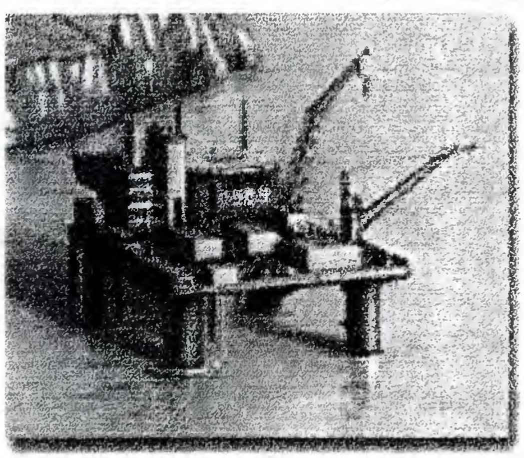

**Figure 4.11** Offshore power plants

The obvious advantages with HVDC Light of course applies also for offshore power plants that generate power from e.g. excess gas on oil platforms, that would otherwise be flared.

### 4.3.7 AC transmission Line Conversio

"A HVDC line can carry more power than an AC line."

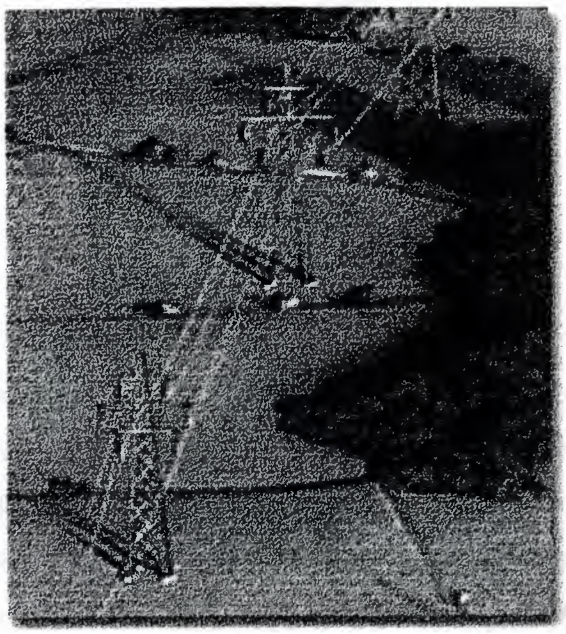

**Figure 4.12** HVDC line

In special cases it might be advantageous to upgrade an AC line to DC in order to push more power through it rather than to build a new line. Converting an AC line to DC brings with several other advantages like better voltage stability and power control (offload power on parallel lines).

## 4.4 HVDC Light Converter Technology

Conventional HVDC converter technology is based on the use of line-commutated or phase-commutated converters (PCC). With the appearance of high switching frequency components, such as IGBTs (Insulated Gate Bipolar Transistor) it becomes advantageous to build VSC (Voltage Source Converters) using PWM (Pulse Width Modulation) Technology .

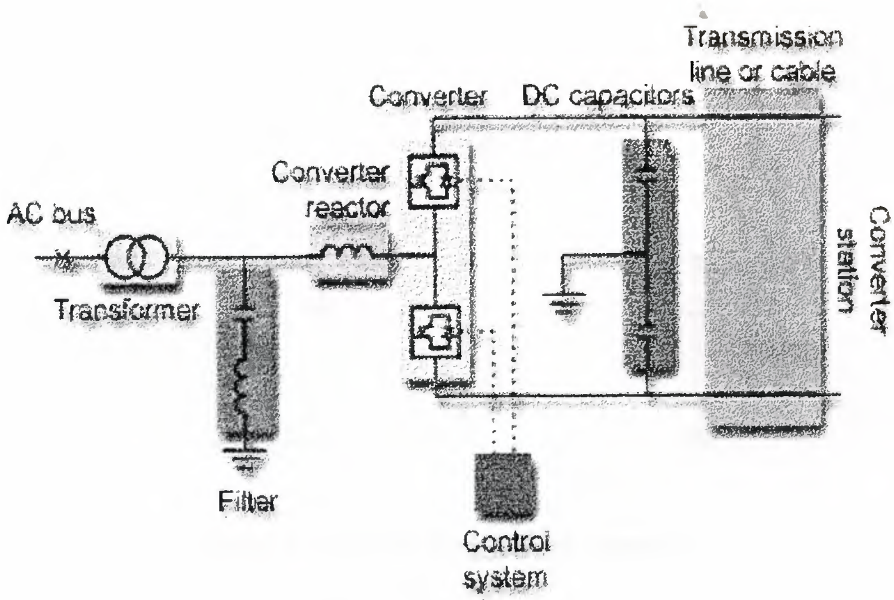


**Figure 4.13** Converter station

The key part of the HVDC Light converter consists of an IGBT valve bridge. No special converter transformers are necessary between the valve bridge and the AC-grid. A converter reactor can in principle separate the fundamental frequency from the raw PWM waveform. If the desired DC voltage does not match the AC system voltage, a normal AC transformer may be used in addition to the reactor. A shunt AC-filter is placed on the AC-side of the reactor. On the DC-side there is a DC capacitor that serves as a DC filter too.

### 4.4.1 Pulse Width Modulation Technology for HVDC Light

An entirely different concept compared with the classical HVDC converter. In the PWM bridge switching very fast between two fixed voltages creates the AC-voltage. The desired fundamental frequency voltage is formed through low pass filtering of the high frequency pulse modulated voltage.

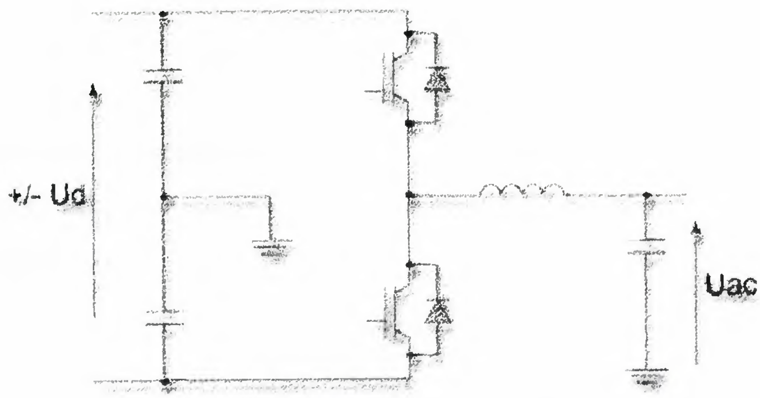


**Figure 4.14** One phase of a VSC converter

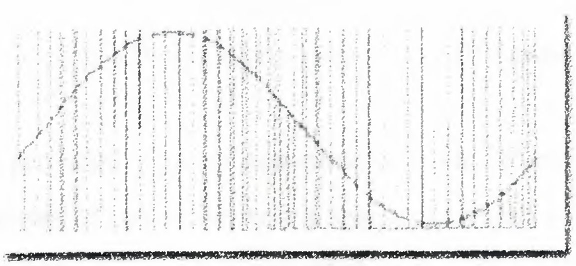

**Figure 4.15** The PWM pattern and the corresponding power frequency voltage of a VSC converter

With PWM it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneous. Hereby PWM offers the possibility to control both active and reactive power independently.

This makes the Pulse Width Modulated Voltage Source Converter a close to ideal component in the transmission network. From a system point of view it acts as a motor or generator without mass that can control active and reactive power almost instantaneously. Furthermore, it does not contribute to the short circuit power as the AC current can be controlled.

### 4.4.2 Insulated Gate Bipolar Transistor For HVDC Light

The valve bridge used in HVDC Light is in its basic form a two-level, three-phase topology with six valves and series connected IGBTs in each valve.

The IGBT is characterised by:

1. Multi-chip design (chip paralleling is easy)
2. Forward blocking only
3. Current limiting characteristics
4. Gate turn-off fully controllable
5. High speed device

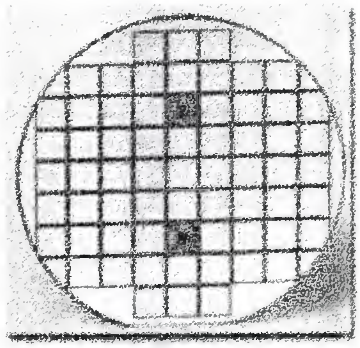

**Figure 4.16** The silicon wafer with IGBT chips

Every IGBT is provided with an anti-parallel diode. Even voltage distribution is achieved during all phases of operation with a special gate unit and a voltage divider for each IGBT level. The gate drive unit is mounted in the stack along with its associated IGBT. Turn on/off of each single IGBT is ordered via an optical link from the control equipment on ground potential.The semiconductors are cooled with de-ionised water.

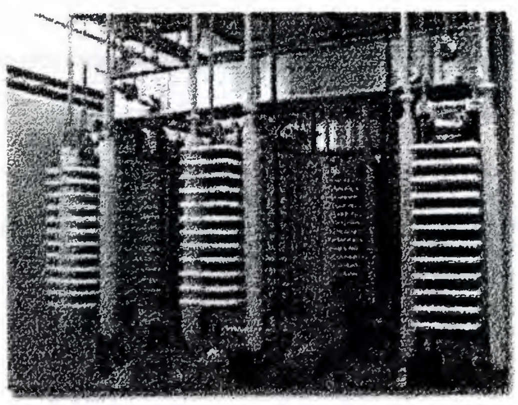

**Figure 4.17** VSC with IGBT Valves

The previous photo illustrates a VSC with IGBT valves for use in a back-to-back HVDC Link or in a STATCOM. For transmission voltages more IGBT levels with higher voltage ratings would be connected in series.


**Figure 4.18** Series connection of IGBTs

### 4.4.3 Components Connected to the HVDC Light Converter on the AC Side (Converter Reactor and AC-Filter for HVDC Light)

No special converter transformers or phase shifting transformers are needed. But a series reactor is necessary to separate the AC fundamental frequency from the raw PWM waveform. The series reactors consist of air core devices. They are housed in an aluminium enclosure to eliminate the high frequency disturbances from the PWM process. If necessary, voltage matching can be accomplished with regular transformers. Transformer tap changers are generally not required to regulate AC voltage, maintain nominal firing angles or help match reactive power demand as with conventional HVDC converters.

The Light converter has a switching frequency of 2 kHz. That is 40 times faster compared to a phase-commutated converter operated at 50 Hz. Since there are only high frequency harmonics, shunt filtering is therefore relatively small compared to the converter rating. It is sufficient with a high pass-filter and no tuned filters are needed.

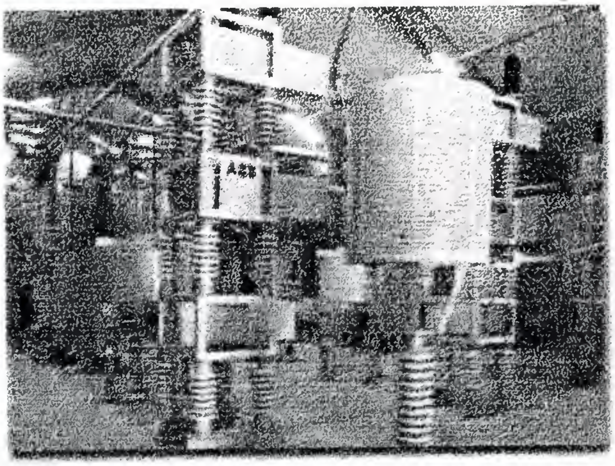

**Figure 4.19** A filter in the Gotland HVDC Light project

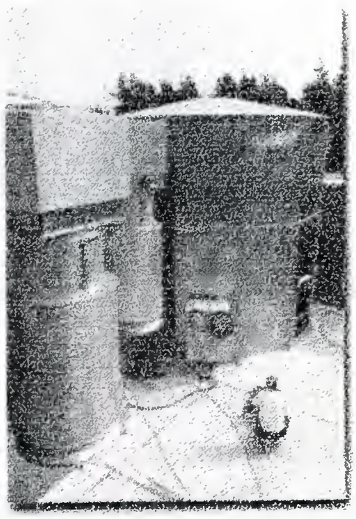

**Figure 4.20** A series reactor in the Gotland HVDC Light project

### 4.4.4 Active and Reactive Power Control

The fundamental frequency voltage across the converter reactor defines the power flow between the AC and DC sides. Changing the phase angle between the fundamental frequency voltage generated by the converter (Ug) and the voltage on the AC bus controls the active power flow between the converter and the network. The reactive power flow is determined by the amplitude of Ug, which is controlled by the width of the pulses from the converter bridge.

The control is performed by the MACH 2 system. All functions for control, supervision and protection of the stations are implemented in software running in a family of microprocessor circuit boards.

### 4.4.5 Station Design

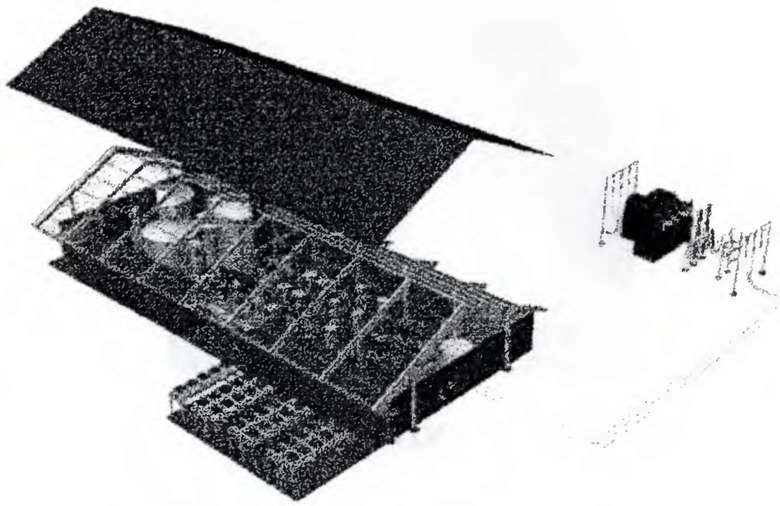

**Figure 4.21** HVDC Light station design

The key to short delivery times is standardisation. The Light concept lends itself to a modular standardised design with a high degree of factory testing. Different types of Light stations have many modules in common, which shortens the time for design and manufacturing. The absence of buildings and a minimum of civil works also contribute to short delivery times. A normal delivery time for a complete Light project today is about 12 month.

## 4.5 HVDC Light Cables

With HVDC Light cables there is no need to get permits for an overhead line!

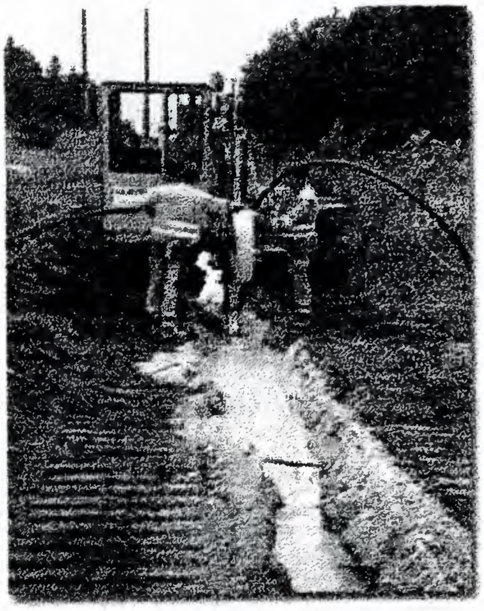

**Figure 4.22** HVDC Light cables

The new HVDC Light cables have insulation of extruded polymer. The insulation is triple extruded together with the conductor screen and the insulation screen. In HVAC there has been a change of technology going from paper insulated cables to extruded cables, mostly XLPE. The preference of extruded cables also for applications in HVDC has been obvious for a long time. Several reports have been published in the past, where XLPE has been tested for HVDC applications but without success. One reason has been the existence of space charges in the insulation leading to uncontrolled local high electric fields causing dielectric breakdowns. Another reason has been uneven stress distribution due to temperature dependent resistivity causing overstress in the outer part of the insulation

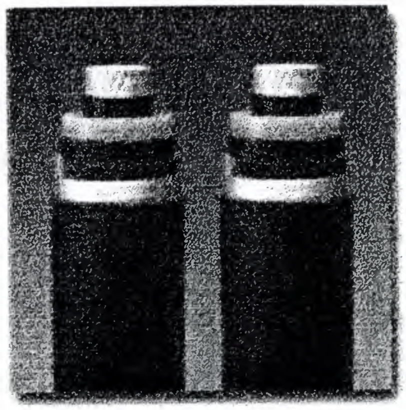


**Figure 4.23** Gotland HVDC Light cables

The HVDC Light cable development has overcome these problems and has resulted in an extruded cable for HVDC that is an important part of the HVDC Light concept. The cables are operated in bipolar mode, one cable with positive polarity and one cable with negative polarity. The cables are installed close in bipolar pairs with anti-parallel currents and thus eliminating the magnetic fields.

## 4.6 Differences Between HVDC Light and Classical HVDC

HVDC Light is what all power transmission engineers have dreamt of. Differences between classical HVDC and HVDC Light can be classified in the following categories:

1. Power range
2. Modular
3. Converter circuits
4. Converter station circuits
5. Independence of AC networks
6. Works as an SVC

### Power Range

Classical HVDC is most cost effective in the high power range, above approximately some 250 MW. HVDC Light on the other hand comes in unit sizes range from a few MW to presently 300 MW and for DC voltages up to ±150 kV.

### Modular

HVDC Light is based on a modular concept with a number of standardized sizes for the converter stations. Most of the equipment is installed in enclosures at the factory. Conventional HVDC is always tailor made to suit a specific application.

### Converter Circuits

The HVDC Light is by nature bipolar. The DC circuit is not connected to ground. Therefore two conductors (cables) are needed.

### Converter Station Circuits

HVDC Light converter stations are Voltage Source Converters (VSCs) employing state of the art turn on/turn off IGBT power semiconductors. Therefore the circuit is quite different from conventional HVDC.

| Function in converter station | Conventional HVDC | HVDC Light |
|---|---|---|
| Valves | Thyristor valves | IGBT valves |
| Connection valve - AC grid | Converter transformers | Series reactor (+transformer) |
| Filtering & reactive compensation | 50% in filters and shunt capacitors | Only small filter |
| DC current smoothing | Smooting reactor + DC filter | DC capacitor |
| Telecommunication between stations controls | Needed | Not needed |

**Figure 4. 23** Conventional HVDC versus HVDC Light

**Independence of AC network**

HVDC Light does not rely on the AC network's ability to keep the voltage and frequency stable. Unlike conventional HVDC, the short circuit capacity is not important. HVDC Light can feed load into a passive network (i.e. lacking synchronous machines)!

**Works as an SVC**

Conventional 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 and therefore extra cost. The HVDC Light control makes it possible to create any phase angle or amplitude, which can be done almost instantly. This offers the possibility to control both active and reactive power independently. In fact the same converter can be used as a SVC and it is then called SVC Light. It is extremely effective to eliminate flicker e.g. from arc furnaces.

# CONCLUSION

After going through all of the previous topics explained through this thesis and studying them we get out with a valuable knowledge of transmitting high voltages using the HVDC and HVDC Light technologies and the benefits of using such technologies instead of AC transmissions.

HVDC and HVDC Light technologies over come most of the difficulties that were faced when using AC transmission. They -as we saw- introduce many valuable solutions for long distance water crossing transmissions, Oil and gas offshore platforms, Network interconnections, supplies, Multiterminal DC grids, Lower power losses, Asynchronous connections and many other powerful applications not forgetting the economical benefits presented in the lower investment costs as a result of installing such technologies. Also, one of the most important advantages is related to the possibility to accurately control the active power transmitted on a HVDC line. This is in contrast to AC lines, where the power flow cannot be controlled in the same direct way. Not to forget the environmental impact, which is less than with AC due to the fact that transmission line used for HVDC or HVDC Light is much smaller and needs less space than AC lines for the same power capacity. Thus, these new technologies are in that respect favorable in many cases over AC transmissions.

With the development of the HVDC technology (HVDC Light, HVDC 2000 and the development of the components composing them) its applications are growing, becoming larger and preferable in many installations all around the world.

One of the possible future applications is to island the connection between the main land of Turkey and TRNC (Turkish Republic of Northern Cyprus), which is around 90 km, from sea. This distance is in the limits where HVDC is advantageous over AC transmissions for under water connections. As a matter of fact, this application has been discussed for many years but unfortunately was unfeasible in those days. Today's development of HVDC technology provides some advantages that could make such an interconnection feasible. The development in rectifier-inverter models allows this interconnection to be used for AC transmission at anytime besides DC transmission as well, [1] ELECO 2001. So, as for this ability and all of the other benefits of using

HVDC technology in such a connection we can clearly see that for this connection HVDC is more advantageous as they are more flexible systems as well.

Finally, we have to mention that installing HVDC systems has its difficulties and problems as well. Expensive converters, Difficulty of high power generation, Difficulty of circuit breaking for multi-terminal operation, Reactive power requirement, Difficulty of voltage transformation and some other difficulties that could be the reason why an HVDC system is not preferable. But, with the continuing fast development of this technology such problems can be overcame and better solutions can be provided.

## GLOSSARY

**CCC** Capacitor Commutated Converters: Commutation capacitors are connected between the valve bridge and the converter transformers

**Cone Tune** Automaticly tuned AC filter: It has electromagnetic tuning that adjusts to the inherent frequency variations and temperature variations of the filter components.

**FACTS** Flexible AC Transmission Systems : The collective acronym FACTS has been adopted in recent years to describe a wide range of controllers, many of them incorporating large power electronics converters, which may be used to increase the flexibility of power systems and thus make them more controllable.

**HMI** Human Machine Interface

**HVAC** High Voltage Alternating Current: HVAC transmission systems are commonly used to transport energy from power plants to main consumption centers. Systems up to 800 kV are presently in commercial operations.

**HVDC** High Voltage Direct Current technology: Is used to transmit electricity over long distances by overhead transmission lines or submarine cables. It is also used to interconnect separate power systems, where traditional alternating current (AC) connections cannot be used.

**HVDC Light** A fundamentally new power transmission technology, particularly suitable for small-scale power generation/transmission applications and extends the economical power range of HVDC transmissions down to just a few Megawatts (MW).

**IGBT** Insulated Gate Bipolar Transistor

**MACH 2** A control and protection system for HVDC.

| | |
|---|---|
| **MSSC** | Mechanically Switched Series Capacitors |
| **OCT** | Optical Direct Current Transducer |
| **PCC** | Phase-Commutated Converters |

**PWM** Pulse Width Modulation : From a system point of view it acts as a motor or generator without mass that can control active and reactive power almost instantaneously. Furthermore, it does not contribute to the short circuit power as the AC current can be controlled.

| | |
|---|---|
| **SCCL** | Super Conducting Current Limiter |
| **SCM** | Station Control and Monitoring |
| **SMES** | Super Conducting Magnetic Energy Storage |

**STATCOM** Static Synchronous Compensator:This compensator has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs.

**SVC** Static Var Compensation: The characteristics of Static Var Compensators are their flexibility, dependability and their exceptional controllability. SVC can be used for symmetrical three-phase control or phase-by phase control.

**SVC Light** SVC Light: is a device of the STATCOM type, based on voltage source converter technology equipped with IGBT.

| | |
|---|---|
| **SVR** | Synchronous Voltage Reversal |
| **TCU** | Thyristor Control Unit |
| **TCSC** | Thyristor Controlled Series Capacitors |
| **TSSC** | Thyristor Switched Series Capacitors |

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