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New Converter Topologies for High-Voltage Dc Converters

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Outline

- Brief History of HVDC Transmission
- Conventional HVDC and its Problems
- Capacitor Commutated Type Converters
- Voltage Sourced Converter Based HVDC
  - PWM Based
  - Multi-level Modular

HVDC: Brief History

- Originally HVDC was used for Distribution (Edison's Dc Dynamo) (pre 1900)
- Disadvantages: Complicated machinery (dc commutator), lack of voltage transformability
- Ac overcame these disadvantages
- However:

  Long distance DC transmission is not adversly affected by Transmission Line or Cable inductance/capacitance

HVDC: Brief History…

- Why not generate and consume ac but transmit dc?
- Thury (early 1900's) in France: ~100 km Dc tranmission
  - Disadvantage: Ac/Dc Converter – motor generator set
- Use of Power Electronic Devices (Mercury-Arc Valves) made for more efficient Ac/Dc Conversion

HVDC: Brief History…

- First Scheme Based on Modern day concepts:
  - Gotland (Sweden Mainland-Island) 1954,. Used Grid Control Mercury Arc Rectifiers. Manufacturer ASEA 100 kV (Monopolar), 20 MW under-sea transmission spanning 96 km.
- First Canadian Scheme:
  - Vancouver - Vancouver Island, 1968, +/-130 kV , 312 MW, 41 km overheadline, 32 km underwater cable.
- Last Mercury Arc Scheme:
  - Nelson River Bipole 1 in Manitoba (1800 MW, +/-450 kV)

HVDC: Brief History…

- First Canadian Scheme:
  - – Vancouver - Vancouver Island, 1968, +/-130 kV , 312 MW, 41 km overheadline, 32 km underwater cable
- First Use of Solid-State Thyristors :
  - – Eel River (New Brunswick-Quebec, Canada) :1972, +/-80 kV, 350MW. Back to back connection between two utilities.
- Large HVDC Systems:
  - – Itaipu (Brazil, Generation: Paraguay/Brazil) +/- 600 kV, 6000 MW, over850 km. Main reason for Dc: Paraguay is 50 Hz, Brazil is 60 Hz.
  - – Volvograd Dunbas: USSR, 6000 MW?
  - – Three Gorges, China (10,000 MW), +/- 600 kV

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HVDC: Brief History…

- Manitoba:
  - Nelson River Bipole-I (Radisson-Dorsey) +/- 450 kV, 1800 MW, over 900 km, originally based on Mercury Arc (1972, 1993, 2004)
  - Nelson River Bipole -II (Henday-Dorsey): +/- 500 kV, 2000 MW, approx. 900 km, Thyristor (1982-88)
  - Nelson River Bipole –III (Henday-Riel)
  - 1400 km? 2200 MW +/- 500 kV

Manitoba Hydro's Nelson River HVDC Transmission System: 4 GW over 950 km (approx. 70% of total Manitoba installed generation)

Approx. 40% of MH revenues come from exports

Manitoba Dams are a reservoir that permits power cycling

Revenue generated includes power cycling (day/night)

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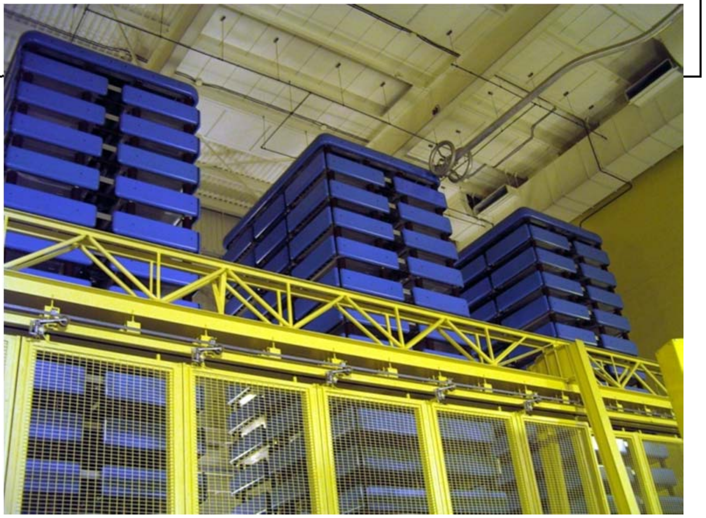


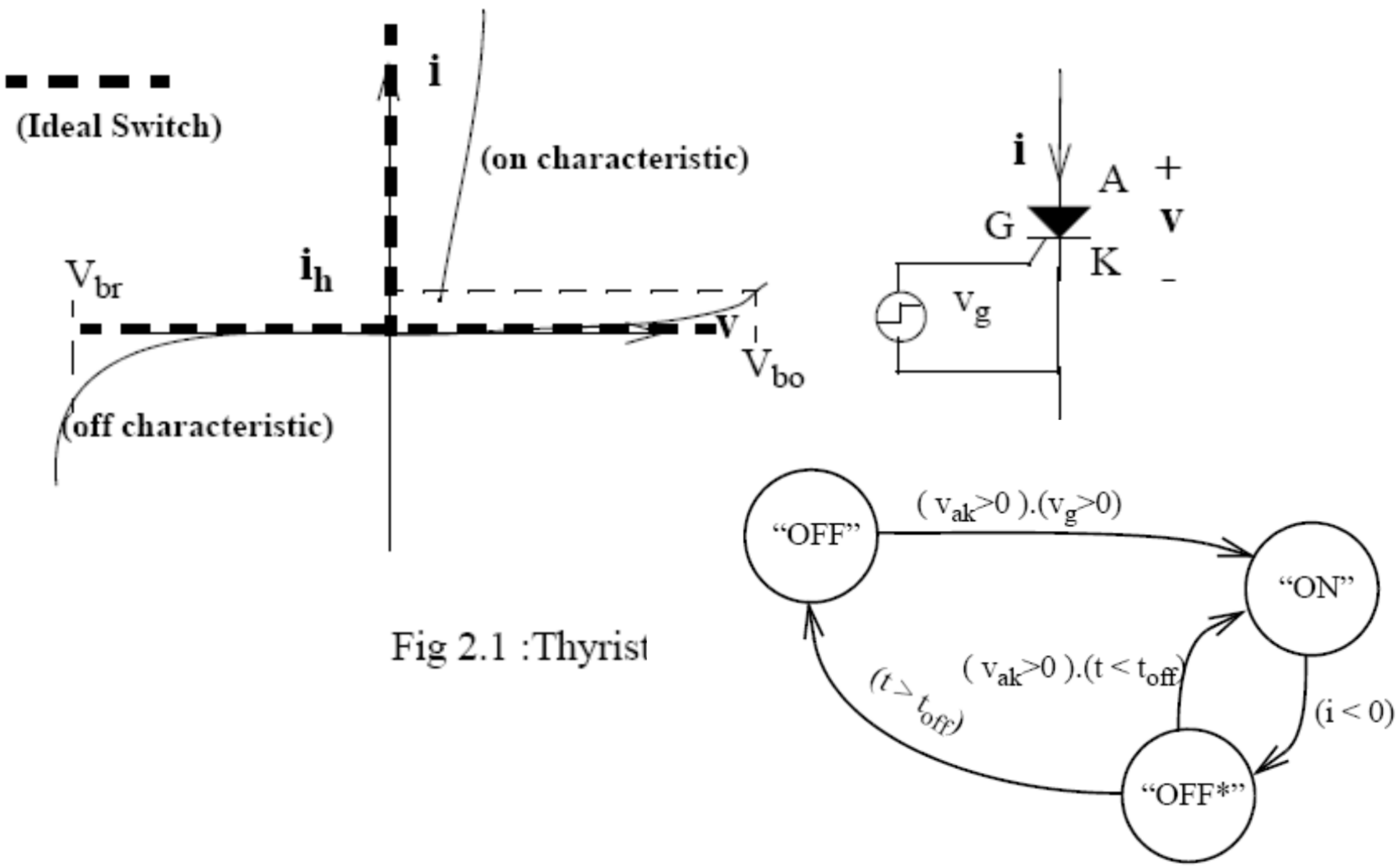
Many technology revisions

Conventional HVDC Transmission-Advantages

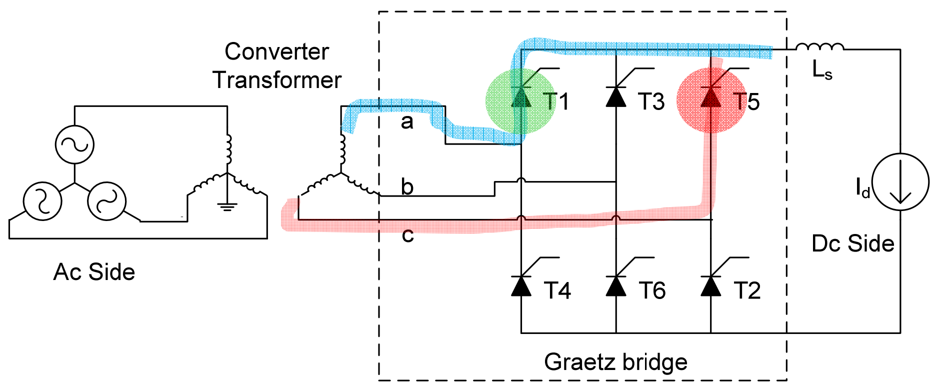
- HVDC Offers many advantages over Ac Transmission
  - Lower Transmission losses
  - Smaller rights of way
  - Asynchronous Connection Between Ac Networks- improved stability limit
  - Possibility of Long-distance underground/underwater cable transmission
  - …..etc

Basics of HVDC LCC Converter Operation

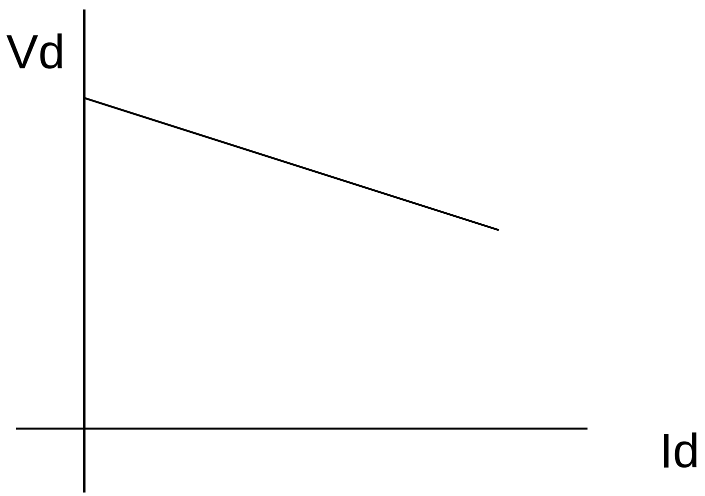
Dc Converter Building Block: Thyristor

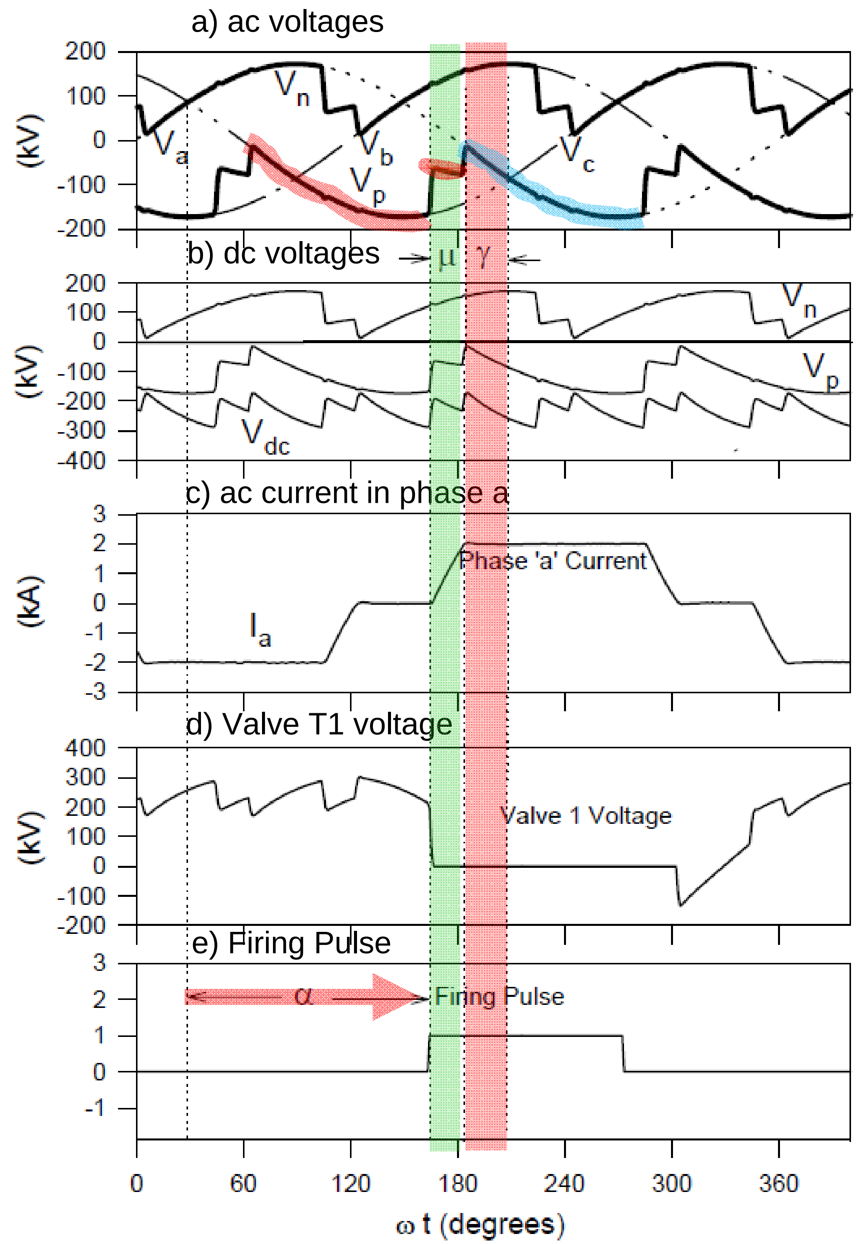


Conventional HVDC: LCC Operation and Limitations:



- Converter Operation is significantly impacted by ac network
- Commutation voltage drop





Conventional HVDC Transmission-Limitations



- However there are some disadvantages:
  - The terminating ac networks must provide the commutation voltage
  - Require reactive power at the converter which must vary with loading (i.e. switched filter banks)
  - Difficulty in operating into weak ac systems (Short Circuit ratios under 2)
  - Generates Ad and Dc side Harmonics

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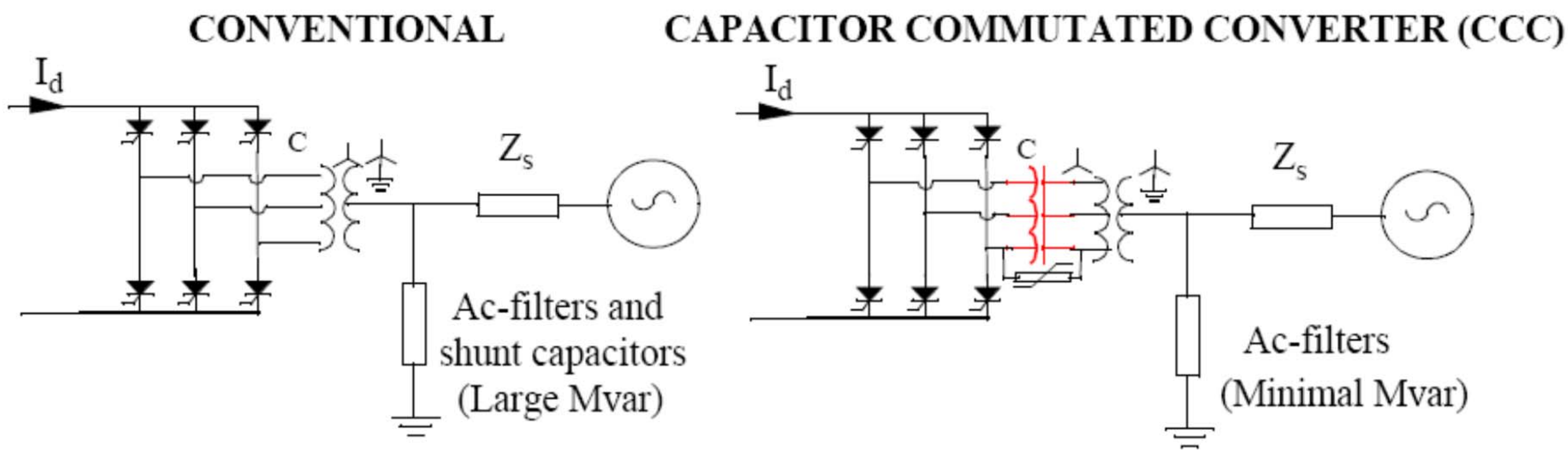
New HVDC Converter Configurations

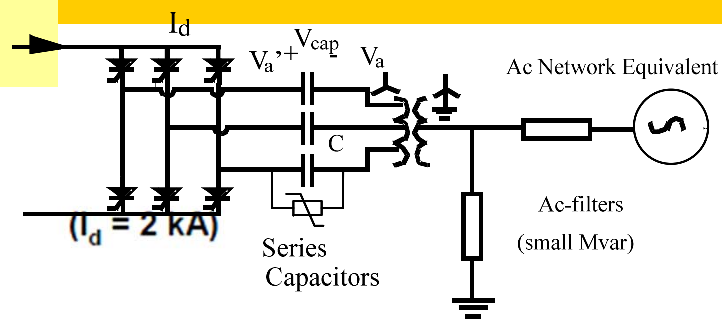
- New converter configurations have been developed to address these issues:
- Capacitor Commutated Configurations
  - CCC
  - CSCC
- Voltage Sourced Converter (VSC) based Configurations
  - PWM / SHPWM based Converters
  - Modular Multilevel Converters (MMC)

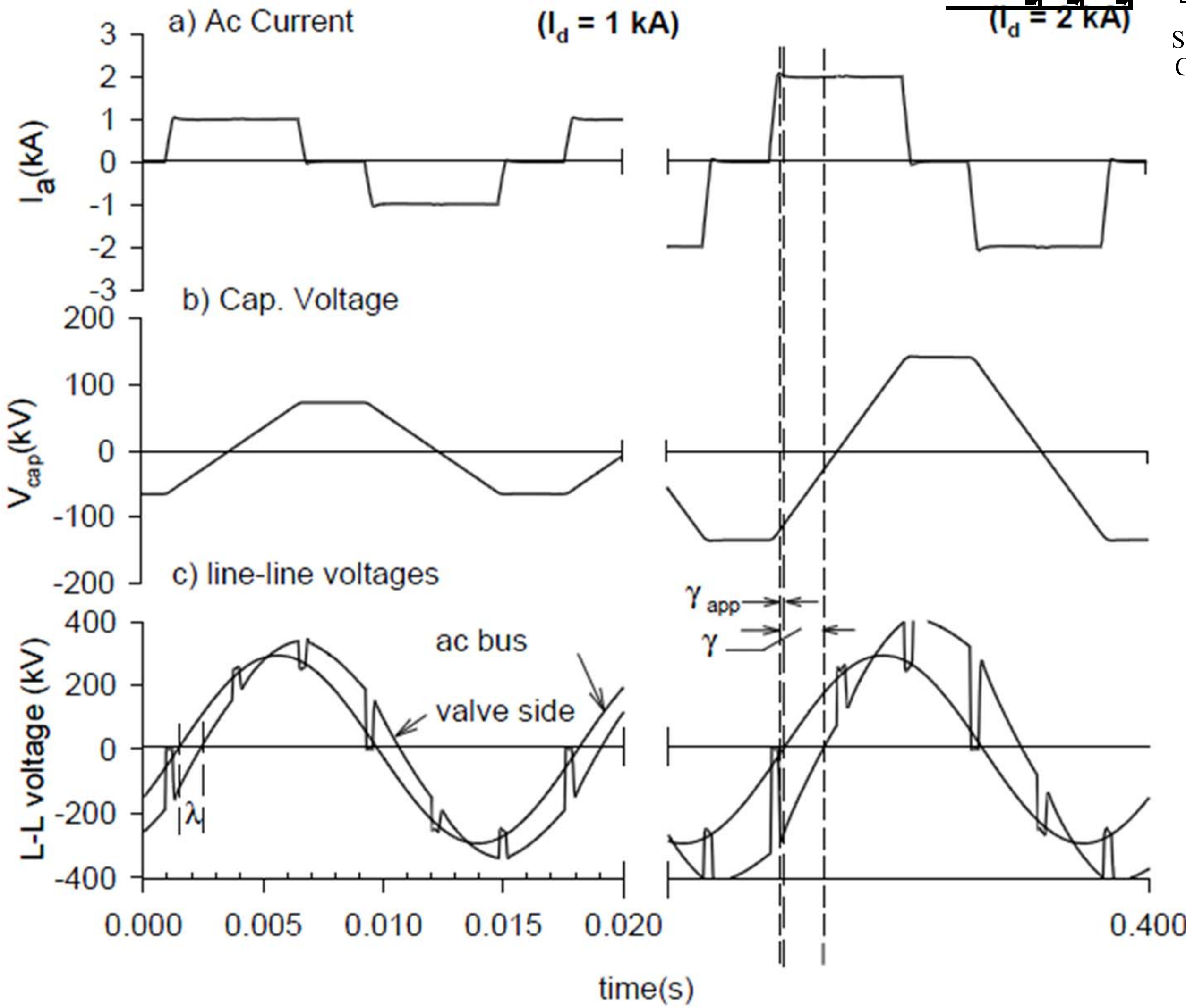
Capacitor Commutated Converter



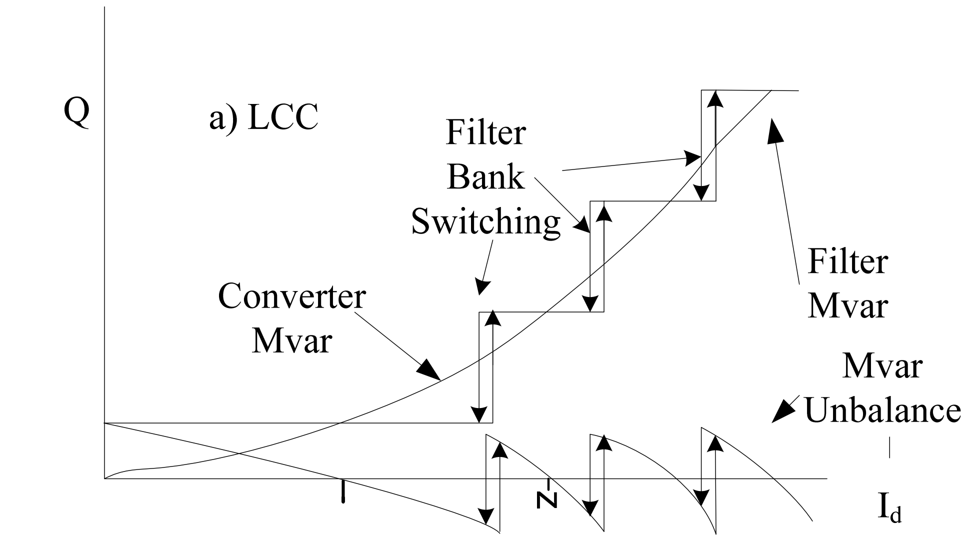
- The CCC Uses the voltage across its series capacitors to assist in the commutation process
- It can operate into very weak ac networks
- The reactive power absorbed by the converter is minimal
- Can be operated even with leading power factor

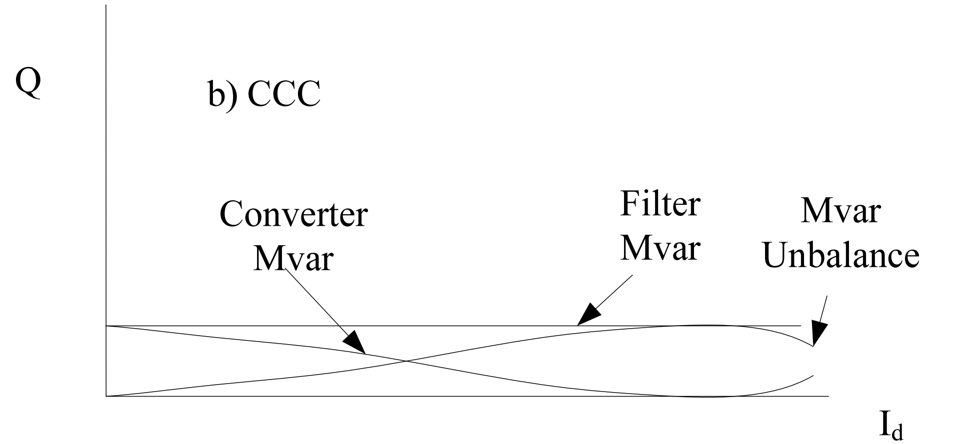
CCC Operation





Reactive Power Requirement

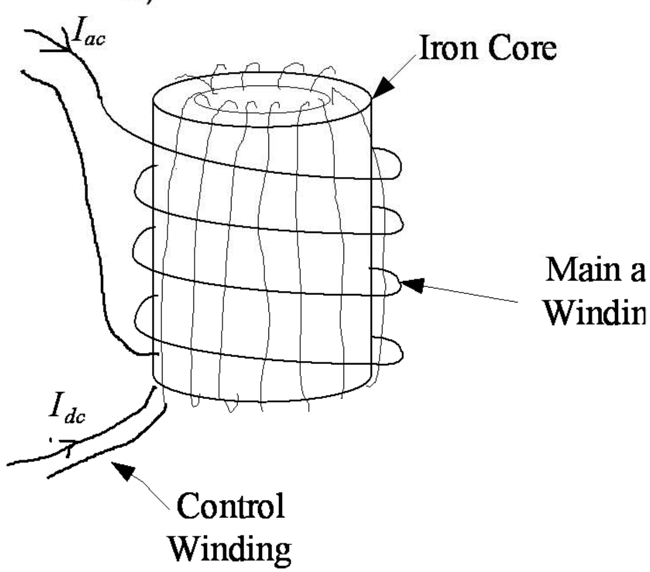




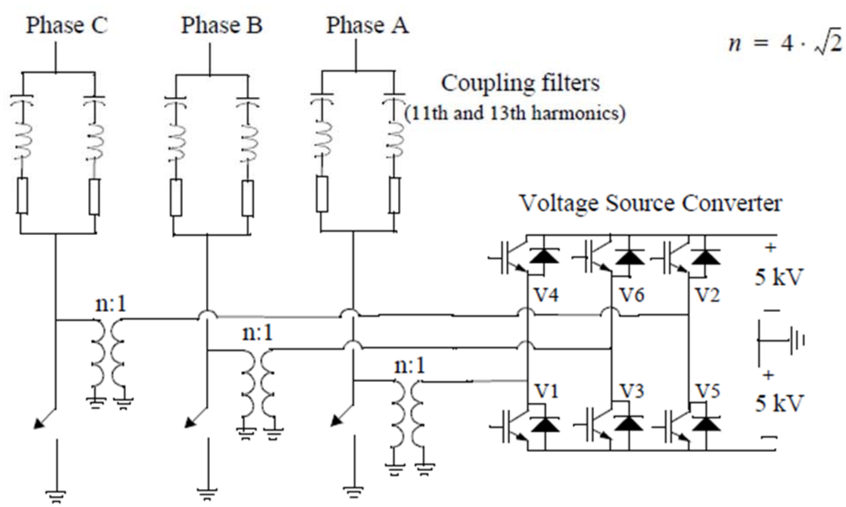
Ac Filter Issues

- A low Mvar filter is also sharply tuned and hence subject to detuning with component variations
- Solution:
  - –Contune Filter (inductor can be tuned via bias dc current)
  - –Active Ac Filter

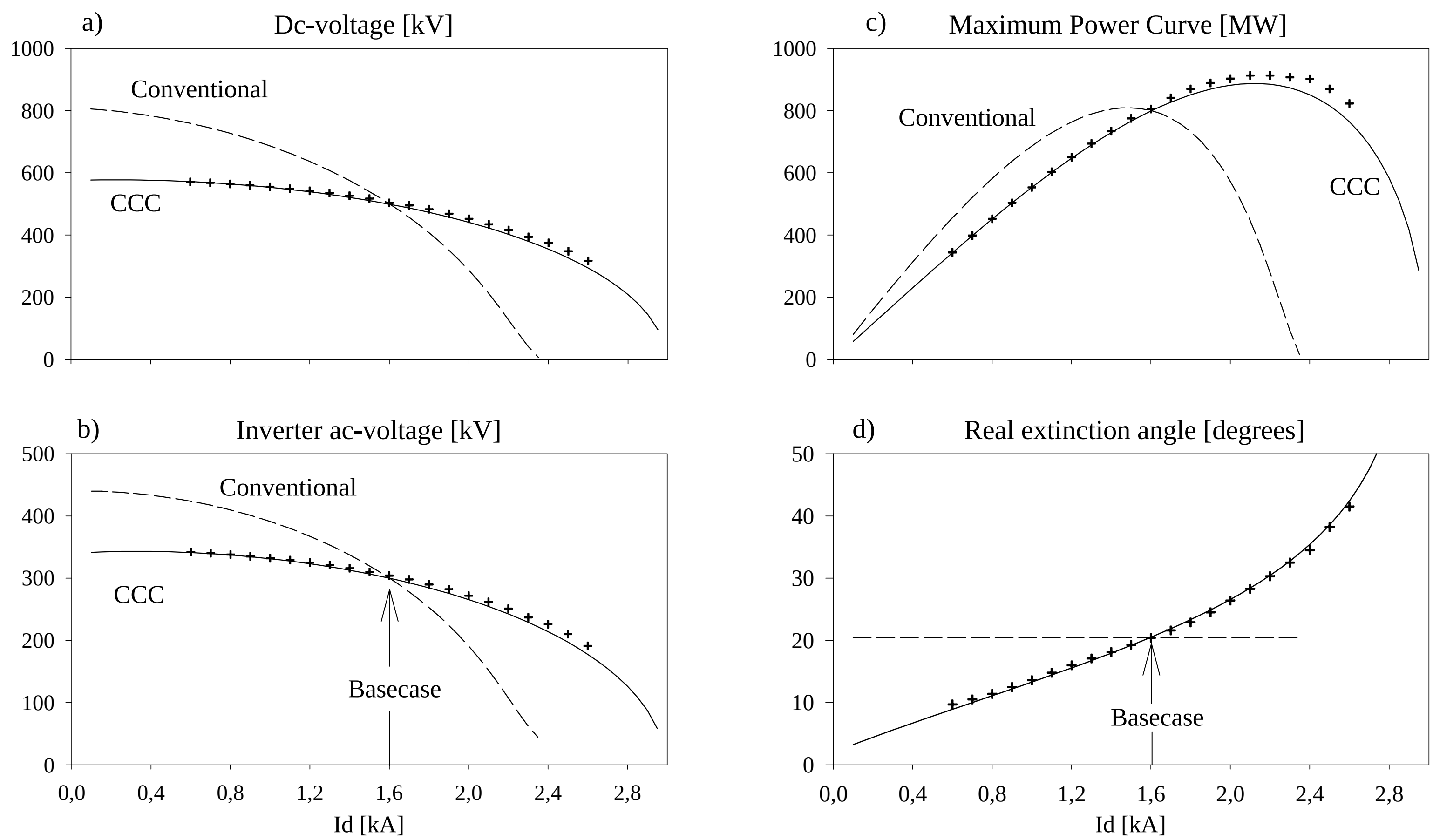
a)



b)



CCC Steady State Operating Charecteristics



CCC Configuration: Advantages

- The risk of commutation failure is minimized- can operate into very weak ac networks
- The apparent extinction angle (measured w.r.t. converter bus) is small, even negative- hence power factor is near 1.0
- Filter switching can be avoided
- Although valves are more expensive, the converter transformer is cheaper and the valve short circuit current is smaller than for the LCC
- The Series Capacitors do not cause ferroresonance, as they are out of the circuit when converter is blocked

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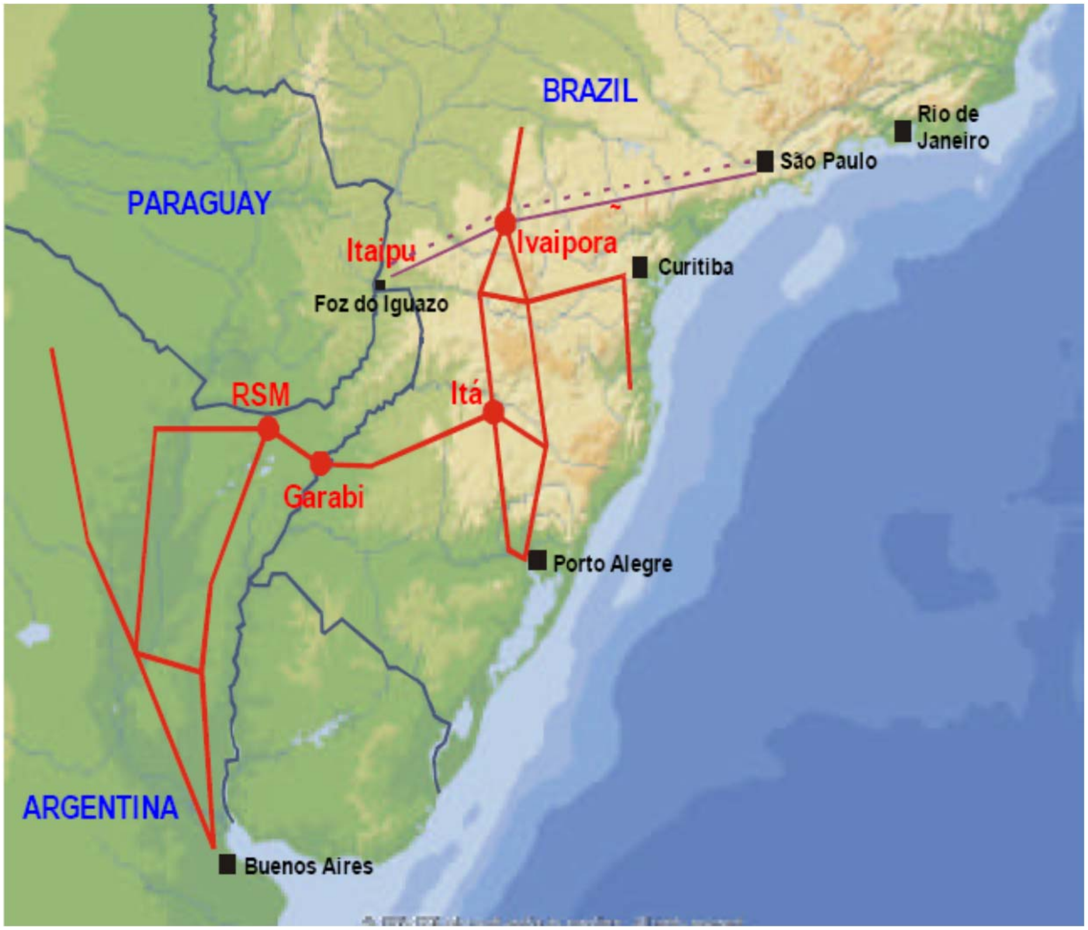
CCC Configuration: Disdvantages

- The converter cost is slightly larger
- The series capacitors must be protected against overvoltages resulting from overcharging
- The energy storage on the series capacitors negatively impacts the dynamic response in unbalanced conditons (i.e. recovery from l-g faults)

CCC Installations worldwide:

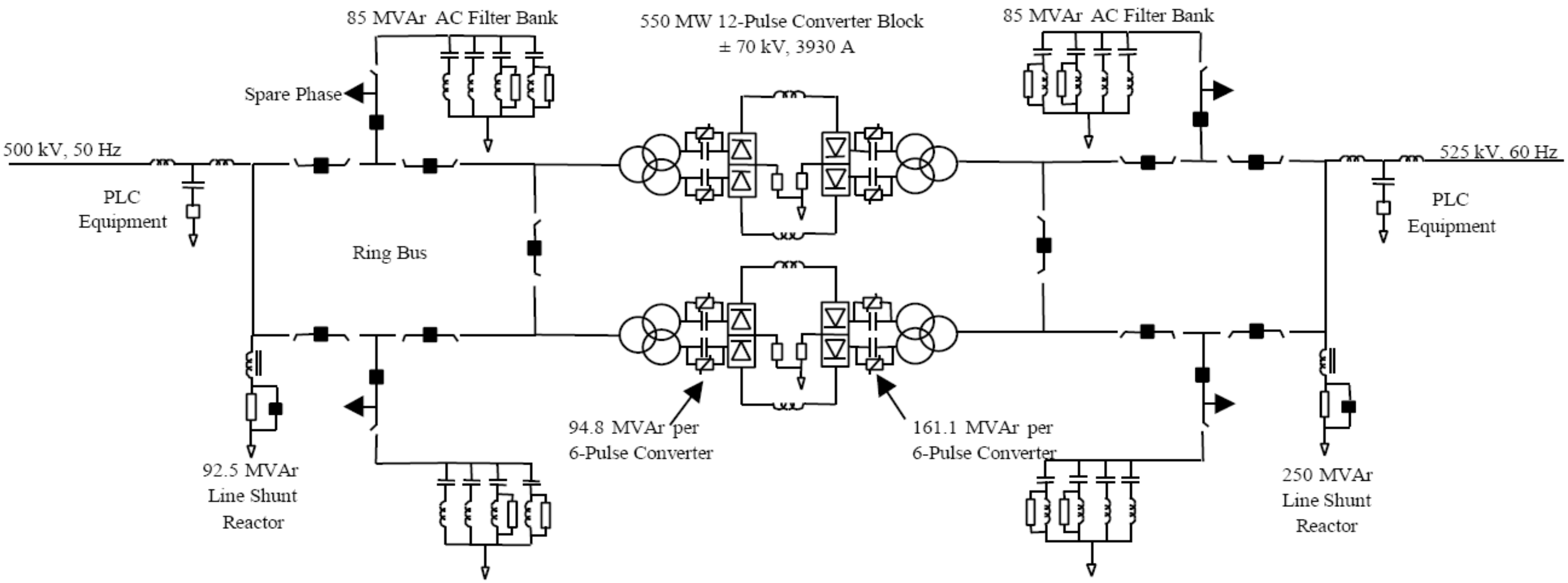
- Garabi Converter Station, Brazil/Argentina

- 2200 MW, +/- 70 kV back to back system connecting 50 Hz and 60 Hz networks
- CCC used because SCMVA can be as low as 2000
- CCC Avoids installation of Synch. Compensator



Courtesy: ABB

Garabi CCC HVDC Station Layout



Courtesy: ABB

Garabi CCC HVDC: Major Components

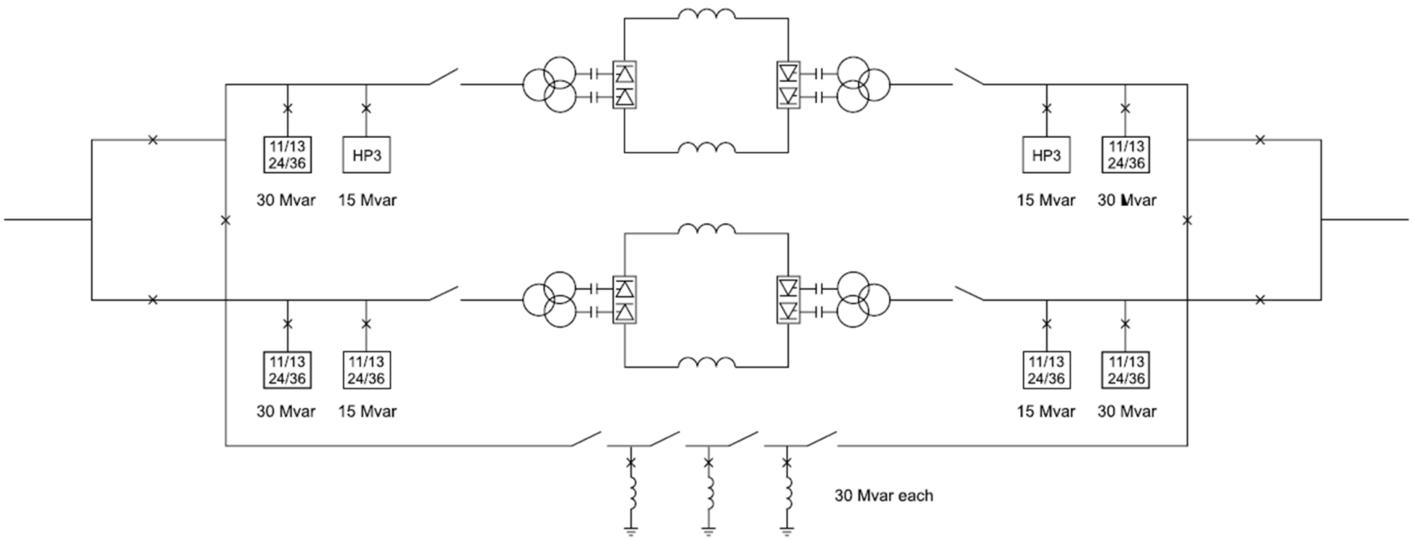
Outdoor Valves

“Contune” Filters

Series Capacitors

All Pictures: Courtesy ABB

Rapid City, USA, Interconnect



- Sixth in sequence of Back to Back HVDC Stations connecting the Eastern and Western North American Systems

- 200 MW, +/- 12.85 kV
- CCC selected to lower comm. Fail risk due to extremely weak ac networks.

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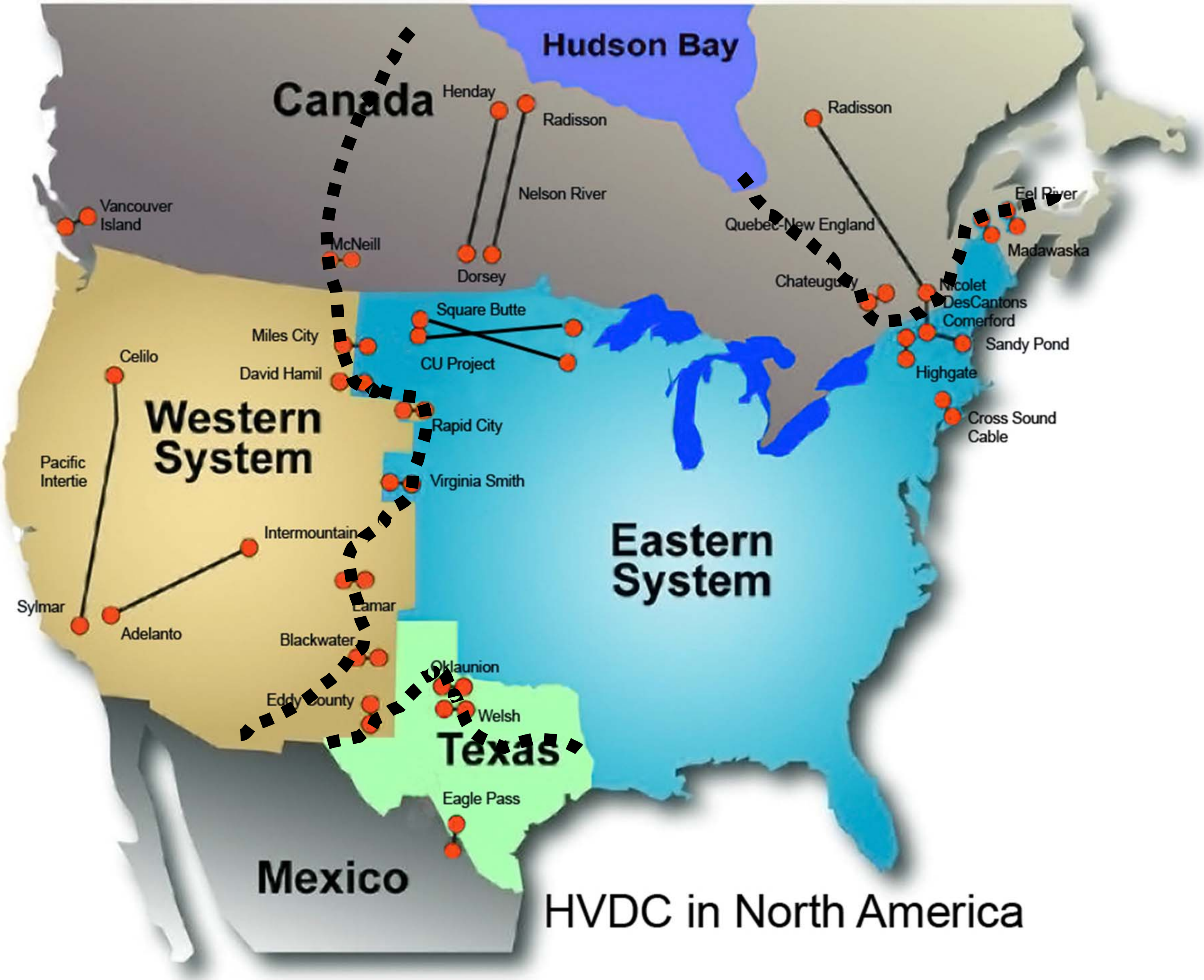
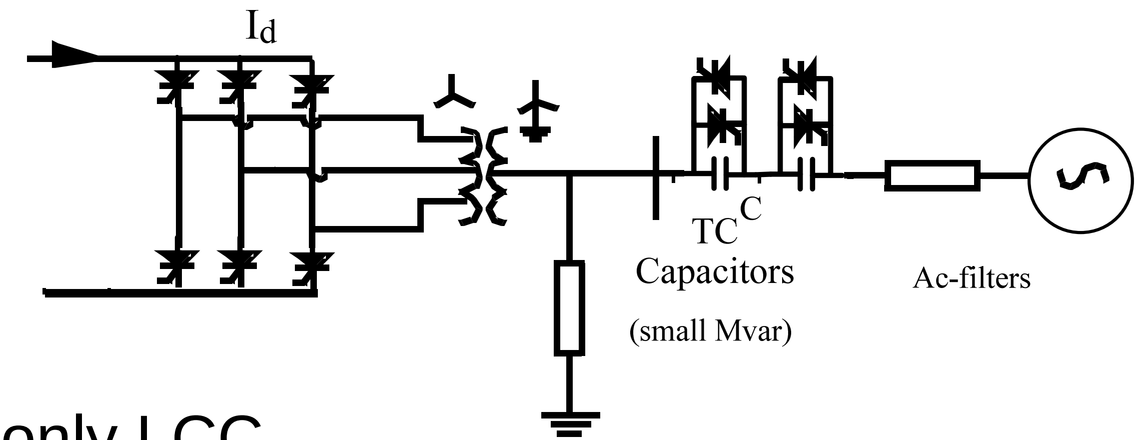


Alternate Topology: CSCC



- Requires only LCC
- Behaviour very similar to CCC
- Series capacitors must be switched to avoid ferroresonance
- Capacitance level can be adjusted as per system conditions

- Simplifies capacitor arrangement in 12-pulse configurations
- For radial ac feeds, capacitors can be placed in each ac line for accurate control of power in each ac feeder

New Approaches to LCC: The GPFC

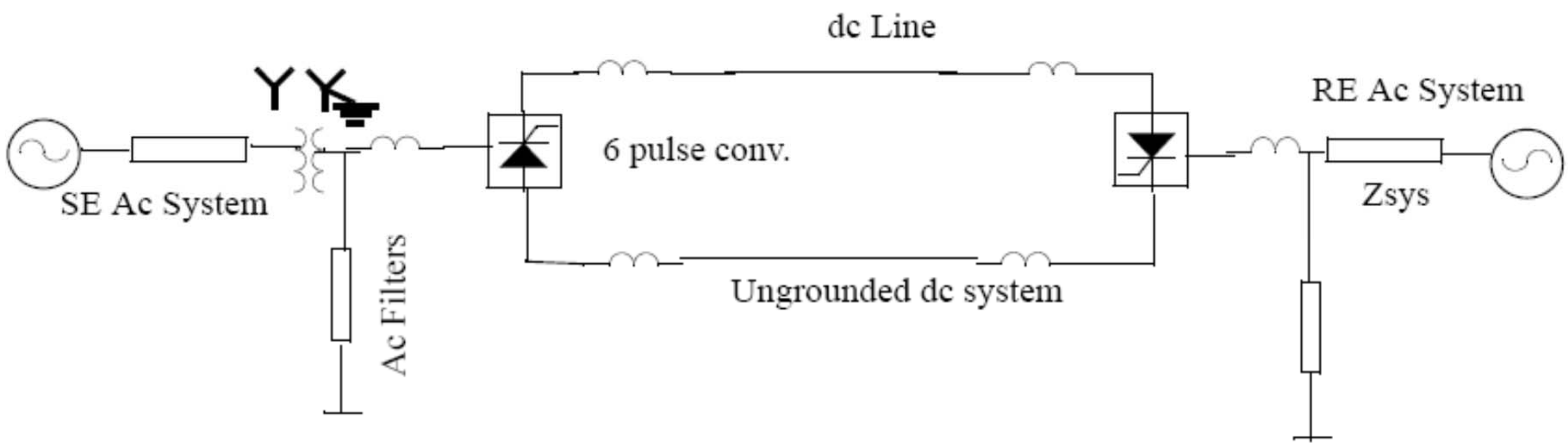


Fig 5.18 GPFC Dc Scheme

- Filters are between transformer and converter
- Uses a *Conventional* Transformer
- Transformer at remote end can be eliminated
- Results in reduced cost

Cost Distribution for Converter Station

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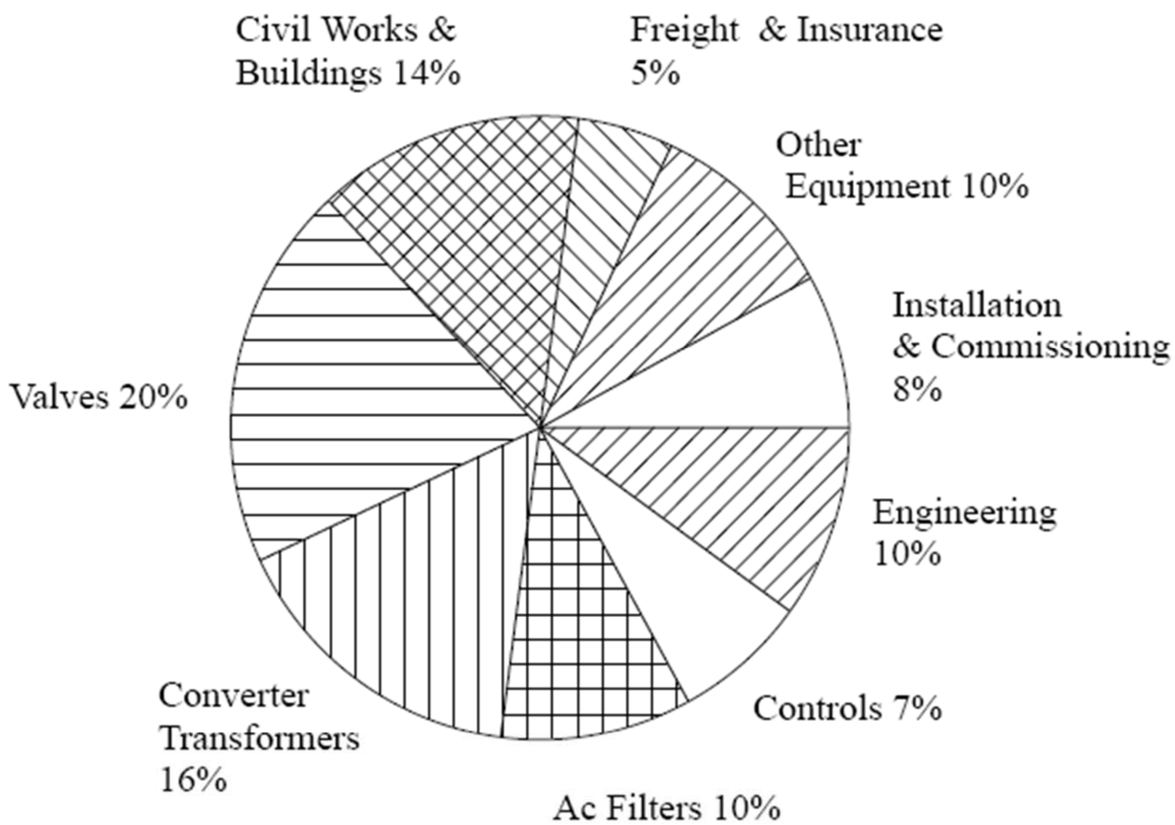


Source: Martin Marietta Energy Systems
Oak Ridge National Laboratories,
PO Box 2002, Oak Ridge,
TN 37831-6501, U.S.A.

Fig 2.24 :Cost Distribution for a Dc Converter Station

GPFC-HVDC 12-pulse arrangement

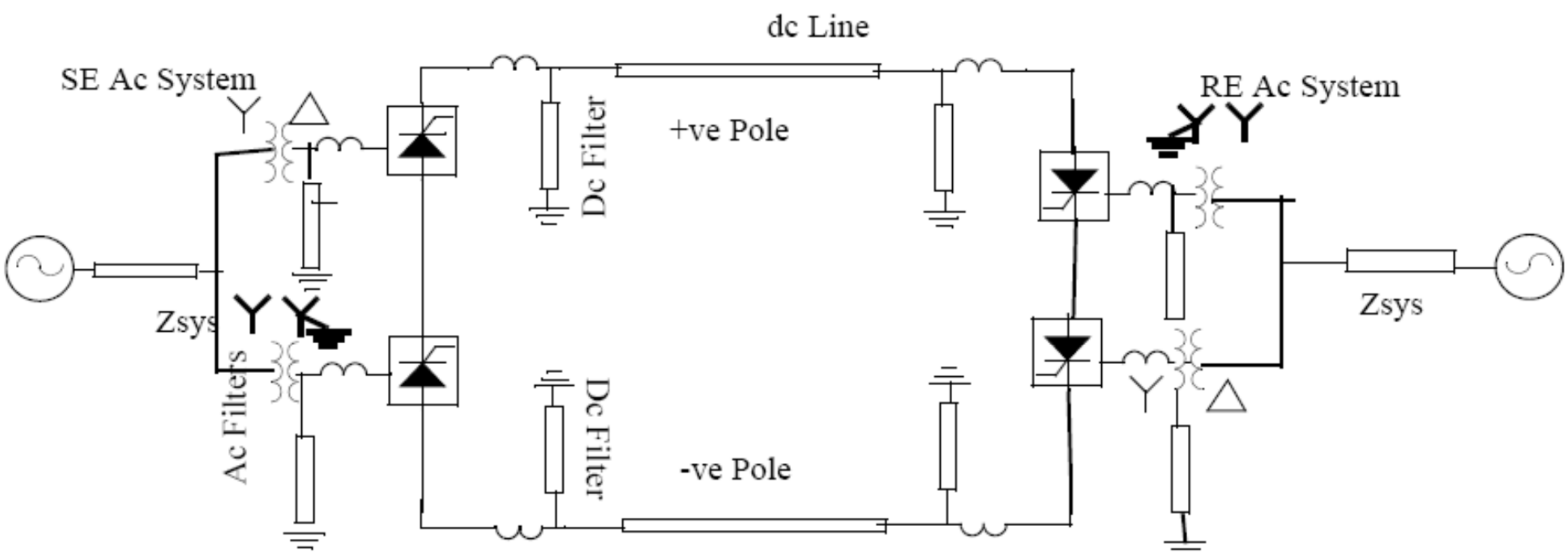


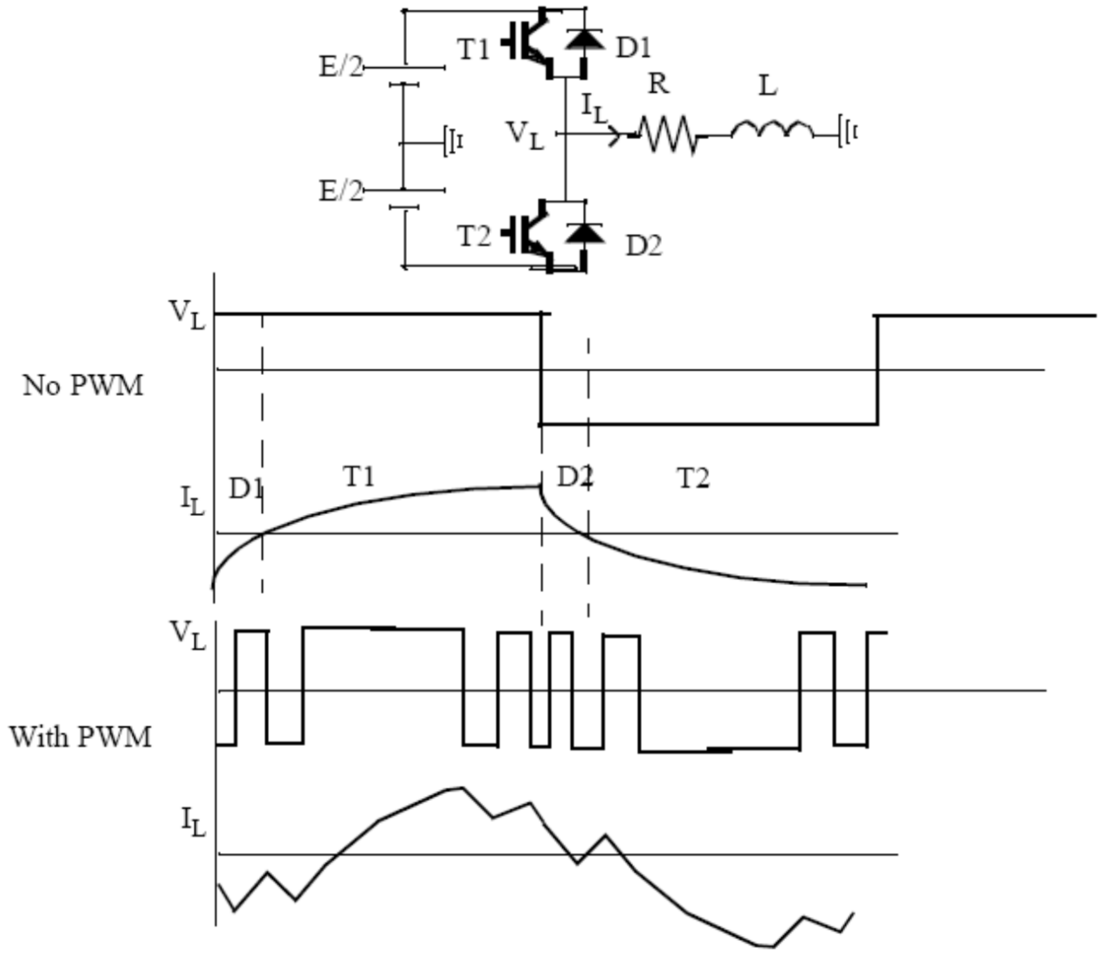
Fig 5.19 Twelve Pulse GPFC Scheme

Voltage Sourced Converter (VSC) Based HVDC



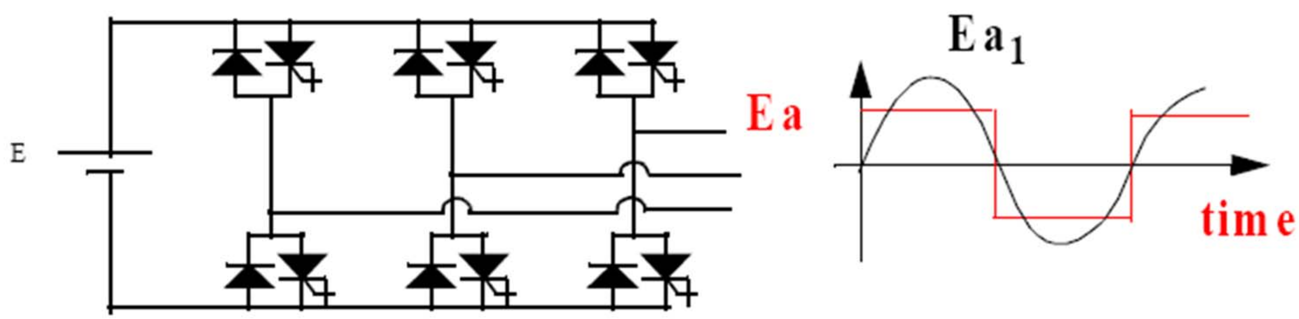
- Thyristor Based Converters generally require an ac network to provide commutation voltage
- Hence they are significantly affected by ac system conditions, etc.
- The VSC uses switches that can be turned on as well as turned-off using externally generated commands
- Hence the impact of ac system conditions on performance can be minimized

VSC: Basic Operating Principle



VSC Switches are turned on and off on command.

Three Phase Arrangement



VSC Voltage Magnitude and Phase Control

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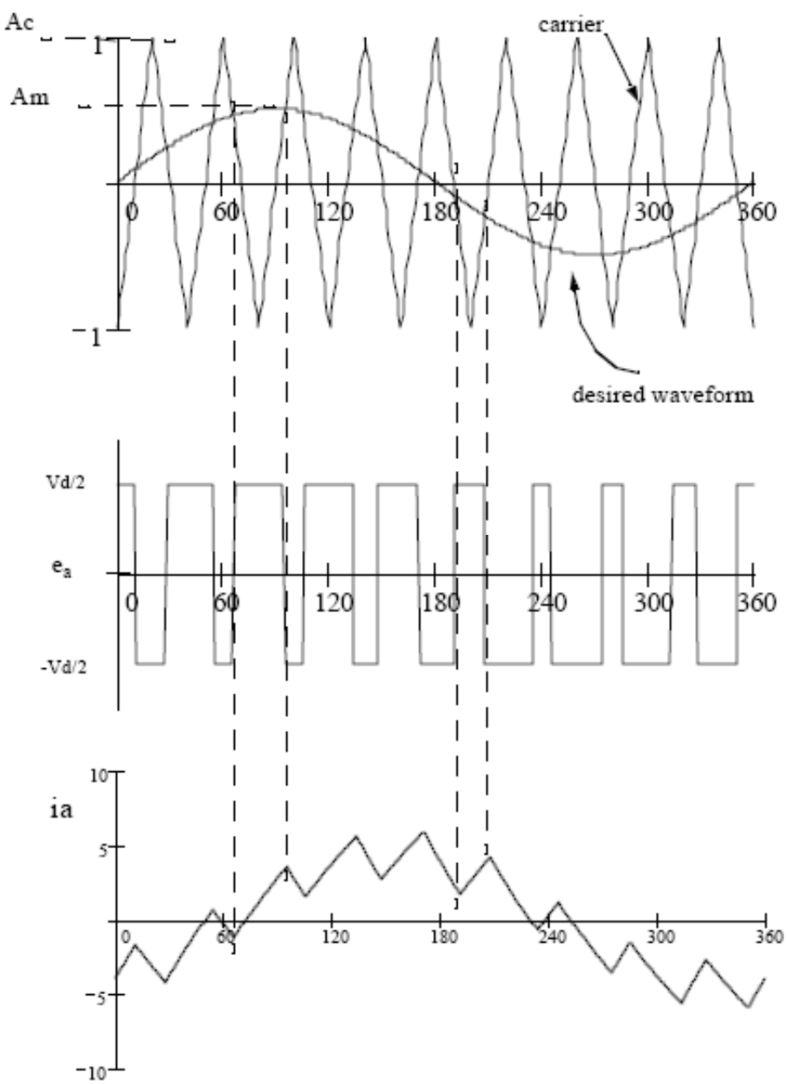
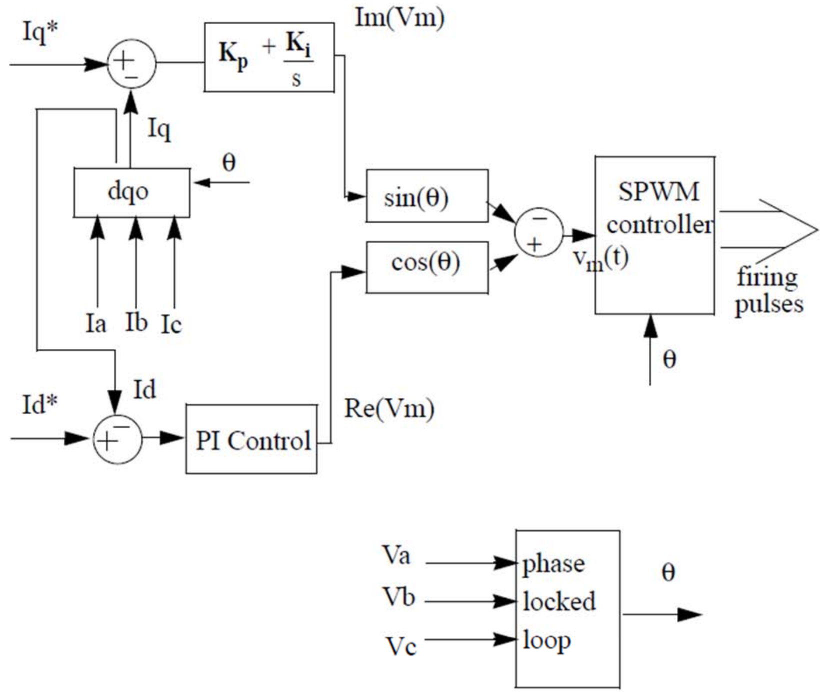
- Pulse Width Modulation
- Fundamental freq. component of output follows the desired 'signal' reference waveform
- Harmonics are pushed to the high (easily filtered) range
- Disadvantage:
  - –Difficult to extend single bridge to High Voltages
  - –High Switching Losses



VSC: Real and Reactive Power Control



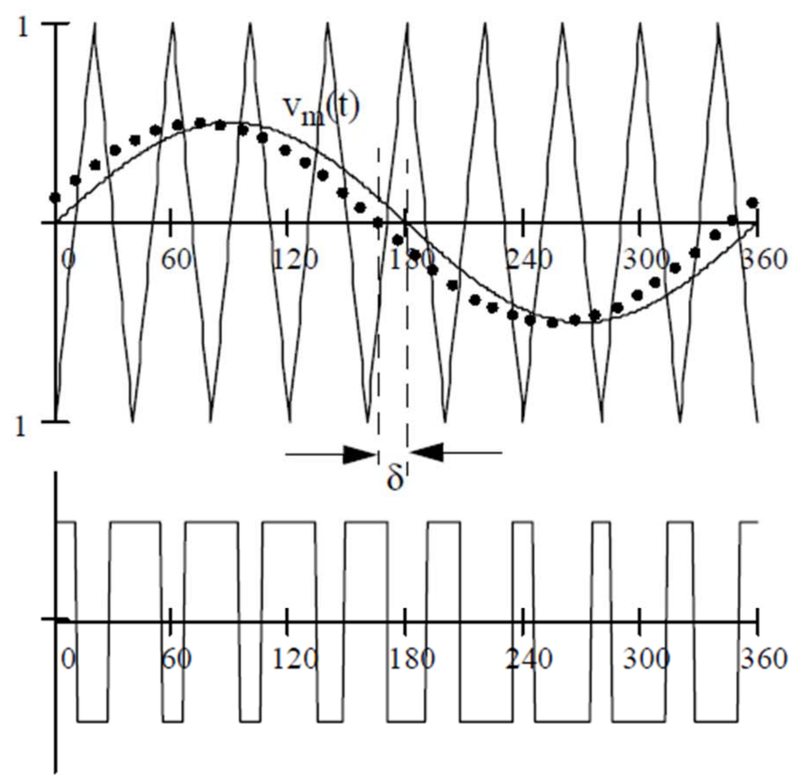


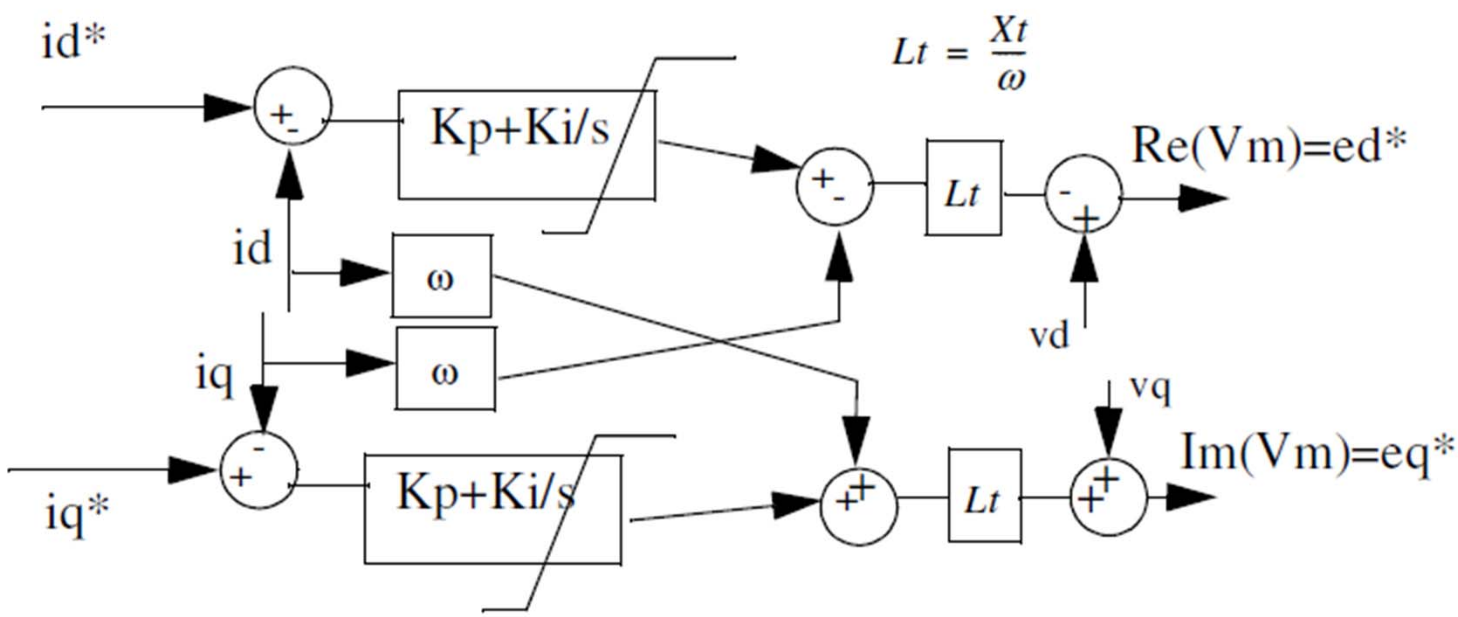
Fig 2: PWM Waveforms

Id* controls the real power
Iq* controls the reactive power

Id* is the output of a dc bus capacitor voltage controller

VSC: Decoupled Control

Decoupled Control ensures that an order change of id* does not cause a transient in iq (and vice versa)



See: . Papič, P. Žunko, D. Povh and M. Weinhold, "Basic Control of Unified Power Flow Controller," *IEEE Trans. Power Systems, vol. 12, no. 4, pp. 1734-1739, Nov. 1997.*

VSC versus LCC HVDC

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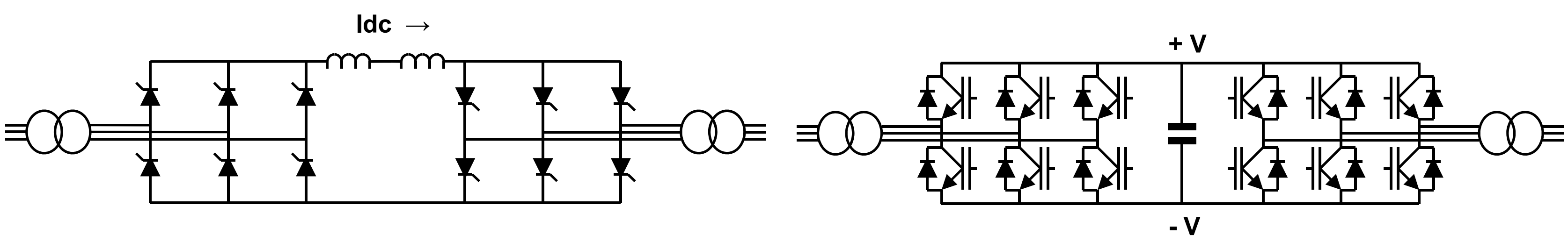
LCC HVDC	VSC HVDC
Line-commutated	Gate-turnoff
Current Source	Voltage Sourced
Poorer performance with weak ac systems	Less affected by system strength
Cheaper for High Power	More expensive, but may be comparable when all aspects are considered
Lower Losses	Higher losses (improved by new topologies)
Power direction reversed by voltage reversal	Power direction changed by current reversal
Difficult to use in a dc grid	Well suited for dc grid
Ideal for dc transmission with overhead lines	Ideal for weak ac systems, cable transmission or dc grids



Example of VSC HVDC: Troll Link

- Purpose: To Run Compressor Motors for Offshore Gas Extraction
- Gas Pressure from Wells decreases as gas is extracted, hence a compressor is needed to force gas through pipeline
- A conventional precompression project, with gas turbines, would have resulted in annual emissions of some 230,000 tons of CO_2 and 230 tons of NO_x.

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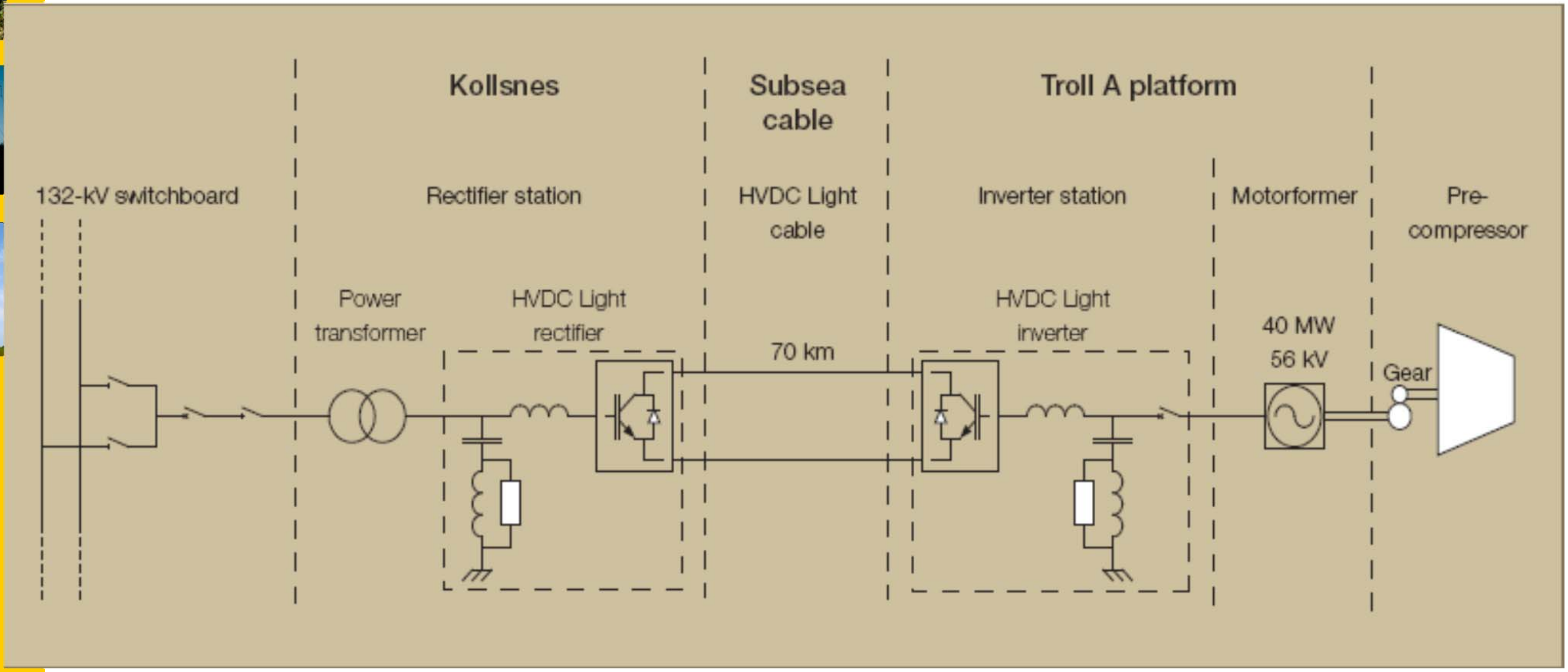
- Location: Offshore Norway

One Half of Troll HVDC System



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Troll VSC HVDC: Ratings

Main data

Rated power 2x40 MW
DC voltage ±60 kV
AC system voltage 132 kV
AC motor voltage 56 kV

AC filters

Kollsnes: 39’th and 78’th harmonic
Troll A: 33’th and 66’th harmonic

IGBT valves

Valve type Two level
Cooling system Water
IGBT type 2,5 kV/500 A

Cable

Type Triple extruded polymer
Cross section 300 mm2
Length 4 x 70 km

Transformers (Kollsnes only)

Type Three-phase, two winding
Rated power 52 MVA

3	HVDC Light™ extruded submarine cable, with double armoring (80 kV rating)

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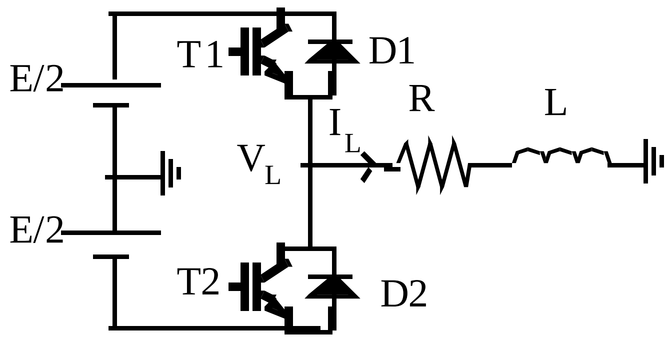
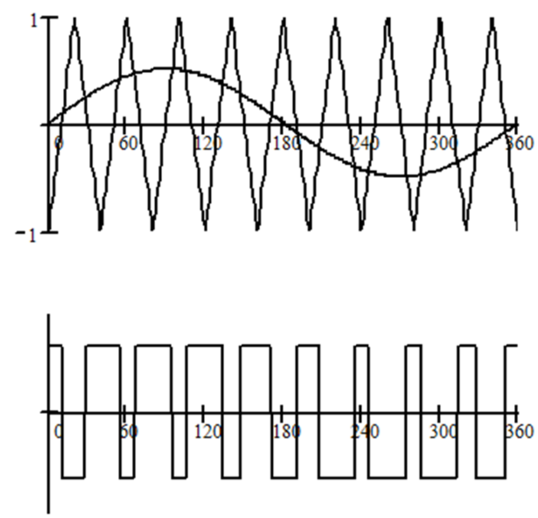
Multilevel Modular Converter (MMC)

- PWM converters produce a waveform with high level of higher order harmonics
- Result: High Switching Losses, EMI, Stresses etc.
- With High Voltages, Device ratings become an issue



Simple Voltage Sourced Inverter



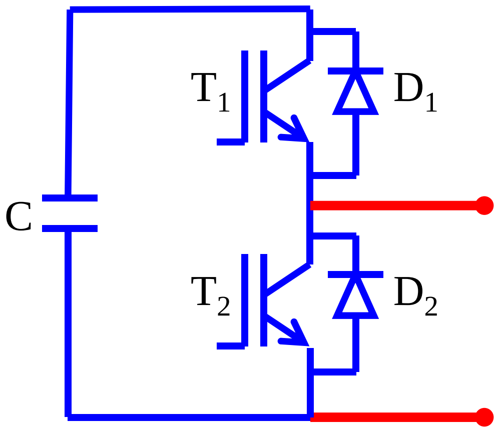
Basic unit of MMC scheme – Submodule

T_x – IGBT

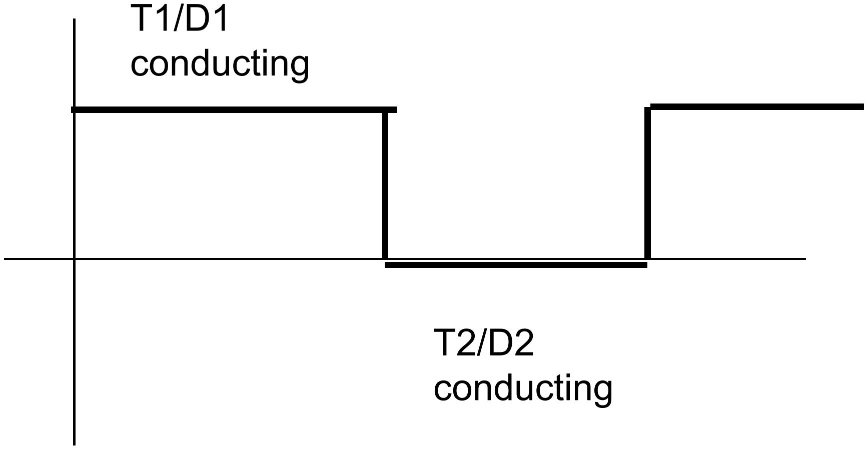
D_x – Diode

C – Storage Capacitor

x = 1,2

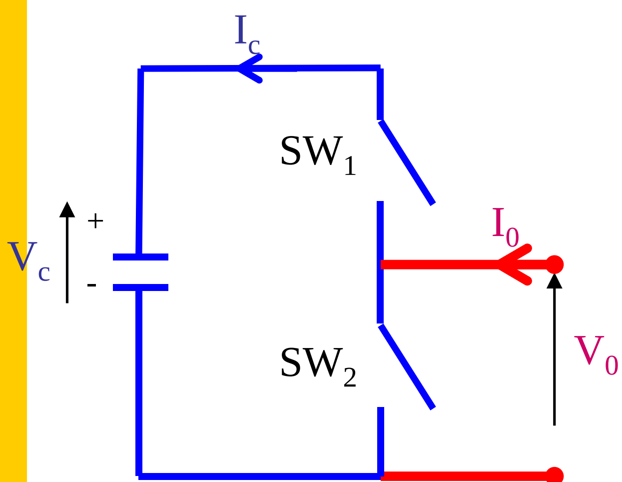


Submodule



MMC Submodule

Each submodule acts as a controllable voltage source.



Submodule

Device ON	V_0
SW_1	V_c
SW_2	0

Control States of a Sub-module

MMC Topology

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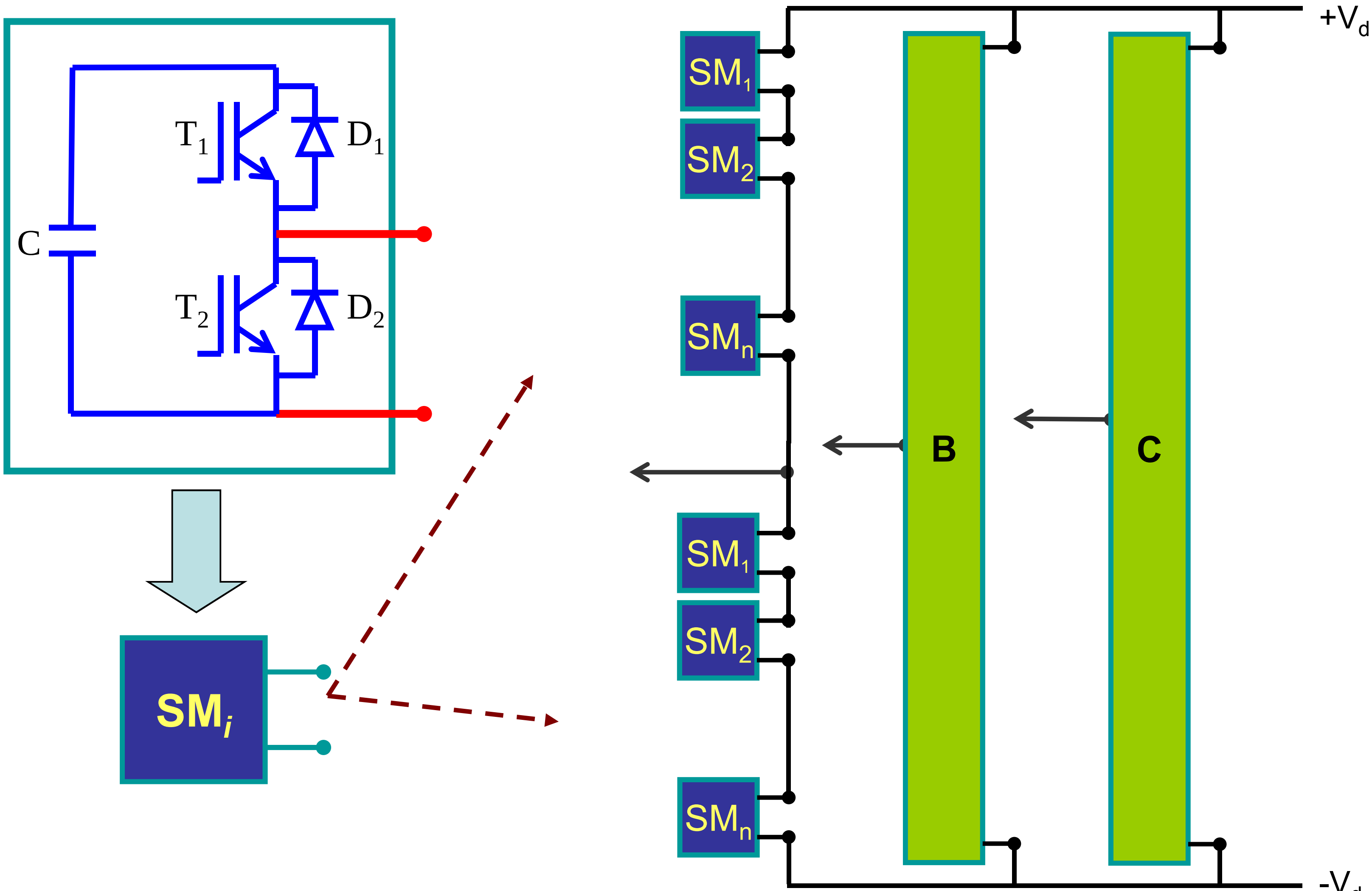
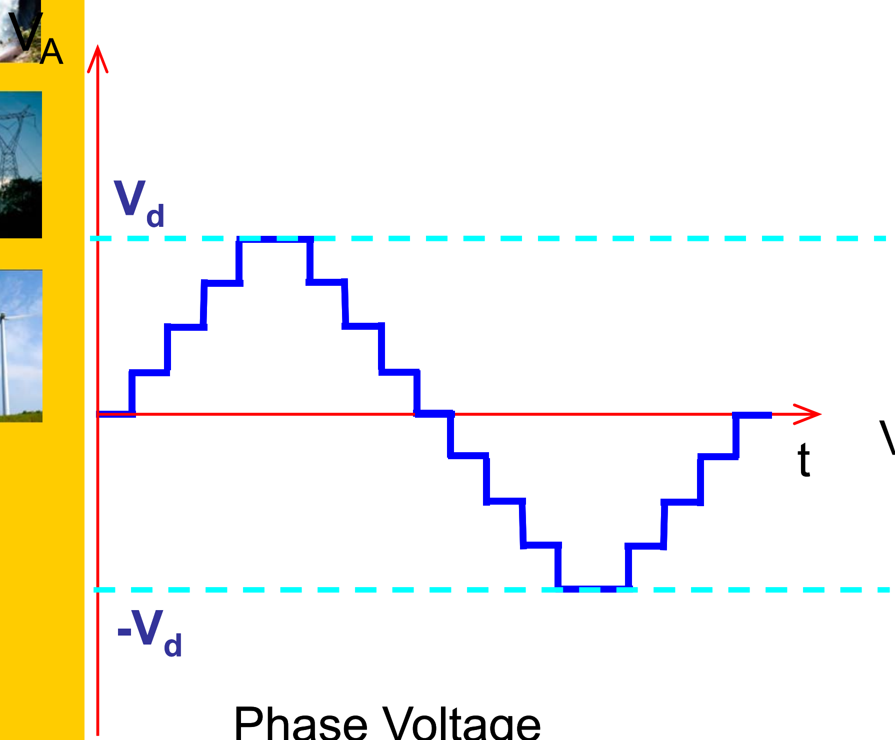
MMC basic scheme

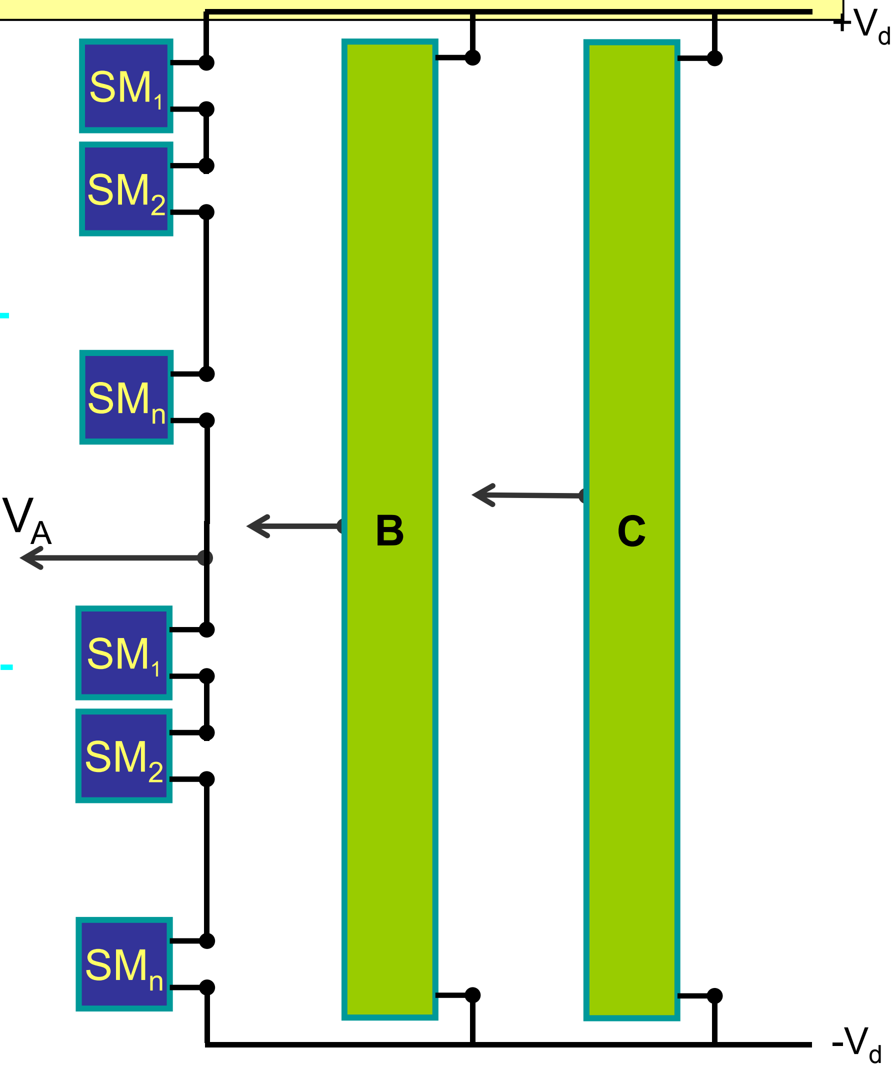


Introduction – MMC Topology



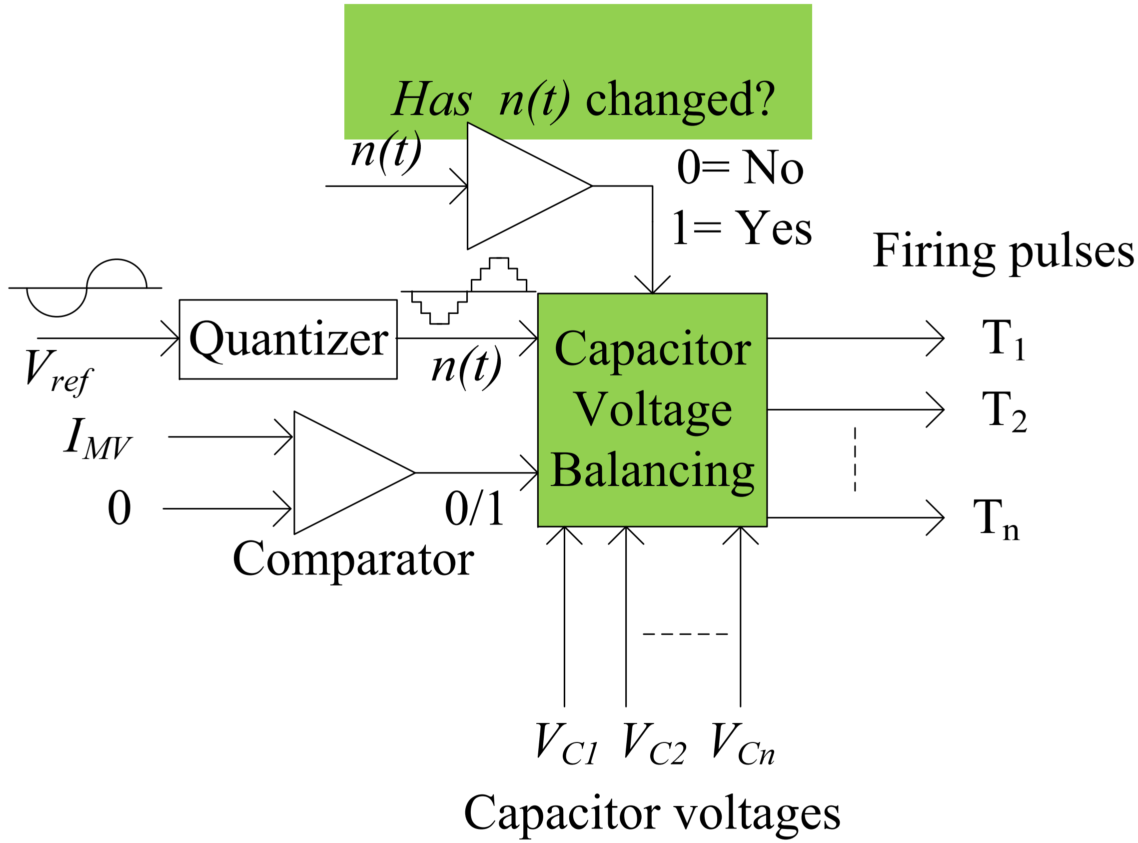
Phase Voltage
(n = 10)

MMC basic scheme



MMC Controls

- Reference Waveform is quantized to determine switching instants
- Special algorithms for Capacitor voltage balancing and ensuring sharing of module duty
- Higher level controls identical to other VSC topologies (i.e. decoupled id/iq control etc.)



Trans-Bay HVDC Project



- **Purpose**:
  - Congestion Relief
  - Improvement of security of supply
  - Retirement of Generation in San Francisco Area
- **Customer** Trans Bay Cable, LLC
- **Location** Pittsburg, California, and San Francisco, California
- **Power Rating** 400 MW
- **Voltage levels** ± 200 kV DC, 230 kV /138 kV, 60 Hz
- **Type of plant** 85 km HVDC PLUS submarine cable
- **Type of Thyristor** IGBT

Transbay Cable (San Francisco-Oakland)

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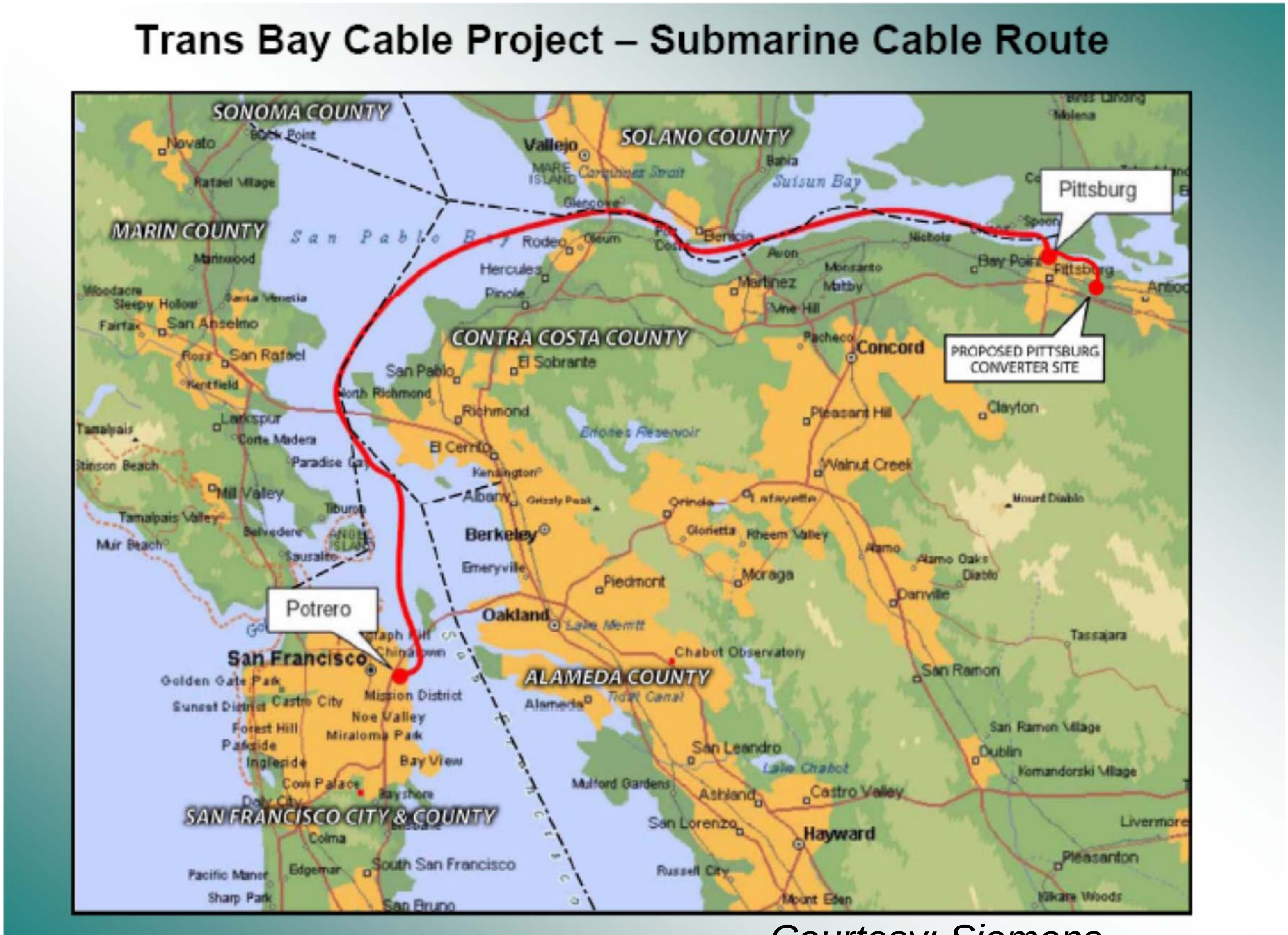
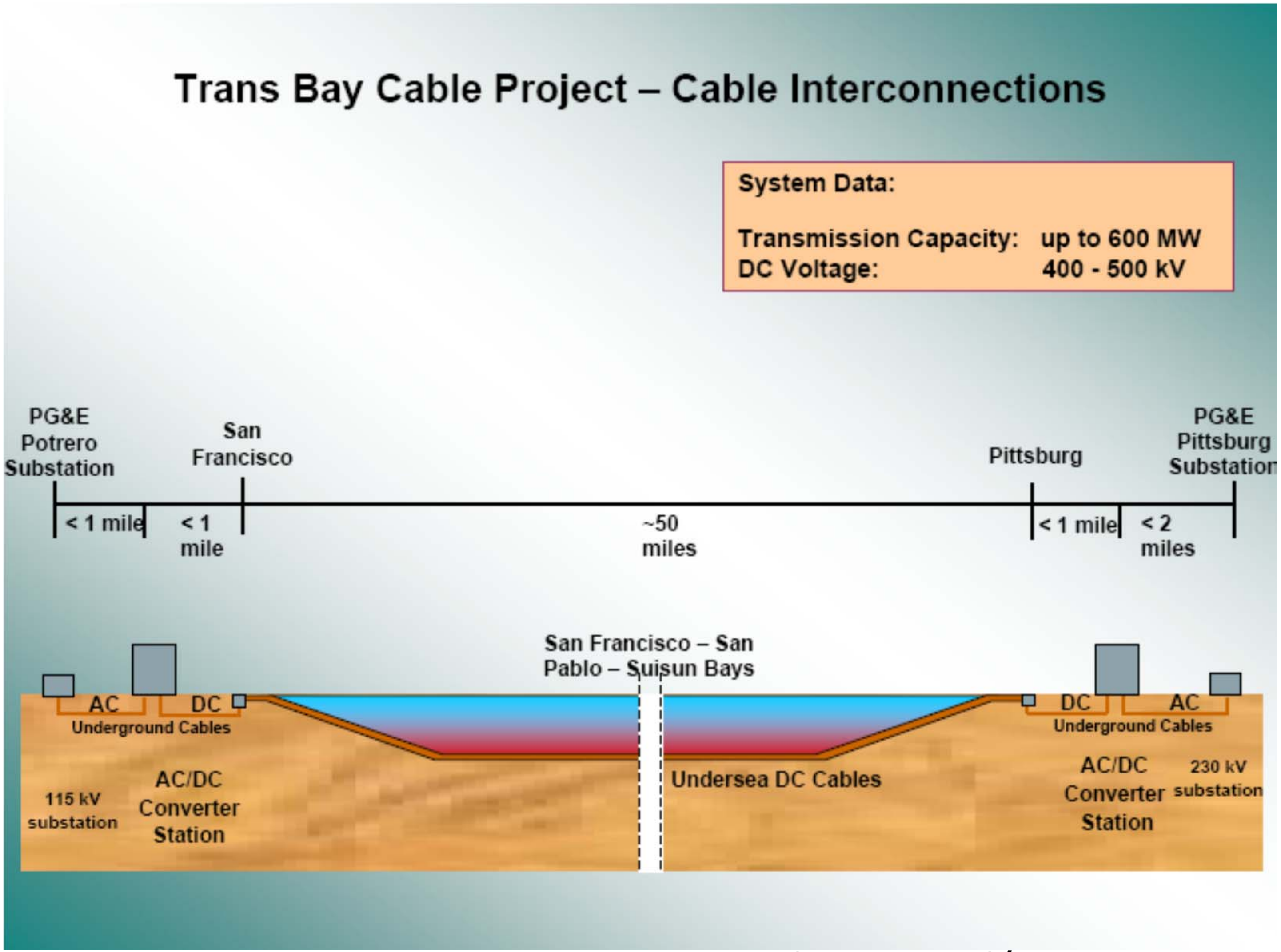


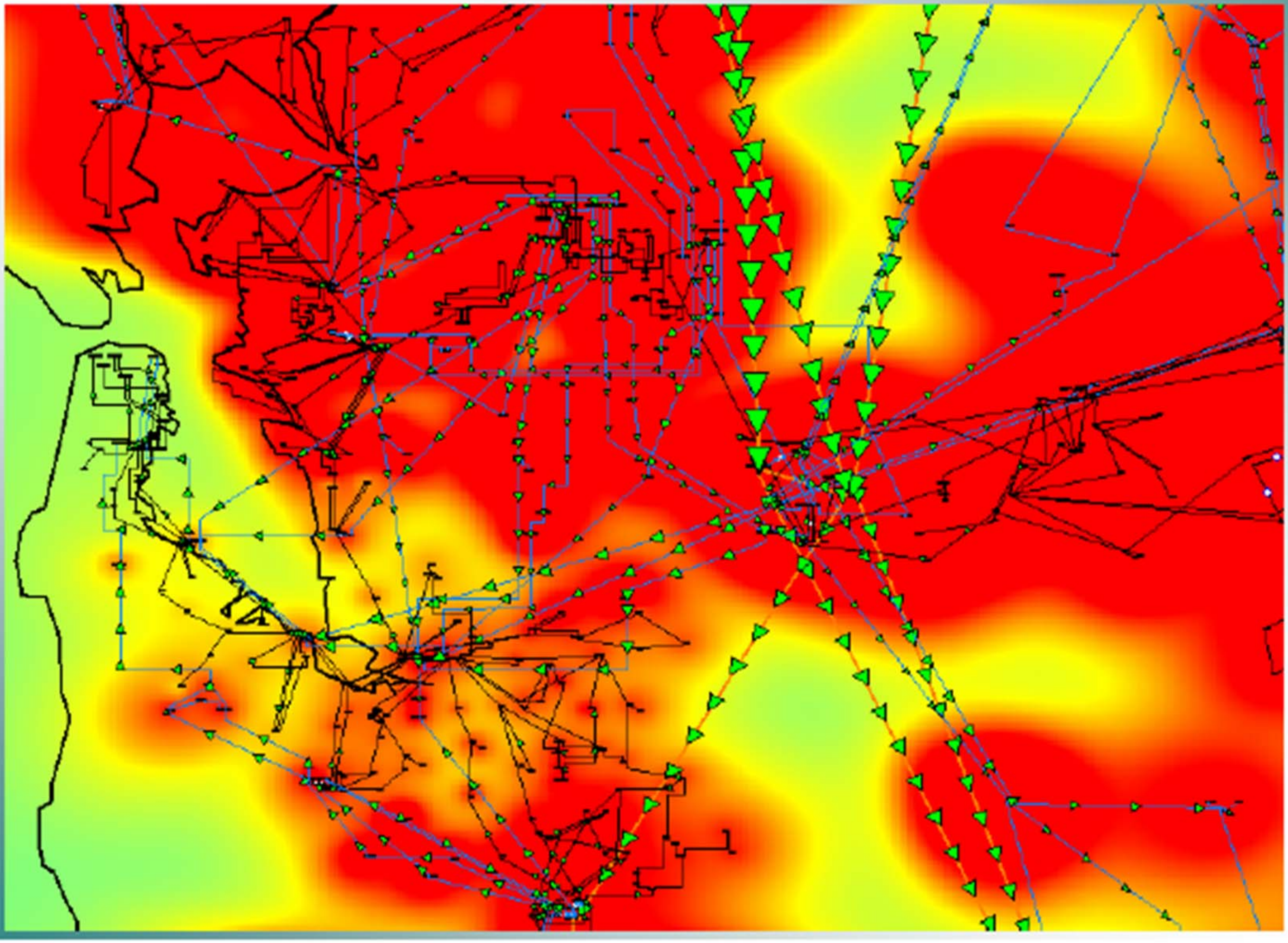
Courtesy: Siemens

Transbay Cable (San Francisco-Oakland)



Courtesy: Siemens

Trans Bay Cable Project – Need Study Results: Plots Showing Greater Bay Area Power Flows – Jefferson-Martin ON, Hunters Point OFF, Potrero (or CCSF Peakers) ON, Trans Bay Cable OFF



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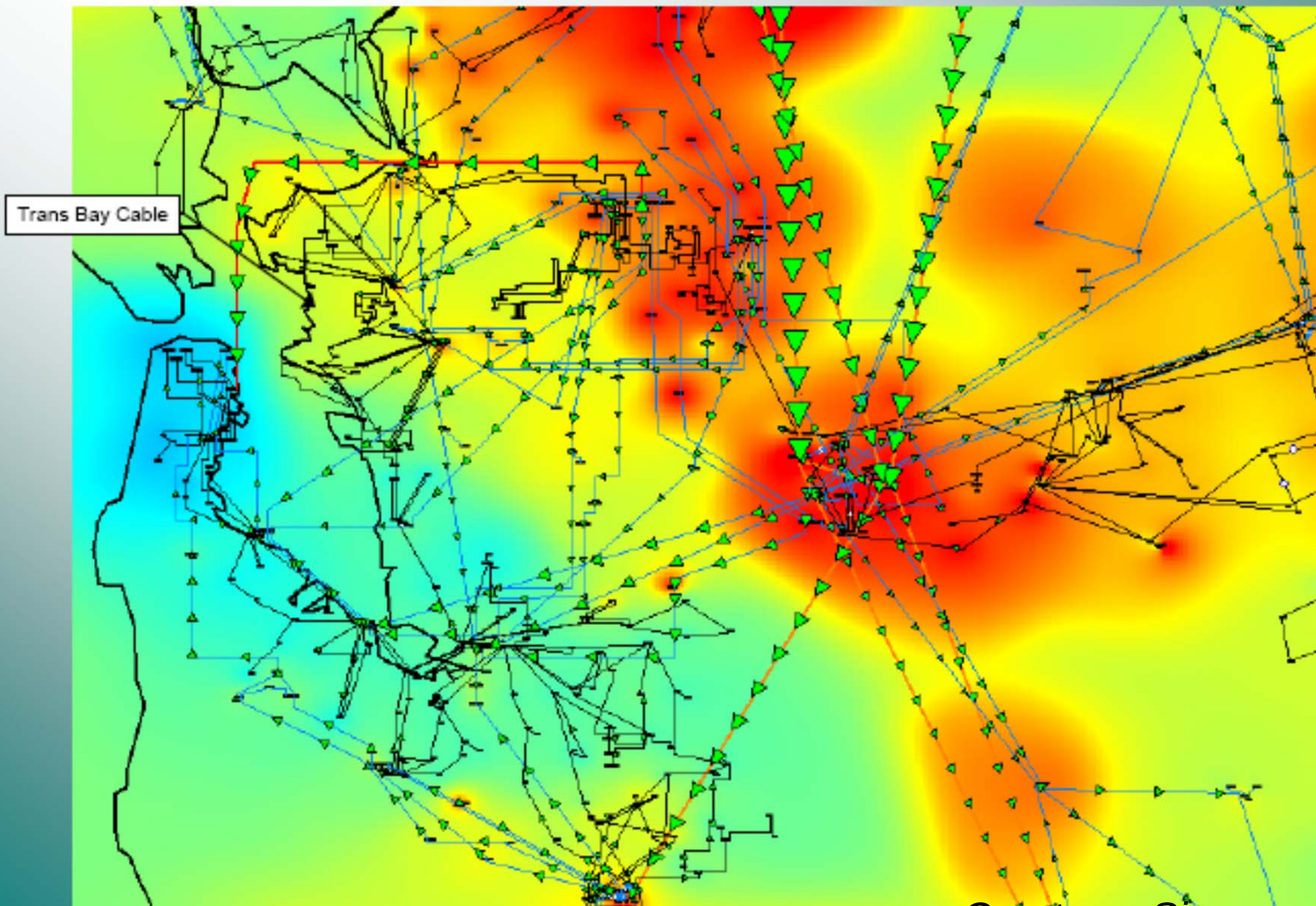

Courtesy: Siemens

HVDC Supergrids?

- VSC Converters enable construction of HVDC Grids
- Reduced Losses
- Increased power capacity per line/cable vs. AC
- Underground/Underwater or reduced rights of ways imply:
  - lesser right of way limitations,
  - lower visual impact and lower EM fields
- Stabilized AC & DC grid operation – AC networks can be asynchronous
- Applicable for Harnessing Multiple off-shore windfarms

Concluding Remarks

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- HVDC Transmission Technology is evolving to adapt to the change in attitudes about energy
- The barriers on conventional LCC HVDC imposed by the ac system conditions are being overcome
- CCC Technology extends the range of thyristor based converters
- VSC technology is promising - less influenced by the ac network
- Recent innovations such as the MMC are reducing losses and making VSC technology very attractive
- The future is bright - radical changes in the power network, such as dc grids are on the horizon