CIGRE
SESSION 2016

TUTORIAL

INTRODUCTION TO HVDC

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SC B4

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INTERNATIONAL COUNCIL
ON LARGE ELECTRIC SYSTEMS

Presentation Layout

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- Advantages of HVDC
- HVDC Applications
- HVDC Technology
  - Line Commutated Converters
  - Voltage Sourced Converters
- Recent Developments
  - DC Grid
- Cigre Activities in HVDC

Advantages of HVDC

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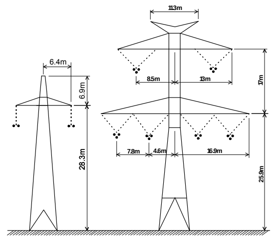
Smaller towers



- HVDC towers are smaller and simpler than HVAC towers with similar transmission power rating

Advantages of HVDC

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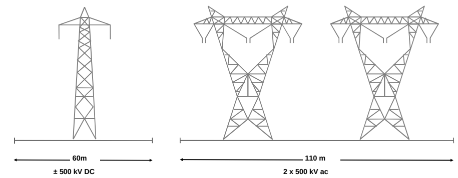
Narrow right of way



Typical transmission line right of way for 3000 MW if two ac towers are used

Advantages of HVDC

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- No need for Series or Shunt Compensation
- Controllable power flow
- Zero or no contribution to short circuit current

Advantages of HVDC

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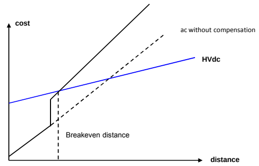

Comparison of capital cost for HVDC and HVAC

Advantages of HVDC

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AC cables are limited in length due to the charging current, HVDC cables have no length limitation

Typical charging currents for land cables*

Cross section (mm^2)	Current rating (A)	Charging current (A/km)
800	870	12.3
1000	960	13.7
1200	1115	15.1
1400	1205	15.9
1600	1280	16.6
2000	1410	17.6
2500	1540	19.2

* 500kV XLPE at 65C, flat formation

Applications of HVDC

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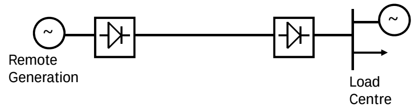
Transmission of bulk power from remote generation



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Applications of HVDC

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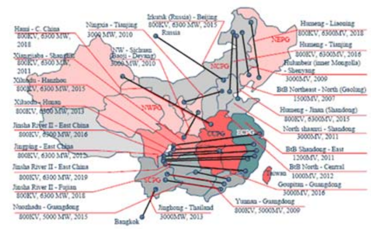
Long Distance Transmission



Examples of long distance HVDC in China

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Applications of HVDC

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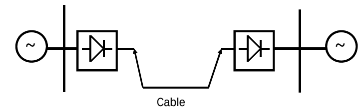
Submarine or Underground Cable Transmission



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Applications of HVDC

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HVDC Submarine Cables

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Applications of HVDC

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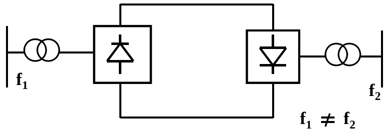
Connecting Systems with Different Frequencies



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Applications of HVDC

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Connecting Systems with Different Frequencies

Argentina-Brazil HVdc interconnect

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Applications of HVDC

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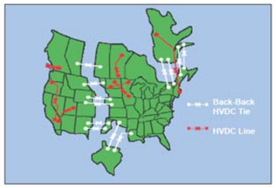
Connecting asynchronous systems with the same frequency



Connections between US east, west and Texas systems

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Applications of HVDC

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- Moving large amounts of power over long distances.
- Moving power by cable over moderate to long distances.
- Moving power between asynchronous systems.
- Forcing power into an area (e.g. loop flow).
- Congested corridors
- Limiting short circuit currents through system segmentation.

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Types of HVdc Converters

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- Line Commutated Converters (LCC) Using Thyristor Valves
- Voltage Source Converters (VSC) Using Insulated Gate Bipolar Transistors (IGBT)

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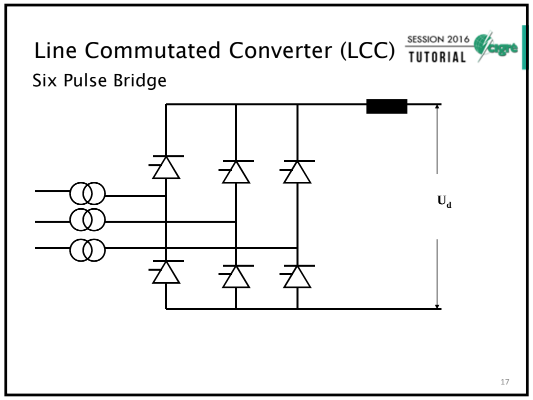
Line Commutated Converter (LCC)
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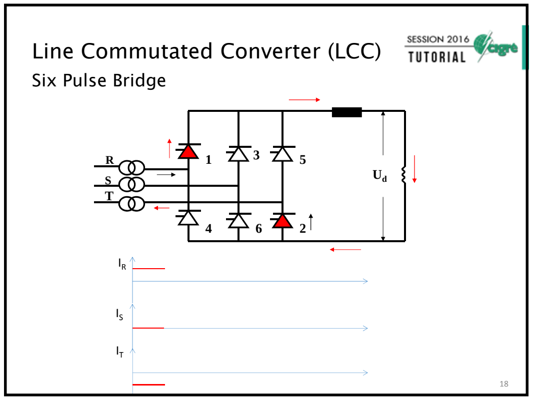
Six Pulse Bridge
Ud
17


Line Commutated Converter (LCC)
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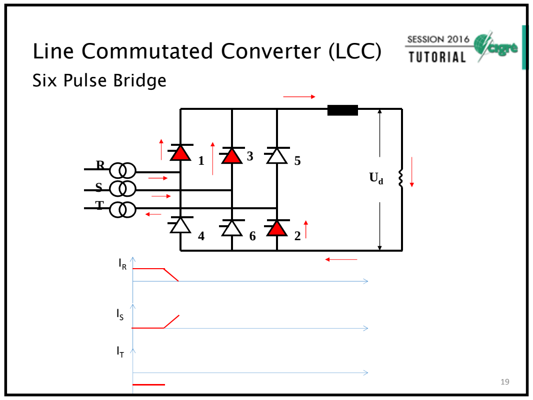
Line Commutated Converter (LCC)
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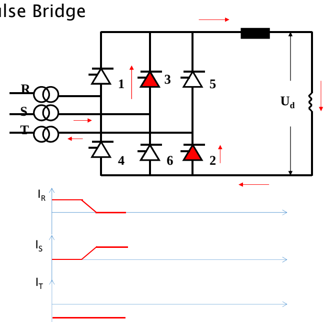
Line Commutated Converter (LCC)

Six Pulse Bridge



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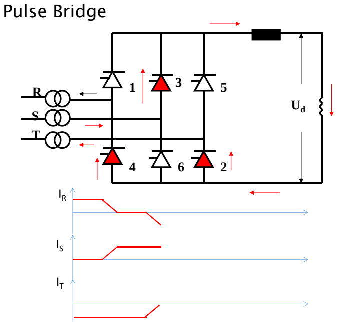
Line Commutated Converter (LCC)

Six Pulse Bridge



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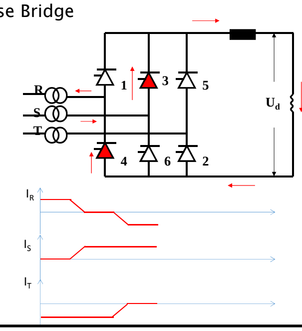
Line Commutated Converter (LCC)

Six Pulse Bridge



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Line Commutated Converter (LCC)

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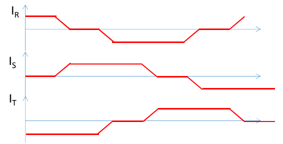
Six Pulse Bridge



AC Current Waveforms

- Currents are not sinusoidal
- Currents lag voltages (converter consumes reactive power)

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Line Commutated Converter (LCC)

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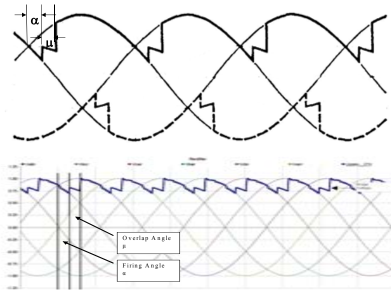
Rectifier Wave Forms



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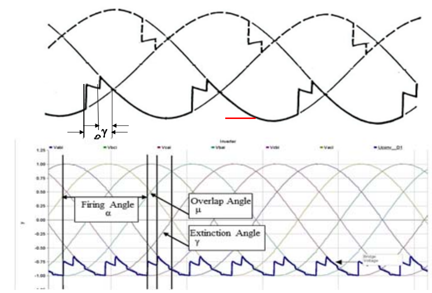
Inverter Wave Forms



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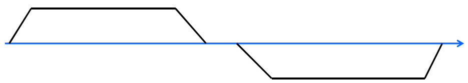
Line Commutated Converter (LCC)

Current Harmonics



The characteristic harmonics in the output current are of the order 6n+/-1

where n = 1,2,3,4,....

The harmonics generated are of the order 5,7,11,13,17,19,....

$I_n = \sqrt{6}\ I_d / n\pi$

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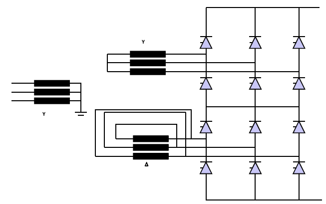
Line Commutated Converter (LCC)

Harmonics



- 12 Pulse arrangement removes 5,7, 17,19,... harmonics from AC currents
- Remaining current harmonics are of order 12n±1
- Remaining DC voltage harmonics are of order 12n

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Line Commutated Converter (LCC)

Filters

- AC Harmonic filters also supply reactive power consumed by the converter

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Line Commutated Converter (LCC)

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Inverter Commutation Failures

- Commutation failures are the result of the incoming valve failing to take over the current, or re-fire of the outgoing valve. Commutation failures are due to:
  - AC system faults & disturbances
  - DC faults or disturbances
  - Equipment failures

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Line Commutated Converter (LCC)

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AC System Strength

$$\text{Short Circuit Ratio (SCR)} = \frac{\text{System MVA (S)}}{\text{DC Power } (P_{dc})}$$

$$\text{Effective Short Circuit Ratio (ESCR)} = \frac{\text{System MVA (S) - Capacitive MVAR } (Q_s)}{\text{DC Power } (P_{dc})}$$

- LCC requires certain level of ESCR, particularly at inverter

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HVDC Configurations

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Two Terminal Mono-polar System
Ground Return

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HVDC Configurations

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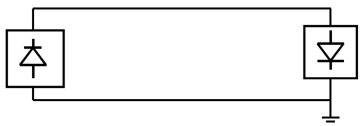
Two Terminal Mono-polar System
Metallic Return



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HVDC Configurations

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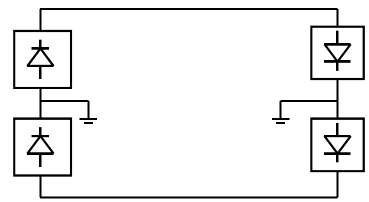
Two Terminal Bipolar System



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HVDC Configurations

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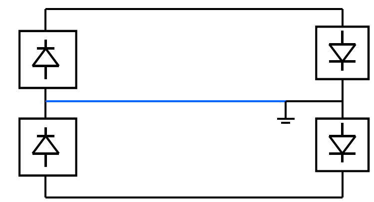
Two Terminal Bipolar System with
Dedicated Metallic Return



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Line Commutated Converter (LCC)

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Available rating

- LCC converters are available up to 5kA and 800kV (DC); 1100kV systems may become available in the near future

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Voltage Sourced Converters (VSC)

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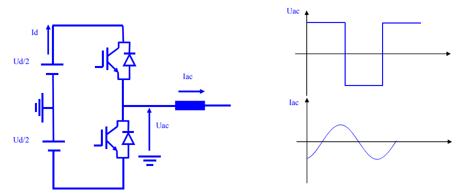
Fundamentals



- Current path during the four quadrants

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VSC Fundamentals

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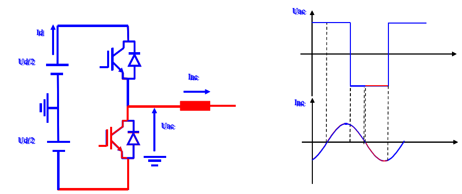
Half bridge



- Current path during the four quadrants

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VSC Fundamentals

Full bridge

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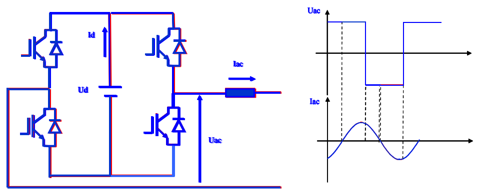

• Current path during the four quadrants

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VSC Fundamentals

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- Problems with the simple converter:
  - Low power rating
  - Harmonic voltages $V_n = (\sqrt{2}/2n\pi)U_d$
  - Fixed relation between AC and DC voltages (Uac=1.56Ud)
    - not suitable for HVDC transmission

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Multi-Module VSC

Operation Principles

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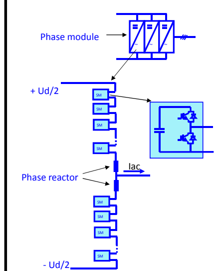

- Each arm contains N submodules
- SM Capacitor voltages are kept almost equal, Uc≈Ud/N
- Each SM can be either OFF or bypassed (lower IGBT triggered, zero voltage at terminals) or ON (upper IGBT triggered, capacitor voltage at terminals)
- $n_u = (N/2)(1 - m.\sin(wt))$,
- $n_L = (N/2)(1 + m.\sin(wt))$

  $V_{ac} = (U_d/2).m.\ \sin(wt)$

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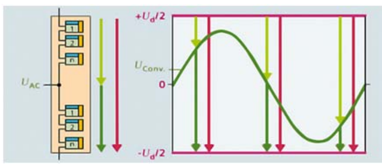
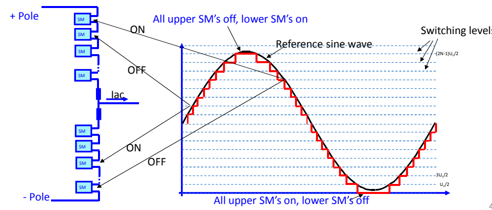
Multi-Module VSC
Operation Principles

- Modulation index m determines the magnitude of the ac voltage
- $V_u = U_c\,(N/2)(1-m.\sin(wt)) = U_d/2 - V_{ac}$
- $V_L = U_c\,(N/2)(1+m.\sin(wt)) = V_{ac} - U_d/2$
- At each moment total of N submodules are ON in each phase



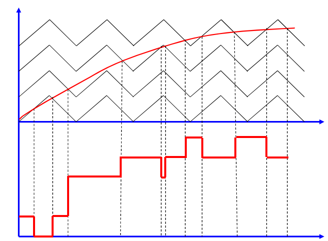
Multi-Module VSC
Modulation Techniques

- Nearest Level Control:
  - reference voltage is compared with fixed levels, every time it crosses a level a sub-module is turned on or off



Multi-Module VSC
Modulation Techniques

- Level shifted PWM



Multi-Module VSC

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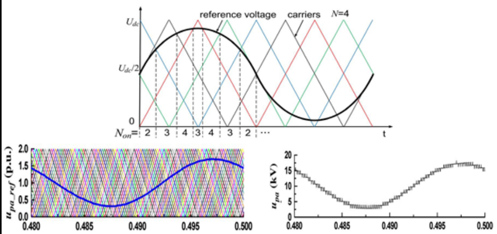
Modulation Techniques

- Phase shifted PWM



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VSC Application

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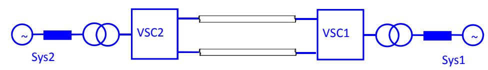
HVDC Transmission



- Similar to conventional HVDC, one station controls DC current and one station controls DC voltage
- Power reversal is through change of DC current direction, DC voltage polarity remains unchanged
- Reactive power is controlled independently at each terminal
- Can use XPLE cables (available up to 525kV)

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VSC-HVDC Transmissio

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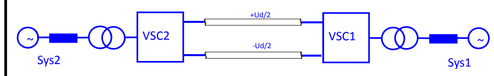
Symmetrical Monopole Configuration



- Regular AC transformer
- Dc to ground fault does not cause high short circuit current
- Uses two high voltage cables, each rated for Ud/2
- Can be realized with half bridge converters without extra equipment
- No power transfer capability with a monopole outage

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VSC – HVDC Transmission

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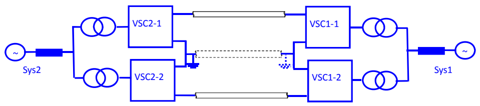
Bipolar Configuration



- Can have ground or metallic return
- Converter transformer (dc stress on secondary windings)
- Dc to ground fault cause high short circuit current affecting ac systems (worse than LCC)
- Uses two high voltage conductors and possibly one low voltage conductor
- Can be realized with half bridge or full bridge converters, in case of HB requires extra equipment for dc and ac fault
- 50% (or more) power transfer capability with a monopole outage

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Symmetrical Monopole

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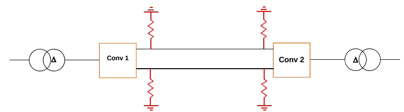
Ground Reference

- In symmetrical monopole configuration dc circuit is floating and therefore can drift.



using voltage divider resistors to prevent DC Voltage shifting

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Symmetrical Monopole

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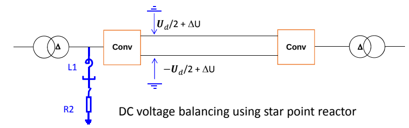
Ground Reference



DC voltage balancing using star point reactor

- Required only at one station (except for STATCOM operation with DC cable disconnected) to avoid zero sequence current (mainly 3rd harmonic) circulation between stations
- Under normal conditions current in L1 is negligible (L1>>)
- The voltage across R2 is equal to ΔU
- Stresses during dc line to ground fault should be considered in selection of R2

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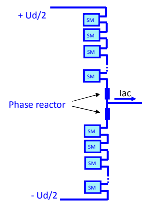
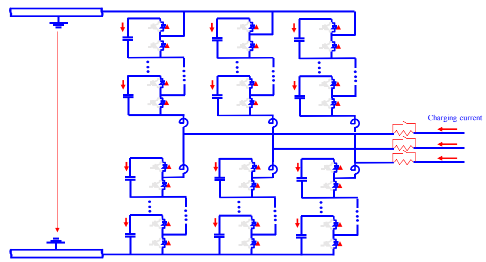
MMC VSC
Phase Reactors

- Limits balancing currents between phases.
- Limits rate of rise for various fault currents



MMC VSC
Converter Charging



Charging current path in MMC VSC

MMC VSC
Charging Resistor

- At the start up converter capacitors and dc cable are charged through diodes before deblocking
- A pre-insertion (charging) resistor is used to limit the charging current. The resistor is bypassed once the charging is complete
- For HB converter at the end of passive charging the sum of capacitor voltages in each arm is approximately equal to peak line to line voltage, i.e.

$$Uc = \sqrt{2}\, V_{LL}/N$$

- This is below the nominal capacitor voltage
- Passive charging is normally followed by active charging to raise capacitor voltages

MMC VSC

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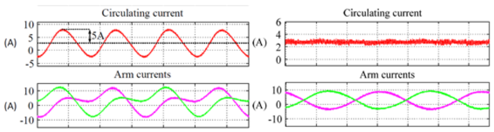
Circulating Current



Without suppression, L=1mH

With suppression, L=1mH

- Caused by the varying capacitance of the arms
- Mainly consists of 2^{nd} harmonic

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MMC VSC

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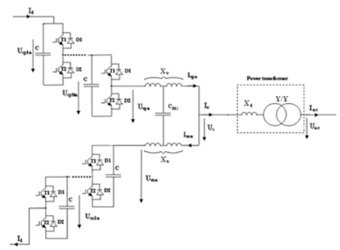
Circulating Current Suppression– AC filter



HVdc Light G4

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Fault Performance

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AC Faults

- AC current is limited to 1pu by control action (reduced modulation index)
- For nearby faults current may be ordered to zero to minimize fault current contribution from converter
- For remote faults reduced amount of power will be delivered
  - This is supperior to LCC behavior where a 10-15% voltage drop at inverter will cause commutation failure and interruption of power transmission
- Fault recovery is generally faster than LCC

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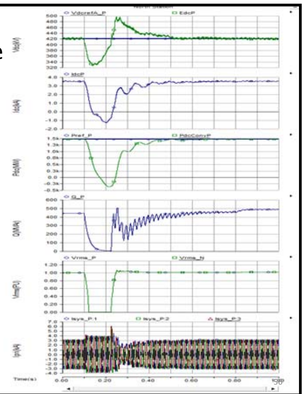
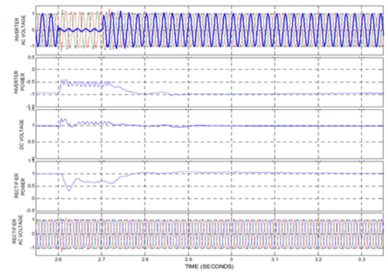
AC Fault Performance



Response to a three phase fault at rectifier

AC Fault Performance



Response to a single phase fault

Fault Performance

Pole to ground fault in symmetrical monopole with HB (no dc breaker)

- Will cause sudden discharge of cable
- Will cause overvoltage on the healthy conductor
- Will be detected and cause blocking of all sub-modules; a trip signal is issued at the same time
- After blocking the pole-pole dc is determined by diodes only (limited to peak phase-phase voltage)
- Normally cleared by opening ac breakers at both ends, can restart after discharging the cable

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Fault Performance

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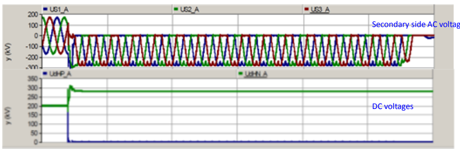
Pole to ground fault in symmetrical monopole with HB



Fault Performance

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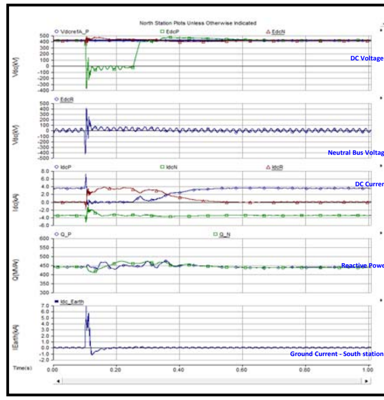
Pole-to-pole fault in symmetrical monopole with HB

- Will discharge both converter capacitors and cables
- Will be fed from all AC systems through diodes
- Will appear like a high impedance fault to all AC systems
- All IGBT's are blocked
- Will cause protective thyristors to be triggered at all sub-modules; trip signal will be issued to all ac breakers

- A pole to ground fault in bipolar or asymmetrical monopole will have the same behavior



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Pole to ground fault in bipolar with **FB**, cleared without blocking converter

LCC vs. VSC

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Function	LCC	VSC
Semi-Conductor Device	Thyristors currently 6 inch, 8.5 kV and 5000 Amps. No controlled turn off capability	IGBTs with anti-parallel free wheeling diode, with controlled turn-off capability. Current rating 4.5 kV and turn off current of ~2000 Amps.
DC transmission voltage	Up to +/- 800 kV bipolar operation	Up to +/- 500 kV currently limited by HVDC cable if extruded XLPE cable is used.
DC power	Currently in the range of 7000 MW per bipolar system	Currently in the range of 1000 MW per block
Reactive Power requirements	Consumes up to 60% of its rating reactive power	Does not consume any reactive power and each terminal can independently control its reactive power.
Filtering	Requires large filter banks	Requires moderate size filter banks or no filters at all.
Black start	Limited application	Capable of black start and feeding passive loads
AC system short circuit level	Critical in the design	Not critical at all

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LCC vs. VSC

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Function	LCC	VSC
Commutation failure performance	Fails commutation for ac disturbances	Does not fail commutation
Over load capability	Available if designed for up to any required design value	Requires increased rating of the link
Application with overhead lines	Can be applied and dc line faults can be cleared by converter control	Can be applied but dc line faults are cleared by trip of ac breaker, or the use of a dc circuit breaker. It has mostly been applied with cables
Small taps	Not economic and affects the performance	Economic and seems not affect the performance
Load rejection over voltage	Large and has to be mitigated because of the large reactive power support	not large because of small size of filters if required.

LCC vs. VSC

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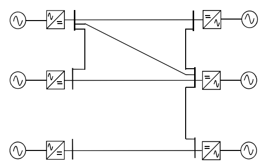
Function	LCC	VSC
Foot print	Can be large	Small for the comparable rating to an LCC
Off shore wind farms	Hard to apply	Straight forward application
Power losses	Typically 0.8% per converter station at rated power	Typically 1% per terminal

DC Grid



- made up of a combination of meshed and radial lines (has at least one mesh)

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DC Grid

- Motivated by
  - Ever increasing HVDC links
  - Need for integration of renewable generation, especially offshore wind
  - Congested right of way and need for cable transmission
  - Extra flexibility and reliability compared to point to point HVDC

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DC Grid

Challenges

- Need for very fast protection
- Need for fast DC breaker
- Power flow and voltage control
- Need for DC/DC converters
- Standarzation
- High voltage cables
- DC grid code

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Cigre' HVDC Activities

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- Cigre' study committee B4:
  - Global leader in HVDC and FACTS
  - Over 70 working groups, 16 ongoing, covering:
    - All technical challenges of DC grid
    - LCC and VSC HVDC equipment
    - Ground electrodes
    - Harmonic filtering
    - AC/DC interactions
    - Modeling and simulation
    - ....

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