HVDC LEARN

Modules for Maturing HVDC Electric Transmission Knowledge

Funded by the US Department of Energy (DOE)
within the Office of Energy Efficiency & Renewable Energy (EERE)

HVDC-Learn Short Course

Thursday, May 22, 2025

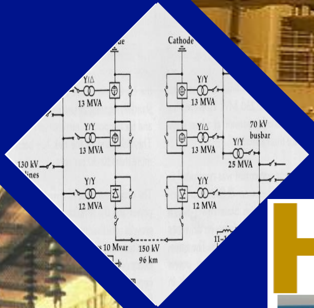
Module 1a: Introduction to HVDC Technology

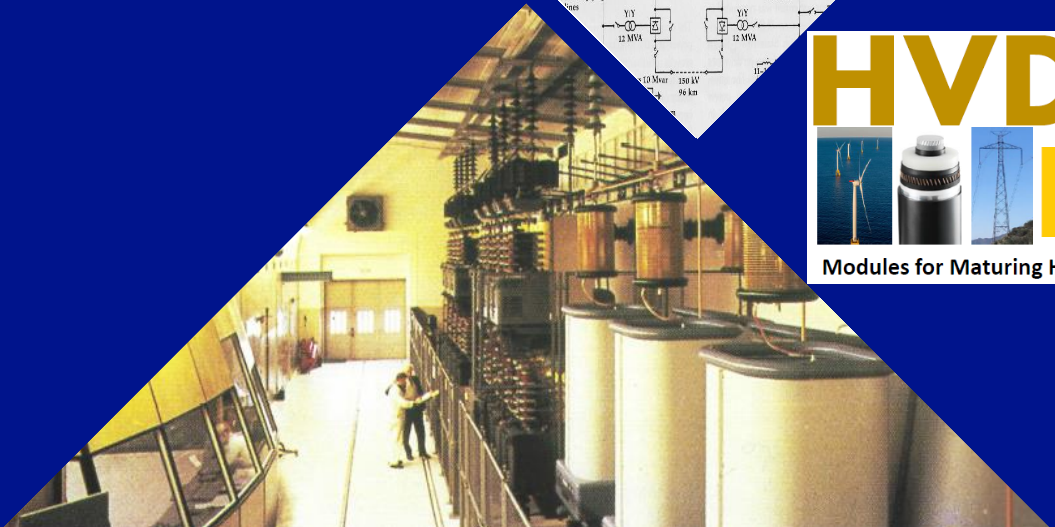
Tufts University
National Grid

Per-Anders Lof, National Grid / Tufts University
Contact info: per-anders.lof@tufts.edu

Introduction to HVDC Technology

Module 1a
Per-Anders Löf
May 22, 2025





HVDC LEARN
Modules for Maturing HVDC Electric Transmission Knowledge

Tufts UNIVERSITY

nationalgrid

01

Introduction

nationalgrid

Prerequisites and Objectives

Prerequisite Competencies:

1. Basic electric power engineering knowledge (electric circuits and electromagnetic concepts)
2. Interest in the development of HVDC technology

Module Objectives:

1. Present historic expose of the development of HVDC
2. Introduce objectives and components of HVDC systems
3. Characterize principal types of HVDC configurations

Introduction

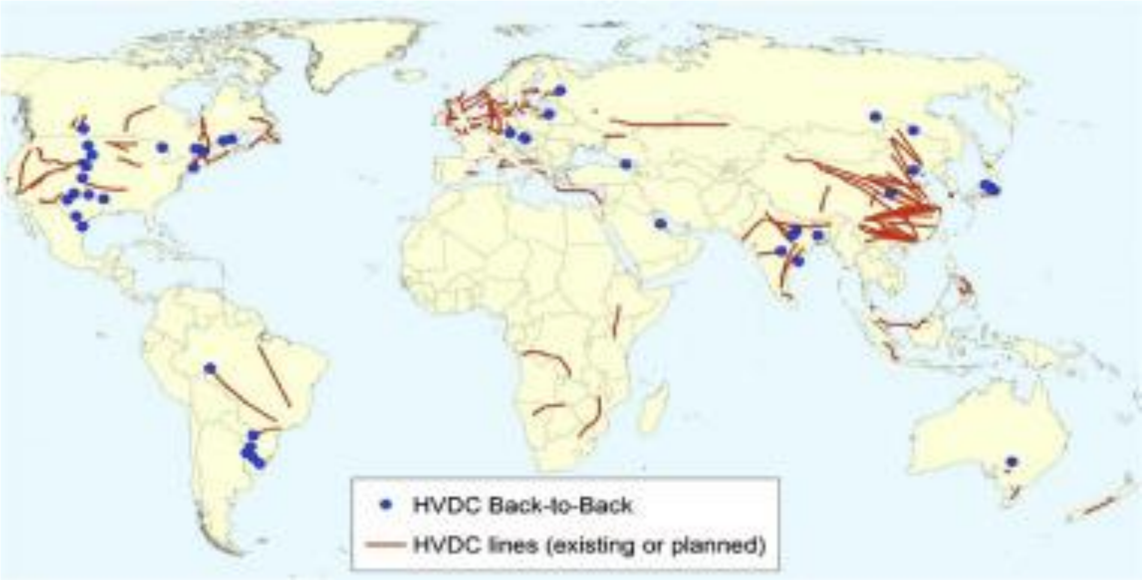
High voltage direct current (HVDC) transmission provides a highly flexible and efficient method of transmitting large quantities of electric power over long distances.

Development of HVDC transmission can be traced back to the early development of direct current and alternating current technologies, including the 'war of currents.'

OBJECTIVE

To provide an introduction to HVDC with either line commutated converter (LCC) or voltage source converter (VSC) technology; with focus on LCC technology.

Module 1a – Table of Content



02

Historic Expose

Tufts UNIVERSITY

nationalgrid

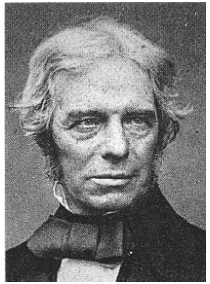
Historic Expose

Early History

Invention of electric battery (voltaic pile) by Italian physicist and chemist Alessandro **Volta** around 1800.

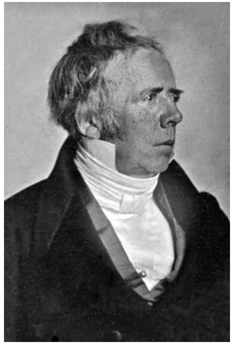
Invention of solenoid by French physicist and mathematician André-Marie **Ampère** in the first part of the 19th century.

English physicist and chemist Michael **Faraday**, developed conceptual models for the electrical generator, motor, and transformer. Travelled to continental Europe, where he met with Alessandro Volta and André-Marie Ampère.

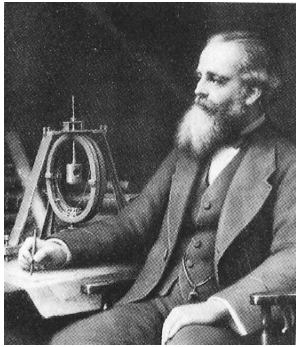


Historic Expose

André-Marie Ampère is together with Danish physicist Hans Christian **Ørsted** are considered ‘founders’ of understanding of electromagnetism.

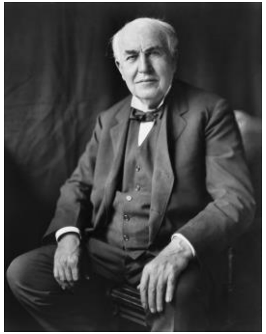


The phenomenon of electromagnetism was further developed and described by Scottish physicist and mathematician James Clerk **Maxwell** in the publication ‘A Treatise on Electricity and Magnetism’ in 1873.



$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

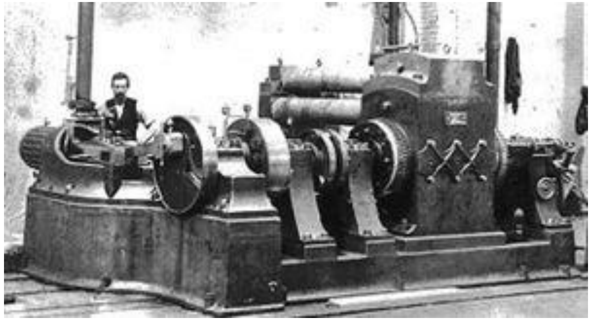
Pearl Street



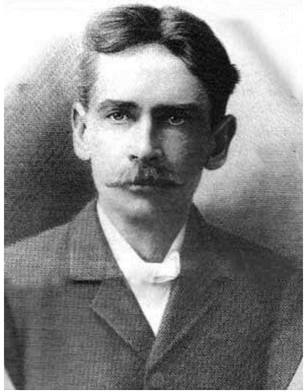
In October 1879, American invertor Thomas Alva **Edison** successfully tested an incandescent light bulb.

In August 1880, Edison filed the patent application ‘System of Electric Lighting’ - Term ‘central station’ was adopted from railway terminology.

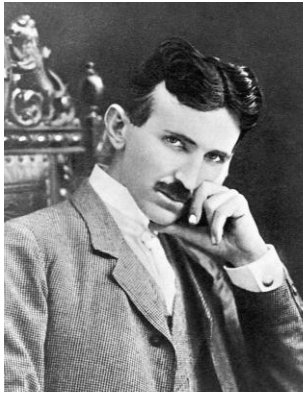
Pearl Street station started generating electricity on September 4, 1882, with six 100 kW dc dynamos, initially serving 400 lamps at 82 customers.



AC vs. DC



Longer distance transmission of electric power using alternating current became feasible first with the development of transformers for stepping-up or stepping-down voltages. The American inventor and engineer William **Stanley** developed first practical transformer in 1886.

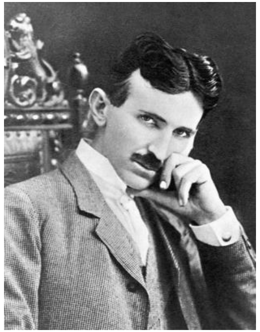


In November of 1887, Serbian American engineer and inventor Nikola **Tesla** filed a series of seven US patents in the field of polyphase ac motors, power transmission, generators, transformers, and lighting.

Abstract

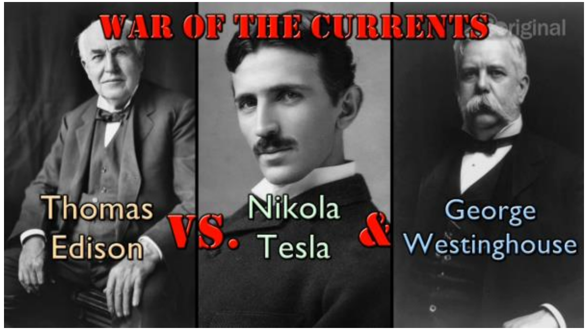
During the early 1890s, American mathematician, engineer, and philosopher Charles Proteus **Steinmetz** developed mathematical understanding of ac power systems.

The Russian Mikhail **Dolivo-Dobrovolsky**, the American Nikola **Tesla**, the Italian Galileo **Ferraris**, and the Swede Jonas **Wenström** pioneered polyphase ac power systems.



War of the Currents

In the late 1880s and early 1890s there was a competition between Thomas Edison’s direct current (dc) and George **Westinghouse**’s (based on Nikola Tesla’s inventions) alternating current (ac) electric power transmission systems, sometimes referred to as ‘the war of currents.’



1893 Chicago World’s Fair, a.k.a. the Columbian Exposition, turned the exhibit into a ‘city of light,’ and demonstrating that ac power systems were both practical and available.

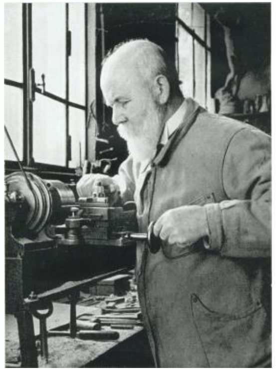
03

Early HVDC Development

nationalgrid

Early HVDC Development

While alternating current prevailed in the ‘war of currents,’ the direct current option was never really abandoned.



Swiss engineer René **Thury** pioneered dc transmission using series connection of multiple dc generators, in the 1890s which continued to be in service for more than 30 years. Genoa's Thury dc power system was upgraded to finally serve 630 kW at 14 kV over 120 km.

After rotary converters, mercury-arc valves were invented, developed, and used to convert between ac and dc. During the 1940s experimental high power dc transmission based on mercury-arc valve technology were developed and came into existence in Germany, Sweden, and the U.S.

Uno Lamm

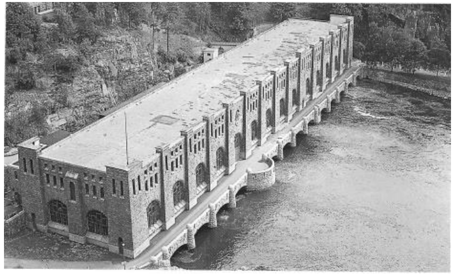
All HVDC systems since the 1940s use electronic (static) converters.

In 1928, Uno **Lamm**, was assigned the problem of solving the so-called arc-back (or backfire) of mercury-arc valves.

Application of mercury-arc valves were at that time limited to 1,500 V, and used e.g., in the electrochemical industry.

Uno Lamm has often been referred to as the ‘Father of High Voltage Direct Current’ power transmission.

In Sweden, a 60 km 6.5 MW 90 kV experimental HVDC link between Mellerud and Trollhättan was energized in 1946.



Vattenfall and ASEA

Long-term industrial relationship, resulting in an intimate collaboration between a large state customer (Vattenfall) and a large manufacturing company (ASEA) has been referred to as a ‘development pair.’

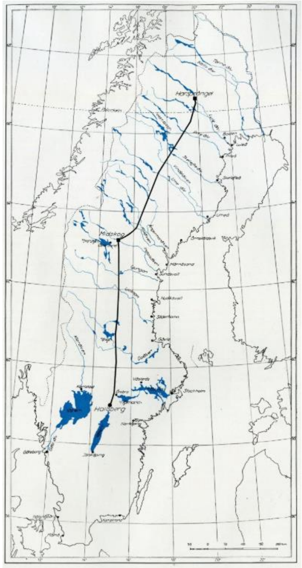
The collaboration during the first half of the 1900s was important factor during the development of both alternating current and direct current for electric bulk power system applications.

During this period Vattenfall built a laboratory for testing of mercury-arc valves. Vattenfall provided the laboratory facility, electric power for the experiments, and operational staffing while ASEA provided experimental equipment, measurement equipment, and technical expertise.

No monetary transactions took place between the two entities.

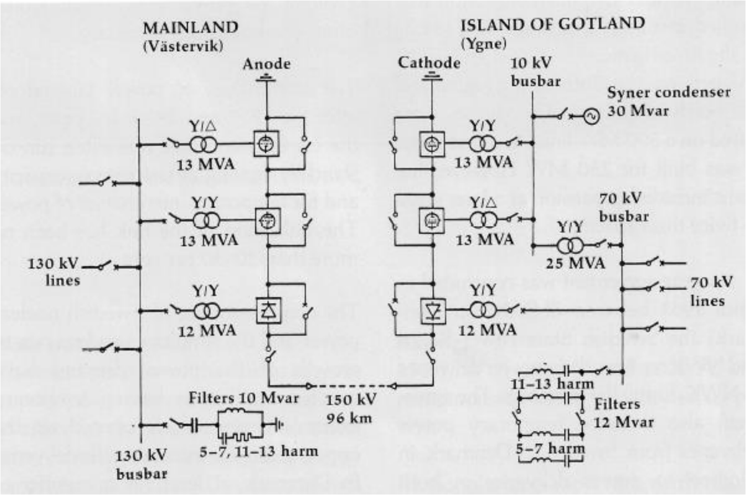
VATTENFALL

ASEA



Gotland

The world's first commercial HVDC transmission was built between the Swedish mainland the island of Gotland – 100 kV ~90 km underwater cable and development of the converter in three phases: 10, 20, and 40 MW.



International Project

In May 1957, British Electricity Authority (BEA) and Electricité de France (EdF) signed a letter of intent to purchase a HVDC system from ASEA.

In 1961, English Electric Company UK signed an agreement with ASEA for the design and manufacturing of mercury-arc valves.

The first HVDC Cross-Channel scheme (IFA1) 160 MW at ±100 kV with a 45 km undersea cable went into service in 1961.

Mercury-arc valves were used for the initial HVDC projects. In May 1967, a thyristor prototype was installed for testing in the Gotland HVDC scheme.

[Thyristor valves in foreground and mercury-arc valves in background]

04

Semiconductor Development

Tufts University

nationalgrid

Semiconductors

Power semiconductors can be classified based on their controllability:

- Diodes where on and off states are controlled by the power circuit;
- Thyristors which are switched on by a control signal but must be turned off by the power circuit; and
- Controllable switches which can be turned on and off by control signals.

Semiconductor devices have during the decades been evolving from low power devices to high power electronics devices.

While mercury-arc valves are not semiconductors, they are static converters, i.e., a forerunner to the use of thyristors. Mercury-arc valves were in the 1970s replaced with thyristors in HVDC application.

Thyristor Projects

First thyristor devices were released commercially in 1956.

First HVDC scheme completely based on thyristors, Eel River in 1972.

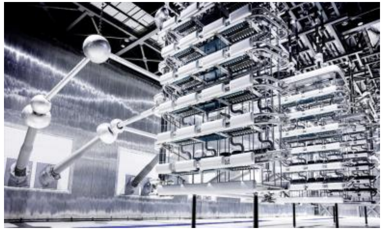
- Volgograd-Donbass system, 720 MW, ±400 kV (1965)
- Sardinia–Corsica–Italy (SACOI) started 1965, third terminal 1992
- Pacific Intertie 1,440 MW, ±400 kV, 1,362 km (1970)
- Cahora Bassa 1,920 MW, ±533 kV, 1,456 km (1979)
- Vyborg back-to-back 1,070 MW (1981-1983, decommissioned 2022)
- Itaipu HVDC 3,150 MW, ±600 kV, 780 km (1985-1987)
- Quebec-New England 2,000 MW, ±450 kV, 1,514 km 3-terminal (1990)

Insulated-Gate Bipolar Transistors

Insulated-gate bipolar transistors (IGBTs), gate turn-off thyristors (GTOs), and integrated gate-commutated thyristors (IGCTs) have been used in motor drive applications since the 1980s. Higher rated devices allowed for development of voltage source converters (VSCs) for HVDC applications.

First experimental HVDC scheme with voltage source converters was a 3 MW, ±10 kV scheme between Hällsjön and Grängesberg (Sweden).

First (non-back-to-back) VSC HVDC scheme in the United States was the Cross Sound Cable, 330 MW, ±150 kV, 40 km bipolar cable between New Haven, CT and Shoreham, on Long Island, NY (2002-2003).



05

Why HVDC?

Tufts UNIVERSITY

nationalgrid

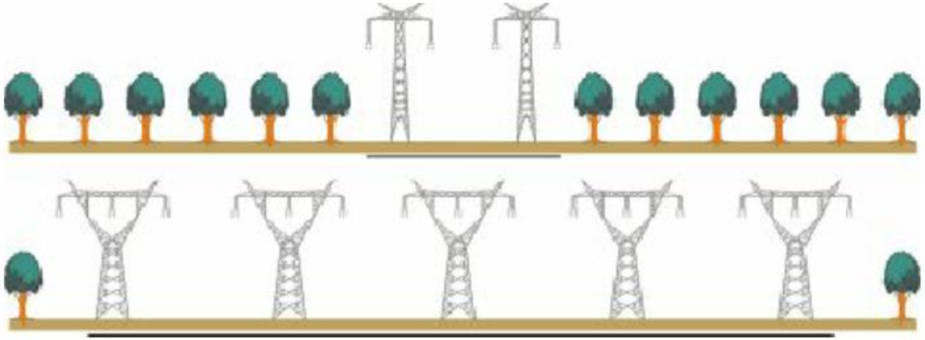
Technology-Friendly Environment

Early development of HVDC was characterized by development of the markets and its applications in parallel with product development.

It was acknowledged that “it will cost more than expected and take more time, but the market is a lot bigger than we first thought,” which created a positive, technology-friendly environment.

[Module 7a]

Reduced Right-of-Way (ROW) requirements, i.e., reduced land-owner impact – and if cable …



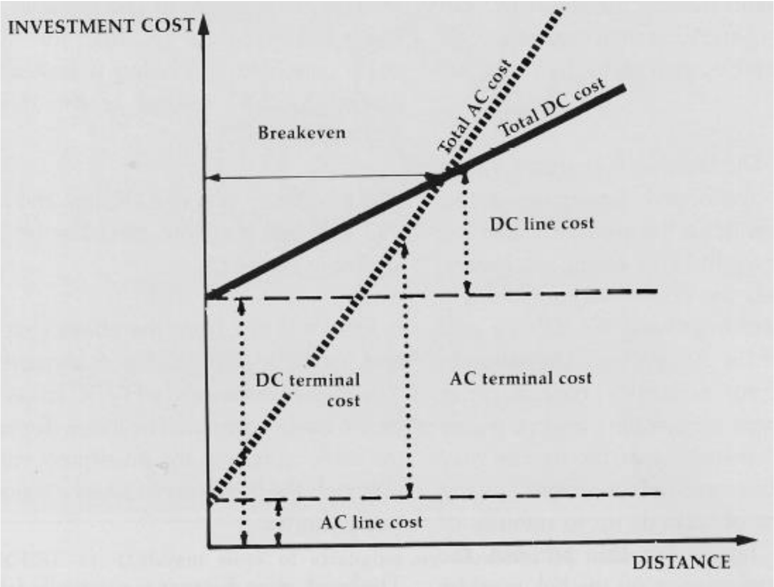
Characteristics of HVDC

Characteristics of HVDC Transmission be separated into:

- Controllable - Power injected where needed
- Facilitates integration of remote diverse resources
- Higher power capacity rating with fewer lines
- Less expensive lines
- No stability distance limitation
- Long cables, in particular undersea cables
- Reactive power demand limited to terminals, i.e., independent of distance
- Lower losses
- No limit to underground or sea cable length
- Asynchronous, ‘firewall’ against cascading outages

AC vs. DC Considerations

Investment Cost as Function of Distance for HVAC and HVDC Links

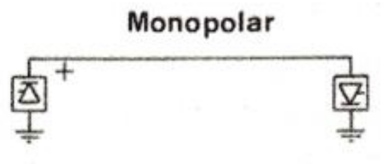


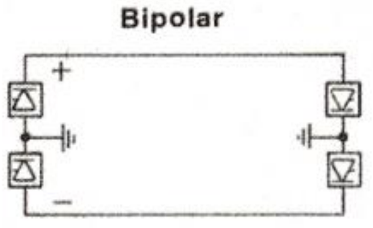
While building of converter stations are more expensive than comparable HVAC substations, the overhead line or cable costs less and the losses are lower. Hence, there is a break-even distance.

The final decision of HVAC vs. HVDC depends on many economic, technical, and environmental considerations.

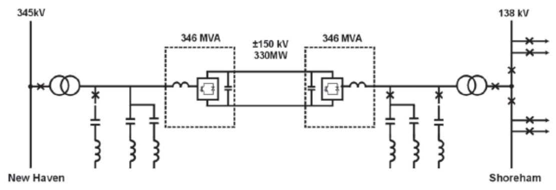
HVDC Topologies

Monopolar vs. Bipolar HVDC LCC schemes





HVDC VSC scheme

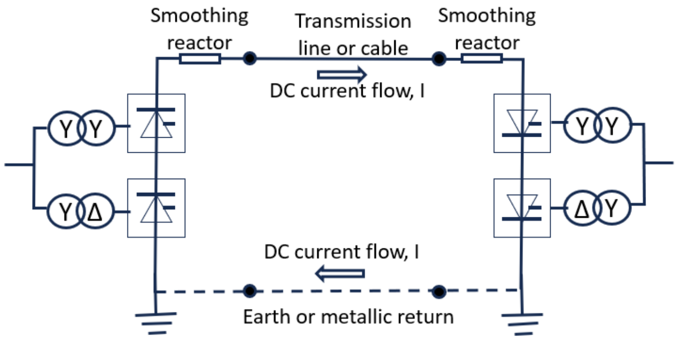


There are also back-to-back HVDC schemes which can be used to provide ‘bridges’ between non-synchronous ac power systems.

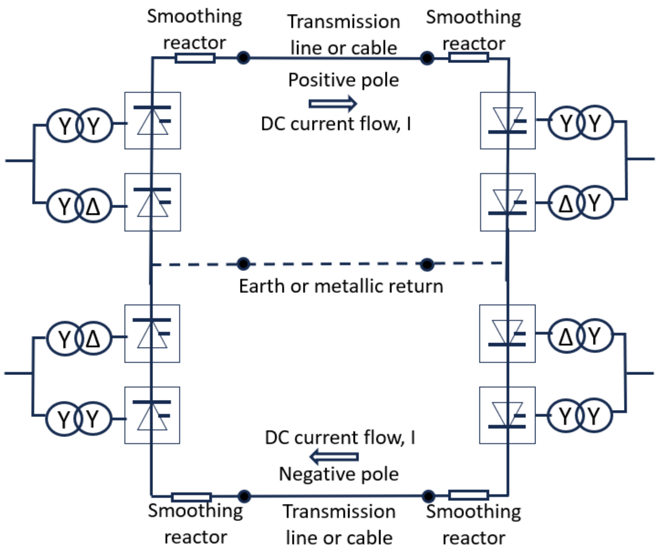
HVDC transmission schemes can be constructed based on number of different dc-side topologies, depending on factors such as technical, economic, redundancy, availability, and environmental impact, and required power transmission capacity.

HVDC Topologies

Electrical Configurations
for Asymmetric Monopole



Electrical Configurations
for Symmetric Bipole



06

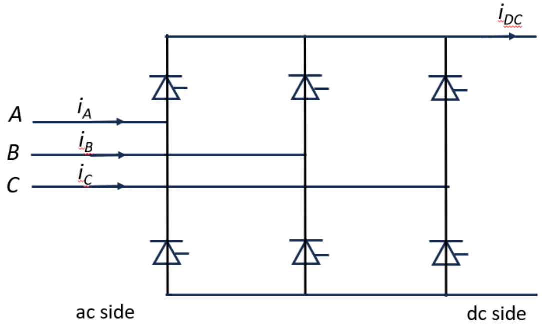
Line Commutated Converters

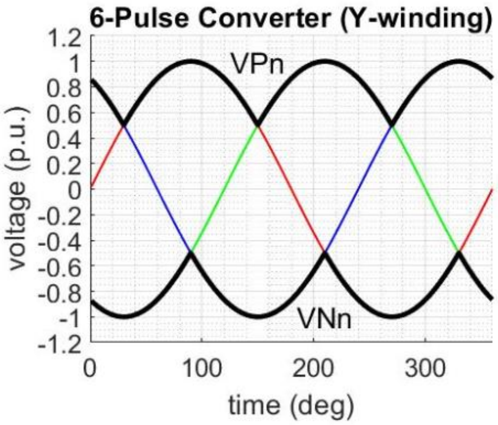
Tufts UNIVERSITY

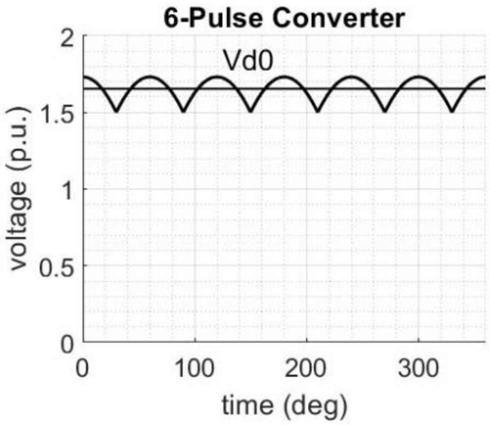
nationalgrid

Waveforms - 1

Three-Phase Six-Pulse Line Commutated Converter

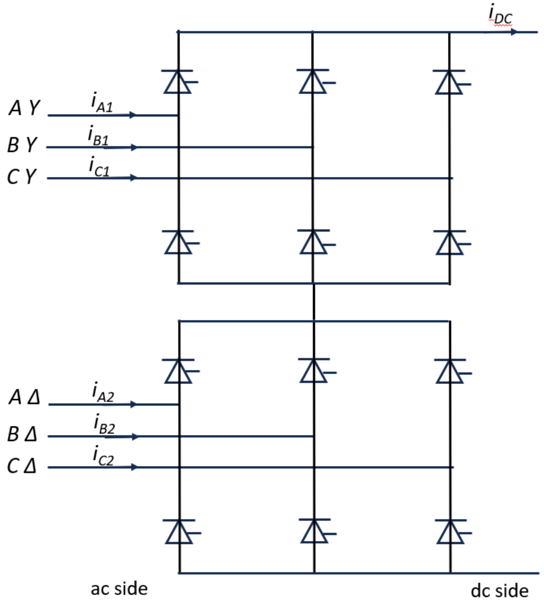


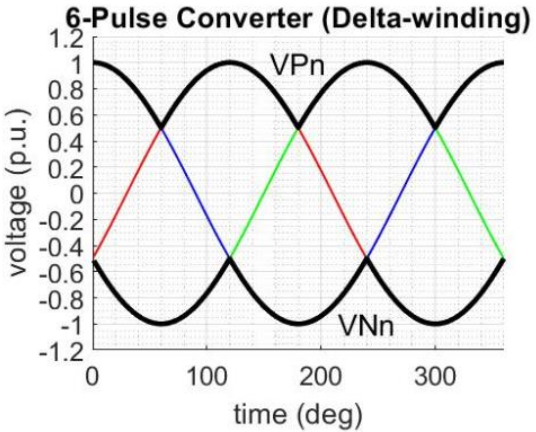


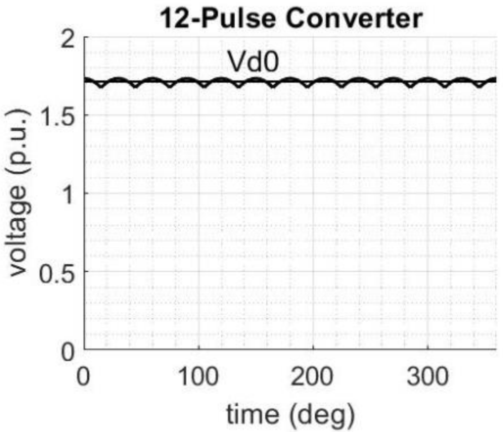


Waveforms - 2

Three-Phase 12-Pulse Line Commutated Converter



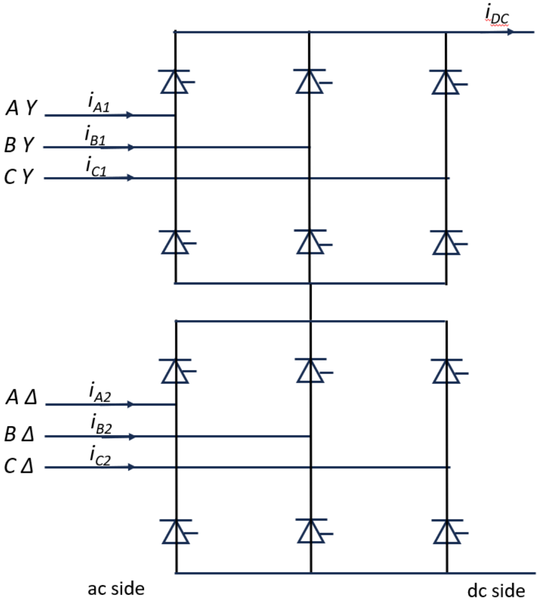




Note: Delta-winding, i.e., with 30° phase shift from the Y-winding.

AC-Side Harmonics

Three-Phase 12-Pulse Line Commutated Converter



Y/Y Six-Pulse Line Commutated Converter

$$i(t) = \frac{2\sqrt{3}}{\pi} I_d \left(\sin \omega t + \frac{1}{5} \sin 5\omega t + \frac{1}{7} \sin 7\omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega - \cdots \right)$$

Y/Δ Six-Pulse Line Commutated Converter

$$i(t) = \frac{2\sqrt{3}}{\pi} I_d \left(\sin \omega t - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega - \cdots \right)$$

12-Pulse Line Commutated Converter

$$i(t) = \frac{2\sqrt{3}}{\pi} 2\, I_d \left(\sin \omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega + \frac{1}{23} \sin 23\omega t + \frac{1}{25} \sin 25\omega t + \ldots \right)$$

07

Voltage Source Converters

Tufts UNIVERSITY

nationalgrid

Voltage Source Converters

Self-commutating semiconductors:

- Insulated gate bipolar transistors (IGBTs)
- Gate turn-off thyristors (GTOs)
- Integrated gate-commutated thyristors (IGCTs)

Converter topologies:

- Two-level VSCs
- Three-level VSCs
- Modular multilevel converters (MMCs)

Three-phase active power

$$P = V_d I_d = \sqrt{3}\, V_{LL}\, I_L \cos\phi$$

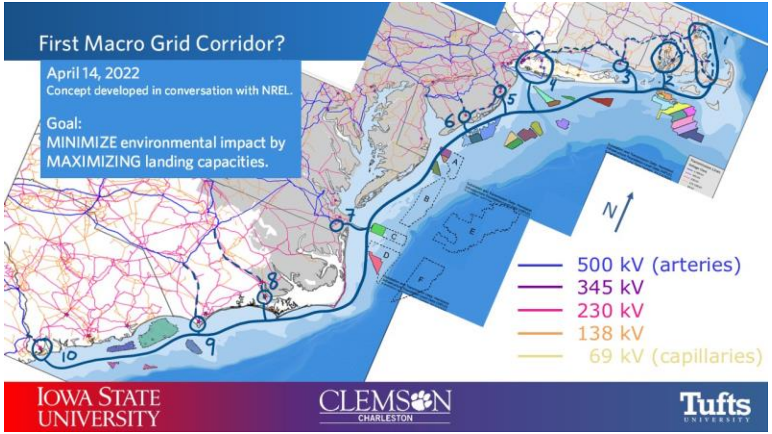
and reactive power

$$Q = \sqrt{3}\, V_{LL}\, I_L\, \sin\phi$$

VSC Applications

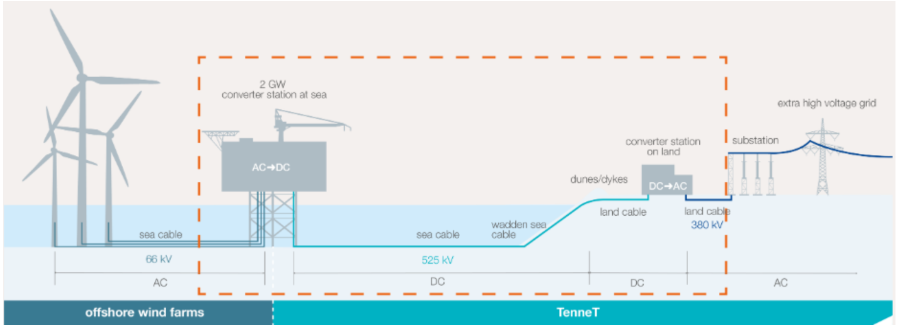
<u>Atlantic Off-Shore Wind</u>

Transmission Expansion Planning Models



<u>TenneT</u>

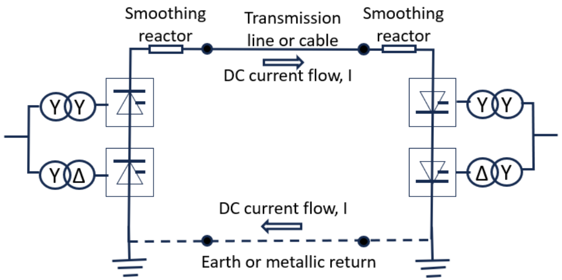
Standardized 2 GW 525 kV (cable) design

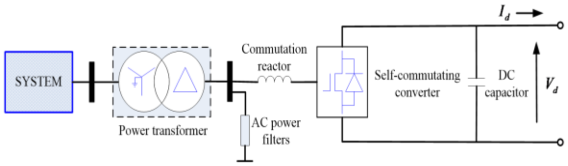


LCC vs. VSC Technology

Some characteristics of HVDC LCC vs. VSC technology

Technology/Capability	LCC	VSC
Semiconductor	Thyristor	IGBT
Controllability	Turn on	Turn on/Turn off
Power Control	Active	Active and Reactive
Converter Losses	Low	Higher
AC Filter Requirements	Yes	No
Blackstart capability	No	Yes





08

Major Equipment Categories

Tufts UNIVERSITY

nationalgrid

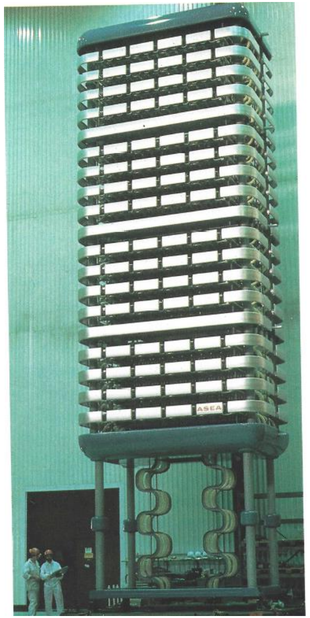
Major Equipment Categories

Converters:
Converters provide connection between ac and dc-sides of HVDC scheme.
Terminology: ac-to-dc converter = rectifier & dc-to-ac converter = inverter

Transformers:
Used to align ac system voltages with the dc voltage of converter design.

Conductors:
Bipolar HVDC schemes requires two lines between the converter stations, while high voltage alternating current transmission requires three lines.

Protection and Control:
HVDC schemes require communication between terminals.
P&C systems are often integrated into computers at HVDC terminals.



Line Commutated Converters

- **Valve hall**
  - Converters (one if monopolar and two is bipolar)
  - Valve Control Equipment
  - Pole Control Equipment
  - Valve Cooling Equipment
  - Valve Cooling Control Equipment
  - DC Bus Equipment

- **Converter Transformers**
  - Load Tap Changers

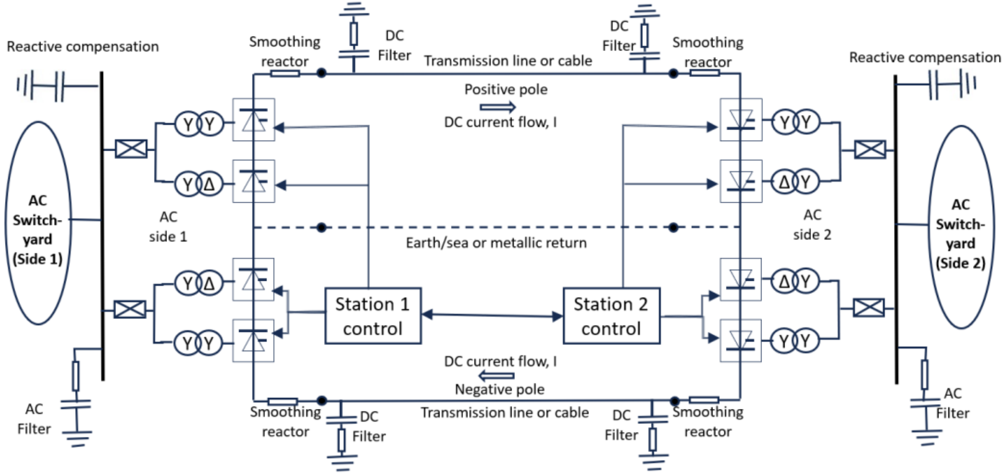
- **DC Lines**
  - Overhead Line, or
  - Cables (underground or undersea)
  - Neutral Conductor (if applicable)

- **AC Switchyards**
  - AC Filter Banks
  - AC Shunt Capacitor Banks
  - AC Bus Equipment
  - AC Circuit Breakers
  - AC Switchgear
  - Shunt Reactors (optional)
  - Electrode Line Equipment (if applicable)
  - Control and Protection Systems
  - Power Line Carrier (PLC) Filters (if applicable)

- **DC Switchyards**
  - DC Smoothing Reactors
  - DC Filter Banks
  - DC Switchgear

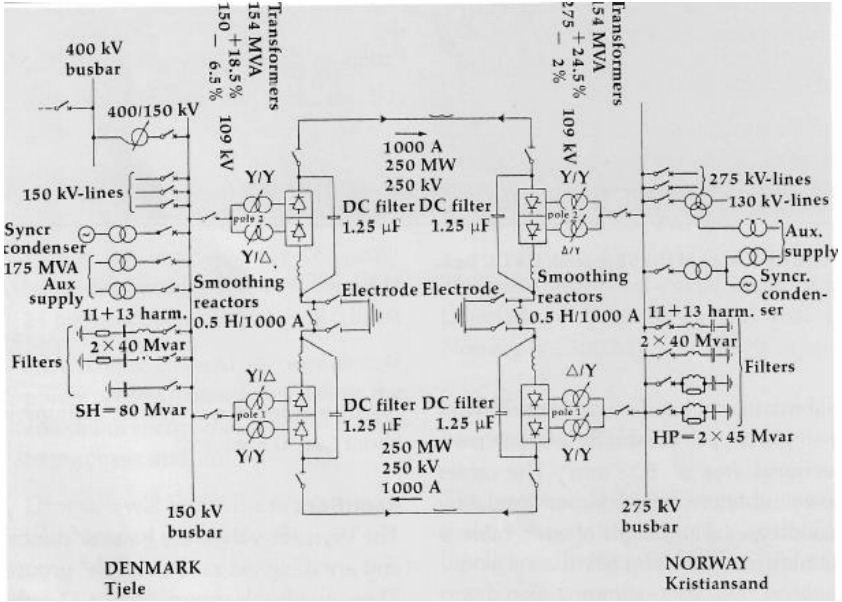
HVDC LCC Scheme

Bipolar HVDC LCC system [Module 7a]



HVDC LCC Scheme - Example

Skagerrak (Denmark – Norway)
#1&2 500 MW (1976-77) → #4 1,700 MW (2015)



Voltage Source Converters

- **Valve hall**
  - Converters
  - Converter Control Equipment
  - Valve Cooling Equipment
  - Valve Cooling Control Equipment
  - DC Bus Equipment

- **Converter Transformers (most installations)**
  - Load Tap Changers (optional)

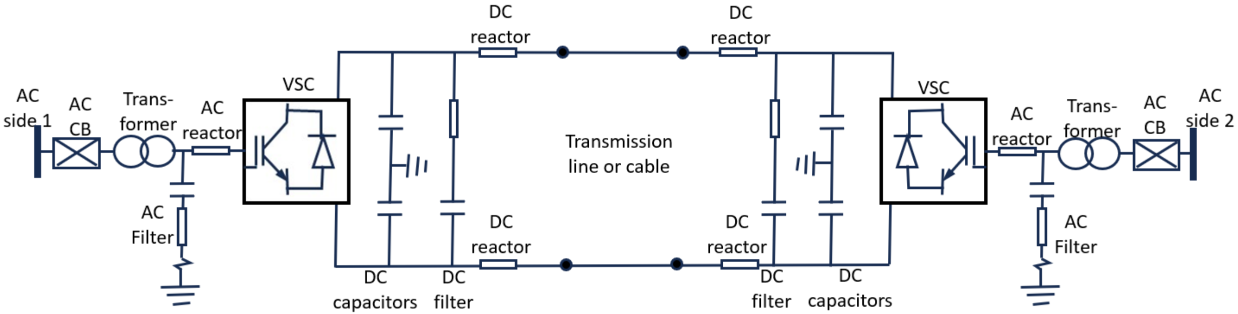
- **DC Lines**
  - Cables (underground or undersea; common)
  - Overhead Line

- **AC Switchyards**
  - AC Filter Banks (optional)
  - AC Bus Equipment
  - AC Circuit Breakers
  - AC Switchgear
  - Control and Protection Systems

- **DC Switchyards**
  - DC Link Capacitors
  - DC Switchgear
  - DC Circuit Breakers (optional; future)

HVDC VSC Scheme

Symmetric Monopolar HVDC VSC system [Module 7a]



09

Summary of Main Learning Points

nationalgrid

Summary

The development of alternating current in the beginning of the 20th century greatly influenced development of the electrical industry and our society as a whole. Today, high voltage direct current technology is experiencing a renaissance based on the on-going electrification and associated need to build out electric energy generation capacity.

This rapid development of HVDC technology is a testament to the growing need for efficient and reliable power transmission systems.

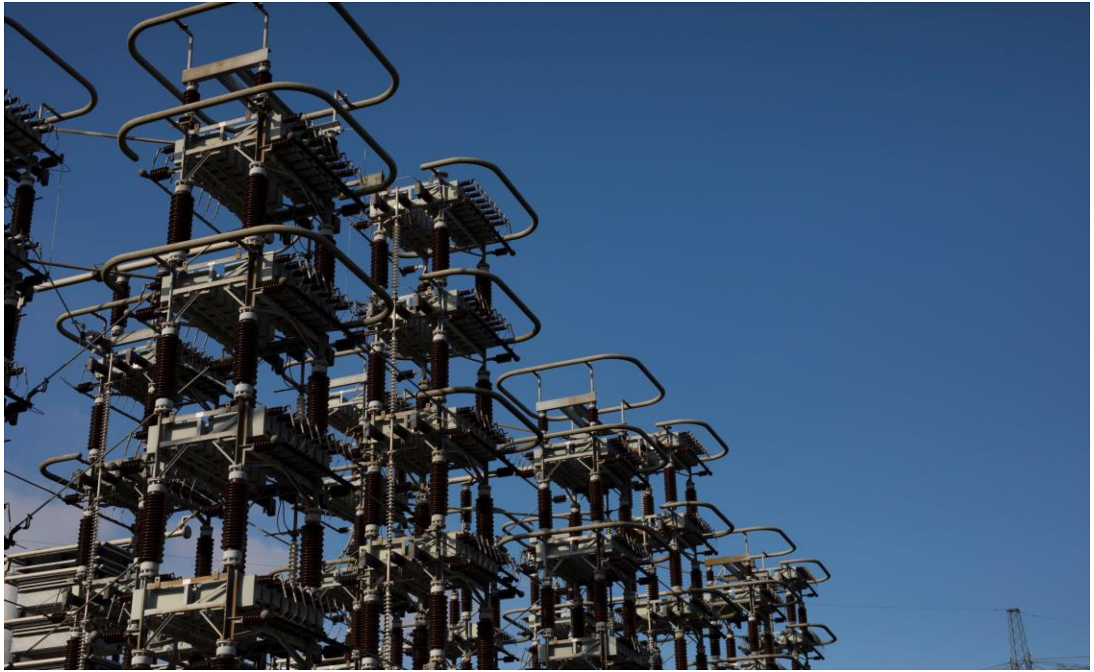
Module 1a is concluded with a set of questions and problems for the user to review and reinforce main learning points from this module.

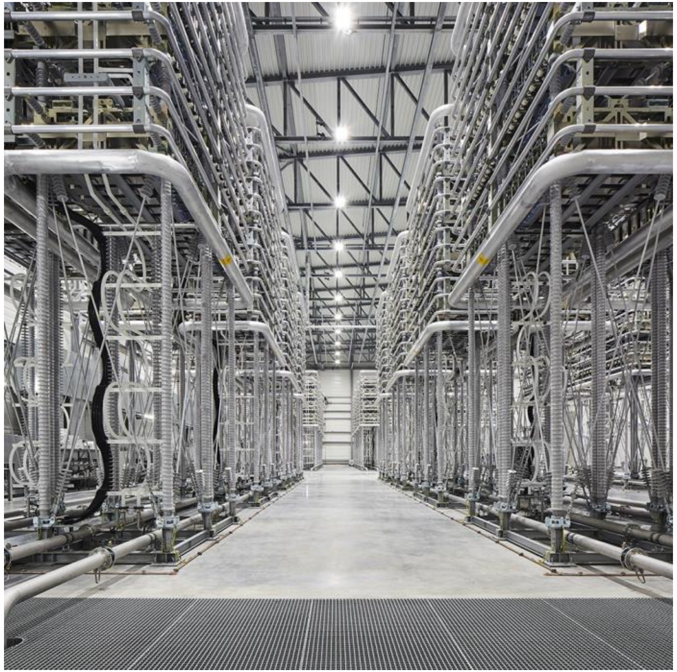
10

Questions?

Tufts University

nationalgrid





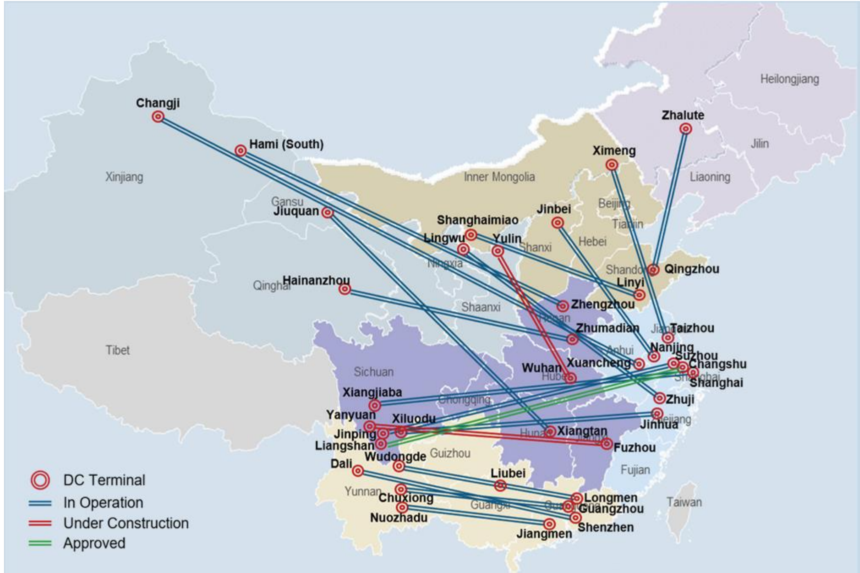
Abstract

The introduction of commercial high voltage direct current (HVDC) technology allowed and made way for transmission of large quantities of power and interconnection of non-synchronous networks. HVDC is economically advantageous in case of long-distance power transmission, in particular where cables have to be used, e.g., for longer water crossings. The objective of this module is to introduce HVDC technology, based on either line commutated converter (LCC) or voltage source converter (VSC) technology. This module will provide basic understanding of technical aspects of high voltage direct current vs. high voltage alternating current (HVAC) transmission as well as examples of installed HVDC schemes. While introducing basic concepts, main components, and configurations for both LCC and VSC HVDC systems, this introductory model will focus on aspects of HVDC schemes based on LCC technology.

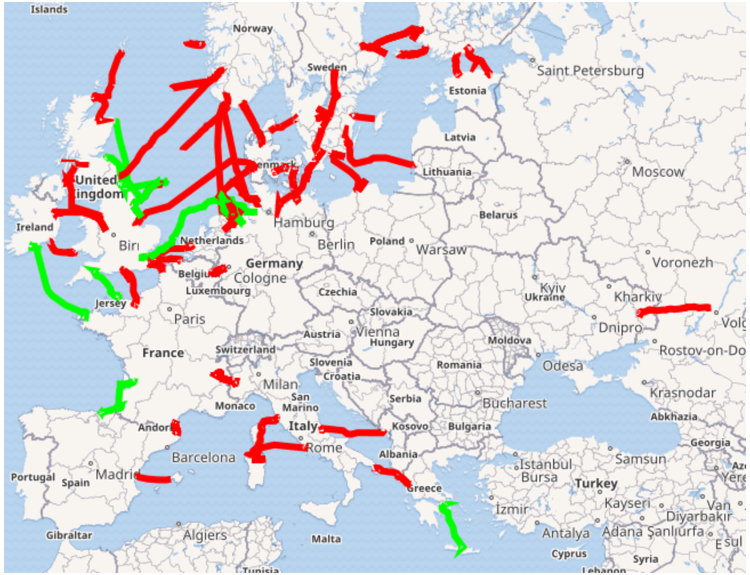
North America

South America

China



Europe



Problem #15

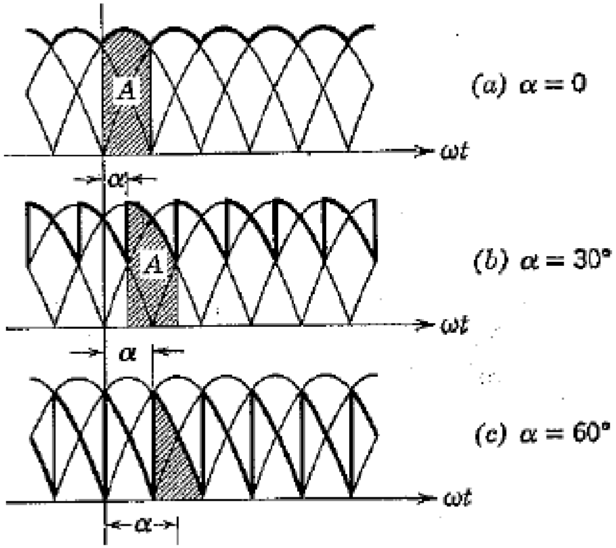
Problem 15: Calculate average dc-side voltage and plot voltage waveforms for a three-phase full-bridge thyristor (six pulse) line commutated converter, assuming it supplies 10 kW of power with ac line side reactance Ls = 0 and ac three-phase (line-to-line voltage VLL = 480 V (rms) at 60 Hz.

a. The delay angle $\alpha = 0^\circ$
b. The delay angle $\alpha = 30^\circ$
c. The delay angle $\alpha = 150^\circ$

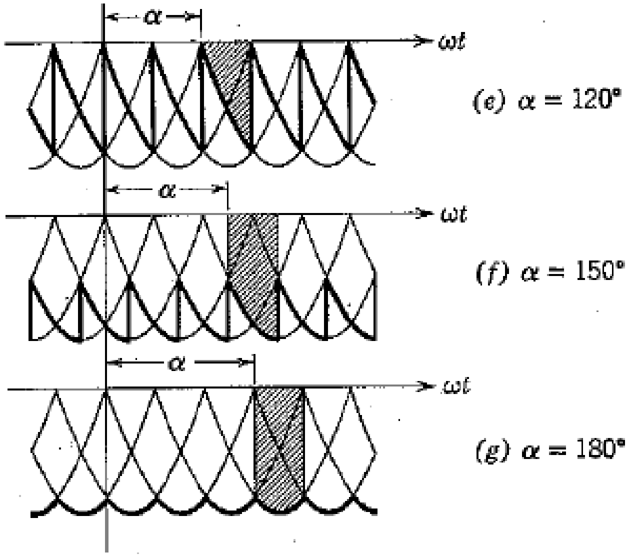
Solution: Use formula for V_dα in Section 1a-7.1 to calculate average dc-side voltage. Voltage (and current) waveforms can be found in many textbooks on HVDC, e.g., Chapter 3 in Kimbark's book 'Direct Current Transmission,' Volume 1.

Problem #15

Rectifier operation



Inverter operation



E.W. Kimbark, ‘Direct Current Transmission,’ Volume 1, Wiley Interscience, 1971 (Chapter 3, Fig. 6)