FACTS and HVDC solutions for Transmission Networks

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Agenda

1. Introduction

2. FACTS Devices

2.1 Shunt FACTS devices

2.1.1. Static Var Compensator (SVC)

2.1.2. Static Synchronous Compensator (STATCOM)

2.2 Series FACTS devices

2.2.1. Fixed Series Capacitor (FSC)

2.2.2. Thyristor Controlled Series Capacitor (TCSC)

3. High Voltage Direct Current (HVDC)

3.1. Line Commuted Converter (LCC)

3.2. Voltage Source Converter (VSC)

4. A vision of the future of Power Electronic in T&D System

Introduction

- **Today electrical energy is mainly generated, transported and distributed in Alternative Current**
  - Easy generation with synchronous machines
  - Easy voltage step up – step down with power transformers
  - Easy current interruption when 0 crossing with circuit breaker)
- **Use of Direct Current at the same scale would have been more complex and more expensive**
  - Generation by direct current generators or converters
  - Voltage change by complex power electronic devices
  - Difficult to interrupt current (no 0 crossing)
- **However, managing increasing energy flows using existing AC networks is a more and more difficult challenge to overcome**
  - Control of energy path in meshed grids (overload control)
  - Reactive power compensation to control losses and voltage drops
  - Setting of frequency and phase angle of the various generators feeding a grid have to be coordinated to insure grid stability
  - Distance between generation plants (close to natural resources) and load centers need to transfer massive amount of electrical energy over very long distance rising the need of reactive power compensation and the difficulties to insure grid stability

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Actual trends and constraints

- **Continuous increasing of energy demand**
  - From 3500 GW in 2000 to 5700 GW in 2020

- **Growing Environmental constraints**
  - Will to reduce dramatically CO² emission
  - Restrictions to build new conventional generation plants or to expand existing one
  - Restrictions to build new overhead lines
  - Will to replace overhead lines by underground cables
  - Will to develop renewable energy (wind, solar, biomass, hydro,…)
  - Will to promote energy savings and losses reduction

- **Natural resources often far away from load centers**

- **Some of existing electrical transmission networks already used at their limits**
  - Bottleneck and overload management
  - Reliability concerns
  - Need to increase capacity

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What are the stakes for Electrical Networks ?

- **Meet increasing consumer demands in all regions**
  - Energy exchang
  - Increase of trans
- **Fulfill deregula**
  - Allow ac
- **Allow a consumers**
  - Including
  - In mass,
    photovo
- **Ensure**
  - Regional
  - Consumers d generation)
  - Power flow
- **Ensure Security, Availability of electrical energy distribution**
  - Sharing of generation sources
  - Prevent from " black out" and limit interruption of service
  - Control voltage drops, frequency variation, reactive power, harmonics, losses, etc....

HVDC & FACTS

Provide the necessary features to overcome actual stakes

Key role of Power Electronic to sustain electrical network evolution

HVDC (High Voltage Direct Current) &
FACTS (Flexible AC Transmission System)
Provide the necessary features to overcome the actual stakes

- **Allow to increase transmission capacity**
  - for existing lines with FACTS solution
  - for new transmission lines with HVDC solutions
- **Reduce losses**
  - by optimization of power flow with FACTS solution on existing lines
  - By using HVDC solutions for new long distance lines
- **Insure grid code compliance**
- **Improve dynamic system stability**
- **Prevent from cascading disturbances**
- **Increase quality of energy**
- **Increase system reliability and availability**
- **Ease interconnectors development**
  - Allow bi-directional power flow management
  - Allow connection of asynchronous grids and weak networks
  - Allow connection of weak networks with VSC built in black start function (off-shore wind farm)

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Reactive Power Compensation
Power Flow Management

Voltage regulation
through **shunt reactive power compensation**:

SVC: **S**tatic **V**AR **C**ompensator
STATCOM: **STAT**ic Synchronous **COM**pensator

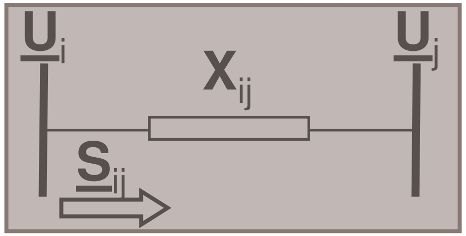
Phase angle control
through phase shifting:

PST: **P**hase **S**hifting **T**ransformer

$$P_{ij} \approx \frac{U_i . U_j}{X_{ij}} . \sin(\delta_{ij})$$

Impedance modification
through **series reactive power compensation**:

SC: **S**eries **C**apacitor
TCSC: **T**hyristor **C**ontrolled **S**eries **C**apacitor



$\underline{U}_i = |U_i|\angle\delta_i$

$\underline{U}_j = |U_j|\angle\delta_j$

$\delta_{ij} = \delta_i - \delta_j$

There are several ways to improve power flows through reactive power compensation.

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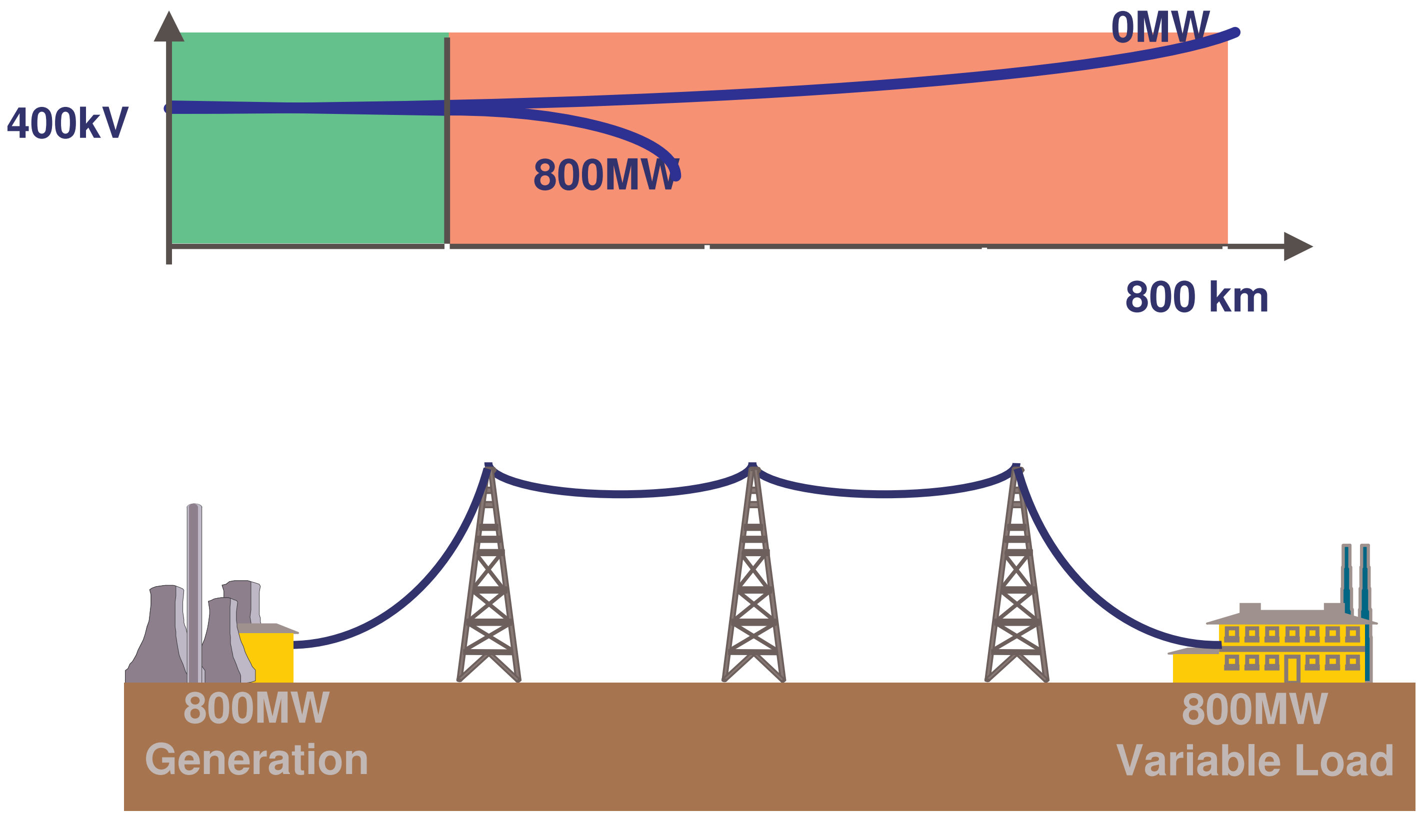
Why use Utility SVCs?



Uncompensated lines are too "short"

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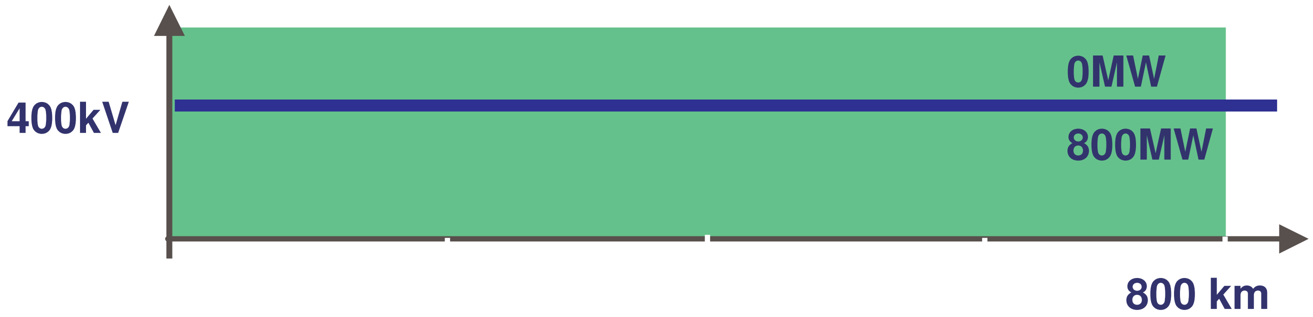
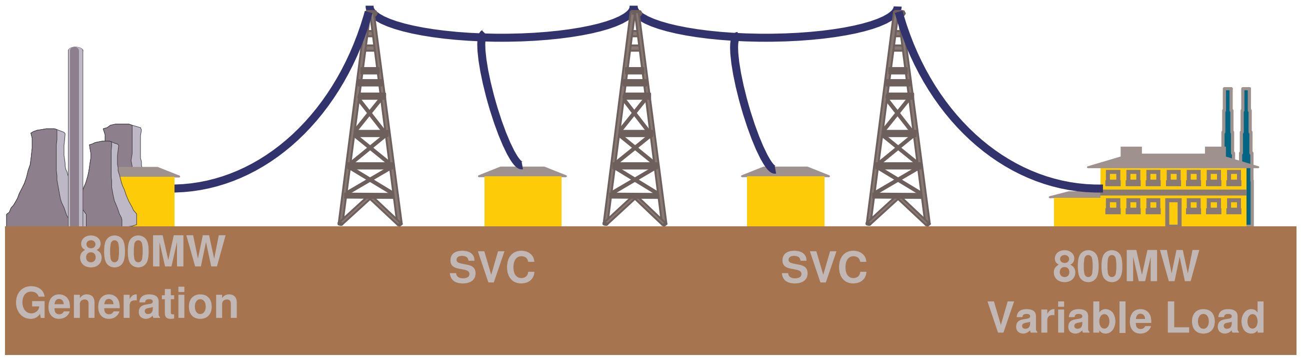
Why use Utility SVCs?





SVC releases transmission line capacity

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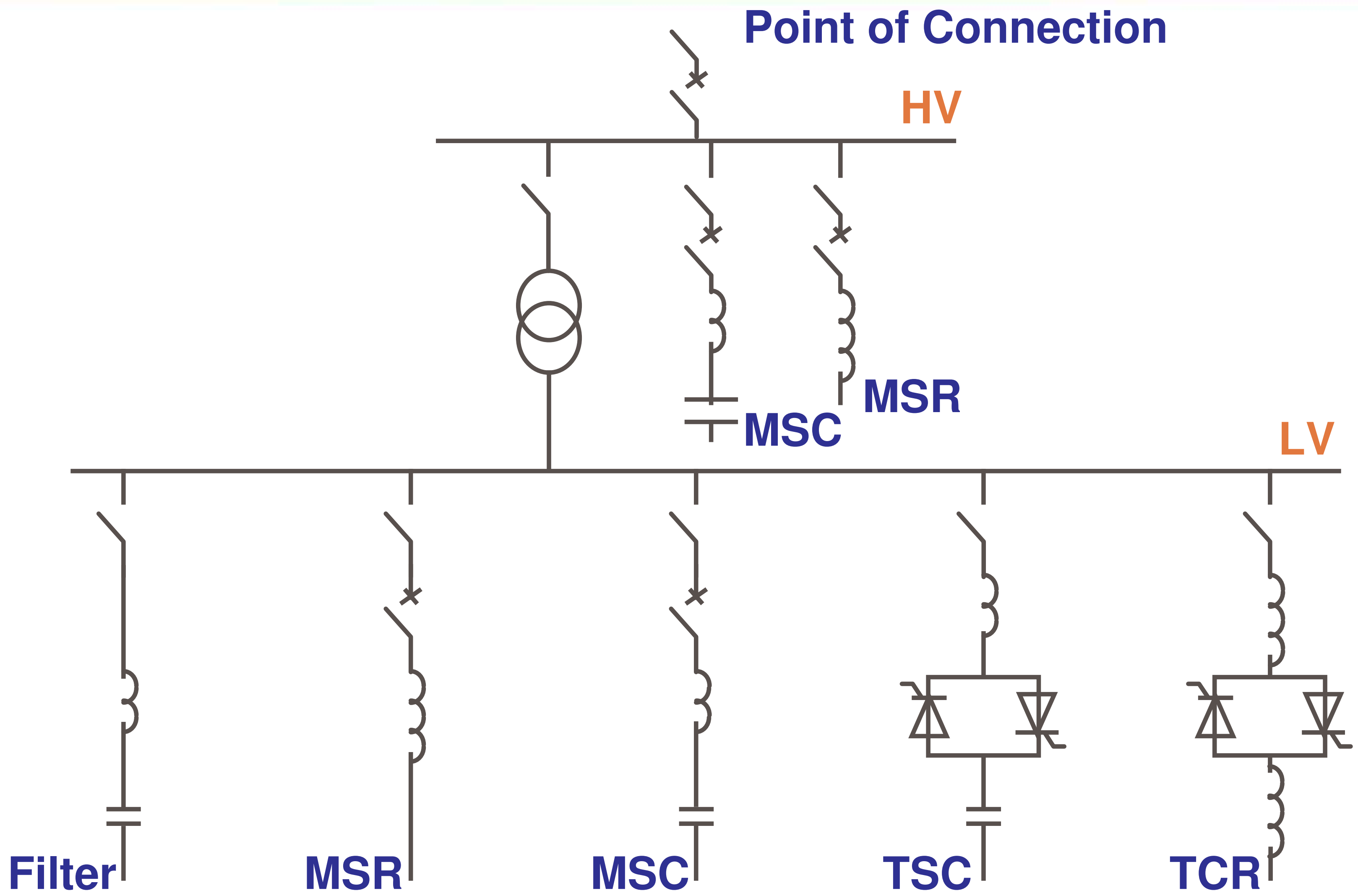
Elements of an SVC



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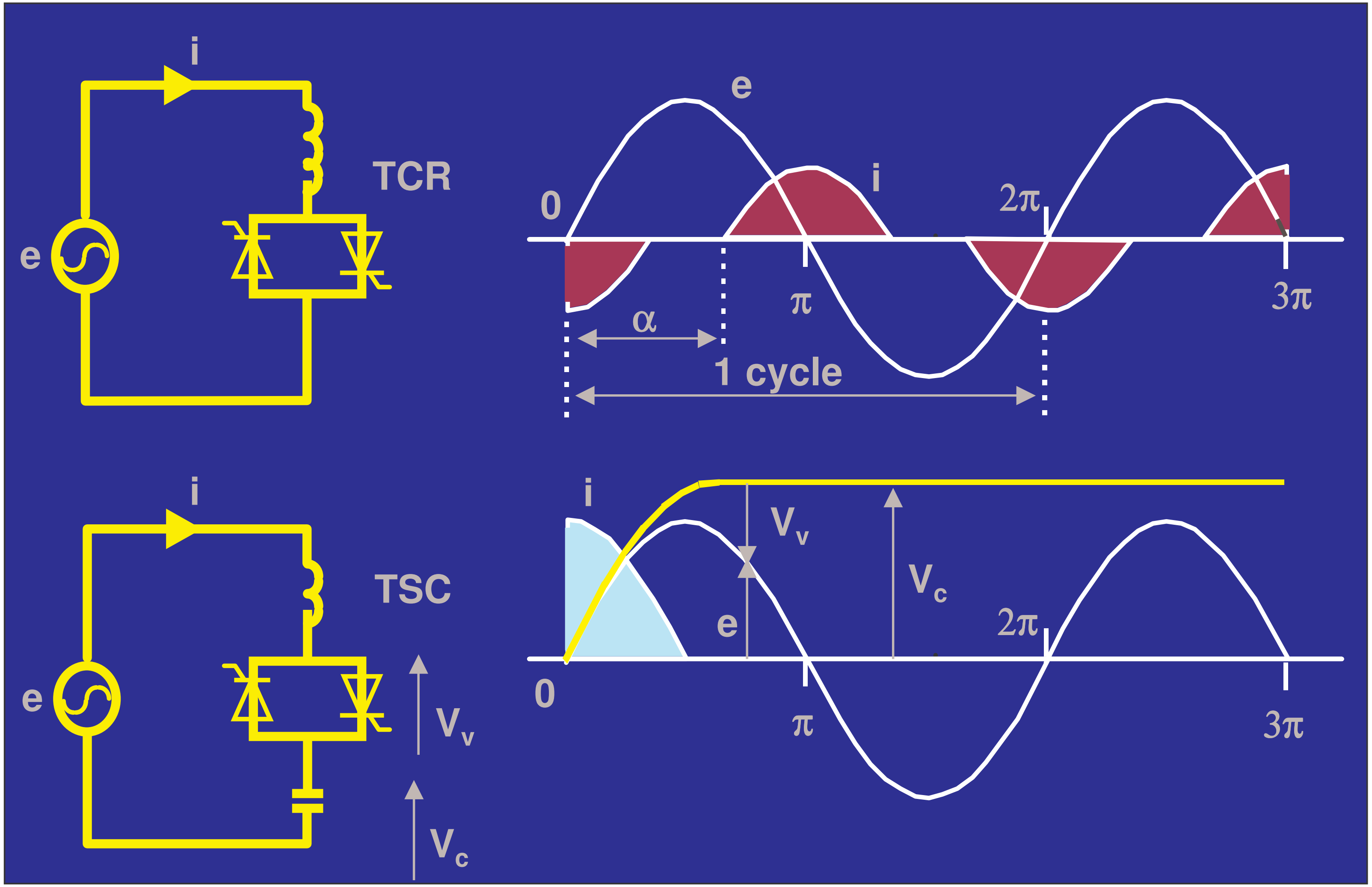
Control of TCR and TSC



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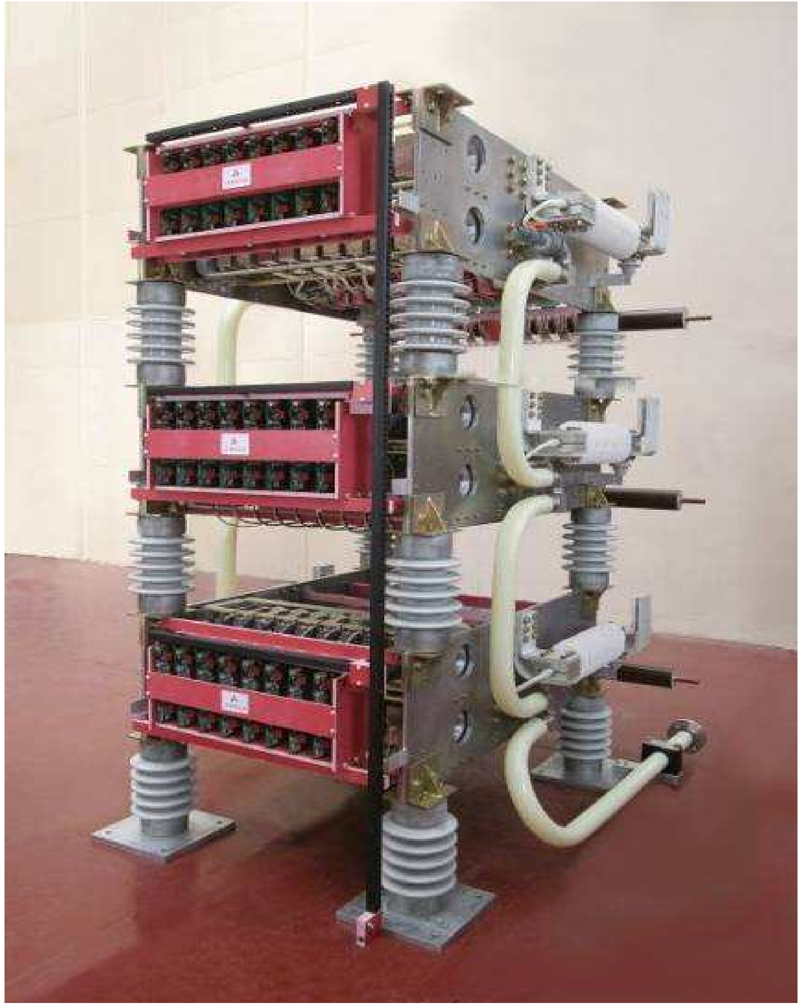
S500 SVC Valve

- 3 phase stack arrangement
- TCR design shown (TSC has no di/dt reactors)
- 1 module per phase
- Voltage up to 18kV
- 7 + 1 thyristor levels per phase
- 1m (w) x 2m (d) x 2.7m (h)



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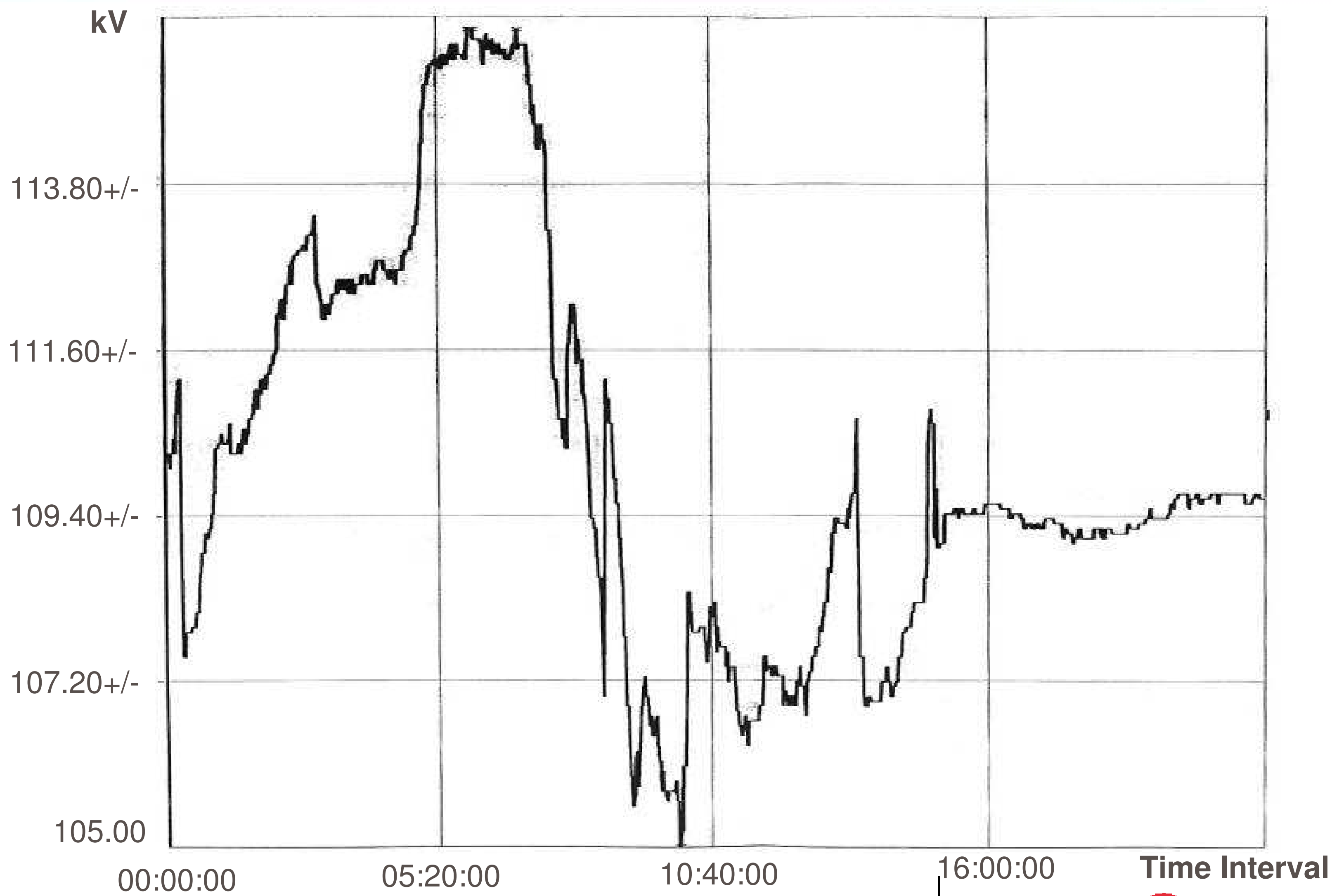
Lovedean SVC

ESB Letterkenny 110kV Bus



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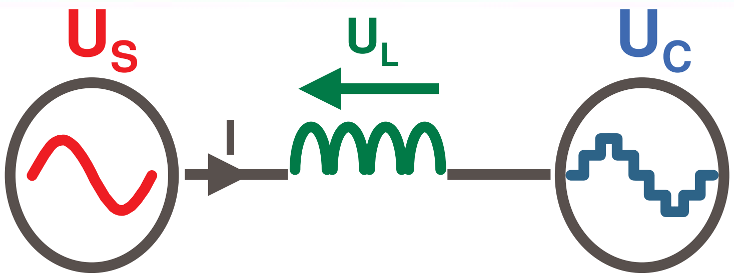
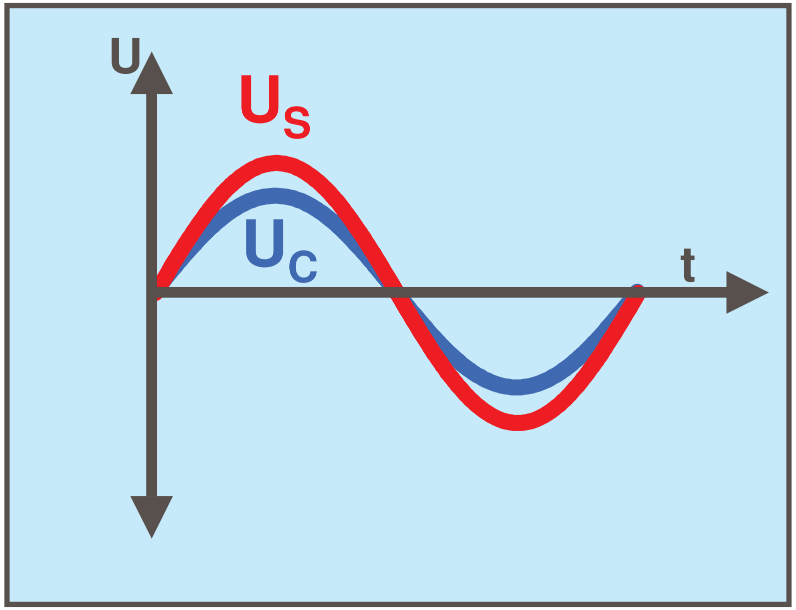
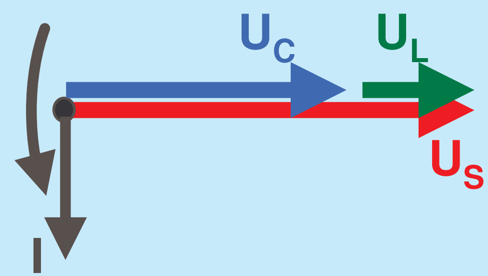
STATCOM Basic Principles
Inductive (lagging) Operation







If $U_C < U_S$, then I is inductive

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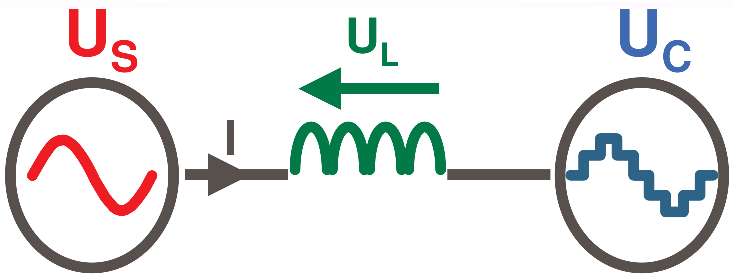
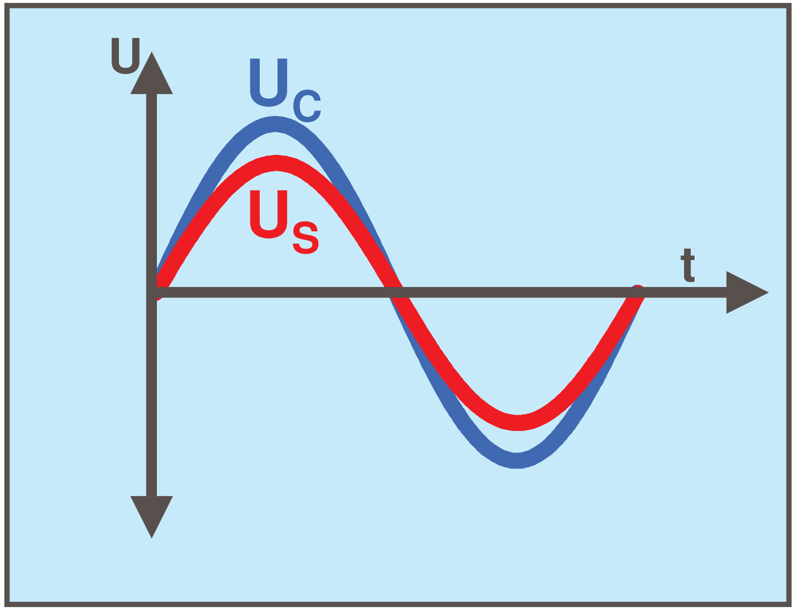
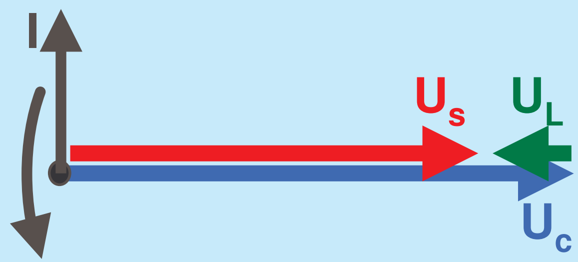
STATCOM Basic Principles
Capacitive (leading) Operation







If $U_C > U_S$, then I is capacitive

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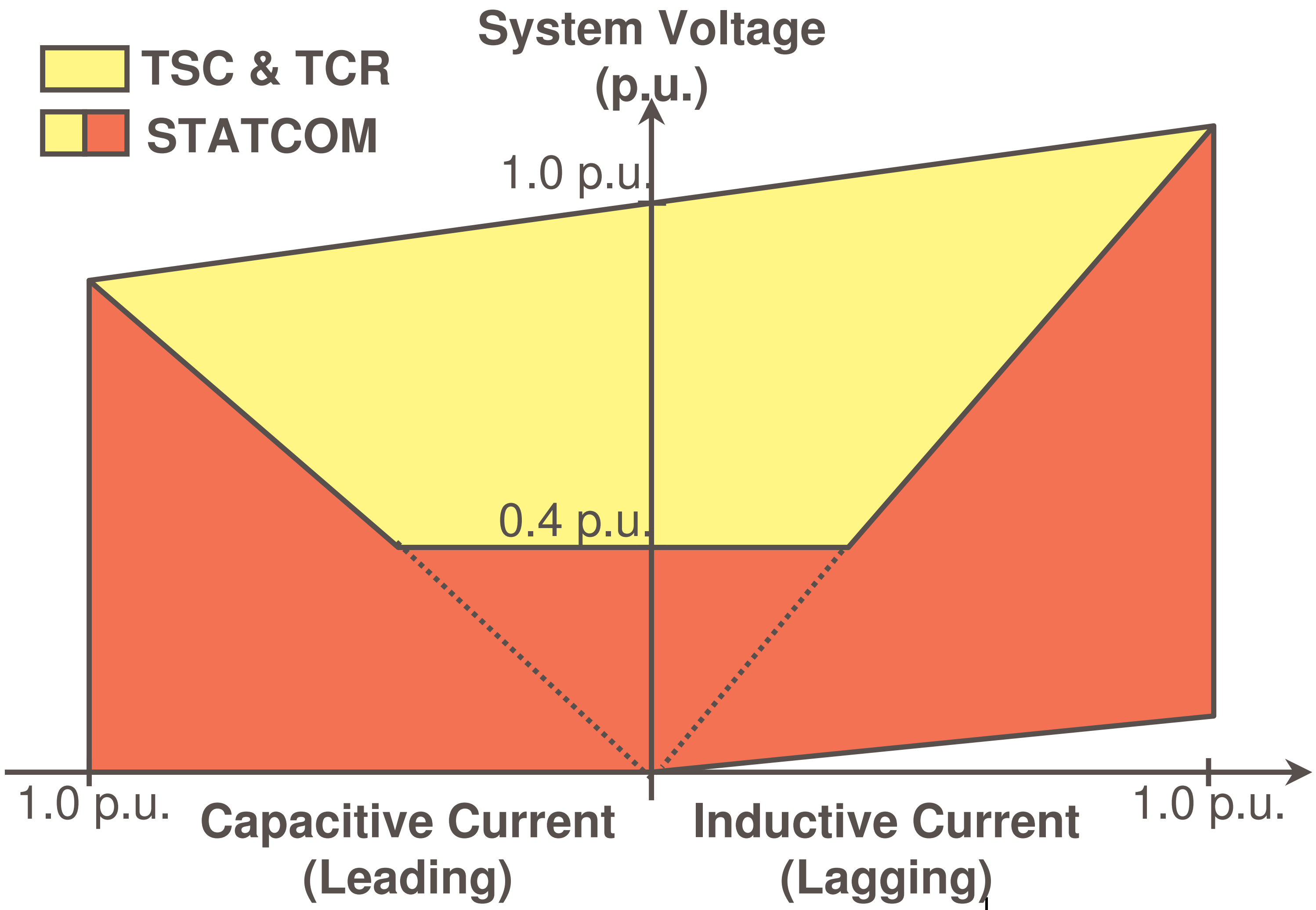
Comparison of Characteristics



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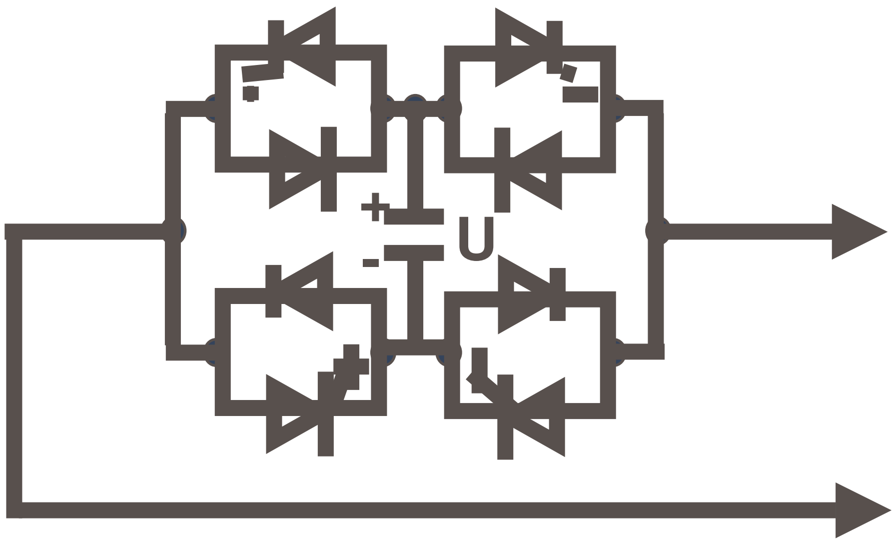
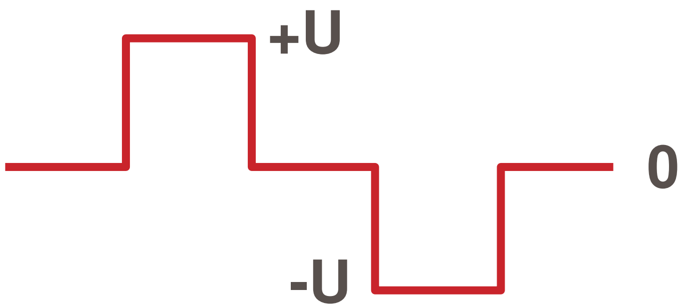
The Chain Circuit



One link



Link Output Voltage

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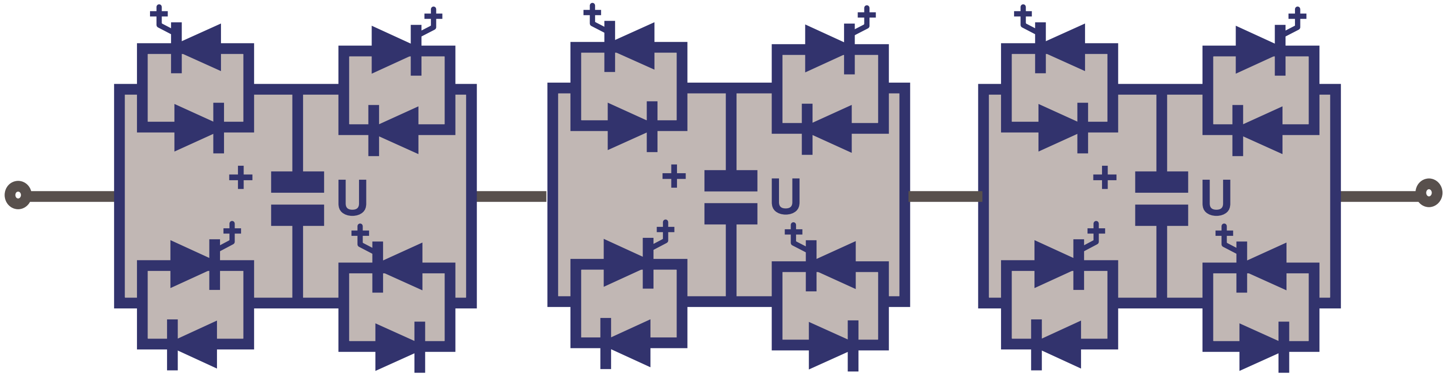
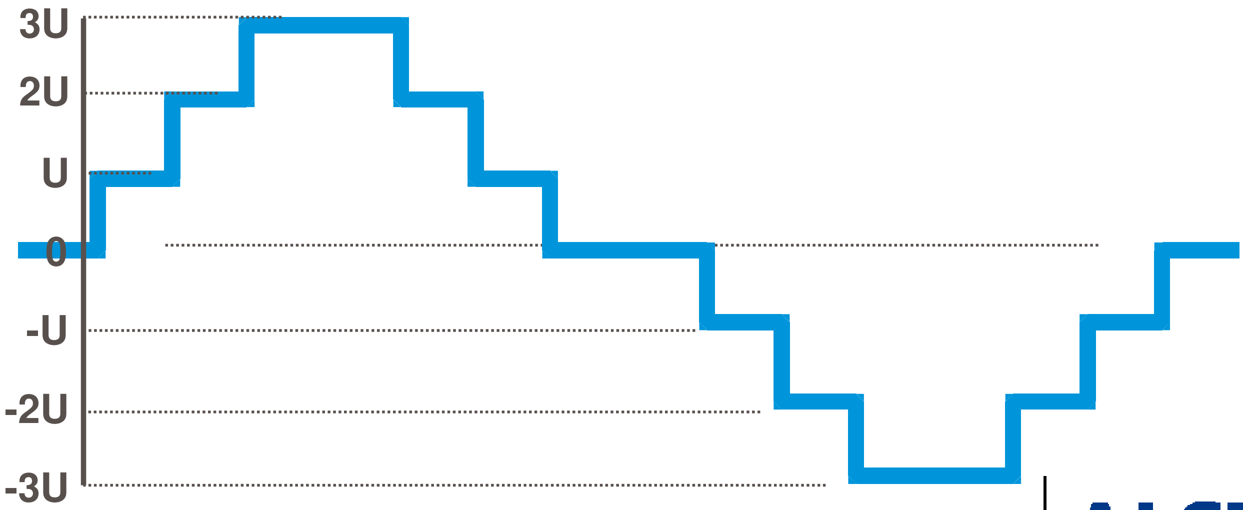
STATCOM Principles

A "Chain" with three "Links"



Output Voltage



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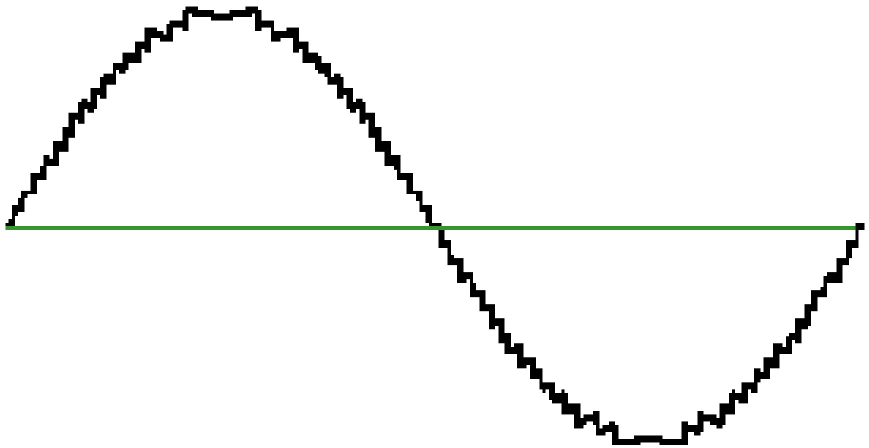
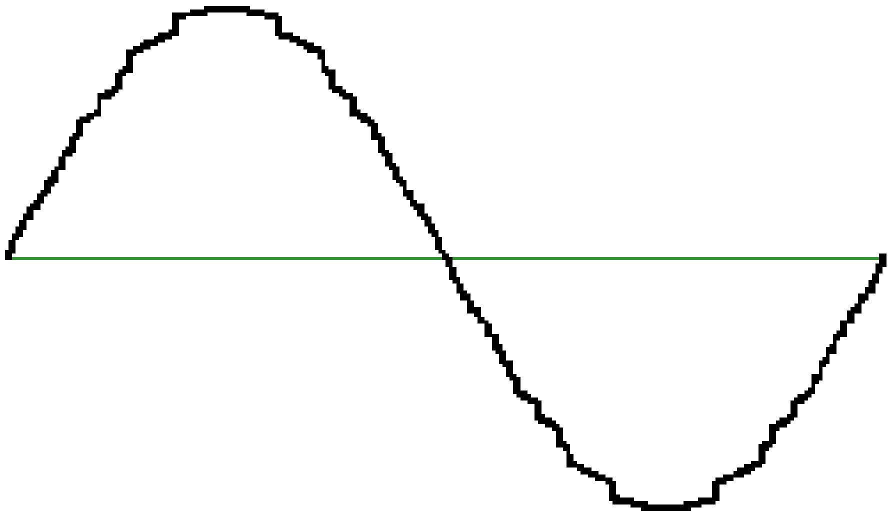
Voltage Waveshape with Ripple Component



Lagging Current Operation



Leading Current Operation

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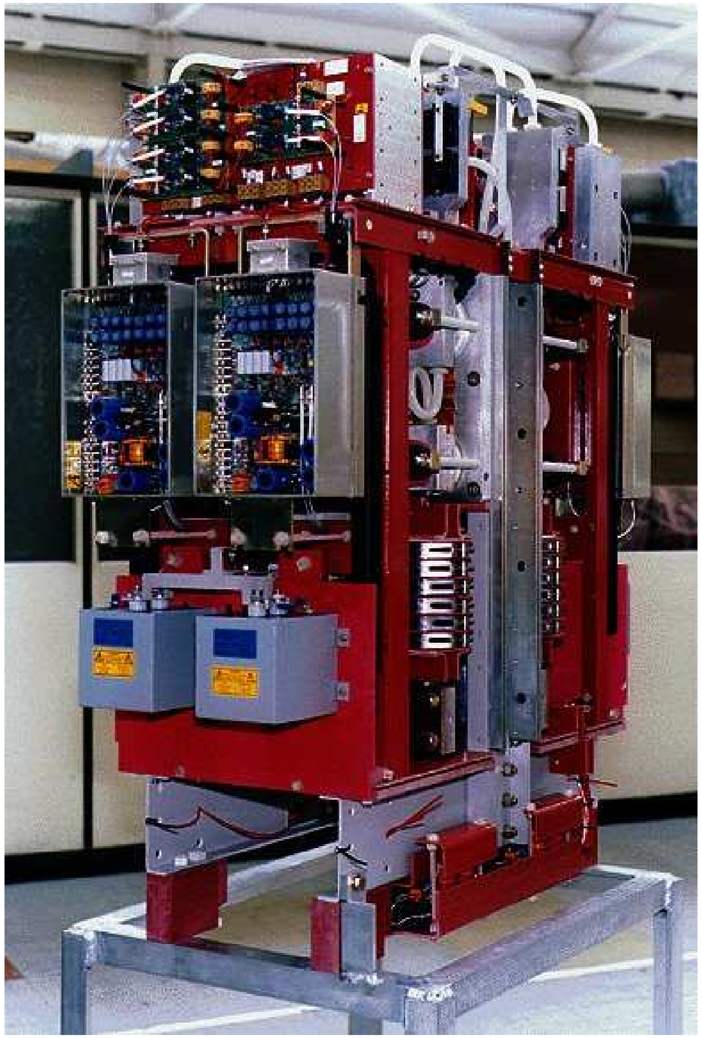
One STATCOM Link



Compact Site Layout

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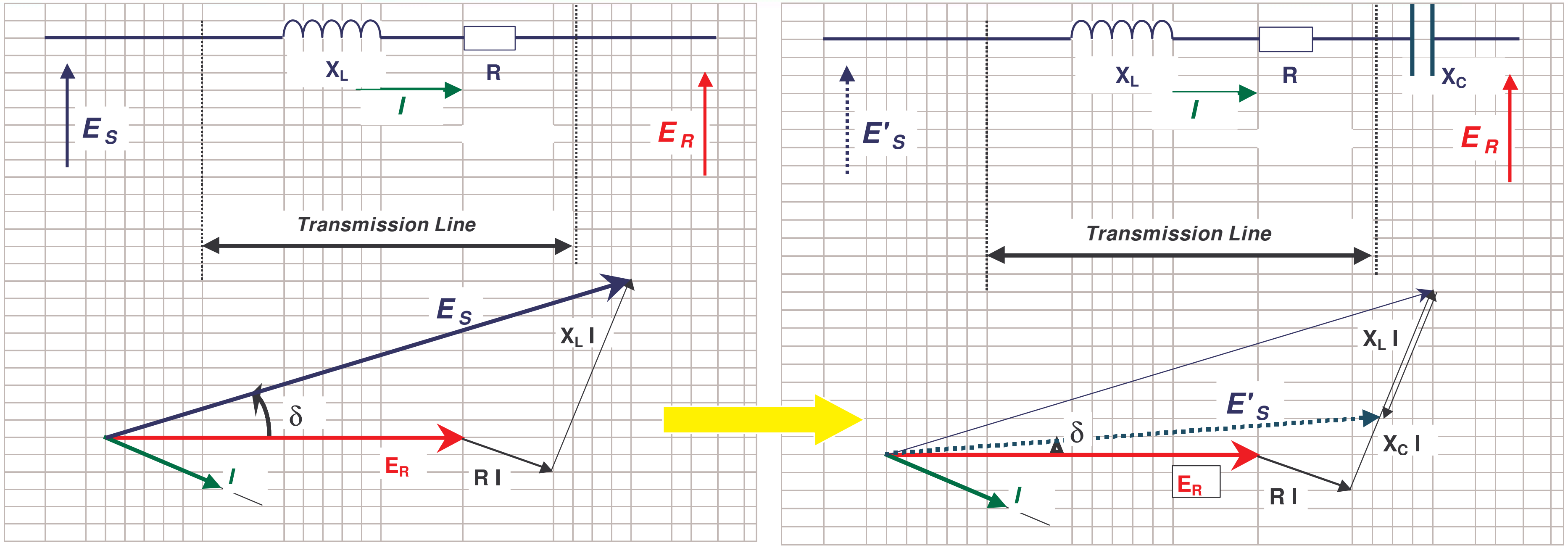
Series Compensation



Very simple principle: insertion of capacitors in series with the T/L

- **Reduction of the "electrical" length of the T/L**
- **Improved voltage profile (E_S - E_R smaller)**
- **Reduction of the transport angle d (enhanced dynamic stability)**
- **Improved Active Power Transmission capacity** [$P = E_S E_R \sin d / (XL - XC)$]

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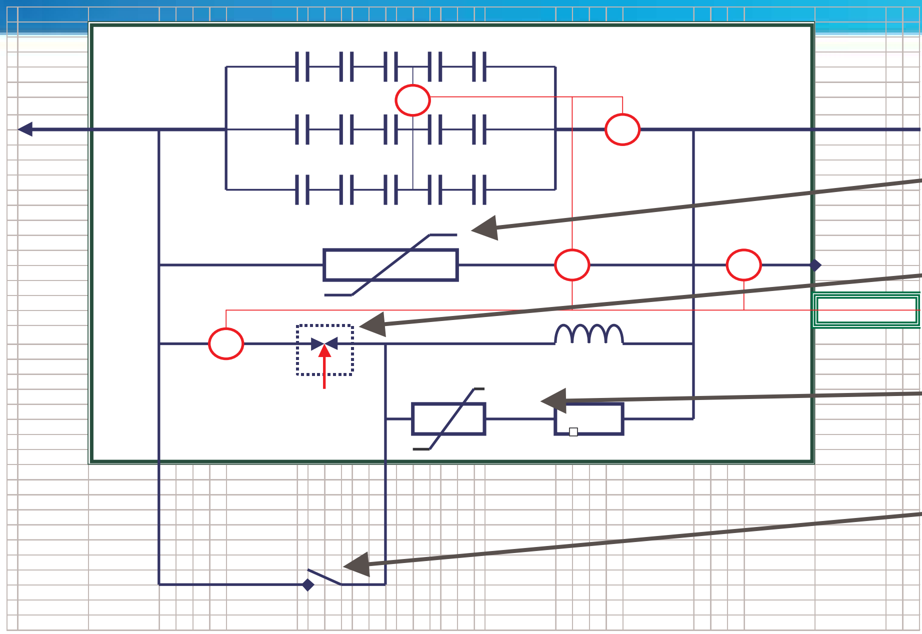
Series Capacitor bank equipment



- **Bypass system operates to keep voltage across the capacitor at its design limit.**
- **Some or all of the capacitor current is bypassed through the bypass system which may include:**
  - Bypass varistor
  - Electrically triggered spark gap
  - Bypass switch with its damping device

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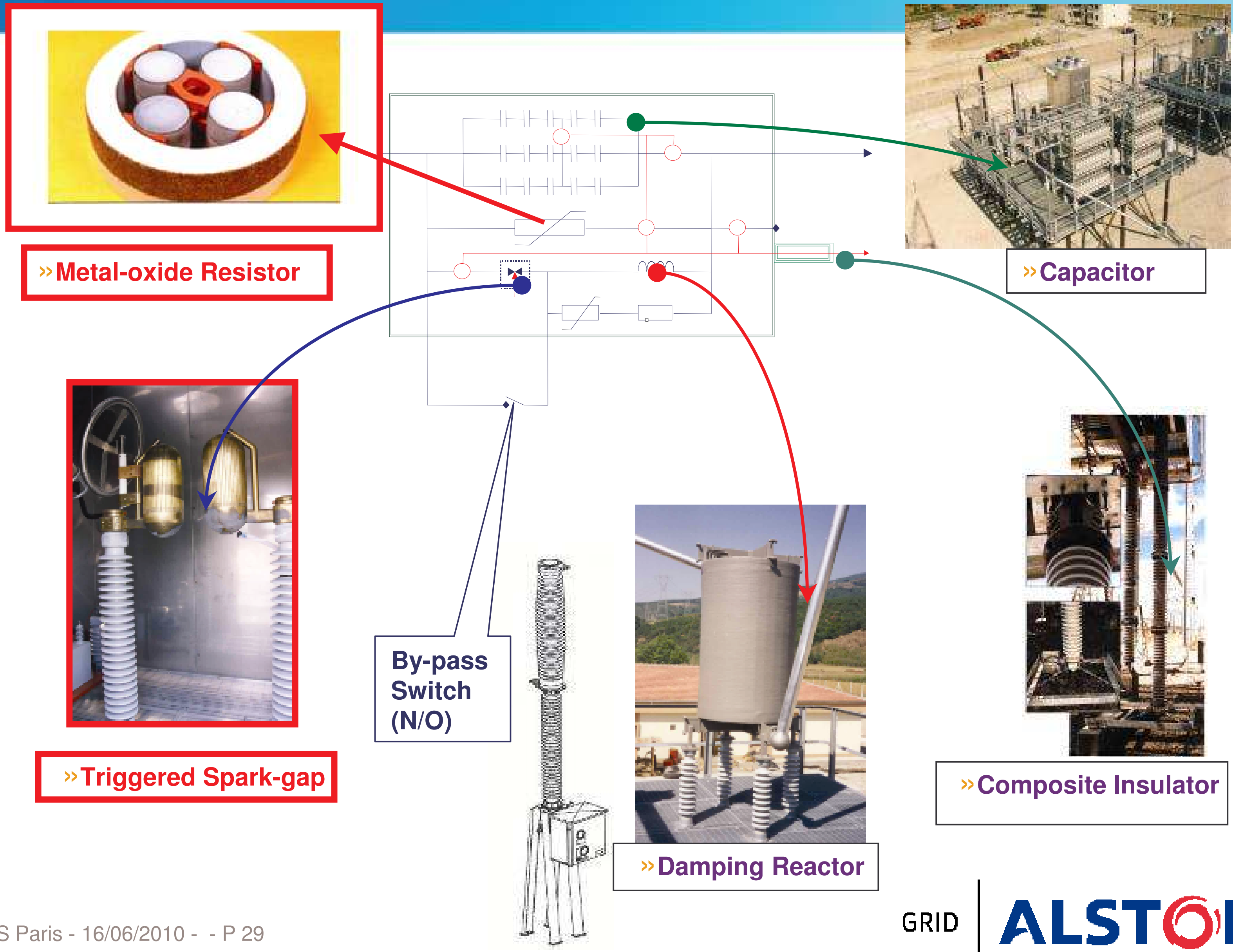
Main Components of a FSC



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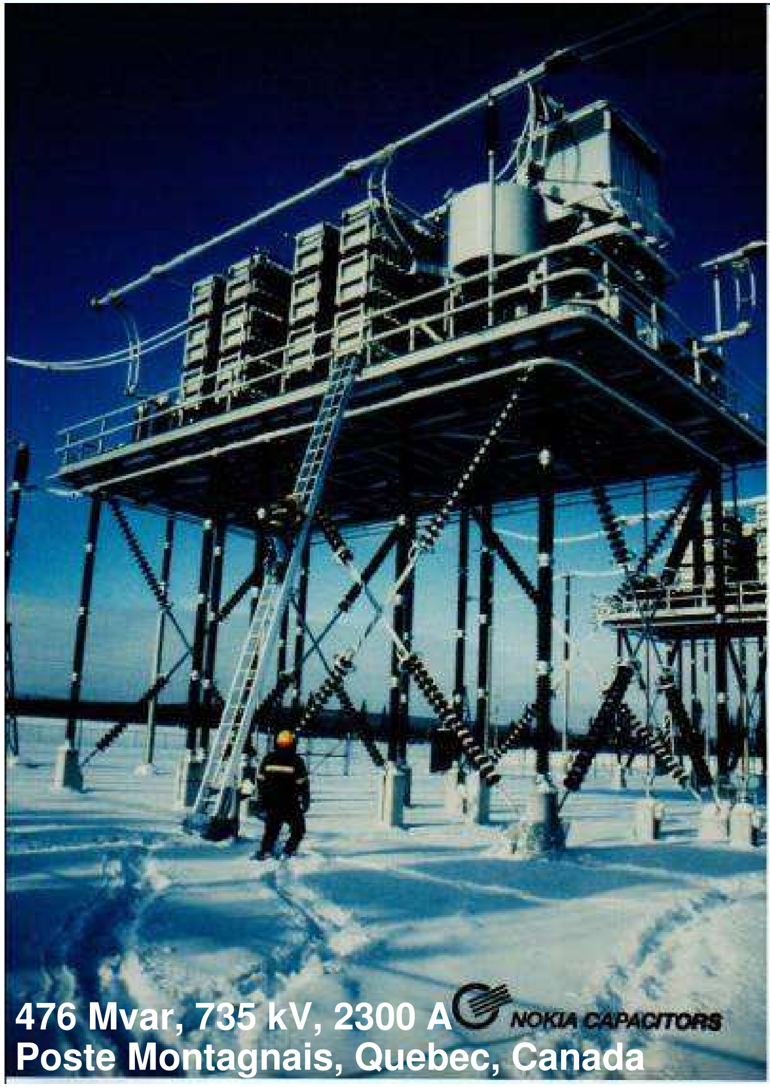
Fixed Series Compensation - Sample Projects



476 Mvar, 735 kV, 2300 A
Poste Montagnais, Quebec, Canada

- **735 kV system**
- **476 Mvar**
- **30 ohm, 2300 A**
- **protective level 2.6 pu**
- **overload cycle**
  - 2.3 pu for 1 second followed by 1.95 pu for 9 seconds within a period of 2 hours
  - 1.35 pu for 30 minutes within a period of 6 hours

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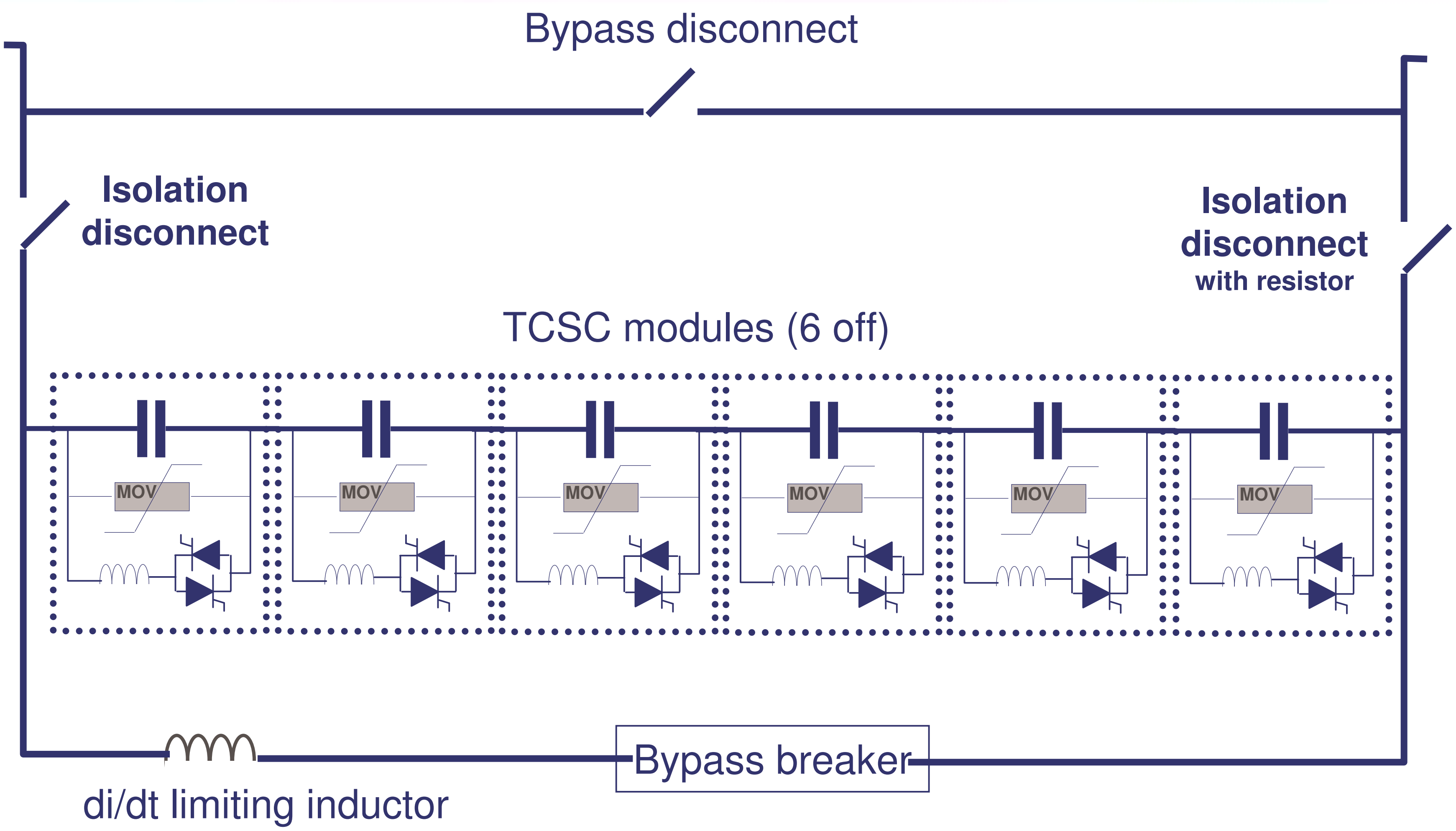
TCSC typical single line diagram



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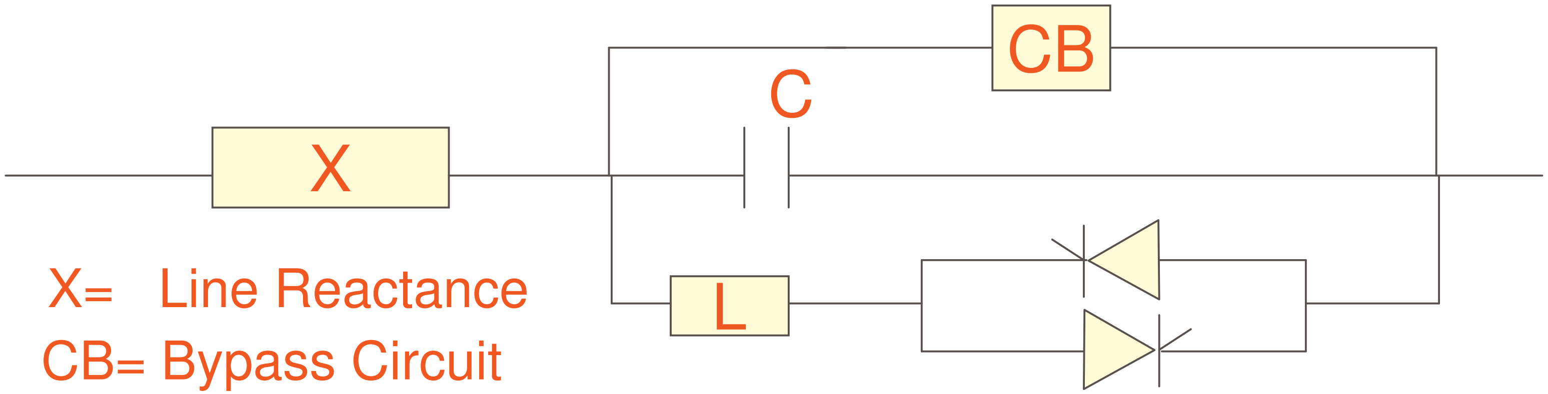
TCSC: Effect on line protection

- **Distance protection on lines uses impedance measurement**
- **Series compensation alters line impedance**
  - Affects protection
- **The compensation system must therefore be bypassed during line fault**
  - A high speed bypass circuit breaker is used
  - Closing time of bypass CB is critical parameter



X= Line Reactance

CB= Bypass Circuit Breaker

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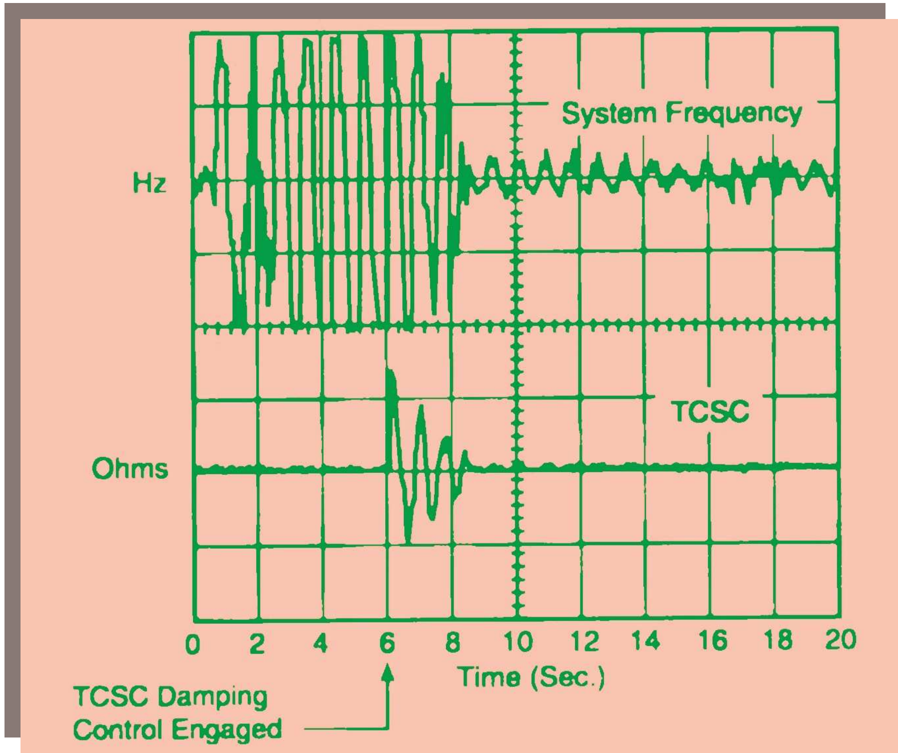
TCSC benefits

In addition to the benefits of Series Compensation Systems, TCSCs provide the following benefits:

- Wide range of variation of the equivalent impedance (from capacitive to inductive)
- Dynamic controllability of power flow, by steps or continuously (Vernier effect)
- Wide range of variation of the equivalent impedance (from capacitive to inductive)
- Under (rare) conditions of Sub-Synchronous Resonance phenomenon, fast and efficient mitigation of the risk



Correct System Study
is critical to performance

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BPA - Slatt Substation

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Major experiences FSC & TCSC

- **FSC (as Main Contractor)**
  - Turkey 420 kV (4 Units rated 95 - 125 Mvar each) - 1995
  - Vietnam 500 kV (several projects - ~145 Mvar each) - 2002 /2003
  - Chile 500 kV (4 Units ranging 227 - 392 Mvar) - 2002

- **TCSC (with GE as Partner)**
  - USA - 500 kV Slatt (Valve 2900 A) for BPA - 1993
  - Brazil - 500 kV Serra da Mesa (Valve 2700 A) for AENEL - 2003
  - Brazil - 500 kV Imperatrie (Valve 2700 A) for AENEL - 2003

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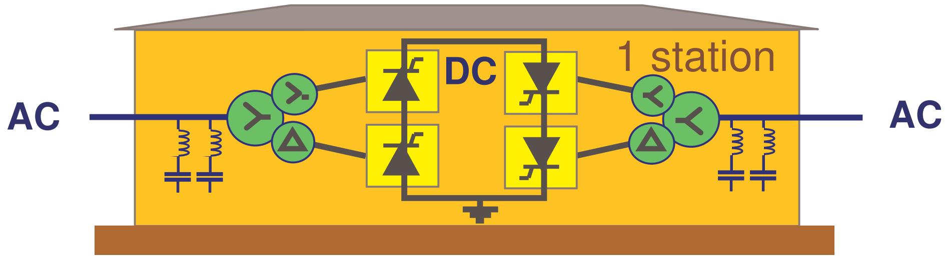
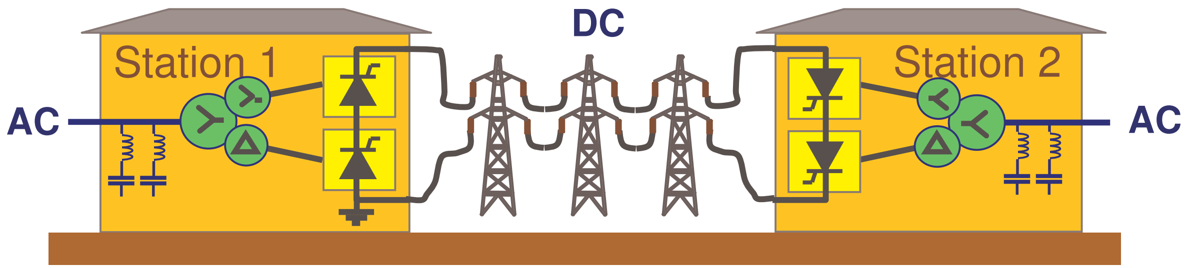
HVDC Scheme Types

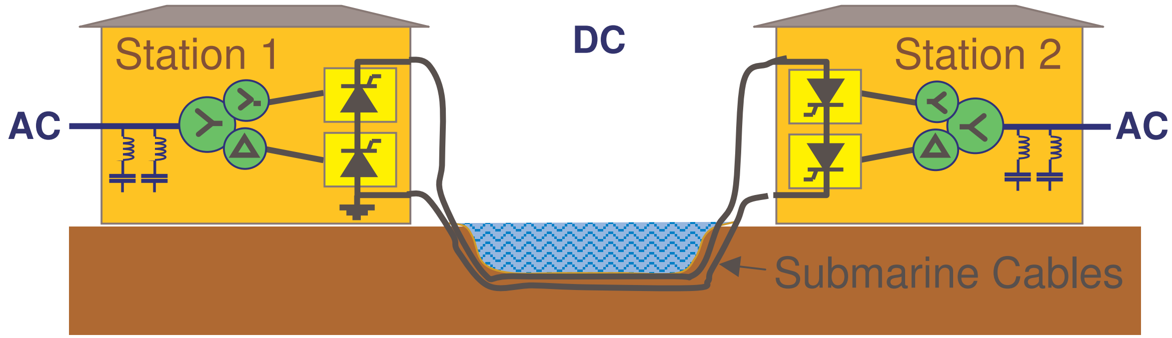
- Back-to-back
  - frequency changing
  - asynchronous connection



- Point-to-point Overhead Line
  - bulk transmission
  - overland



- Point-to-point Submarine Cable
  - bulk transmission
  - under water or underground



Allows better, more efficient use of assets

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Advantages of HVDC Inter-connectors

- **The Power Flow on an HVDC link is Fully Controllable - Fast and Accurate!**
  - The Operator or automatic controller determines how much power flows via the link
  - An HVDC Link is asynchronous - the ac voltage and frequency in the two ac networks can be controlled independently of each other.
  - The HVDC link can be used to assist one (or even both) of the ac networks (e.g. power system damping)
  - HVDC links do not increase the Short Circuit Level of the system
- **HVDC provides increased Transmission Capacity in a fixed corridor**
  - "Up to 3 times more power per tower"
- **HVDC can transport energy economically and efficiently over longer distance than ac lines or cables.**

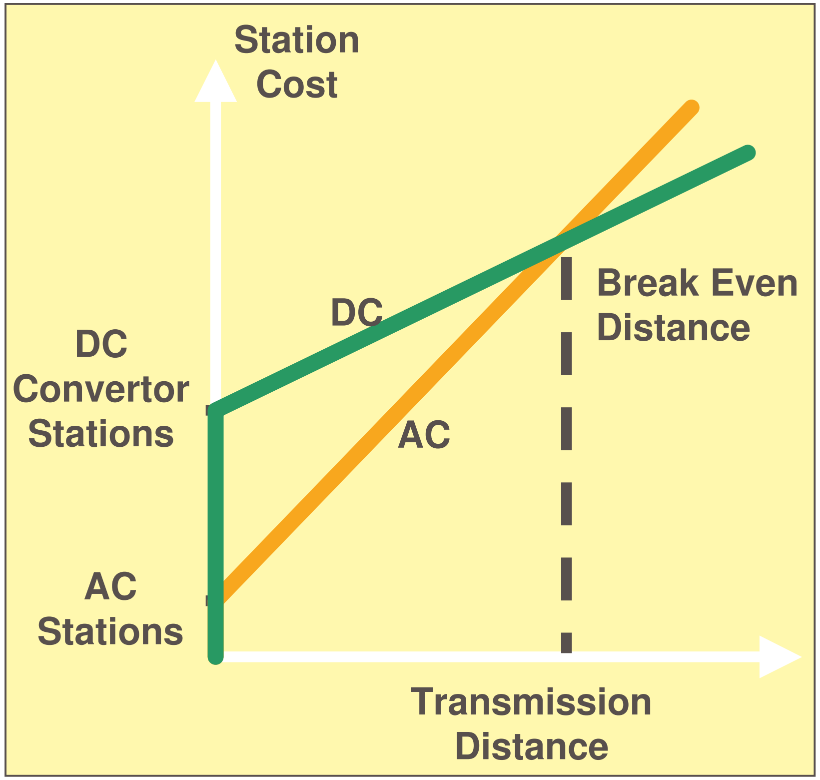
Sometimes HVDC is the only option!

System Economic Benefits

- Shared peak generation and exchange of energy means reduced generation plant margins in each region
- Peak load diversity permits export of surplus energy and operation of thermal plant at base load - with higher efficiency
- Investment in new generation is avoided (or postponed) at a cost of only one fifth
- Improved reliability of AC system through availability of emergency power
- Reduced industrial disruption due to load shedding

When to use HVDC?

- **Overhead line interconnections**
  - Economically driven
  - Breakeven distance=500-800km
- **Submarine or underground cable links**
  - Economically and technically driven
  - Breakeven distance ~40km
  - For cables longer than this, AC is:
    - inconvenient for land cables
    - technically impossible for submarine cables
- **Back to back connections**
  - Technically driven
  - 50/60Hz frequency changers
  - …or cases where the grid frequencies are nominally the same but the connection is too weak to synchronise them



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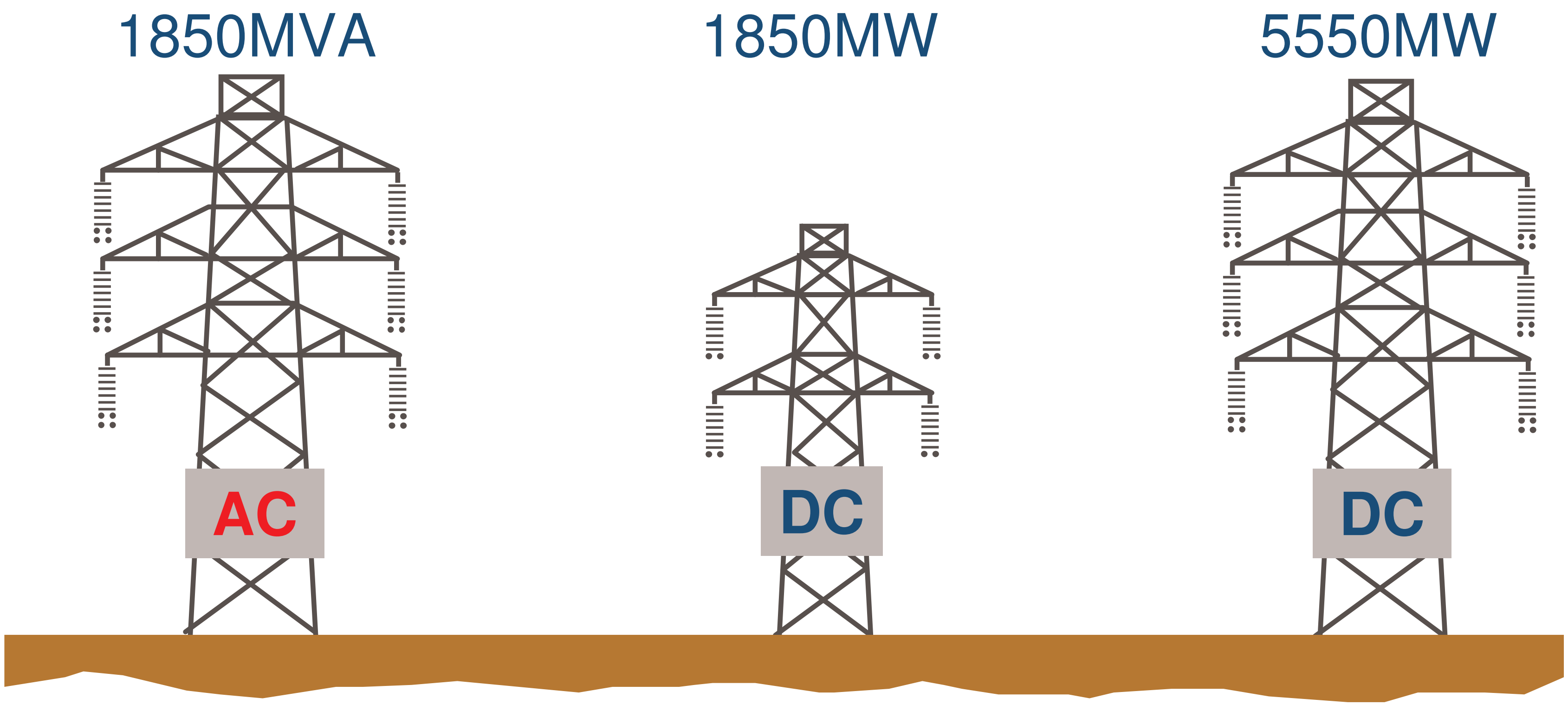
More Power Per Tower



Up to 3 Times More Power

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HVDC – Evolution of Technology

1950s-1970s: Mercury arc valves

1970s: Oil insulated, oil-cooled thyristor valves

1970s-1980s: Air insulated, air-cooled thyristor valves

Since 1980s: Air insulated, water-cooled thyristor valves

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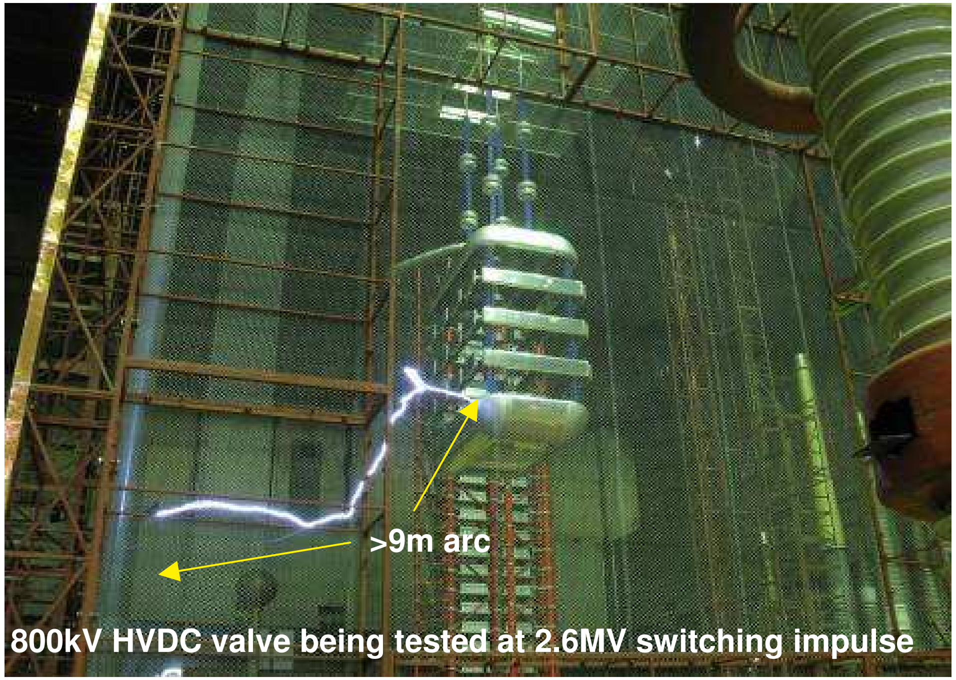
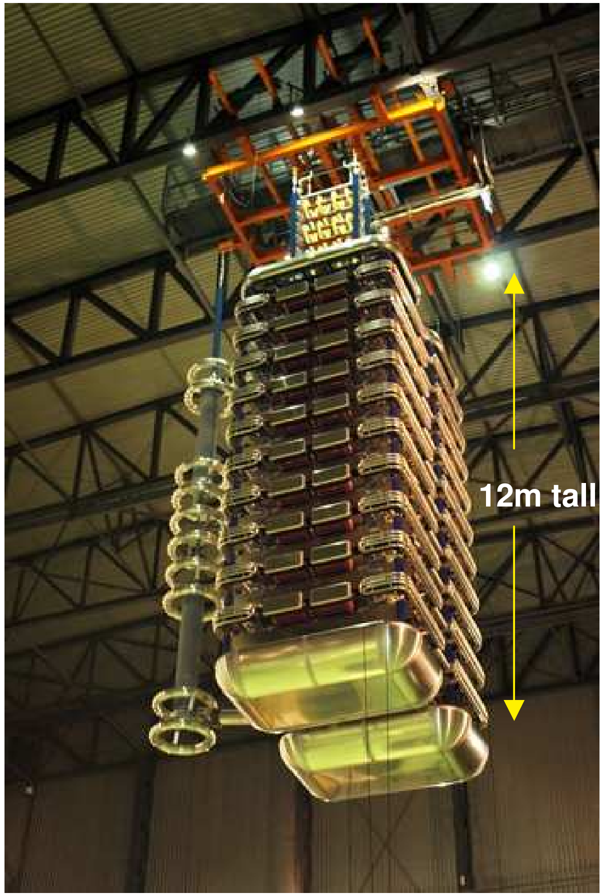
Ultra High Voltage Direct Current

- **Line-Commutated HVDC is evolving fast**
  - ⇨ A 4500A "Back to Back" has been built
  - ⇨ 6.4GW at ±800kV (4000A) is being built
  - ⇨ 7.6GW at ±800kV (4750A) is coming soon
  - ⇨ 9.5GW at ±1000kV (4750A) being planned
  - ⇨ Longest ever DC line (2375km) now being constructed in Brazil at ±600kV





Double valve for Ningdong-Shandong 660kV HVDC project, China

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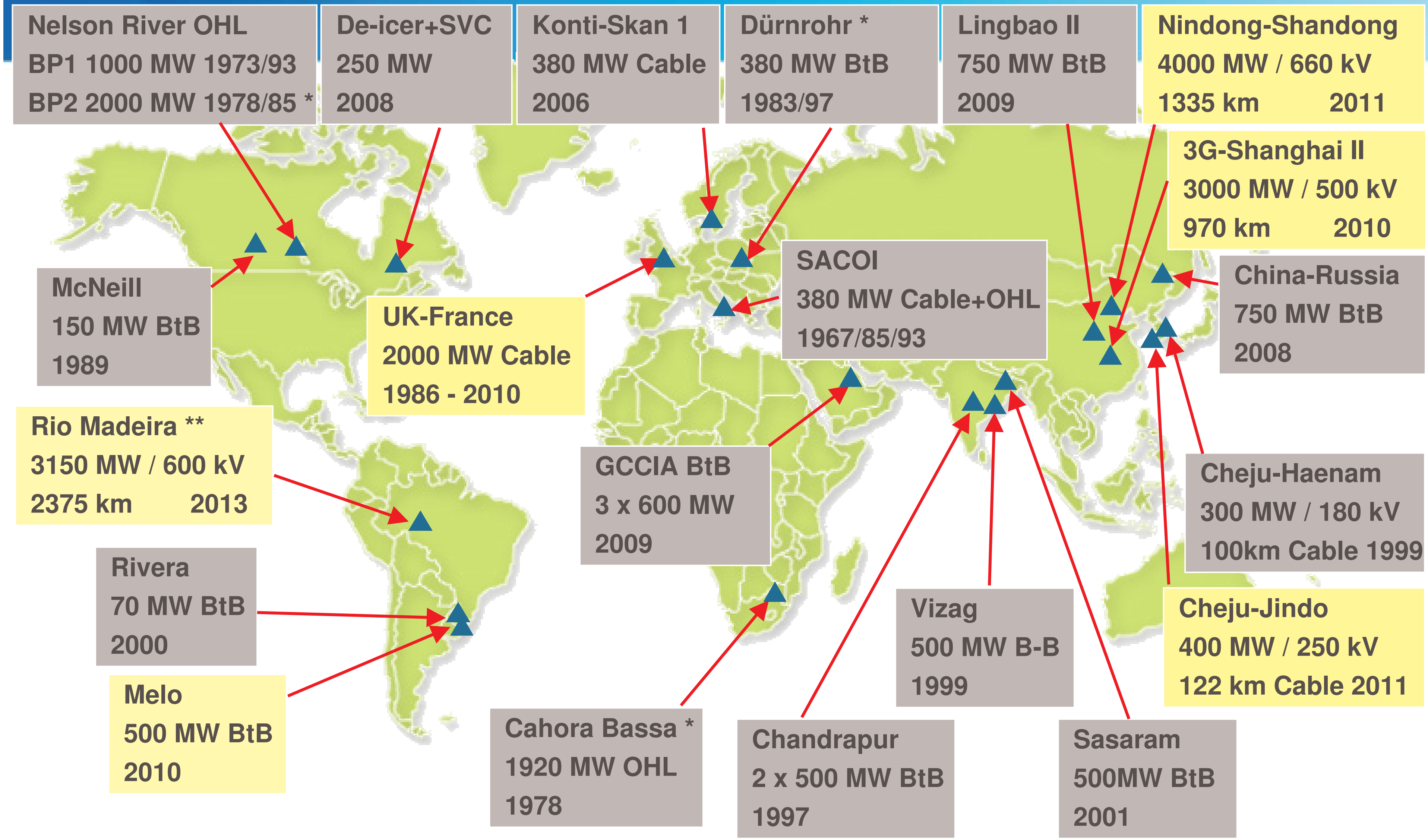
AREVA Experience in HVDC



Contract under execution

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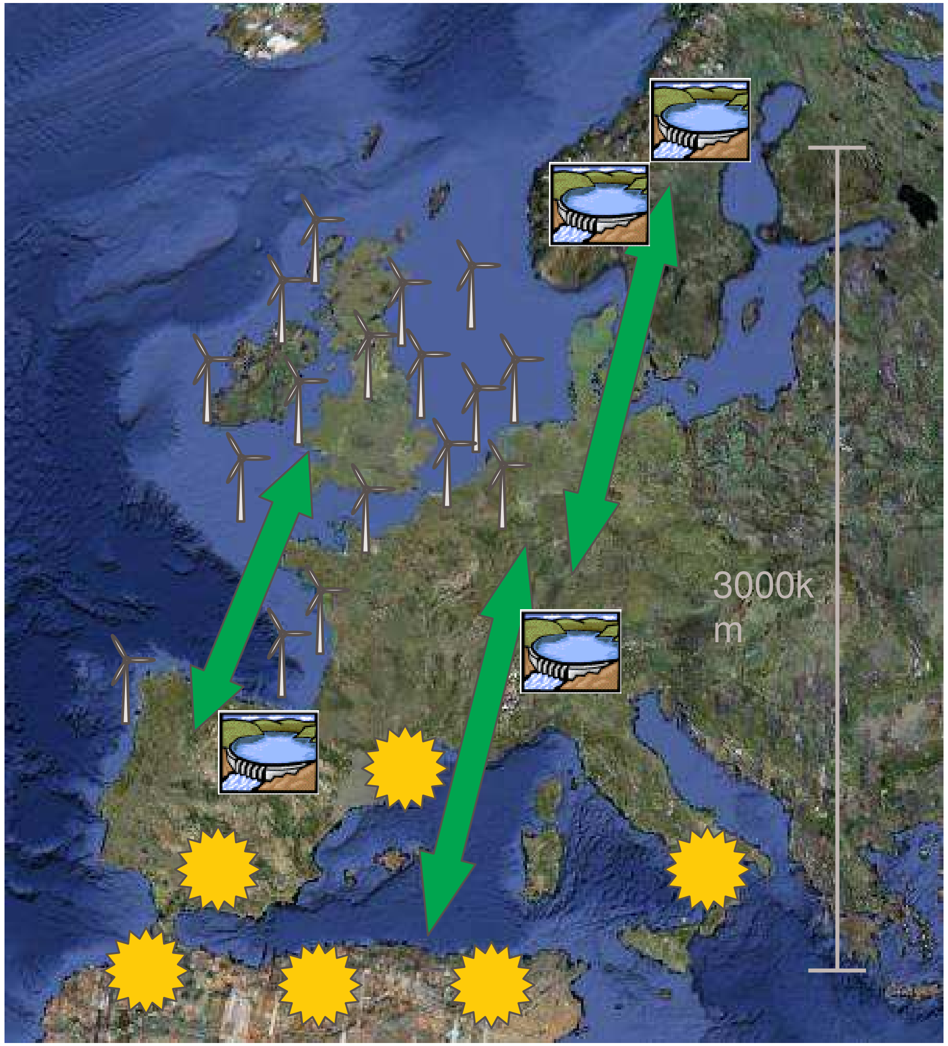
HVDC to re-distribute renewable energy

- **Renewable energy is not evenly distributed**
  - Solar power in N Africa and S Europe
  - Wind power in NW Europe
  - Hydro power (can be used for storage) in mountainous areas
- **HVDC is the most efficient way of transporting energy over such long distances**
- **HVDC also gives great benefits of controllability, "firewall" functionality etc**



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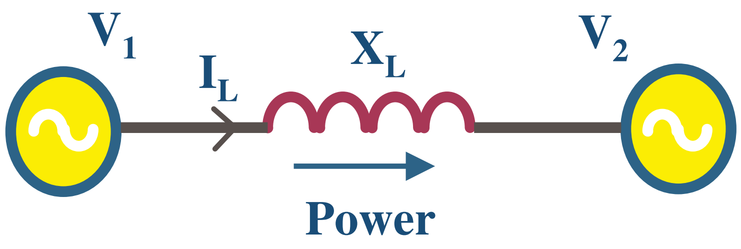
Parallel AC and DC Interconnections



$$\text{Power} = \frac{V_1 V_2}{X_L} \sin\delta$$

V_1 Sending end voltage

V_2 Receiving end voltage

X_L Reactance of transmission network

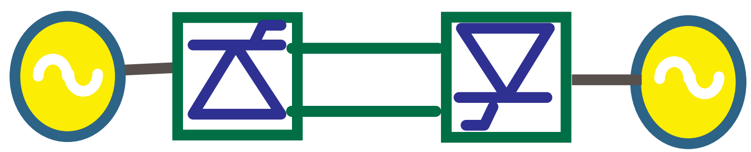
δ Angle between sending and receiving end voltages

Embedded HVDC scheme example
Pacific Intertie (USA)

- **AC transmission scheme typically operated at $\delta = 30°$ to allow for transient stability**

- **With a parallel DC scheme higher stability levels were achieved, allowing AC scheme to operate at $\delta = 45°$**

- **This gives a 40% increase in power in the AC scheme in addition to the controlled power flow in the DC scheme**



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Nelson River HVDC Scheme Canada

- **2000MW bipole at ±500kV**
- **900km route length**
- **Originally built in 1972 – 77**
- **Upgraded in 1992 – 93 and 2000 - 01**

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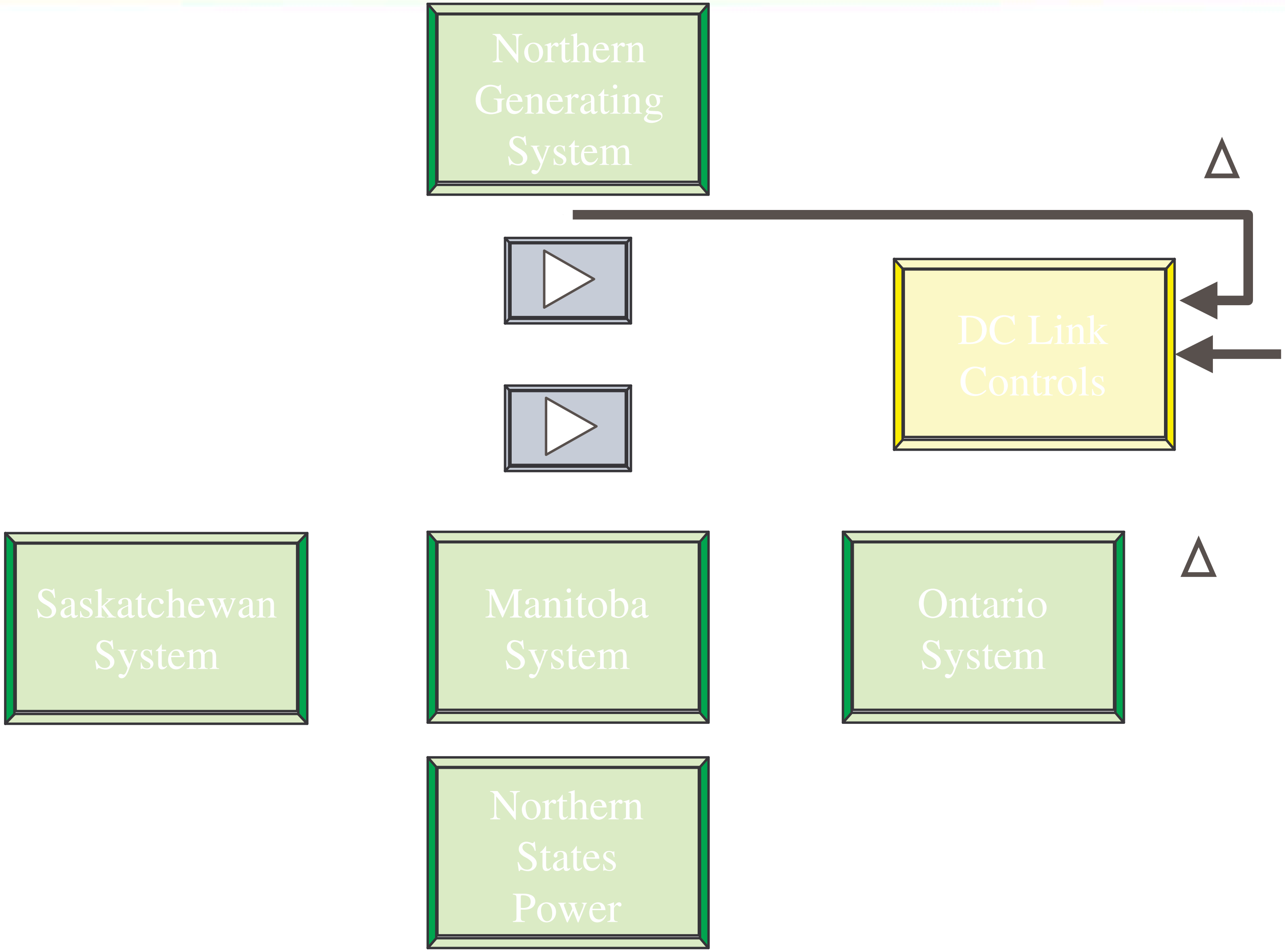
Nelson River HVDC Transmission Scheme



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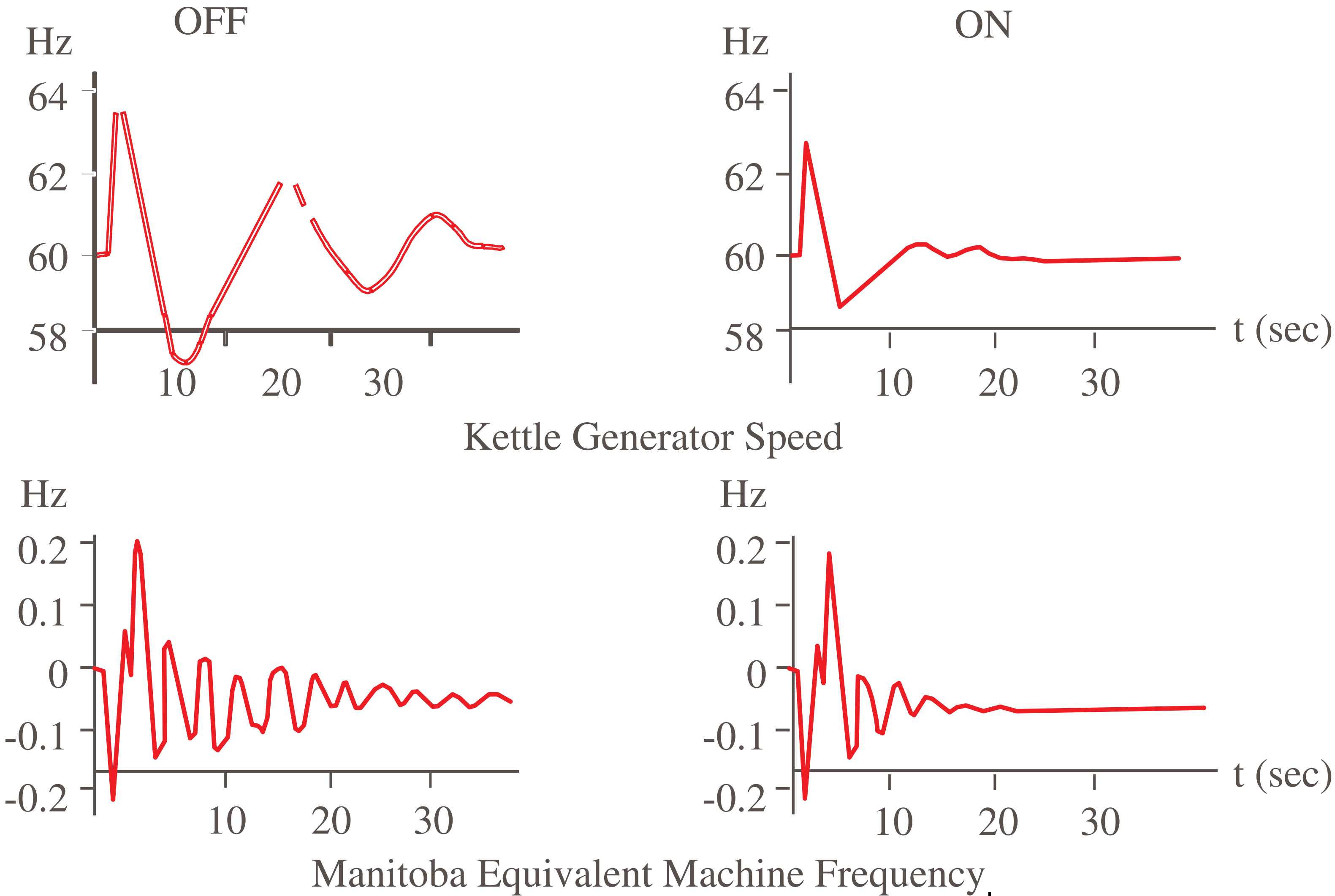
Effect of Damping Controls



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Konti-Skan HVDC Project
Project Location

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Konti-Skan Vester Hassing Site

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Konti-Skan Vester Hassing Site

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Konti-Skan Vester Hassing Site

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Konti-Skan Lindome Site

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Konti-Skan Valve Hall

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Agenda

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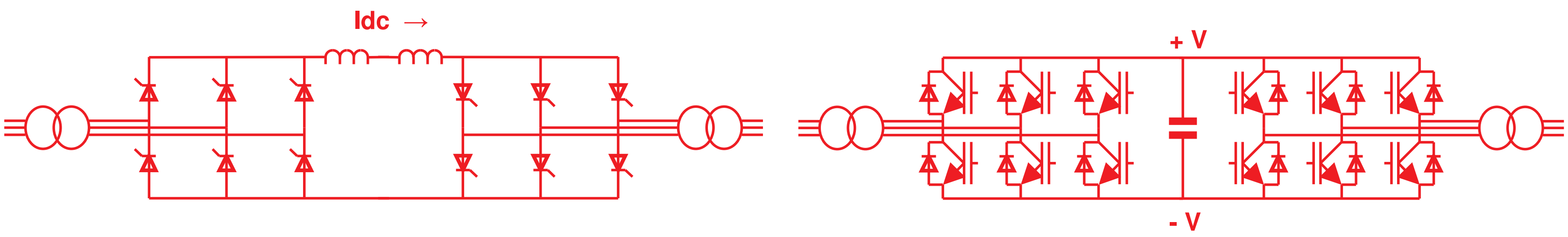
VSC versus LCC HVDC

LCC HVDC
- Current-sourced
- Line-Commutated
- Change power direction by changing voltage polarity
- Cheaper for high power
- Lower losses
- Ideally suited for long distance bulk power transmission over land

VSC HVDC
- Voltage-Sourced
- Self-Commutated
- Change power direction by changing current direction
- Easier to create a “DC grid” (5 to ∞ connections)
- Ideal for feeding dead loads (eg islands)



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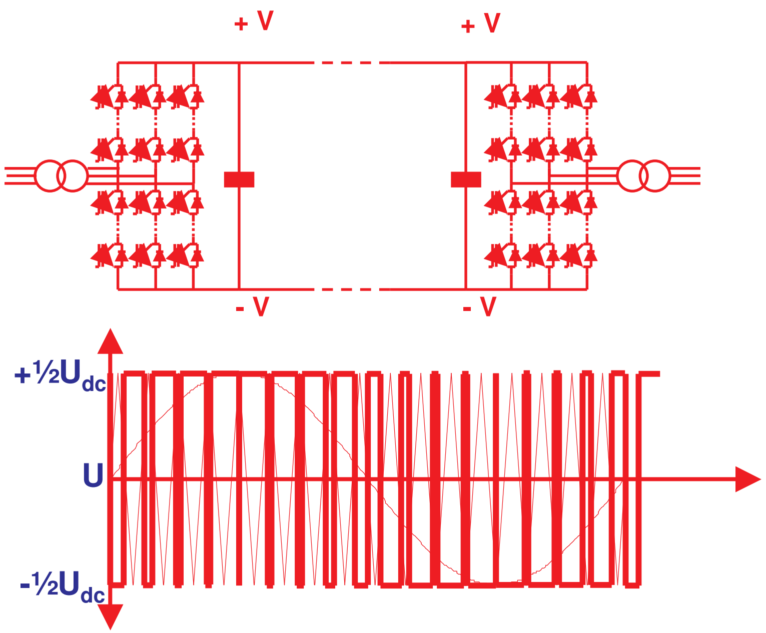
VSC-HVDC
2 Basic Approaches

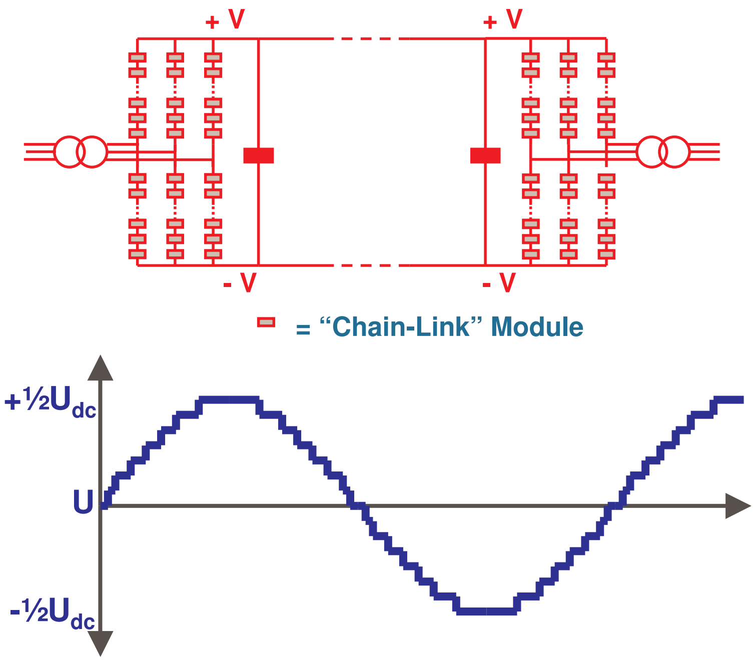
Series-Connected IGBTs

- ✓ Conceptually simple circuit
- × Requires PWM
- × High switching losses
- × Harmonic problems from PWM

Multi-level circuit

- ✓ Low switching losses
- ✓ Easily "scaleable"
- ✓ Virtually no harmonics
- × More complex controls





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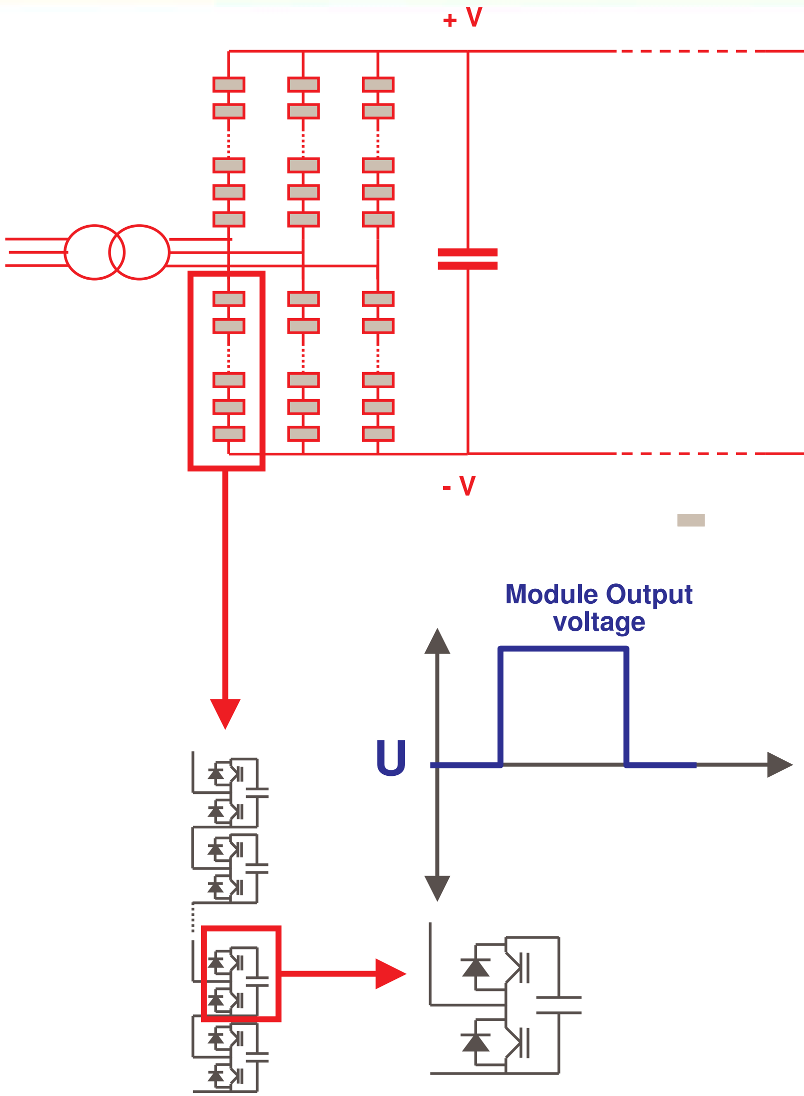
Modular Multi-Level Converter: Half-link



- Lowest component count
- Only one possibility of output voltage polarity
- No capability of suppressing DC-side faults

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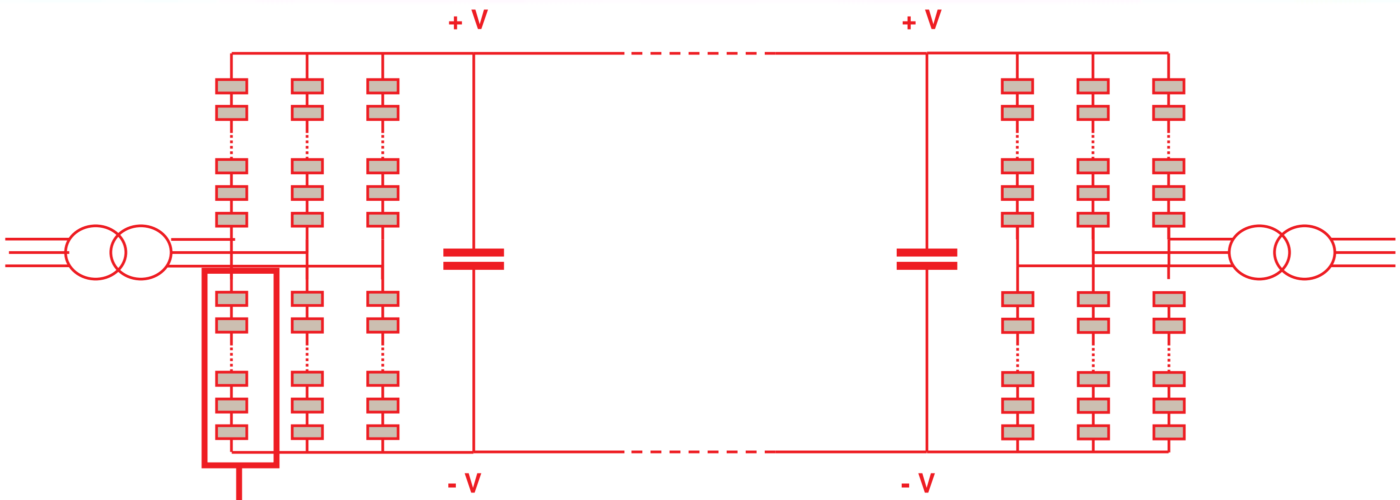
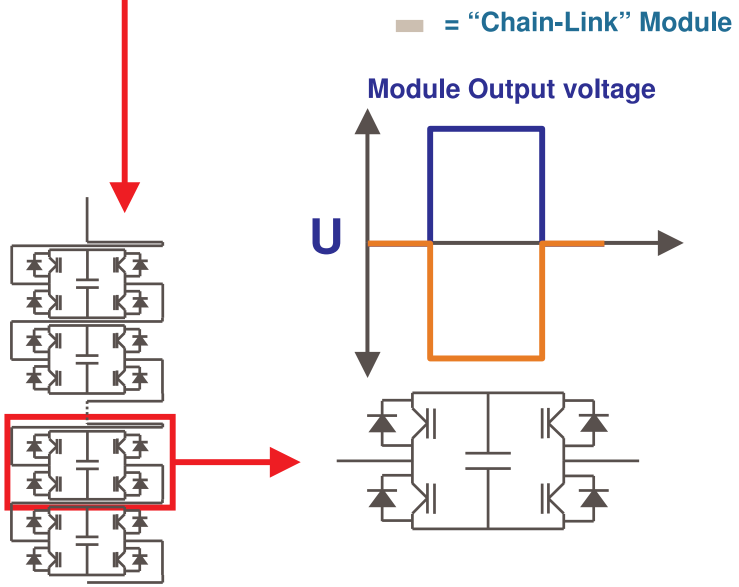
Modular Multi-Level Converter: Full-link





- Same circuit as AREVA STATCOM chain circuit
- Output DC voltage can be either polarity
- Hence can connect as tap to LCC-HVDC link
- Can also suppress DC side faults

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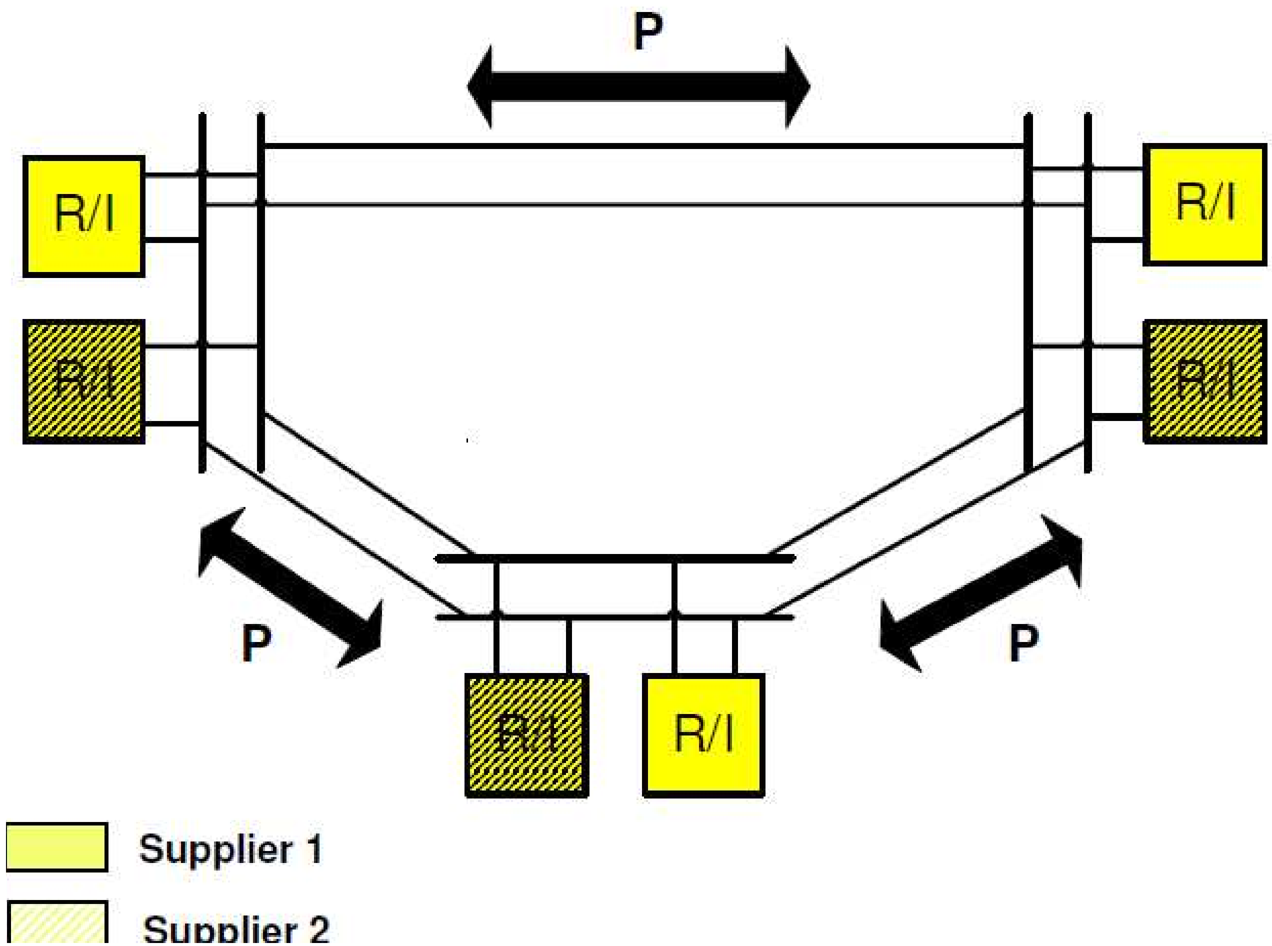
VSC full-link converter allows for Multiterminal application



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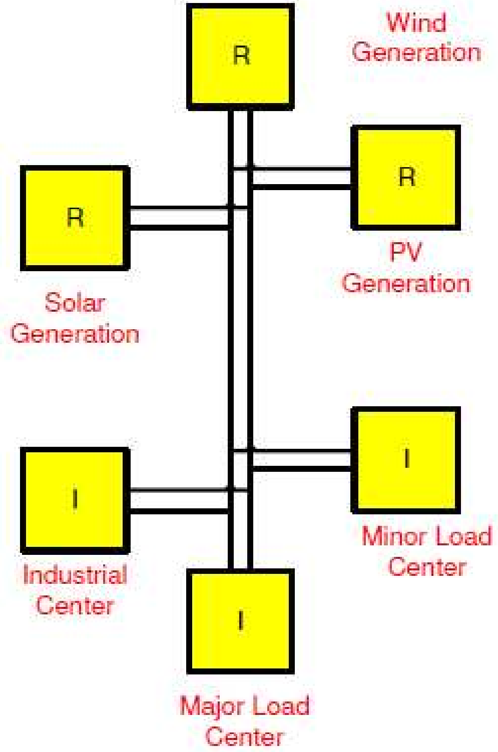
VSC full-link converter allows for Multiterminal application

VSC HVDC technology will allow multi-terminal grids to be formed, with several rectifier and inverter stations



R = Rectifier station

I = inverter station

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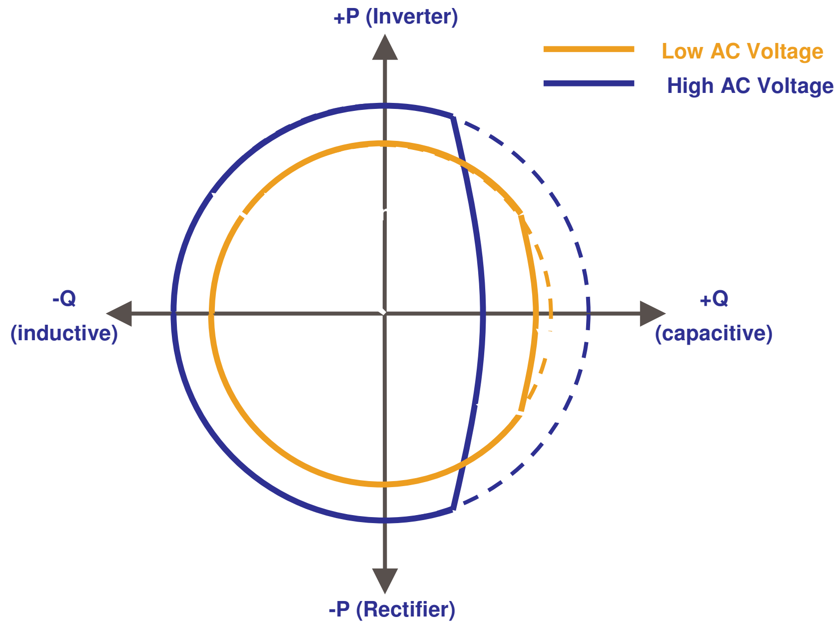
VSC: Real vs Reactive power

- **With Line-Commutated Converters, there is a clear-cut division between HVDC (real power) and FACTS (reactive power)**
- **With Self-commutated, Voltage Sourced-Converters the distinction is less clear-cut**
- **A VSC has a defined operating characteristic in the P-Q plane and can operate anywhere within this envelope:**



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Agenda

1.	Introduction
2.	FACTS Devices

2.1 Shunt FACTS devices

- 2.1.1. Static Var Compensator (SVC)
- 2.1.2. Static Synchronous Compensator (STATCOM)

2.2 Series FACTS devices

- 2.2.1. Fixed Series Capacitor (FSC)
- 2.2.2. Thyristor Controlled Series Capacitor (TCSC)

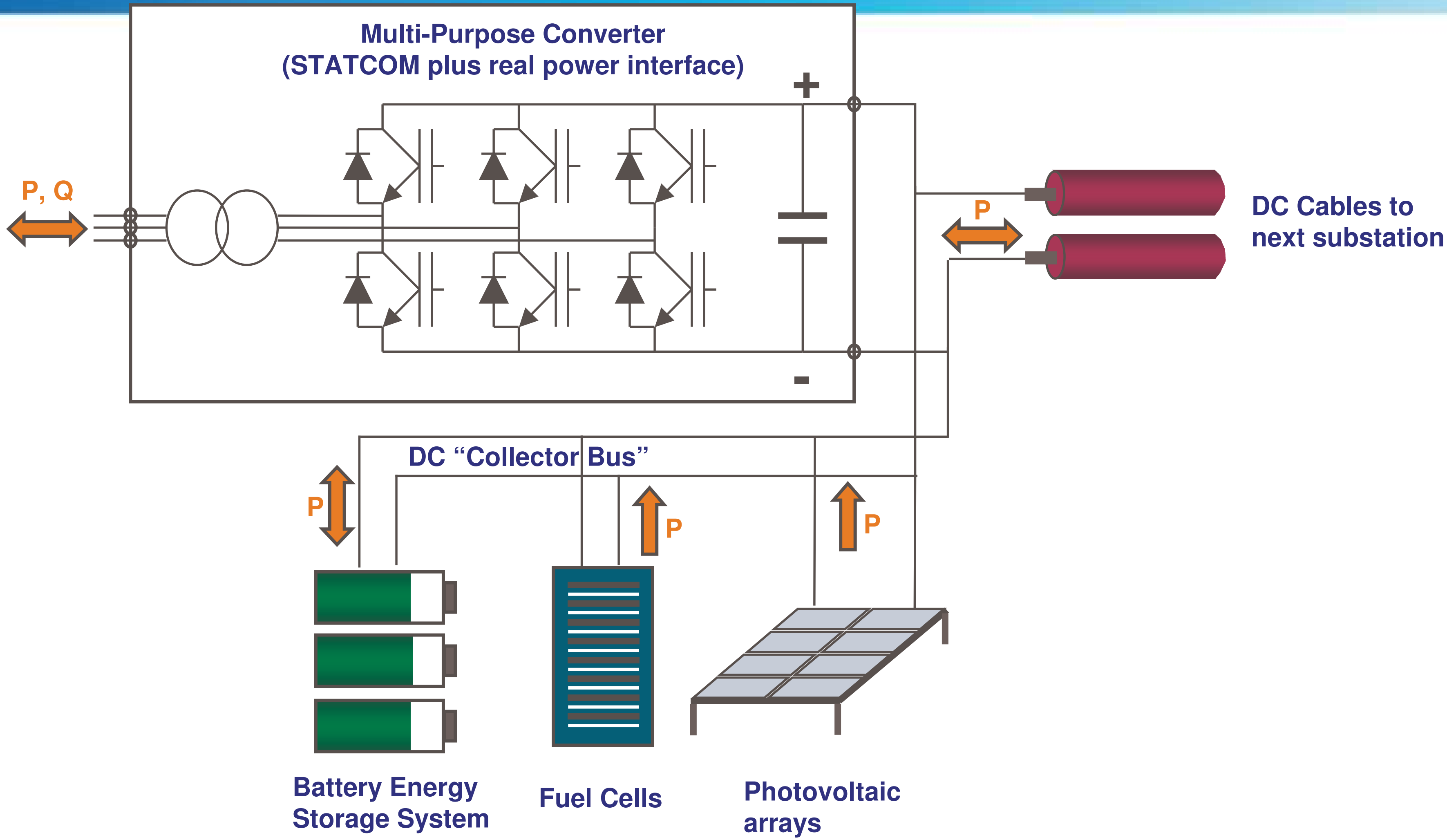
3. High Voltage Direct Current (HVDC)

3.1. Line Commuted Converter (LCC)

3.2. Voltage Source Converter (VSC)

4. A vision of the future of Power Electronic in T&D System

Multi-Purpose Voltage Sourced Converter



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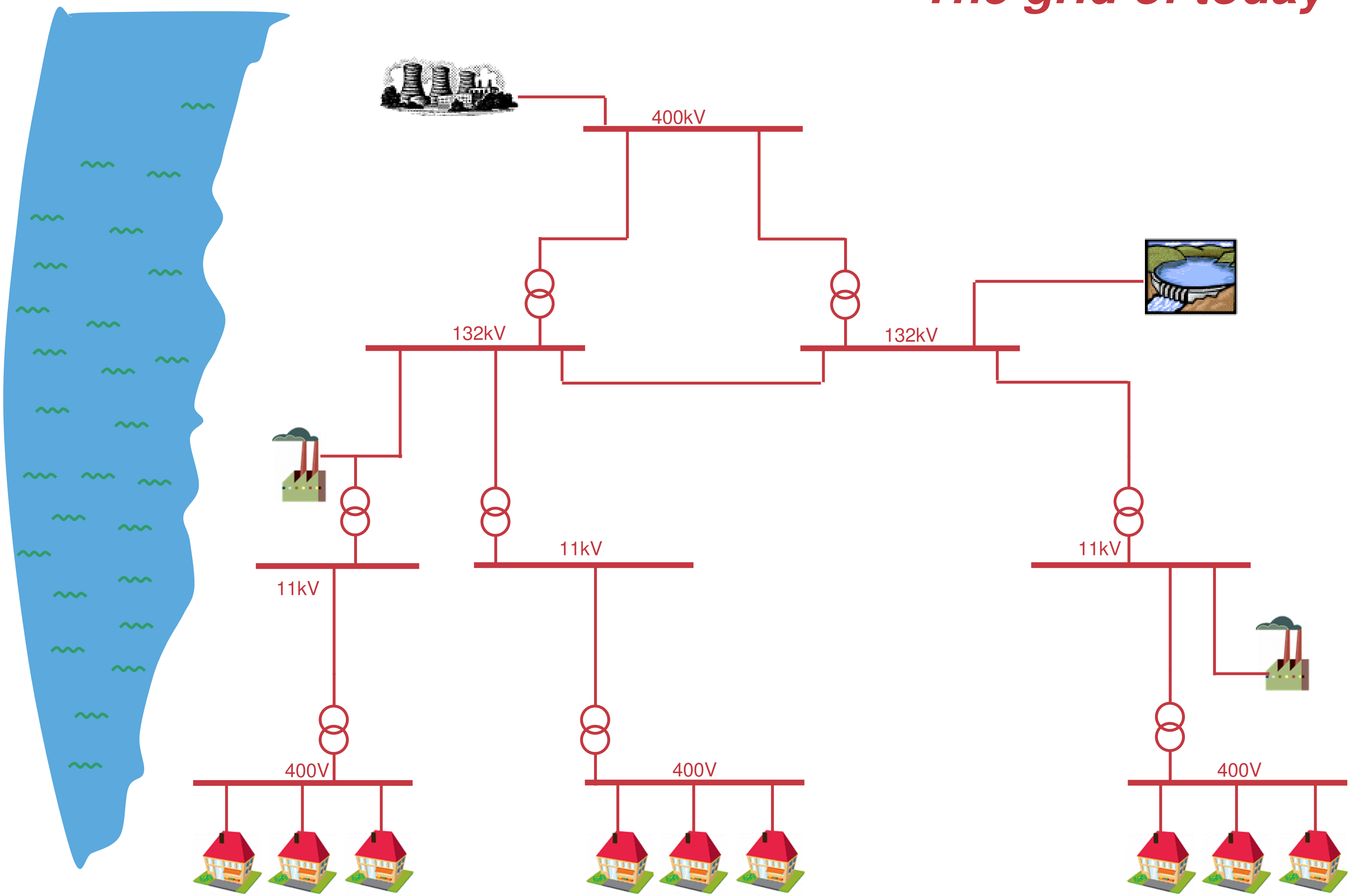
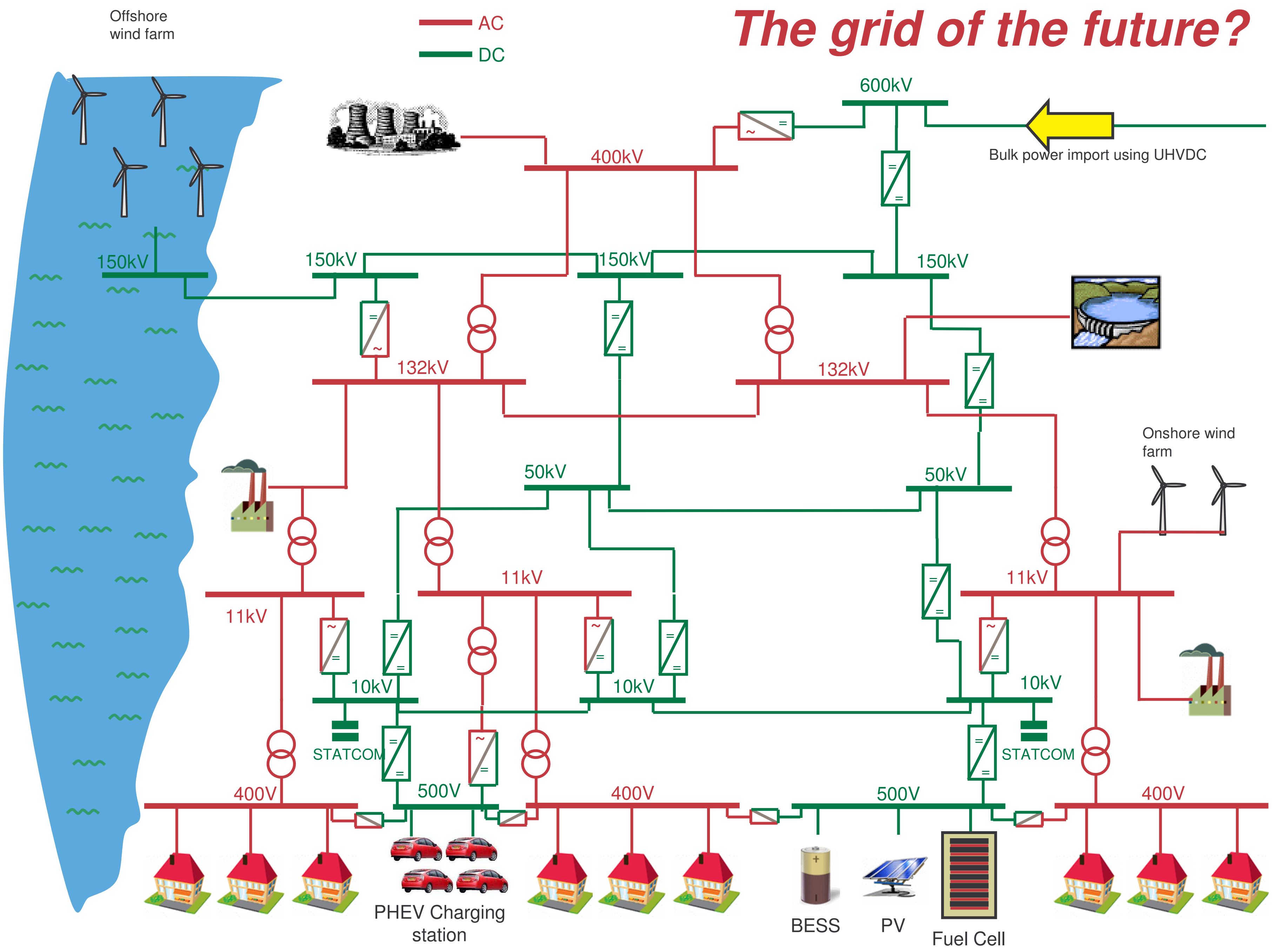
The grid of today

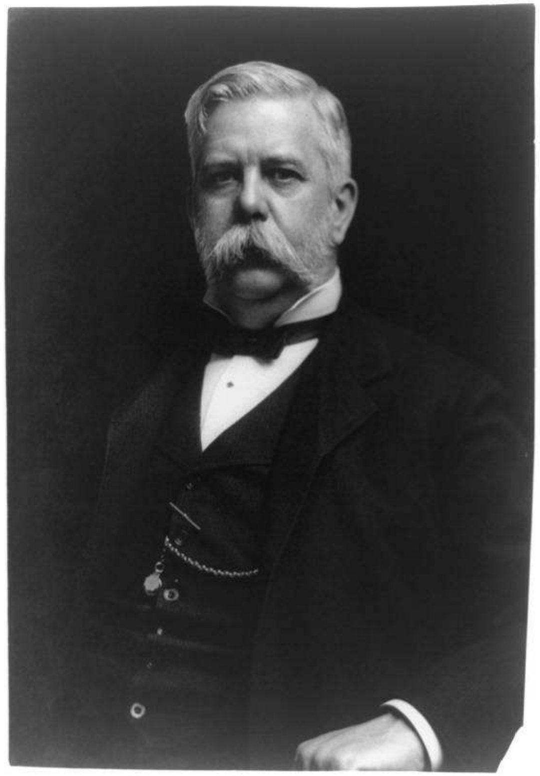


The grid of the future?



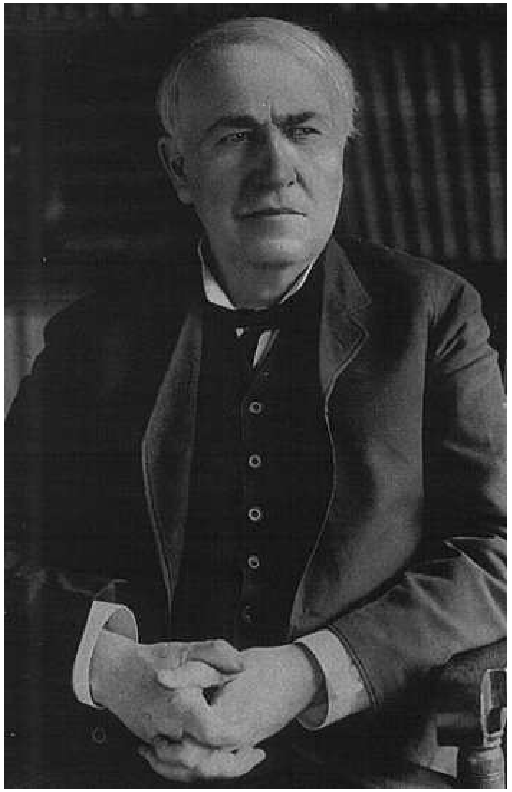
The Battle of the Currents 1885-1890

In the AC corner: George Westinghouse



– VS –

In the DC corner: Thomas Edison



Will Thomas Edison eventually be proved right?

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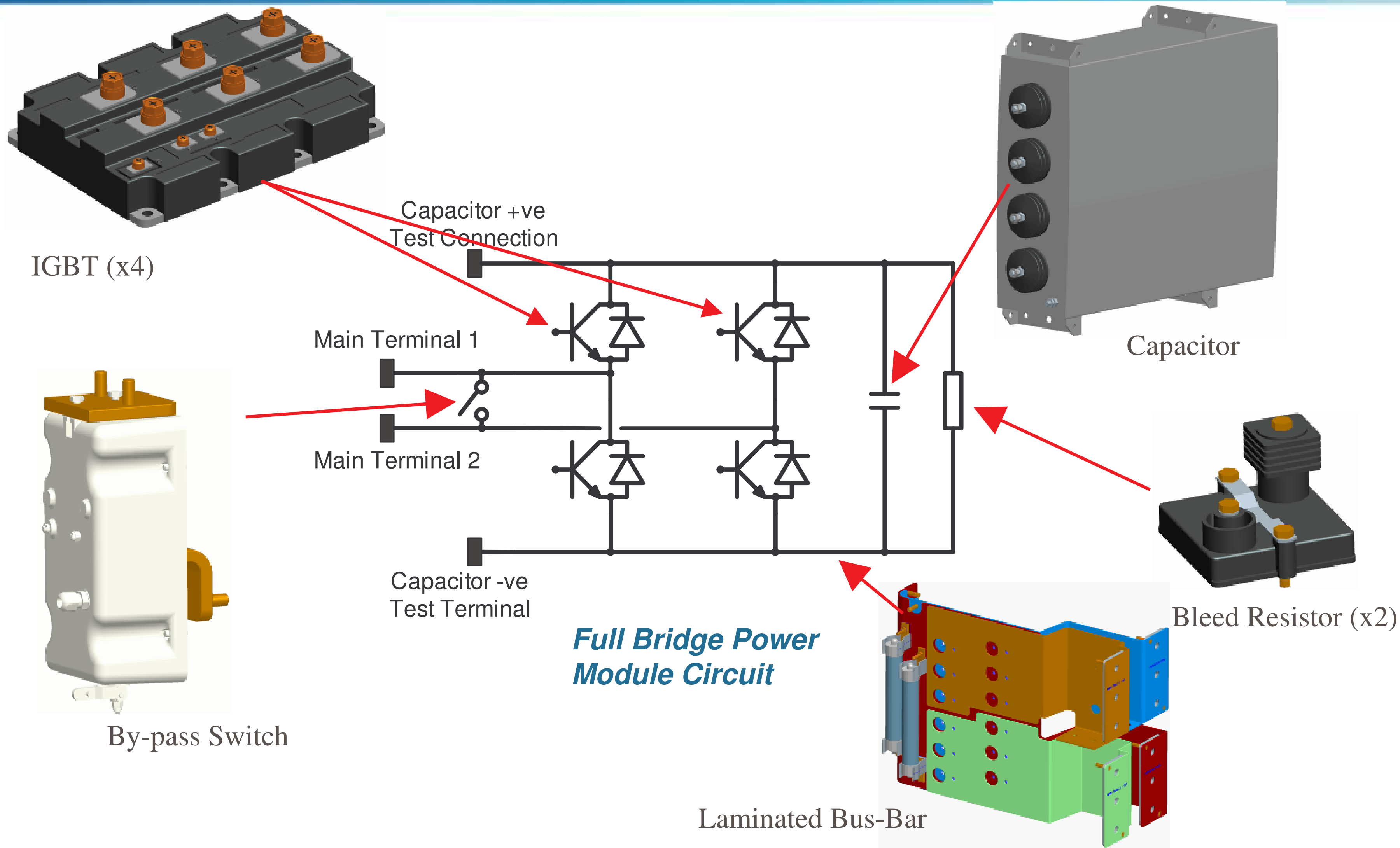
Relating Power Module Circuit Diagram to Power Components – 'Full Bridge'



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Covers partly in place

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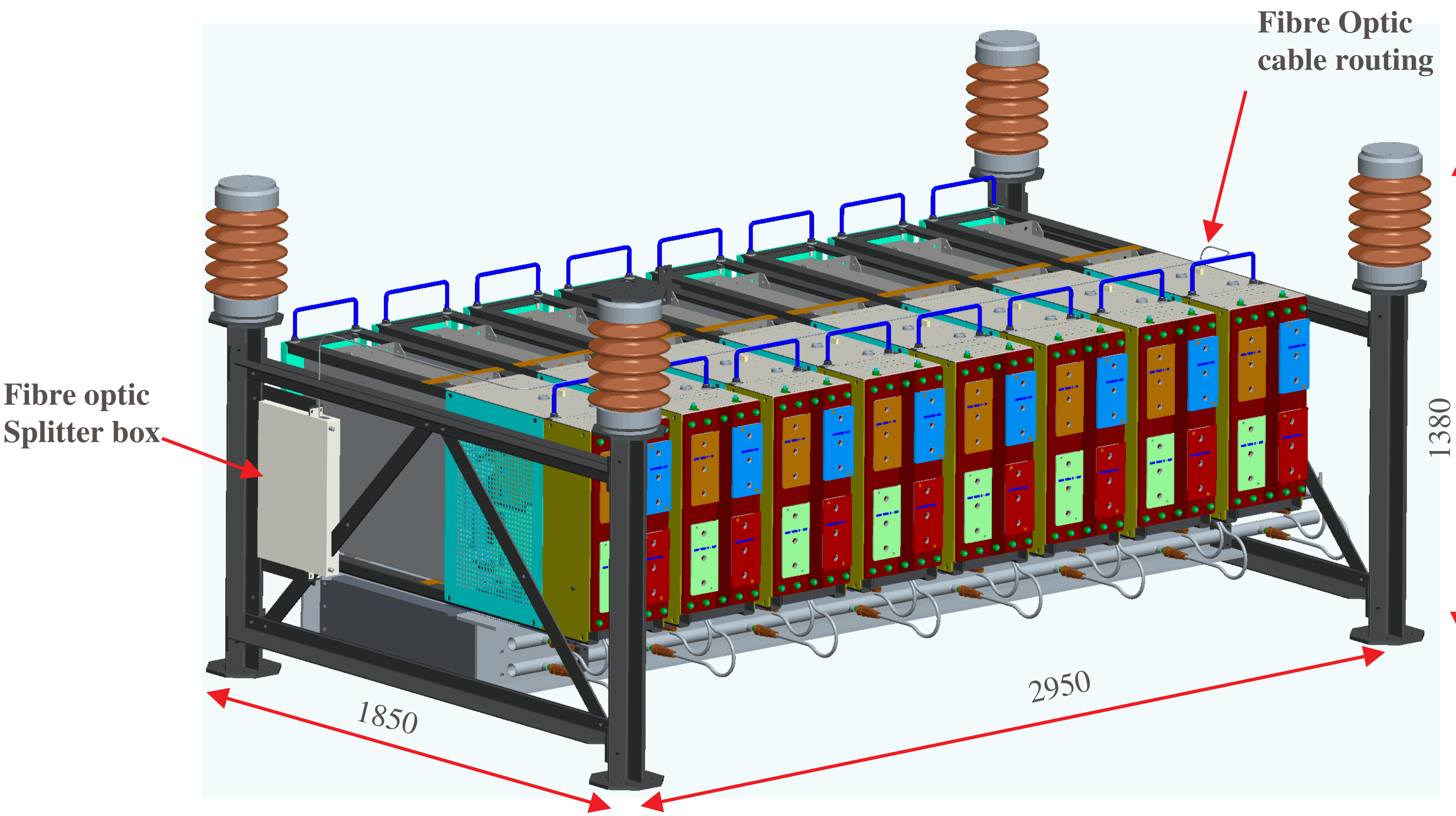
Power Module Tier Assembly



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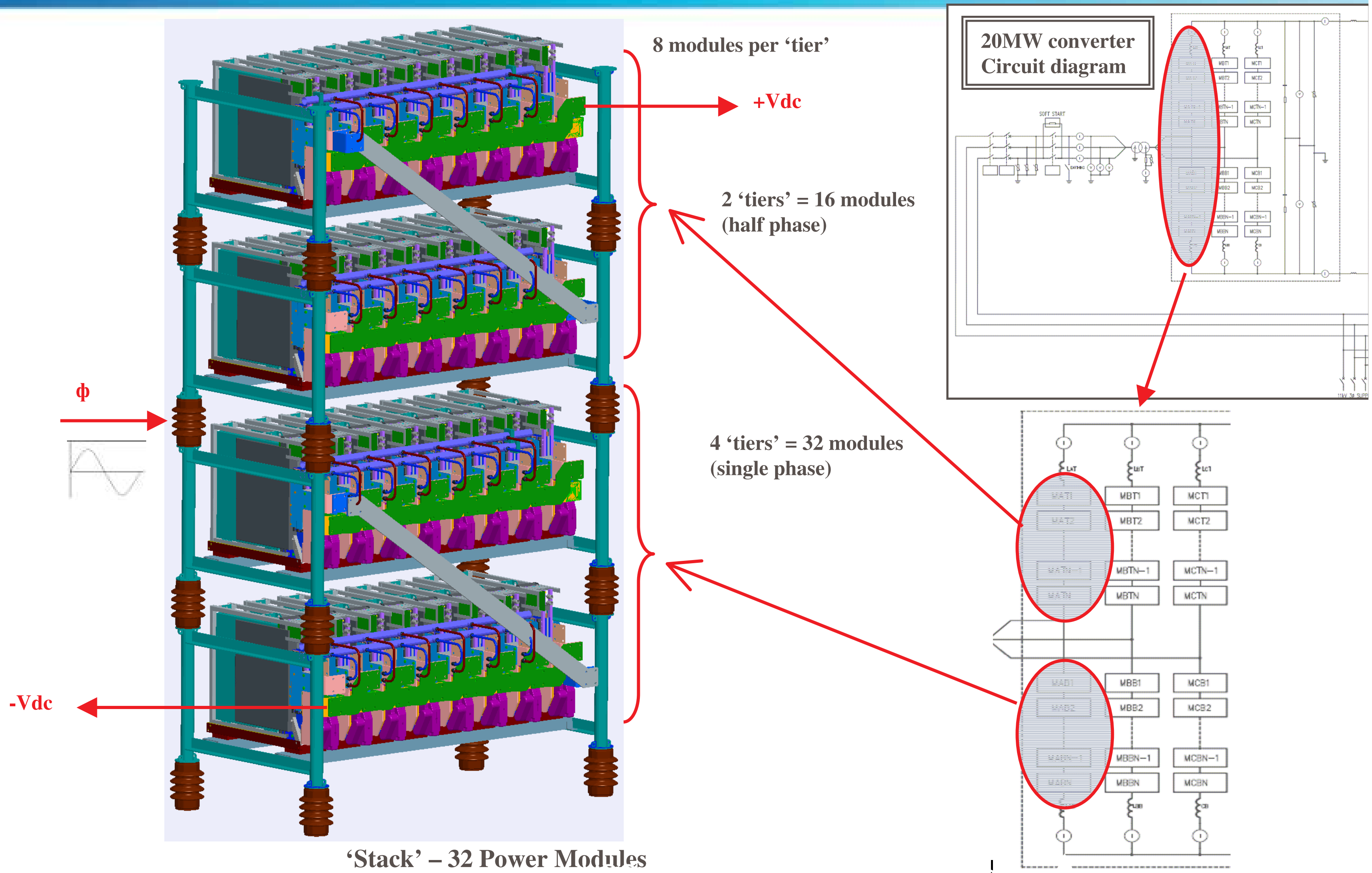
VSC Converter Assembly – 1 Phase



'Stack' – 32 Power Modules
'Stack' - Single phase

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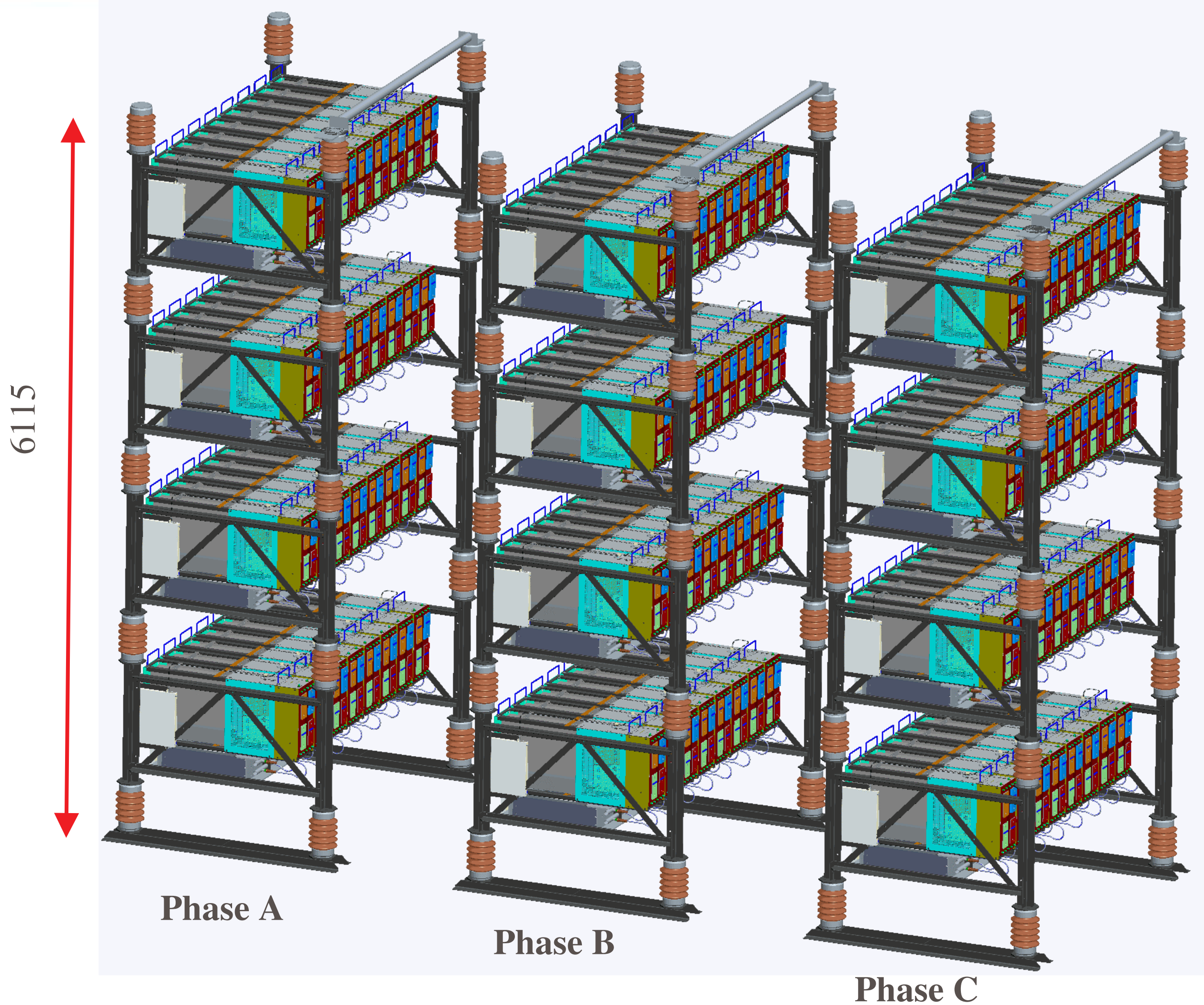
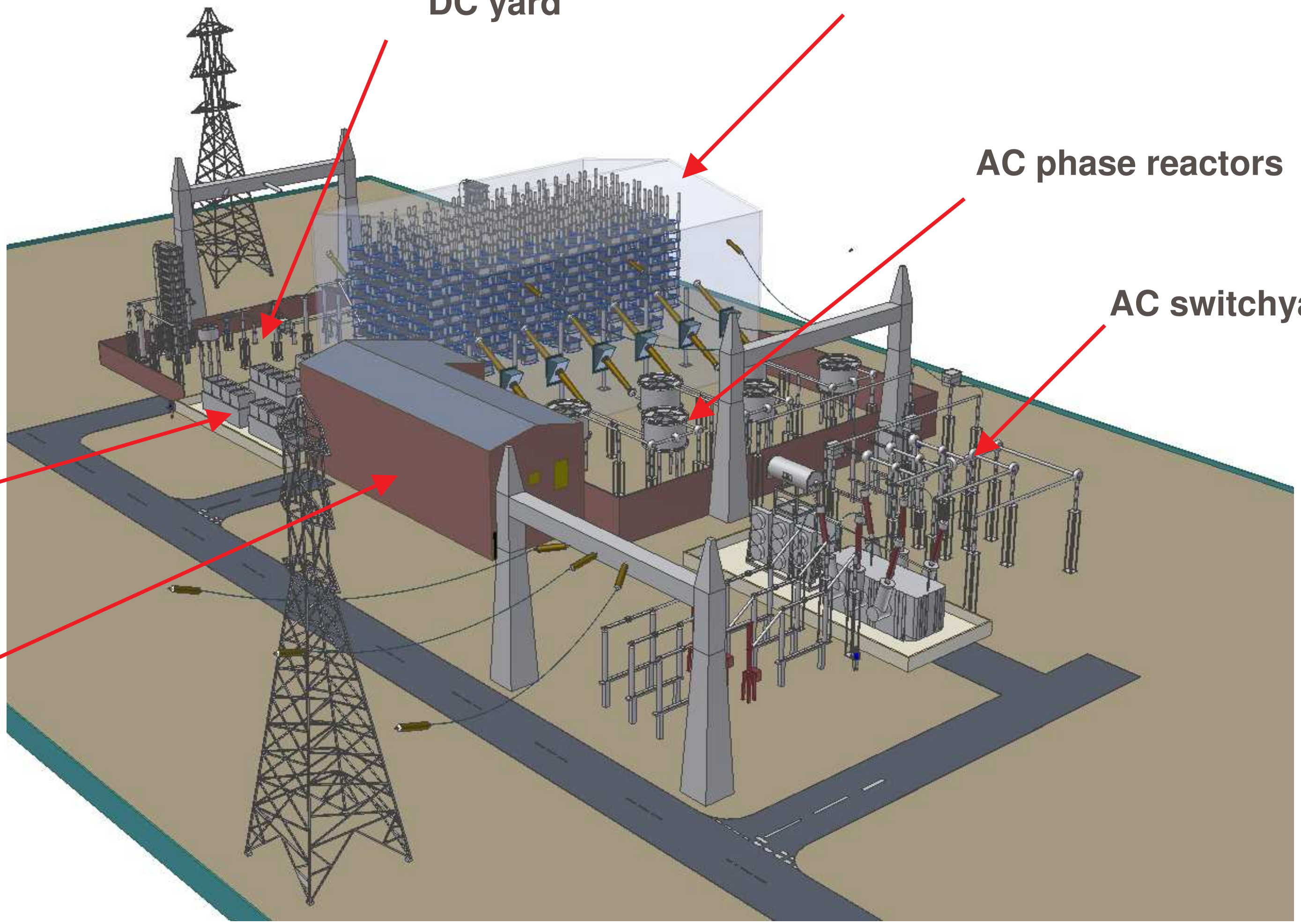
VSC Converter Assembly – 3 Phase



VSC HVDC Station Layout
600MW at ±300kV



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2 x 600MW VSC HVDC station

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