Modern Power-Electronic Converters for High-Voltage Direct-Current (HVDC) Transmission Systems

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Map of Canada

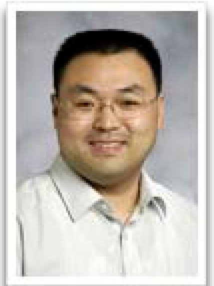
Ryerson University, Department of Electrical and Computer Engineering, and Energy Systems Group

- Located in downtown Toronto (capital of Province of Ontario)
- 43 faculty members in Electrical and Computer Engineering
- 6 (out of 43) faculty members in Energy Systems

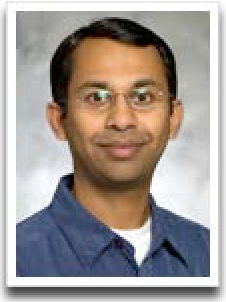
Members of Energy Systems Group at Ryerson University

B. Wu

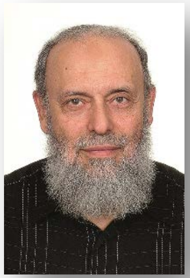
A. Yazdani



D. Xu



B. Venkatesh



A. Hussein

R. Cheung

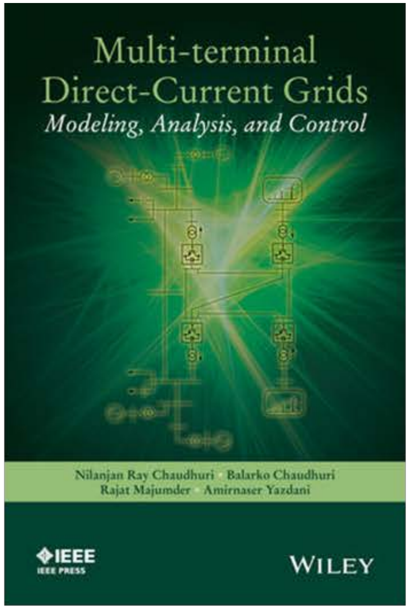
- Power electronics
- Electric motor drives
- Active distribution networks and microgrids
- Power systems operation and control
- Lightning measurement & modeling

Web: www.ee.ryerson.ca

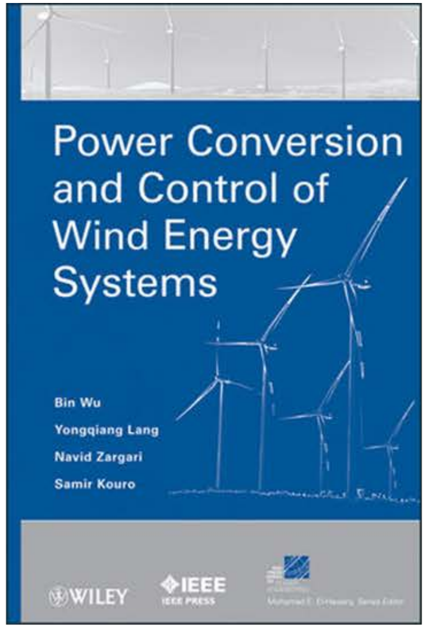
Research Labs for Power Electronics

- Two labs for power electronics only
- Each lab about 200 square meters in area
- Equipped with single-/three-phase ac switchgear up to 600V/150kVA, as well as dc switchgear

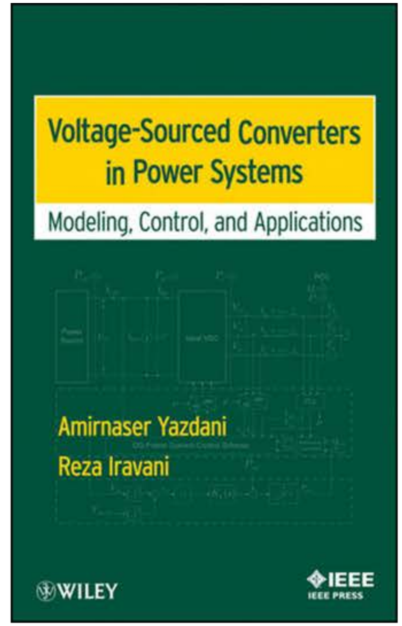
Select Books Authored by Energy Systems Group



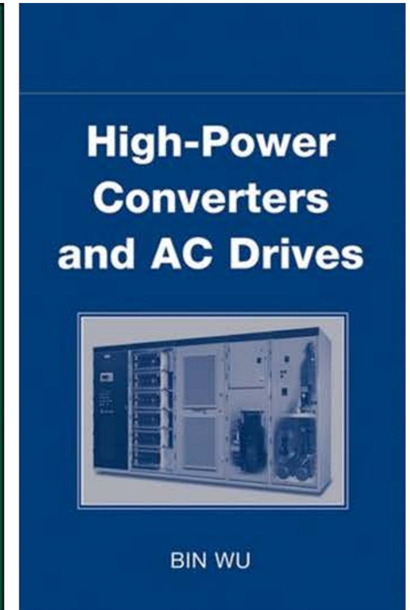
Chaudhuri, Chaudhuri, Mazumder, & Yazdani
288 pages, 2014
Wiley-IEEE Press



Wu, Lang Zargari, & Kouro
480 pages, 2011
Wiley-IEEE Press



Yazdani & Iravani
451 pages, 2010
Wiley-IEEE Press



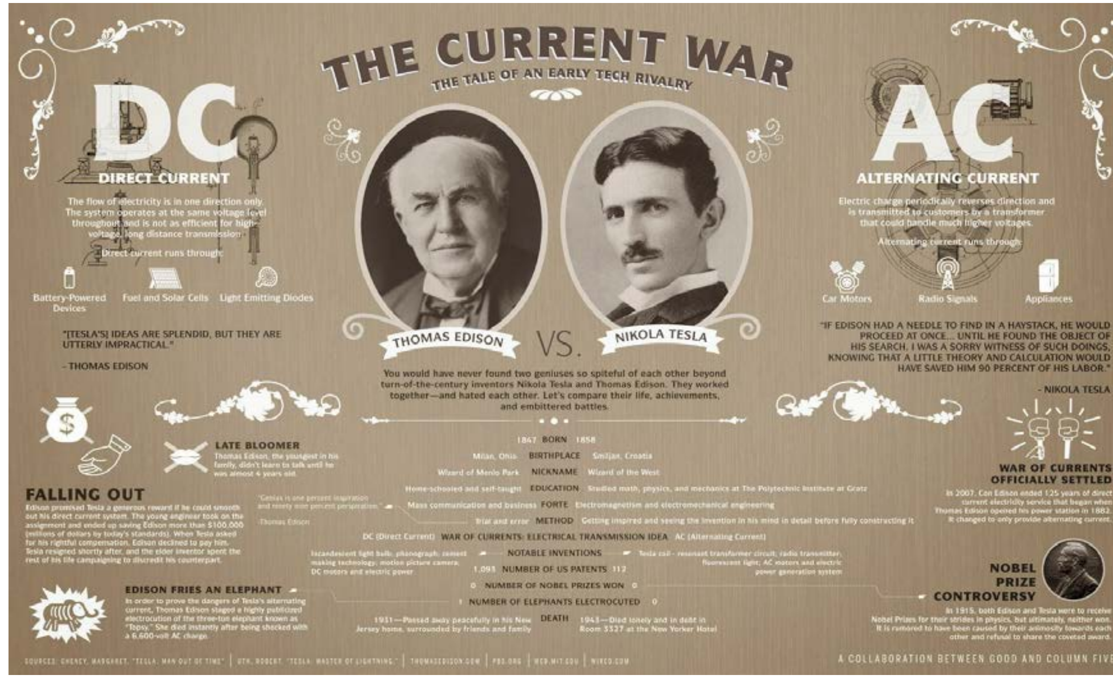
Wu
352 pages, 2006
Wiley-IEEE Press

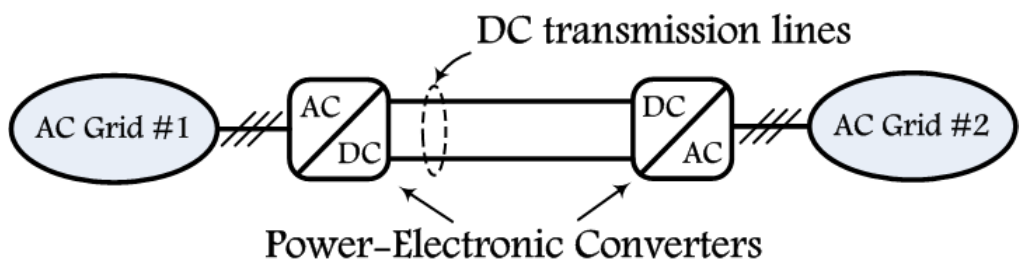
Outline

- **HVDC Transmission Systems**
  - Multi-Terminal Systems
  - DC Grids
- **Power Electronics**
  - Line-Commutated Converter (LCC) Technology
  - Voltage-Sourced Converter (VSC) Technology
  - Modular Multilevel Converter (MMC) Technology
    - Example of an Alternative Sub-Module Configuration
- **Other Applications**
  - Integration of Distributed Energy Resources
  - DC-DC Converters, etc.
- **Summary and Conclusions**

The AC-Based Legacy Power System

- **Legacy power system is based on AC**
  - Tesla won the *Battle*!
- **High-Voltage DC (HVDC) used in niche applications**
  - Since 1950s

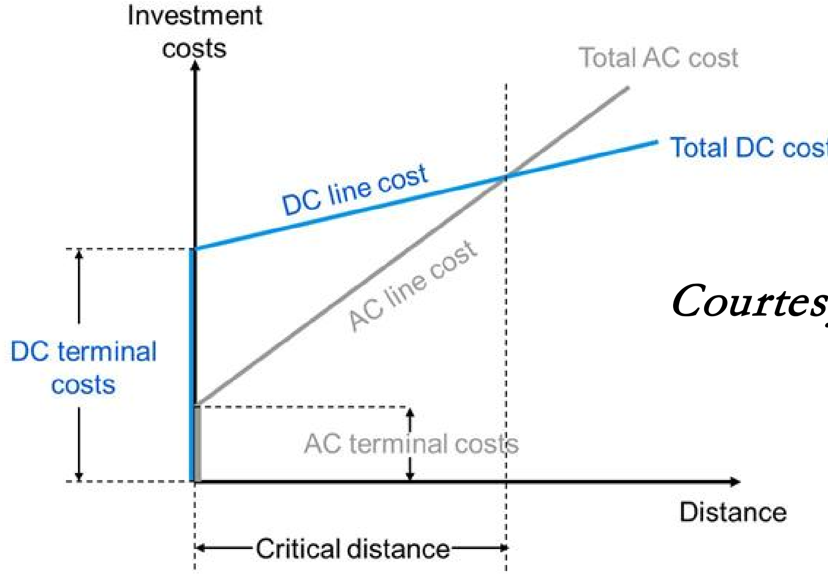




The DC lines can be of zero length (in a back-to-back system), or they can be very long (Rio-Madeira system has the record length of 2375 km).

Traditional Applications of HVDC Systems

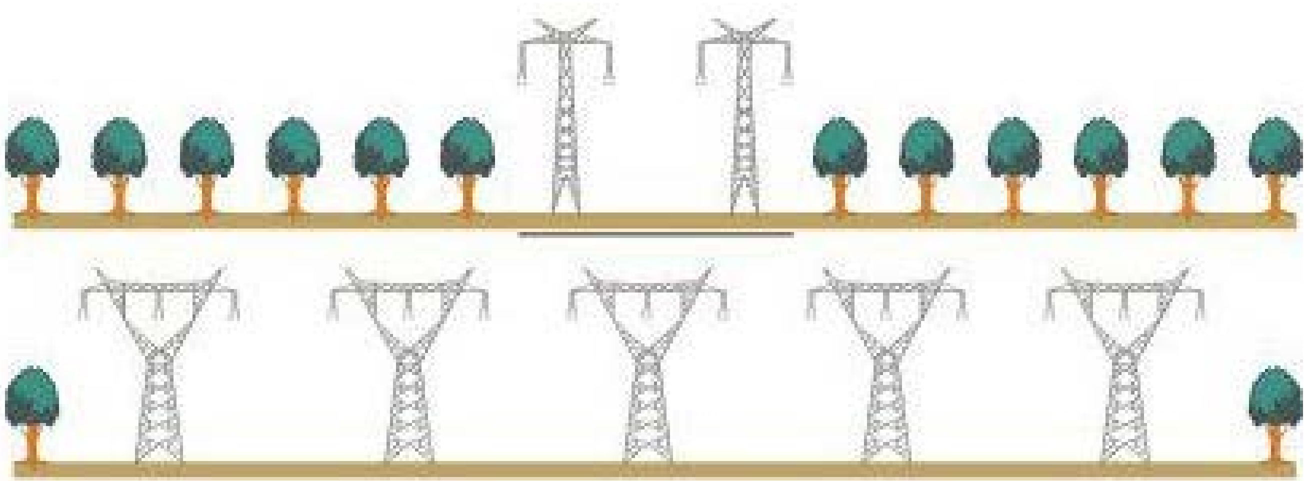
- Long-distance and/or underwater transmission
- Asynchronous system interconnections
- Strategic missions



Courtesy: ABB

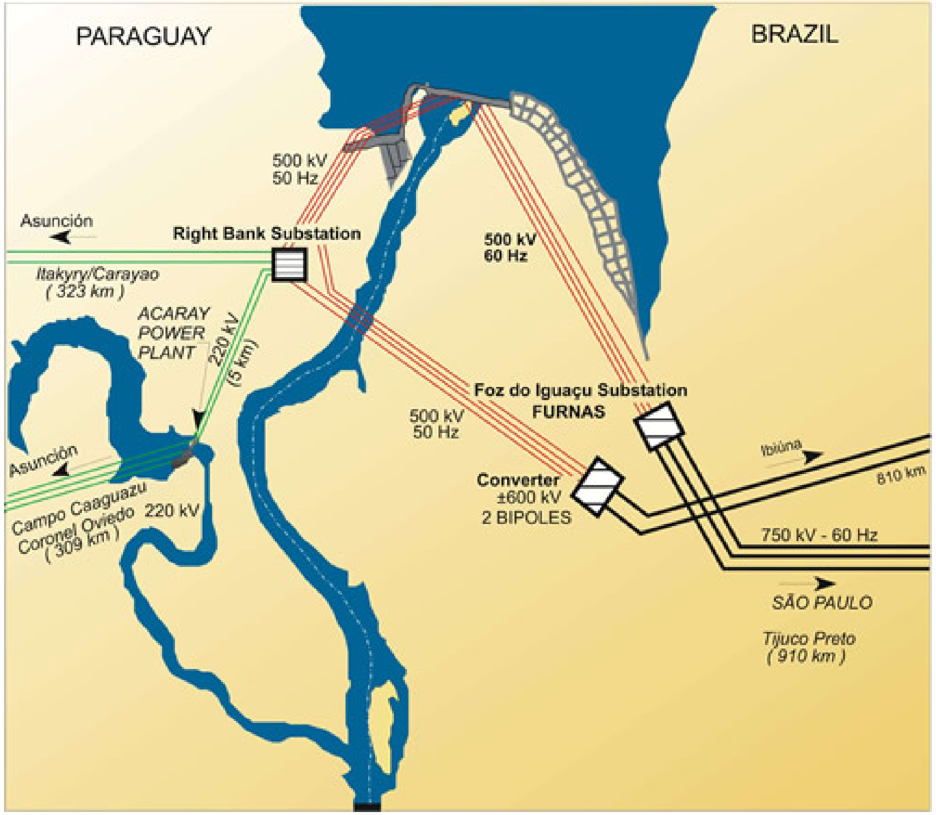
<u>Fact</u>

Right-of-way
is smaller in HVDC



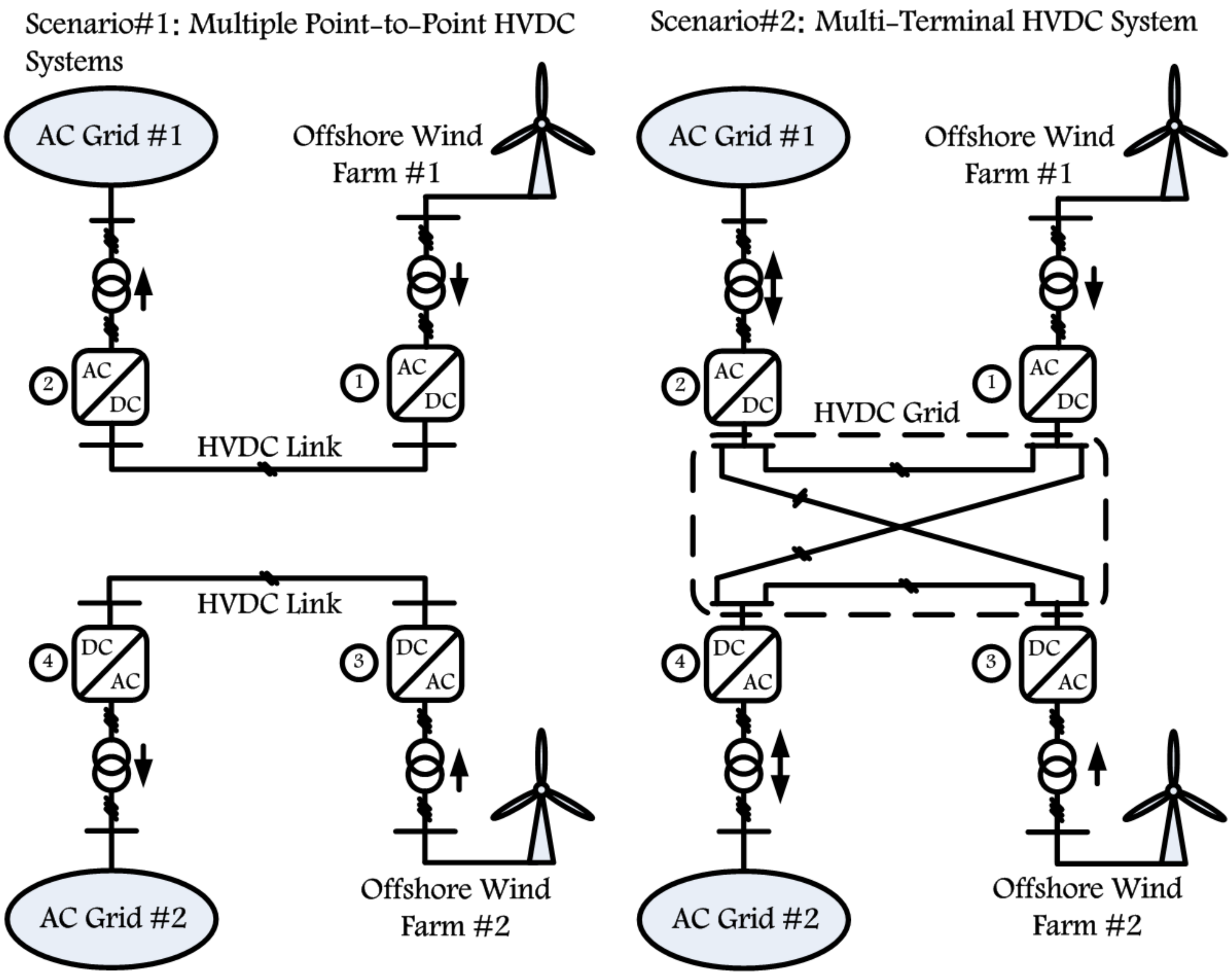
Three-Gorges/Shanghai
(3000 MW; 500 kV)
Courtesy: ABB

Itaipu HVDC System

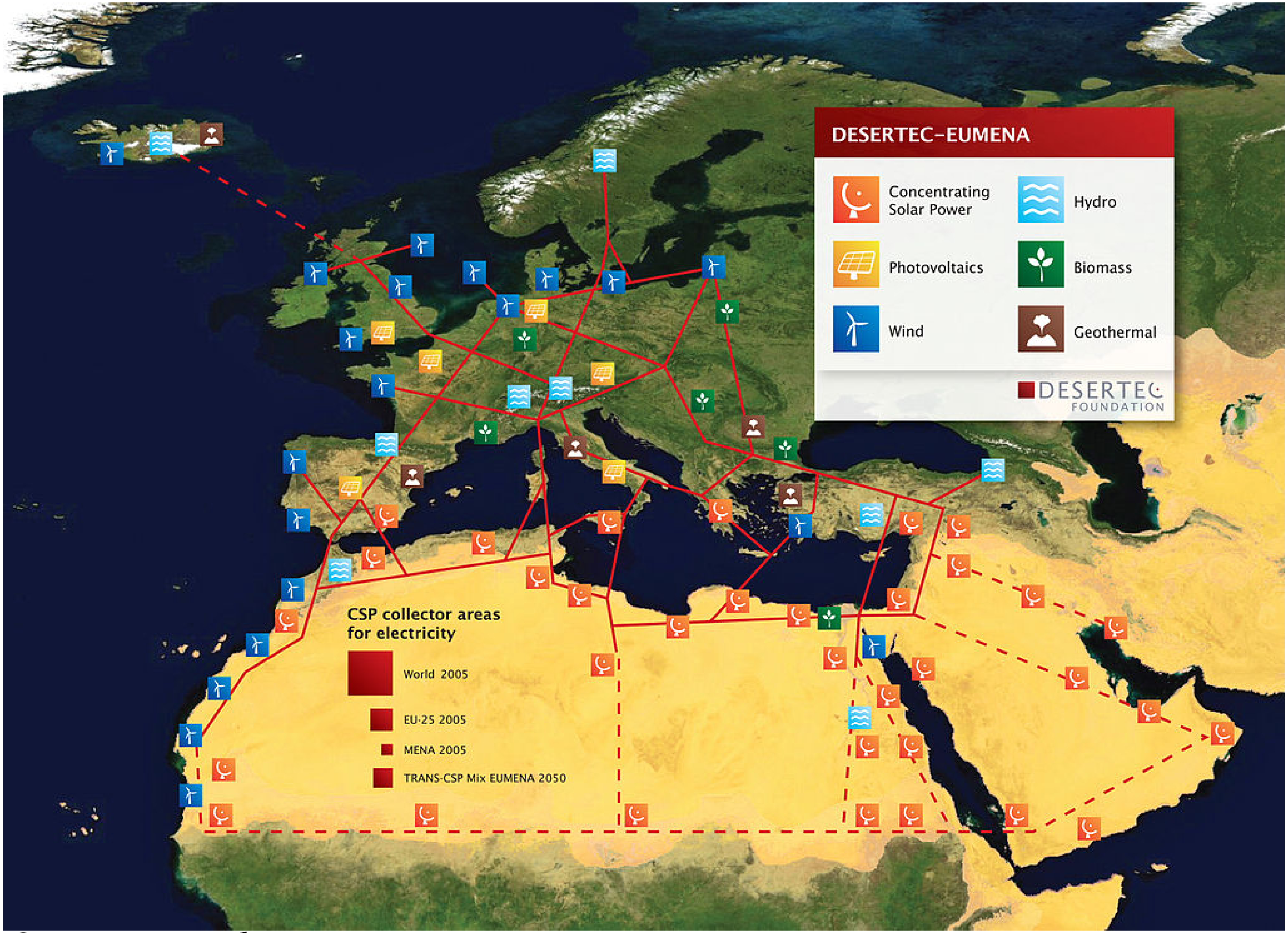


3 AC lines: *765 kV, 6300 MW*
2 DC lines: *± 600 kV, 6300 MW*

Multi-Terminal HVDC Systems and DC Grids

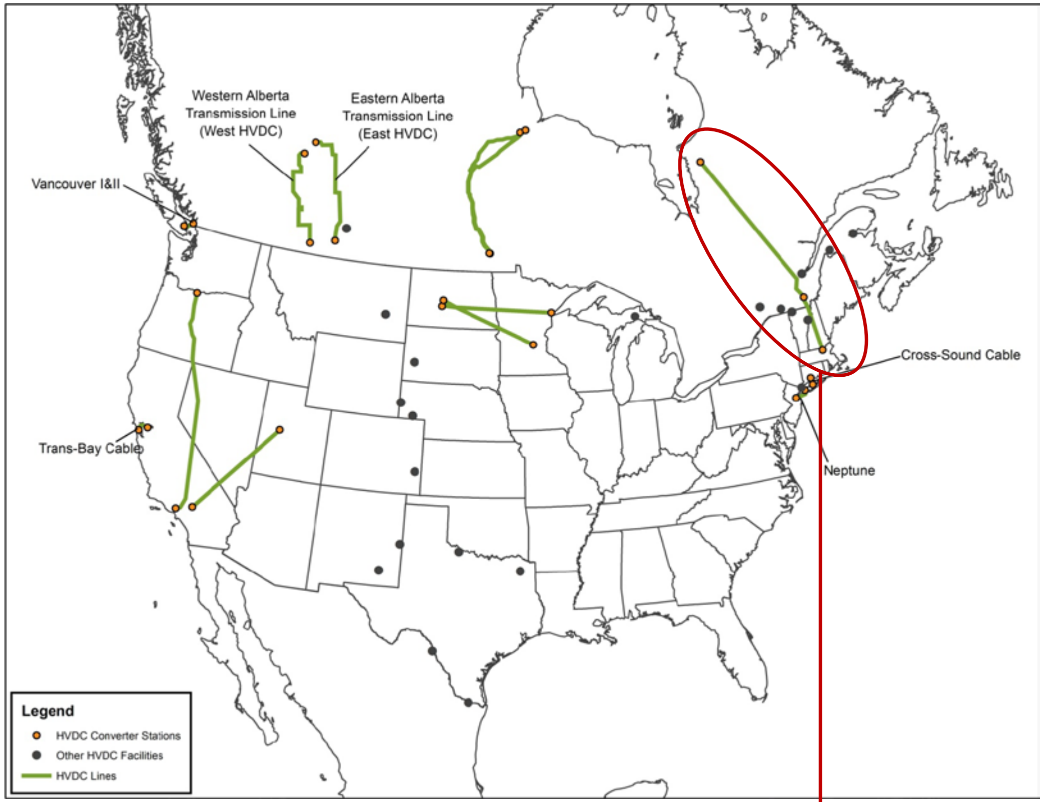


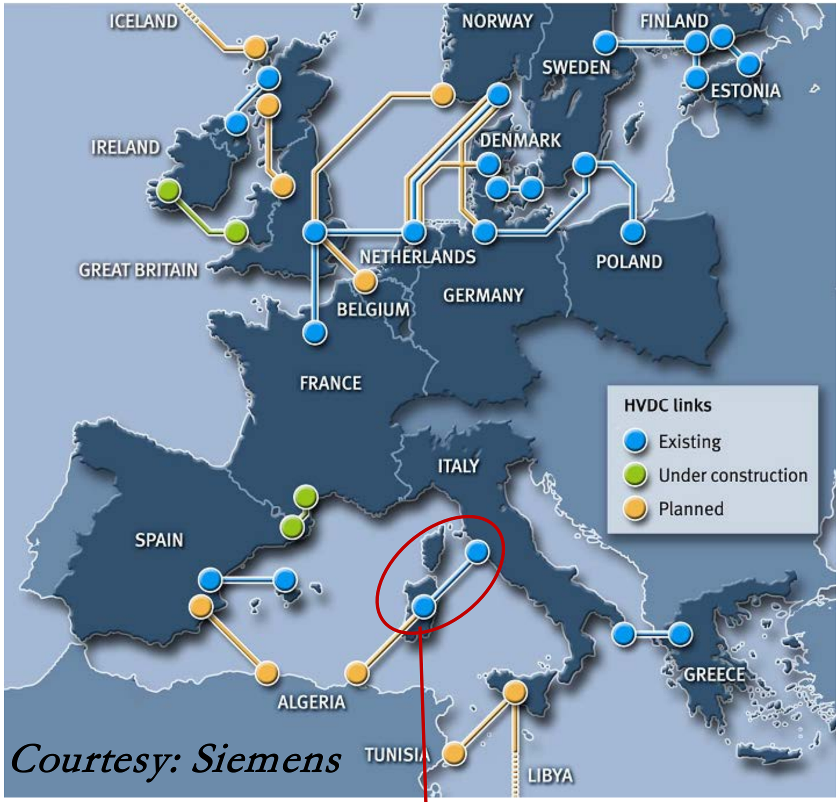
Desertec EU-MENA Vision



Source: www.desertec.org

HVDC Transmission Systems in North America and Europe





Quebec-New England 3-Terminal HVDC System (*±450 kV, 690 MW*)

Sardinia-Italy 3-Terminal HVDC System (*±200 kV, 300 MW*)

Line-Commutated Converter (LCC) Technology

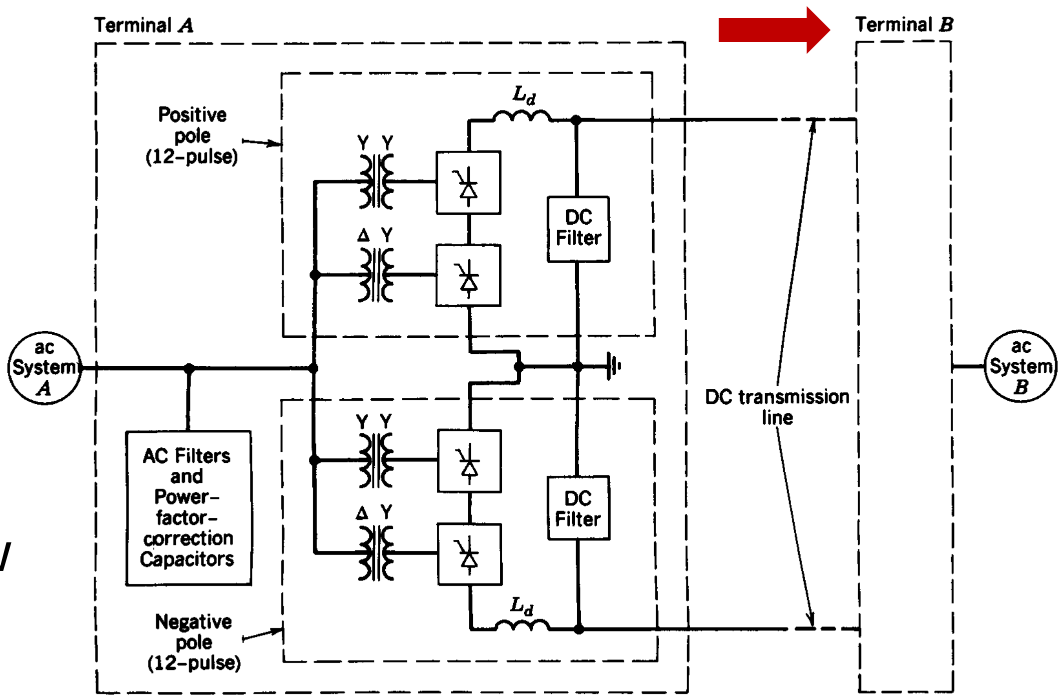
Merits

- Can achieve very high voltages and powers
- Is robust to dc-side faults

Demerits

- DC current cannot be reversed
  - Unidirectional power flow
  - Not suitable for dc grids
- Switching frequency is low
  - High filtering requirements
- Requires stiff AC voltage
  - Cannot energize passive islands

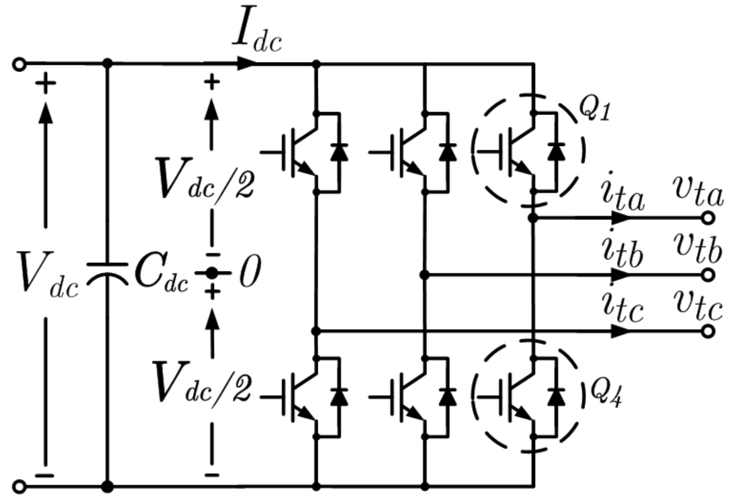
Unidirectional DC Current



Courtesy: Mohan, Undeland, Robbins

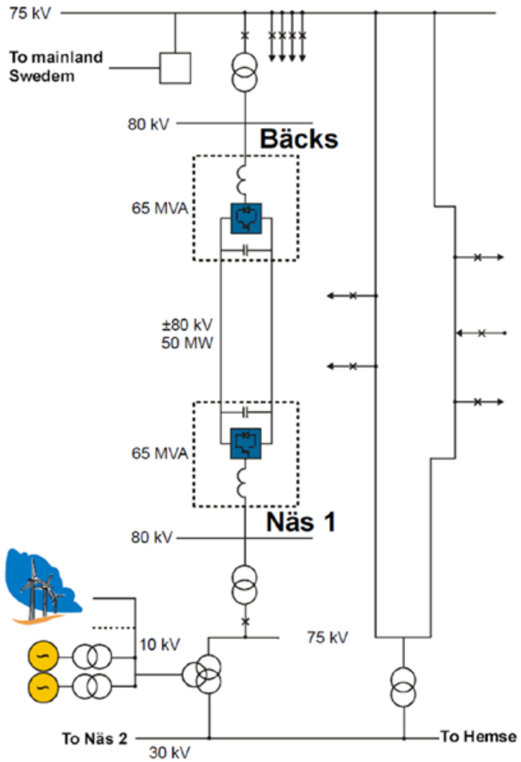
The Voltage-Sourced Converter (VSC) Technology

- **Reversible DC current**
  - Reversible power flow
  - Well suited for dc grids
- **High switching frequencies**
  - Lower filtering requirements
  - Smaller footprint
  - High speed of response
- **Independent real and reactive power Control**
  - Ability to interface with weak ac grids and passive islands



A Few Commercial VSC-Based HVDC Systems

- **Gotland HVDC Light (grid support)**
  - Sweden, 50 MW, ±80 kV, 70 km
- **Eagle Pass (grid support)**
  - USA, 36 MW, ±15.9 kV, back-to-back
- **Troll-A (off-shore gas extraction)**
  - Norway, 80 MW, ±60 kV, 70 km
- **BorWin1 (off-shore wind integration)**
  - Germany, 400 MW, ±150 kV,
  - 75 km (land), 125 km (underwater)



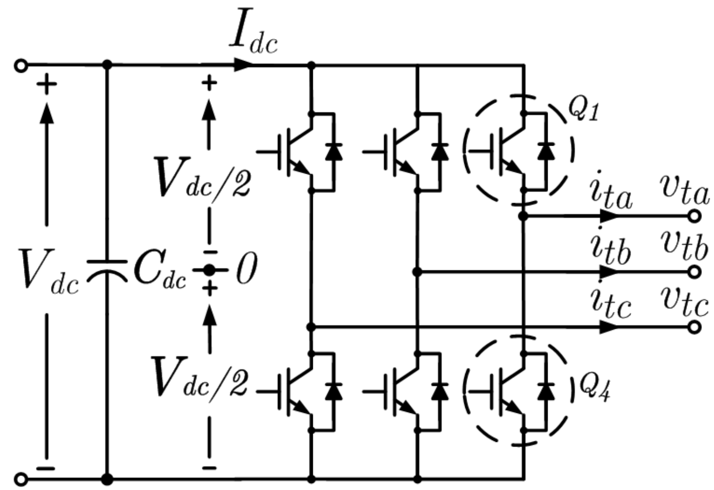
Common Features

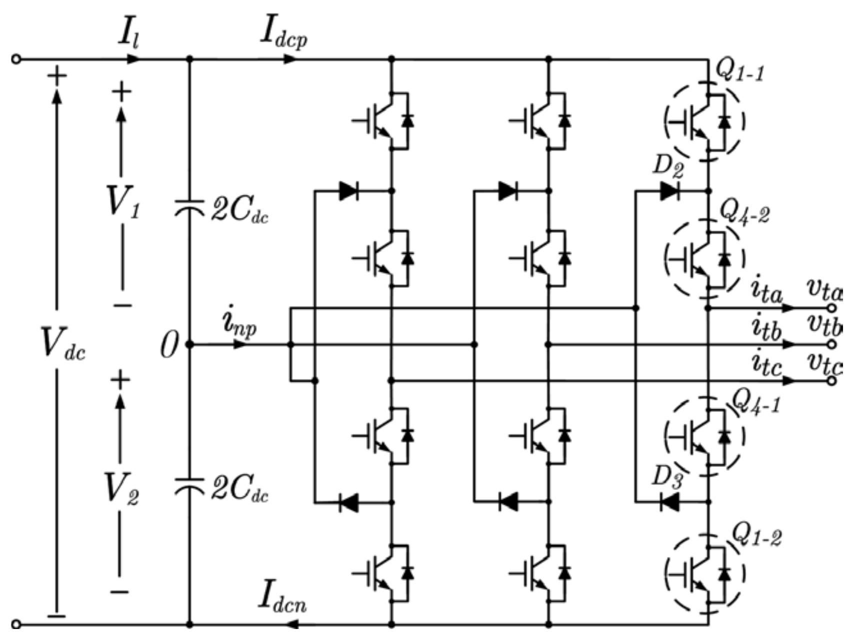
- No overhead lines!
- Relatively small in ratings

Courtesy: ABB

Demerits of VSC-Based HVDC Systems

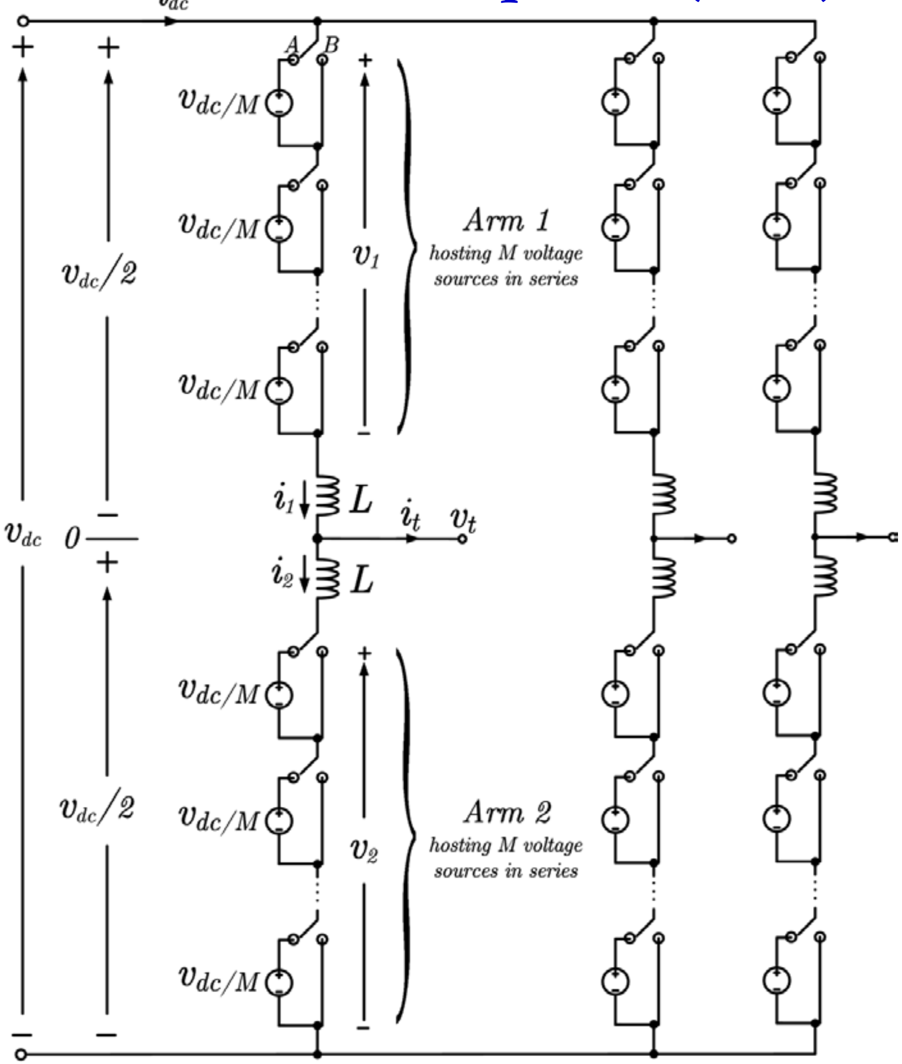
- **Vulnerability to DC-side faults**
  - Not suitable for overhead lines
- **Need for many series-connected switches**
- **Large AC voltage swings and the associated EMI**
- **Need for DC capacitor across the entire link**
- **High switching power losses due to pulse-width modulation**

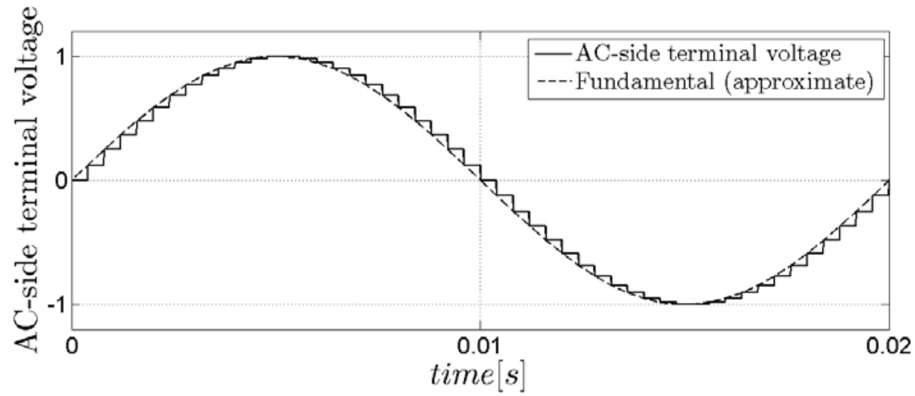




State-of-the-Art:
The Modular Multilevel Converter (MMC)

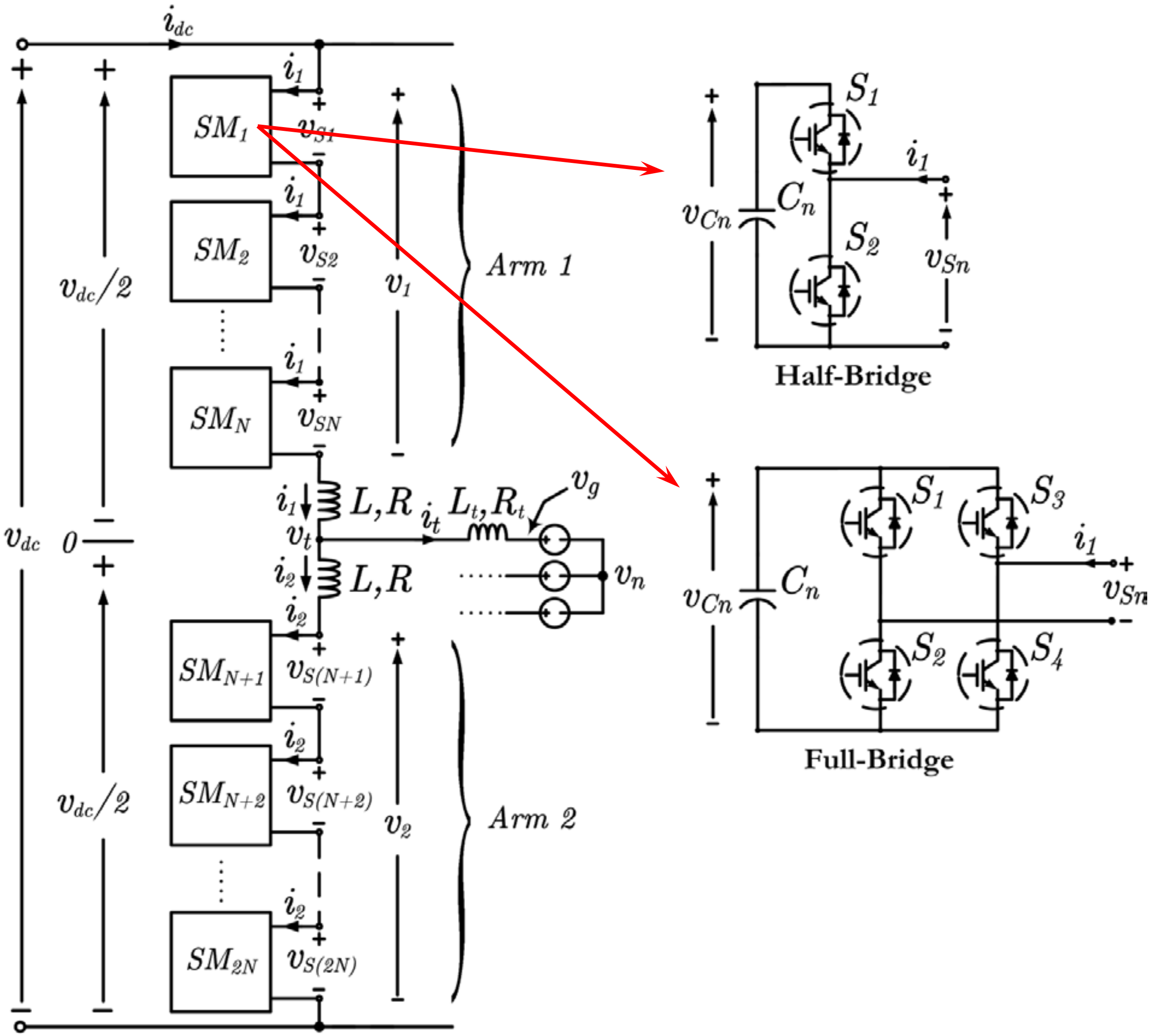
Lesnicar and Marquardt (2003)





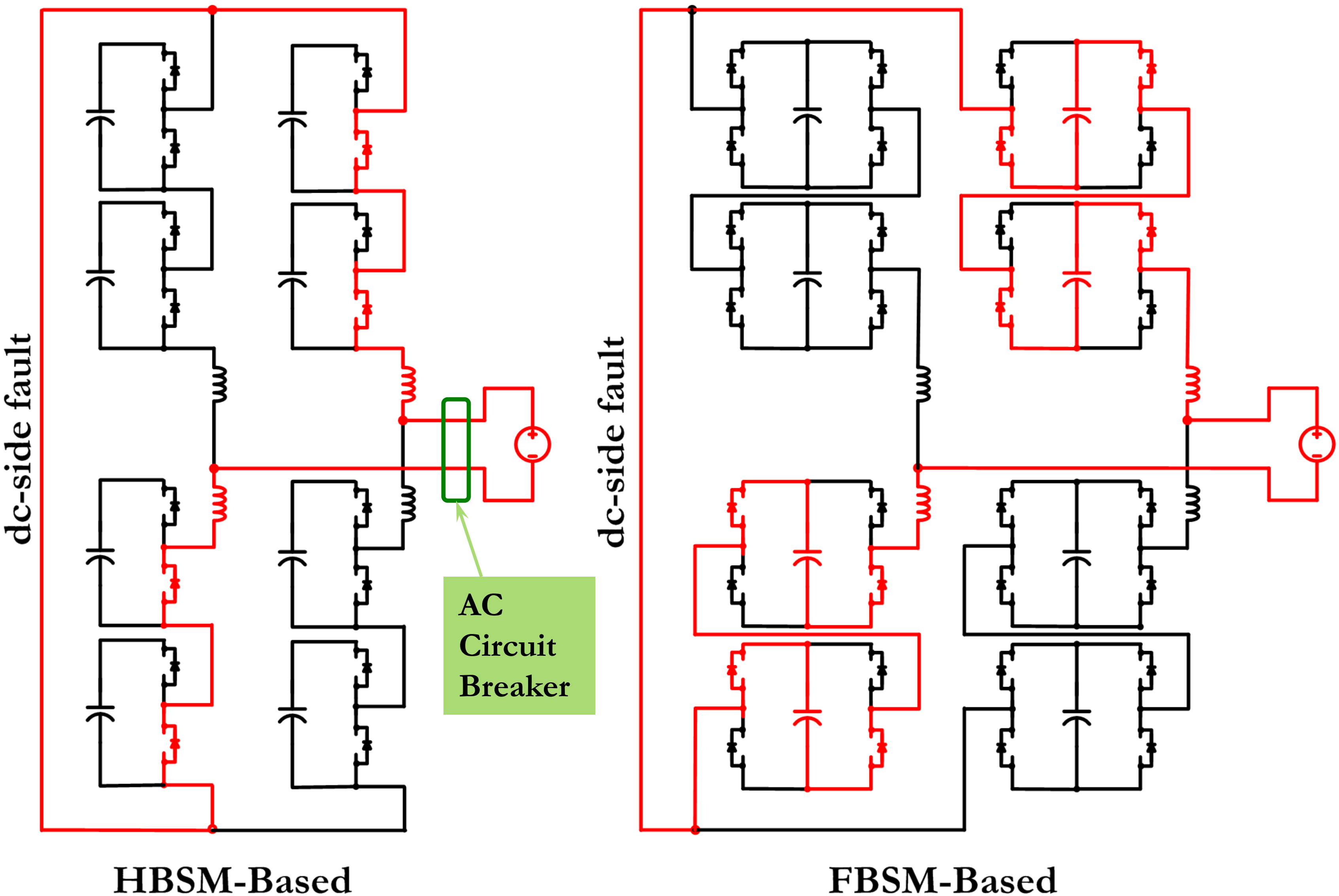
- **Many small voltage steps**
  - Nearly sinusoidal ac voltage
    - *Low filtering requirements*
  - Low EMI
- **No large DC link capacitor**
- **Low switching frequency**
  - Small power losses
- **Modularity**
  - Redundancy and fault tolerance

The MMC:
Dominant Sub-Module (SM) Technologies



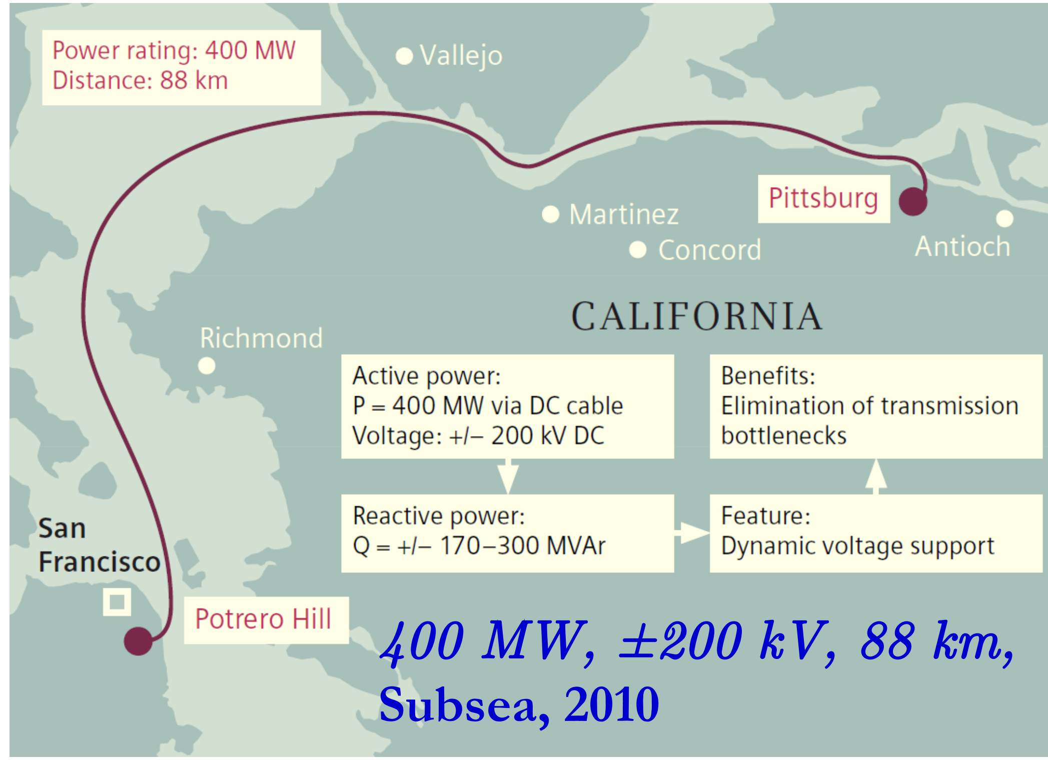
Courtesy: Siemens

Response Under DC Faults



Inelfe and Trans Bay Projects

2000 MW, ±320 kV, 65 km,
Underground, 2014



400 MW, ±200 kV, 88 km,
Subsea, 2010

Courtesy: Siemens

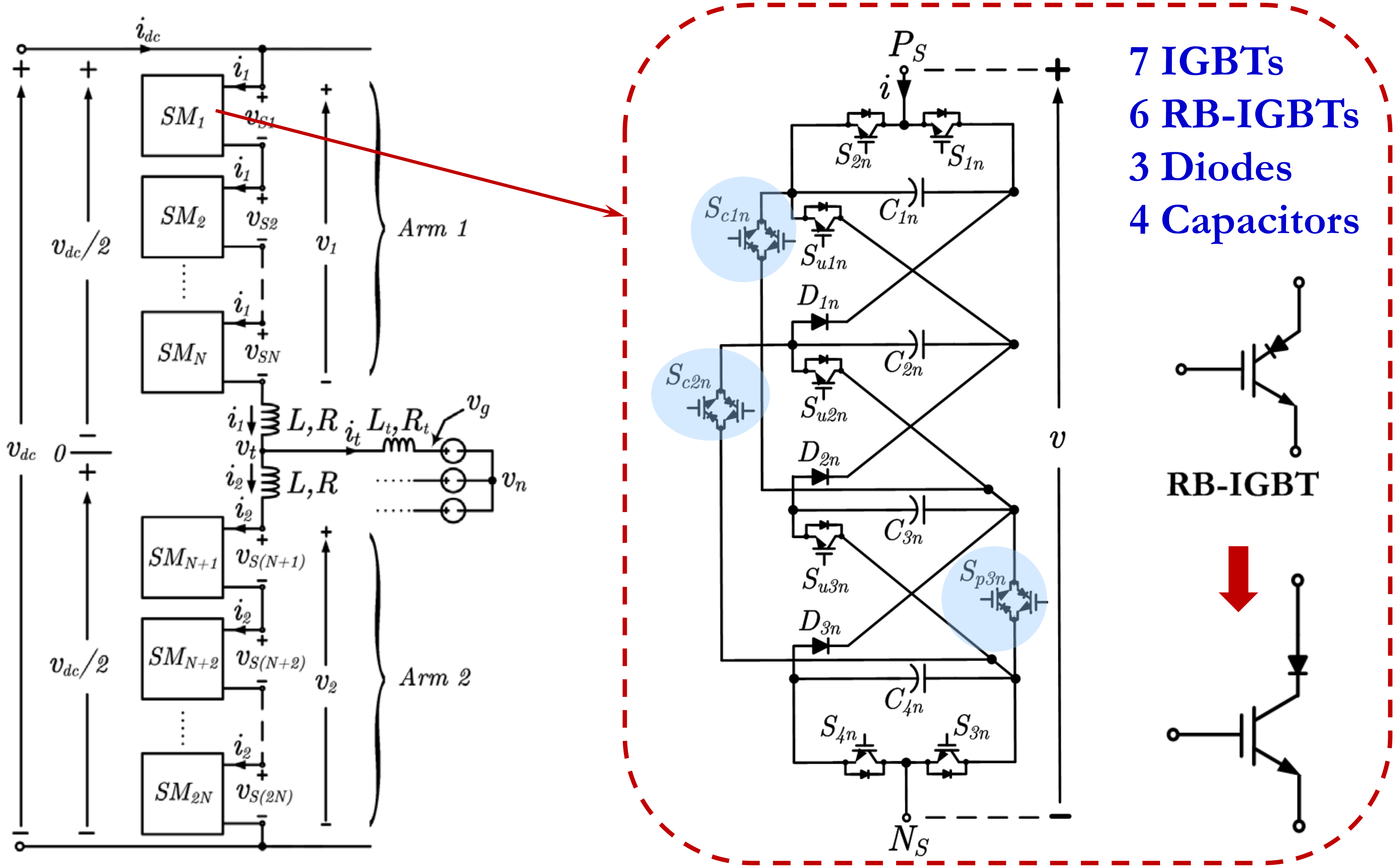
Solutions to DC Fault Problem

- **Half-Bridge Sub-Module (HBSM) with reliance on AC circuit breakers and arm inductance for slow rise of current**
- **Full-Bridge Sub-Module (FBSM)**
  - At the expense of power losses
- **Alternative configurations**
  - Hybrids of HBSM and FBSM
  - Alternative sub-module designs

On our wish list

A topology that is as efficient as the HBSM and with the same dc-side fault handling capability as that of the FBSM

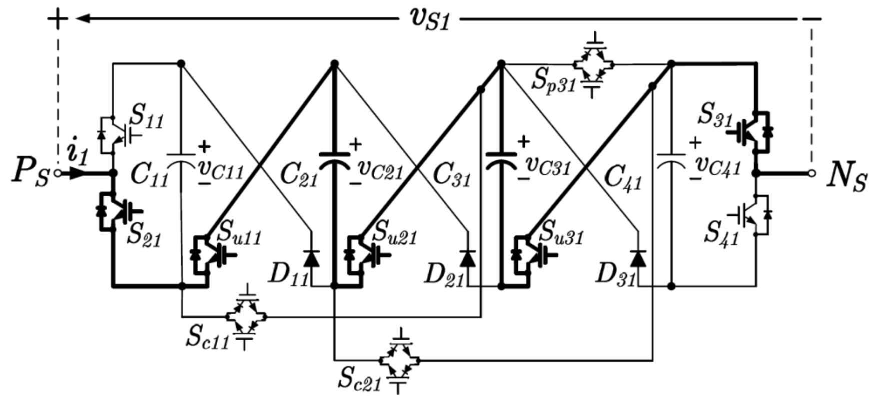
Example:
Lattice Sub-Module (LSM) Based HVDC System



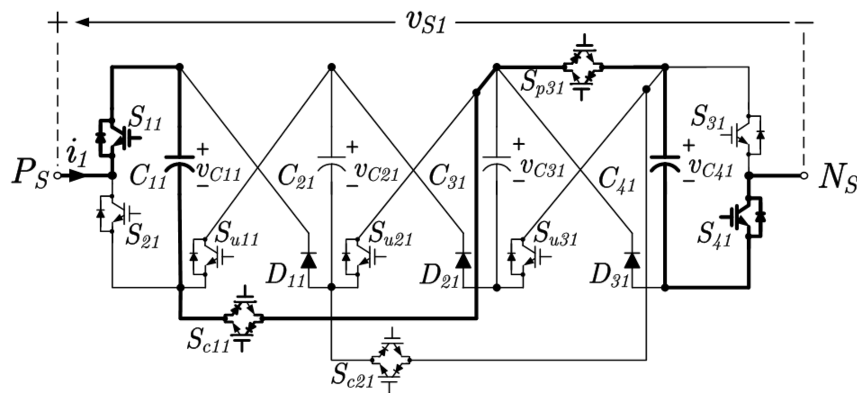
7 IGBTs
6 RB-IGBTs
3 Diodes
4 Capacitors

High-Efficiency Versus Regular Current Paths

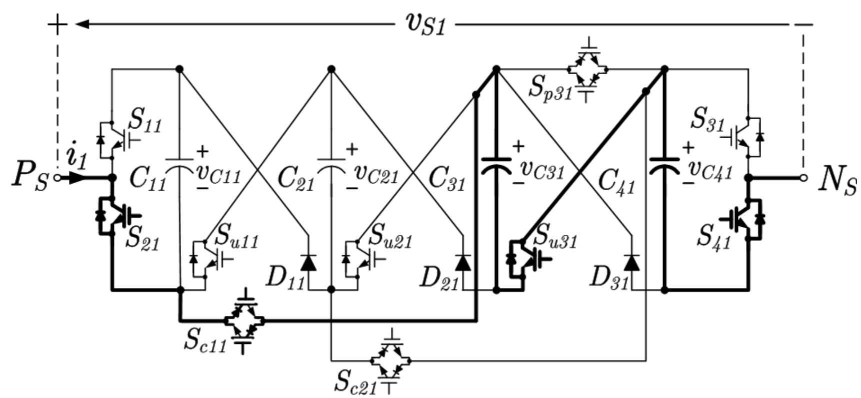
C2 and C3 inserted
(5 switches in series)



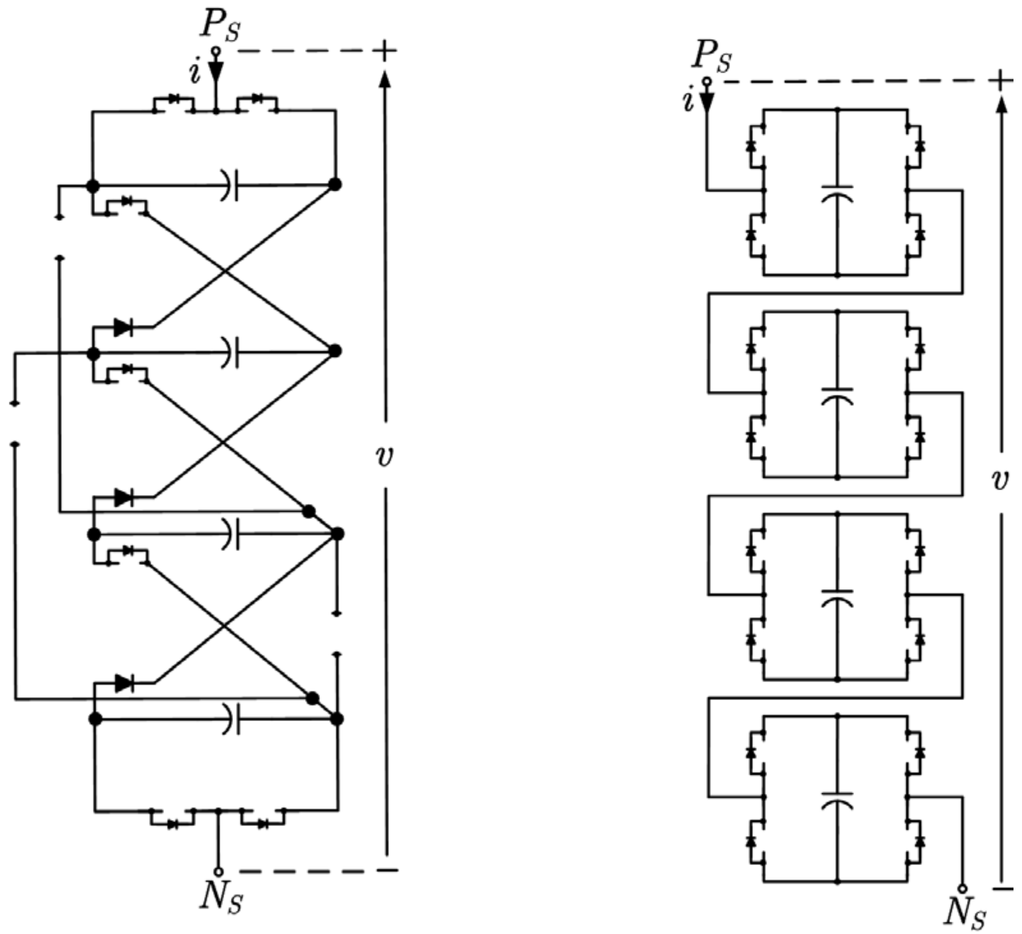
C1 and C4 inserted
(4 switches in series)



C3 and C4 inserted
(4 switches in series)

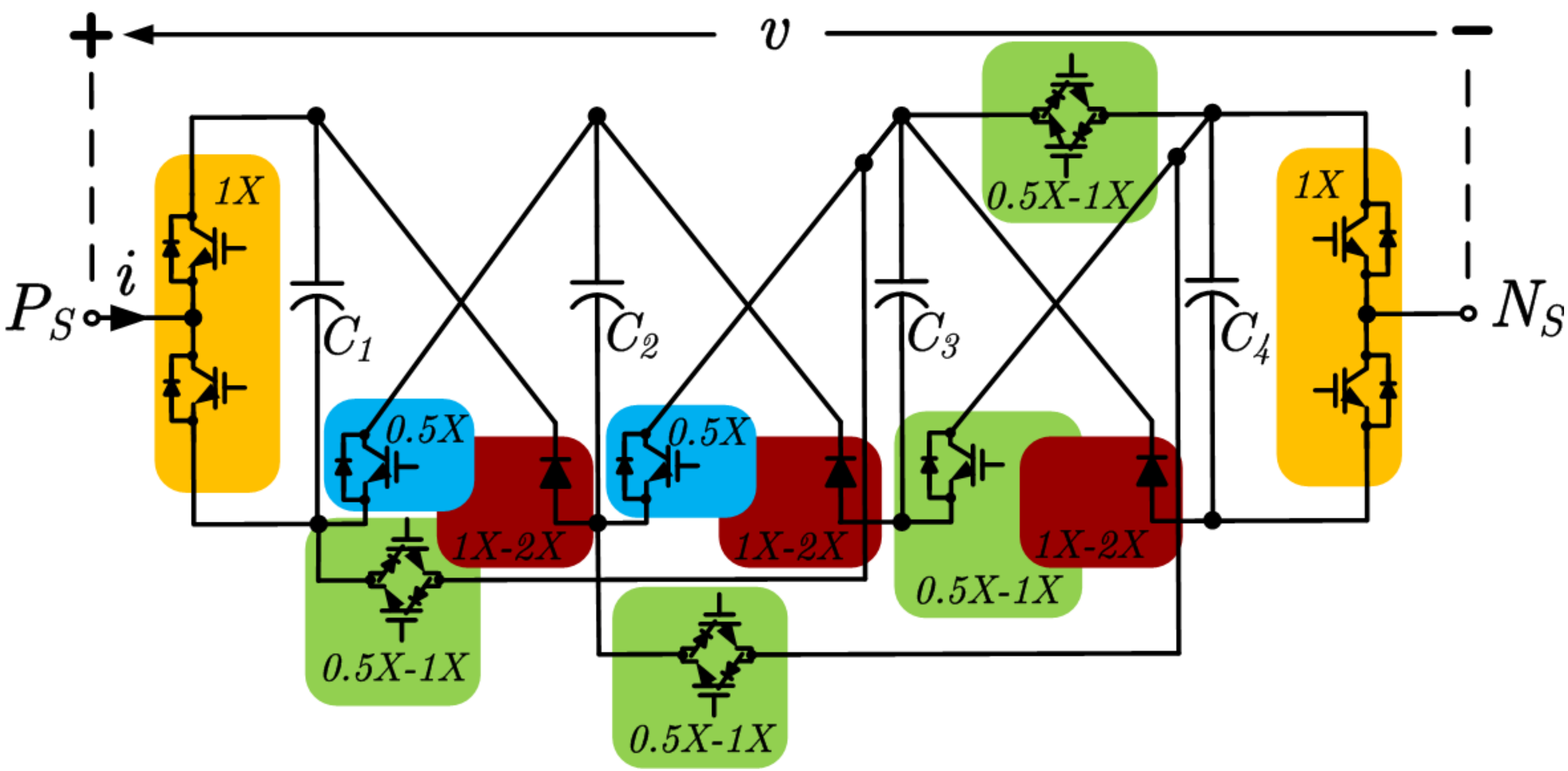


LSM-Based MMC Under DC-Side Fault and with Switches Disabled

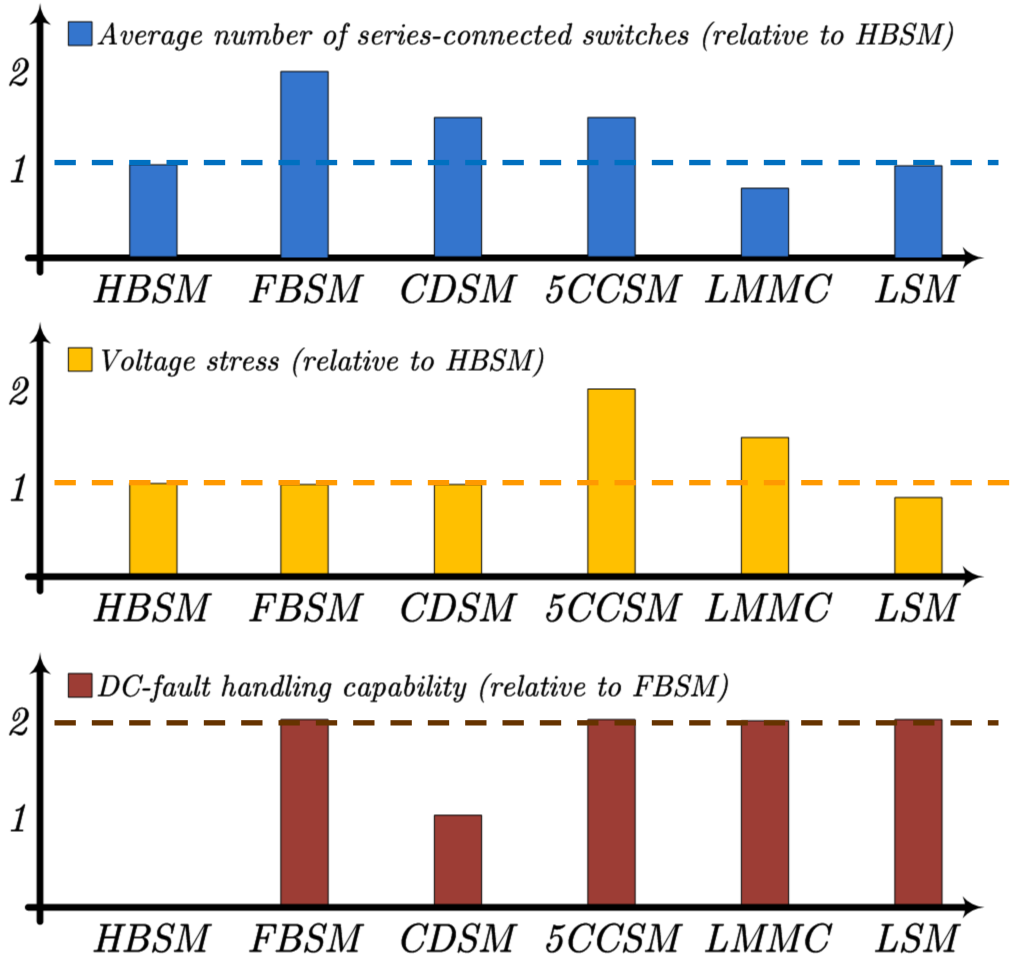


Off-State Switch Voltages

- *Su1* and *Su2* experience half capacitor voltage.
- *Sc1, Sc2, Sp3,* and *Su3* experience half or one capacitor voltage.
- *S1, S2, S3,* and *S4* experience one capacitor voltage.
- Diodes experience either one or, almost always, two capacitor voltages.



Comparison with Other Sub-Module Technologies



Legend

HBSM: Half-Bridge Sub-Module
FBSM: Full-Bridge Sub-Module
CDSM: Clamp-Doubled Sub-Module
5CCSM: 5-level Cross-Connected Sub-Module
LMMC: Lattice Modular Multi-Level Converter

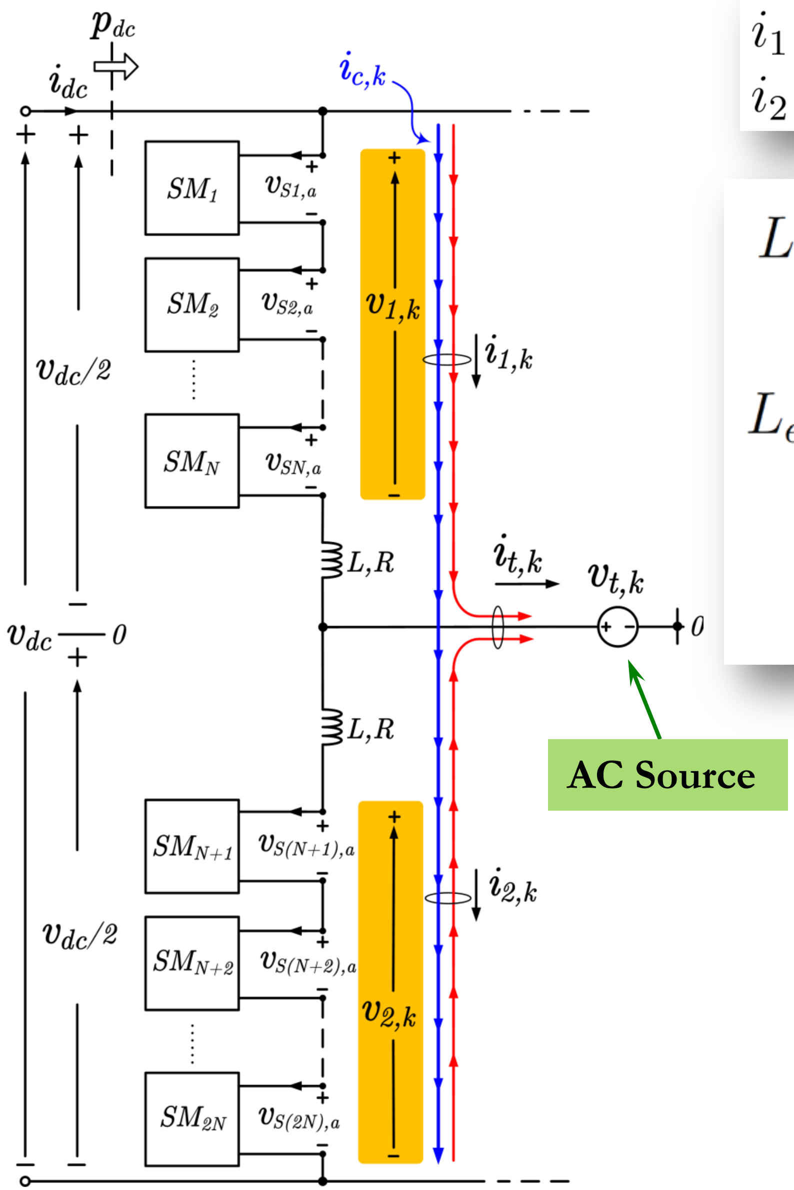
Topical Areas of Research

- **Modelling and Analysis**
  - Control design
  - Component sizing
  - Simulation

- **Power Electronics**
  - Alternative converter
  - Alternative submodule configurations

- **Other Utility Applications**
  - Integration of distributed energy resources
  - DC-DC Converters

Power Routing Capabilities



$$i_1 = i_c + i_t/2$$
$$i_2 = i_c - i_t/2$$

i_c: *Common-Mode Current*
i_t: *AC-side Current*

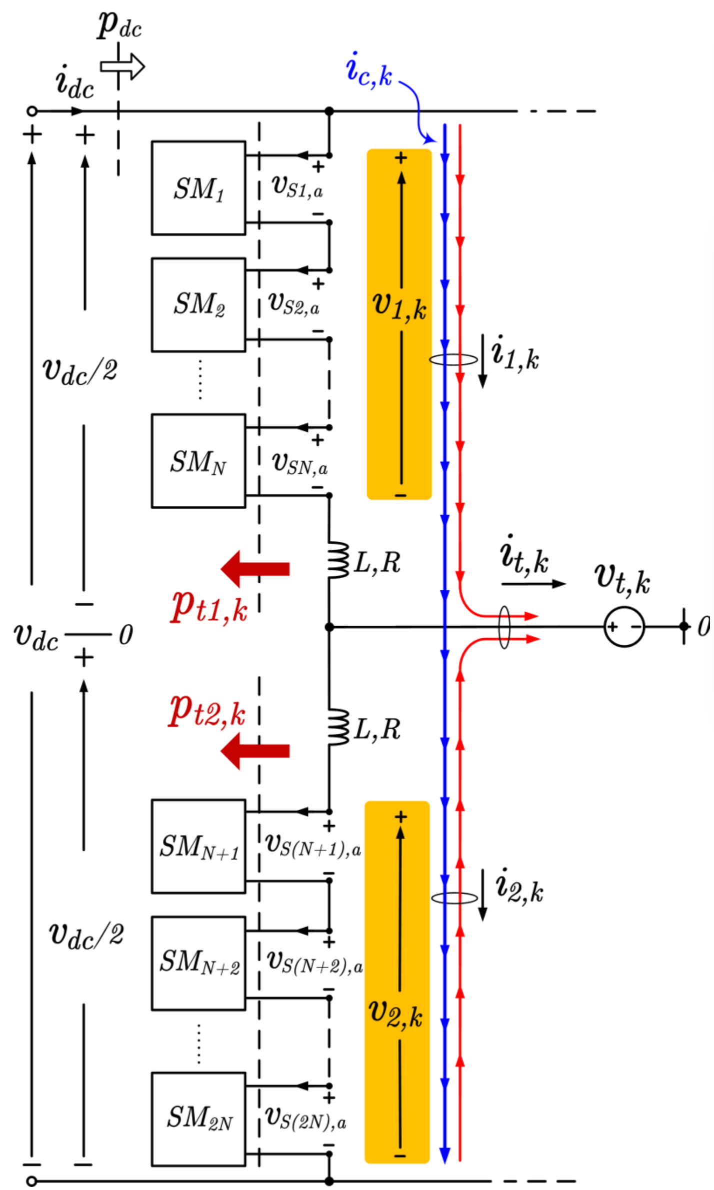
$$L\frac{d}{dt}i_{c,k} + Ri_{c,k} = -\frac{1}{2}\underbrace{(v_{1,k} + v_{2,k})}_{v_{\Sigma,k}} + \frac{1}{2}v_{dc};$$

$$L_e\frac{d}{dt}i_{t,k} + R_e i_{t,k} = \frac{1}{2}\underbrace{(-v_{1,k} + v_{2,k})}_{v_{\Delta,k}} - v_{t,k};$$

$$k = a, b, c$$

- **Common-mode Current Control**
  - By the *Arm Voltage Sum*
  - Per-phase, with a possibility of control in a ***dq*** frame
- **AC-Side Current Control**
  - By the *Arm Voltage Difference*
  - In a ***dq*** reference frame

Power Routing Capabilities (Cont'd)



P_{t1}: *Upper Arm Power*

P_{t2}: *Lower Arm Power*

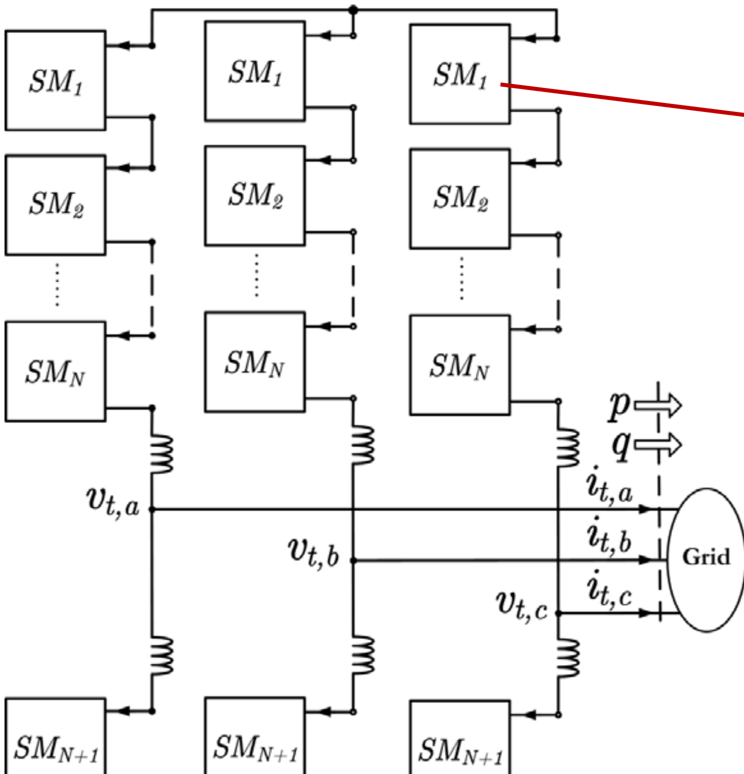
$$\underbrace{p_{t1,k} + p_{t2,k}}_{\text{Arm Power Sum}} = \underbrace{\overline{v_{dc} i_{c,k}}}_{\text{from DC link}} - \underbrace{\overline{v_{t,k} i_{t,k}}}_{\text{into AC Source}}$$

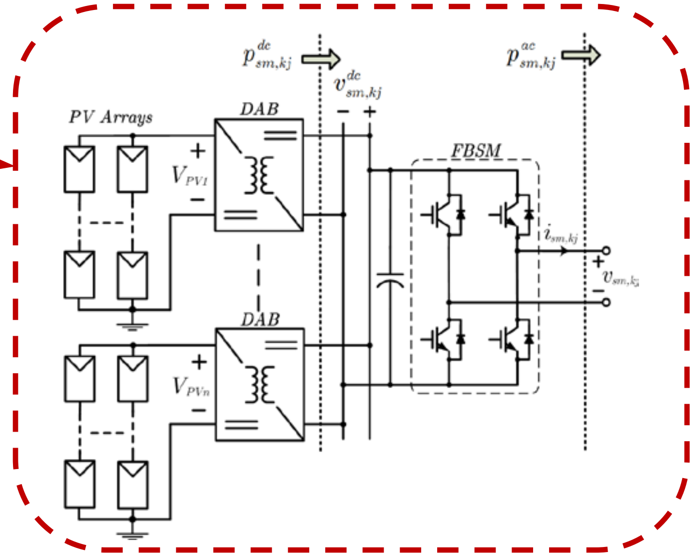
$$\underbrace{-p_{t1,k} + p_{t2,k}}_{\text{Arm Power Difference}} = 2\,\overline{v_{t,k} i_{c,k}} - \frac{1}{2}\overline{v_{dc} i_{t,k}}$$

Conclusions

- **Required components are easy to determine**
- **Power can be transferred from any arm to any other arm!**

Application Example: Integration of Photovoltaic Panels and Batteries



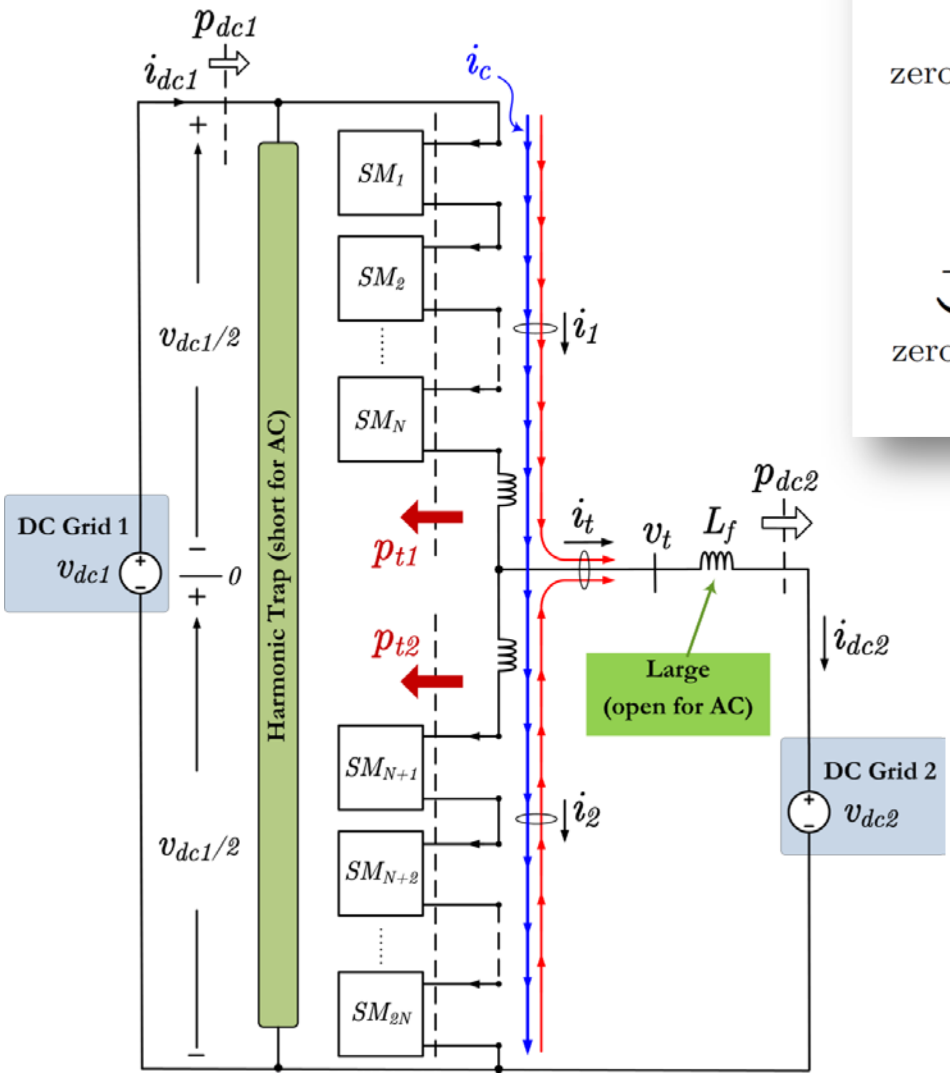


Note that dq-frame control is possible here for controlling the common-mode current components since the three leg currents sum up to zero.

$$\underbrace{p_{t1,k} + p_{t2,k}}_{\text{non-zero}} = v_{dc}\overline{i_{c,k}} - \underbrace{\overline{v_{t,k} i_{t,k}}}_{\text{phase } k \text{ power}}$$

$$\underbrace{-p_{t1,k} + p_{t2,k}}_{\text{non-zero}} = 2\,\overline{v_{t,k} i_{c,k}} - \frac{1}{2} v_{dc} \underbrace{\overline{i_{t,k}}}_{\text{zero}}$$

MMC-Based DC-DC Converters



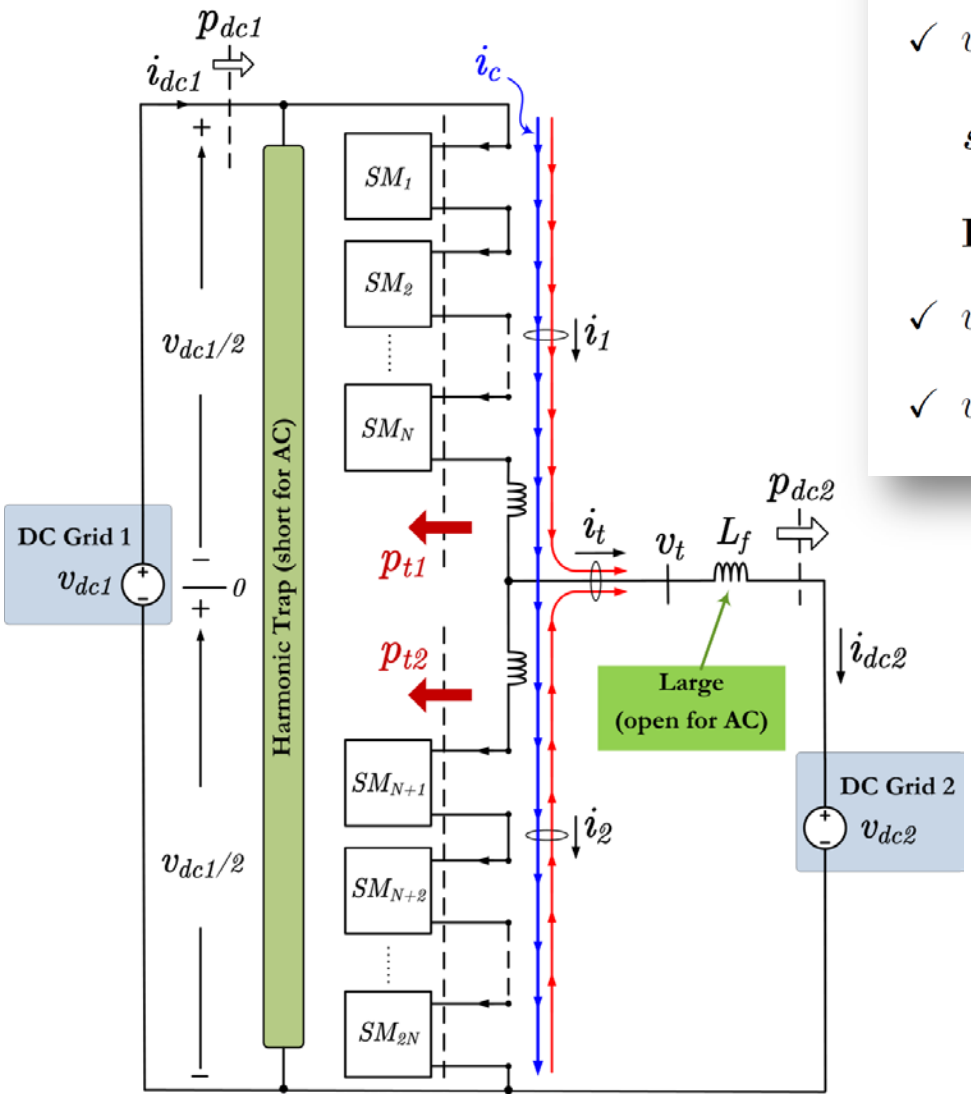
$$\underbrace{p_{t1}+p_{t2}}_{\text{zero in steady state}} = \underbrace{v_{dc1}\left(\overline{i_c}+\frac{i_t}{2}\right)}_{\text{from Grid 1}} - \underbrace{v_{dc2}i_t}_{\text{to Grid 2}}$$

$$\underbrace{-p_{t1}+p_{t2}}_{\text{zero in steady state}} = \underbrace{-\frac{1}{2}v_{dc1}i_t}_{\text{fixed}} + 2\overline{v_t i_c}$$

Conclusions

- i_c must also have an AC component (hence we need a harmonic trap).
- v_t must also have an AC component (hence we need L_f).

MMC-Based DC-DC Converters (Cont'd)



✓ $i_c(t) = (d - 0.5)i_{dc2} + I_m \cos(\omega t)$,

✓ $v_t(t) = (d - 0.5)v_{dc1} + V_m \cos(\omega t)$,

subject to $V_m I_m = (1 - d)P_{dc2}$.

Hence:

✓ $v_1(t) = (1 - d)v_{dc1} + \sqrt{(L\omega I_m)^2 + V_m^2} \cos(\omega t - \alpha)$,

✓ $v_2(t) = dv_{dc1} + \sqrt{(L\omega I_m)^2 + V_m^2} \cos(\omega t + \alpha)$,

where
$d = v_{dc2}/v_{dc1}$
$\alpha = tan^{-1}(L\omega I_m/V_m)$.

Summary and Conclusions

- HVDC Transmission based on the LCC technology has a established track record for niche applications in the predominantly AC legacy power system.
- Multi-terminal DC grids and large-scale integration of renewable energy resources have sparked new applications.
- Emerging multi-terminal HVDC systems are based on the VSC technology where the MMC is showing great promise.
- Research and development efforts are being dedicated to developing fault tolerant and efficient designs, robust control methods, computationally-efficient simulation techniques, and wider applications for the MMC.

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  - Prof. Nilanjan Chaudhuri
  - Prof. Reza Iravani
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The End

Thank You