HVDC Transmission Systems Based on Modular Multilevel Converters

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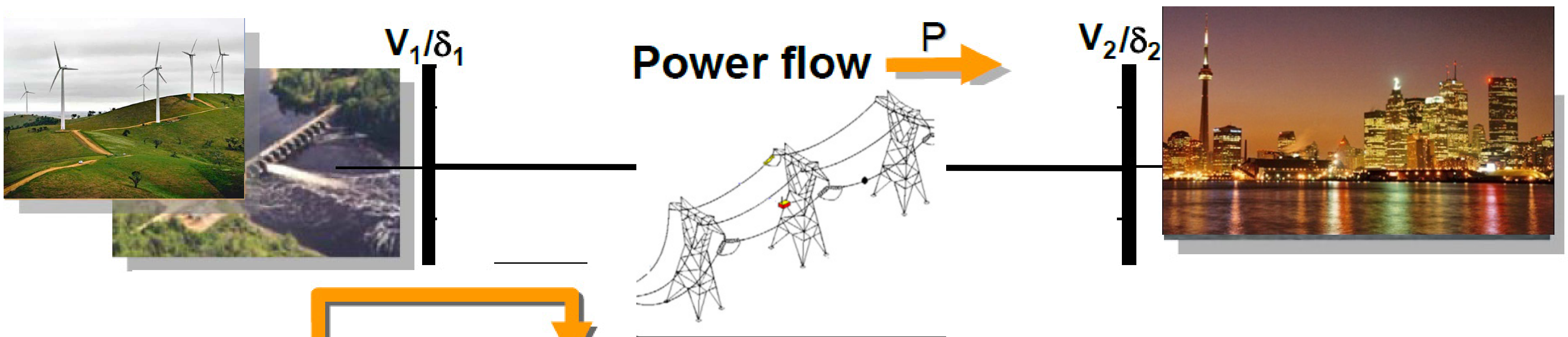
Presentation Outline

- **Introduction to HVDC Transmission Systems**
- **Converter Requirements for HVDC Transmission Systems**
- **The Modular Multilevel Converter (MMC)**
  - **- Features**
  - **- Operational Challenges**
  - **- Solutions**
- **Future Work**

Introduction: AC Corridor's Power Flow Control



$$P = \frac{V_1 V_2}{X_{12}} \sin(\delta_1 - \delta_2)$$

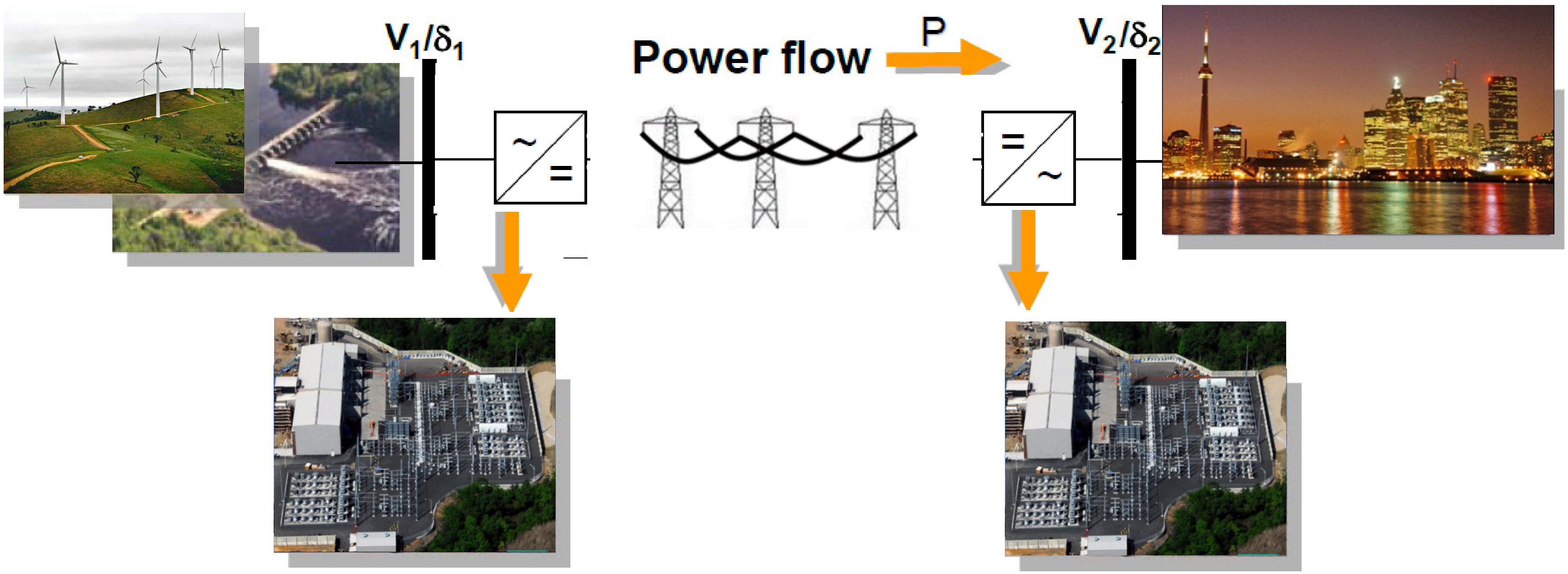
Boost or control ac voltage
(V)

Reduce line reactance
(X)

Regulate phase angle
(δ)

Ref: ABB

Introduction: DC Corridor's Power Flow Control



$$P = V_{DC} . I_{DC}$$

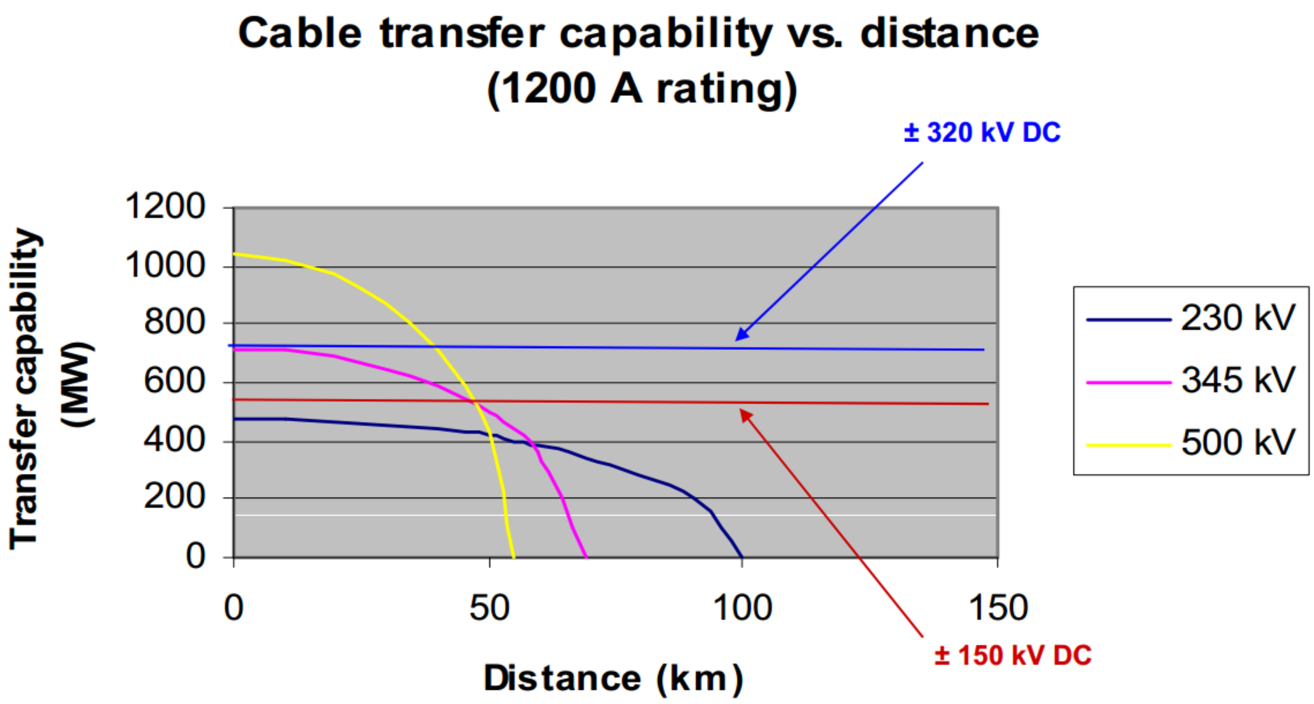
HVDC: High Voltage Direct Current Transmission

Introduction: AC vs DC Transmission

AC Transmission	DC Transmission
✕ Loading a function of Z	✓ Power flow controlled
✕ Charging current a function of voltage level and cable capacitance	✓ No charging current effect or need for shunt compensation
✕ Distance limitation	✓ No distance limitation
✕ 3 cables	✓ 2 cables

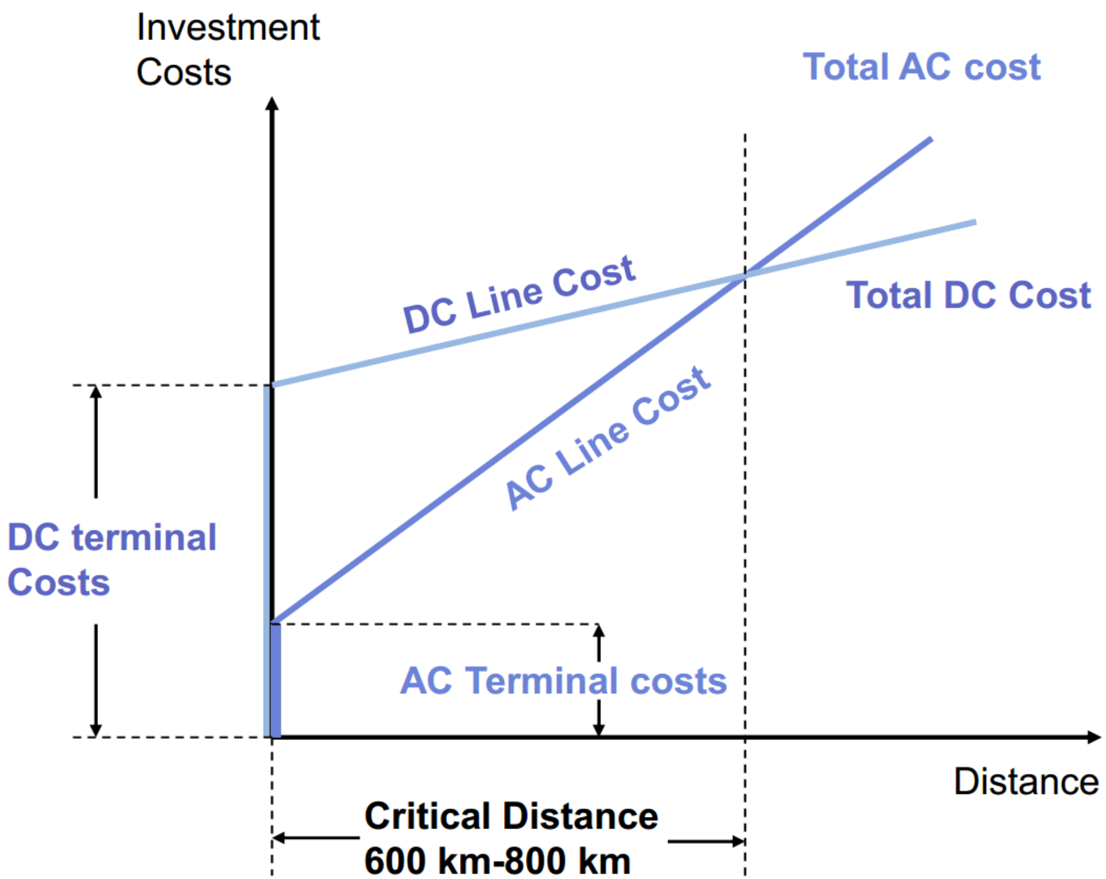
Introduction: AC vs DC Transmission

- Due to reactive power charging, AC transfer capacity is dramatically reduced with distance
- DC transfer capacity is almost independent of distance



Ref: ABB

Introduction: Overhead Line Transmission Investment vs Cost



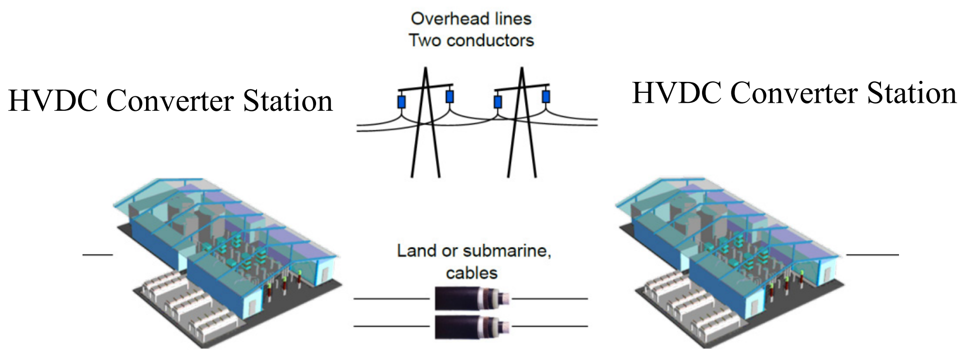
Ref: ABB

Introduction: Types of HVDC Systems

- Point-to-Point Systems

  - Overhead lines

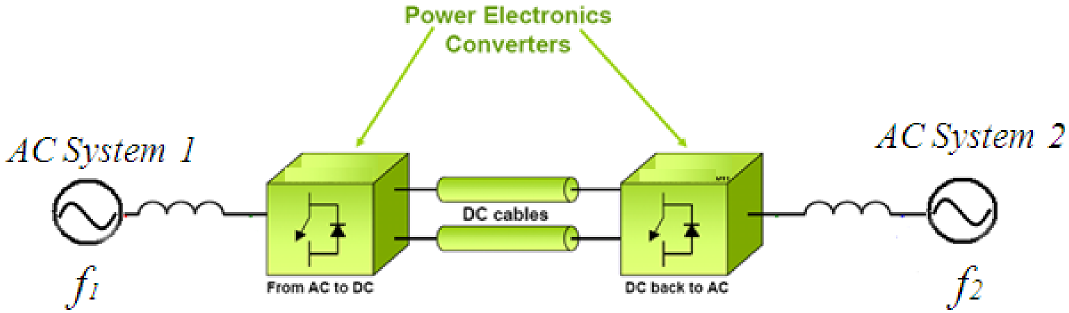
  - Subsea or underground cables

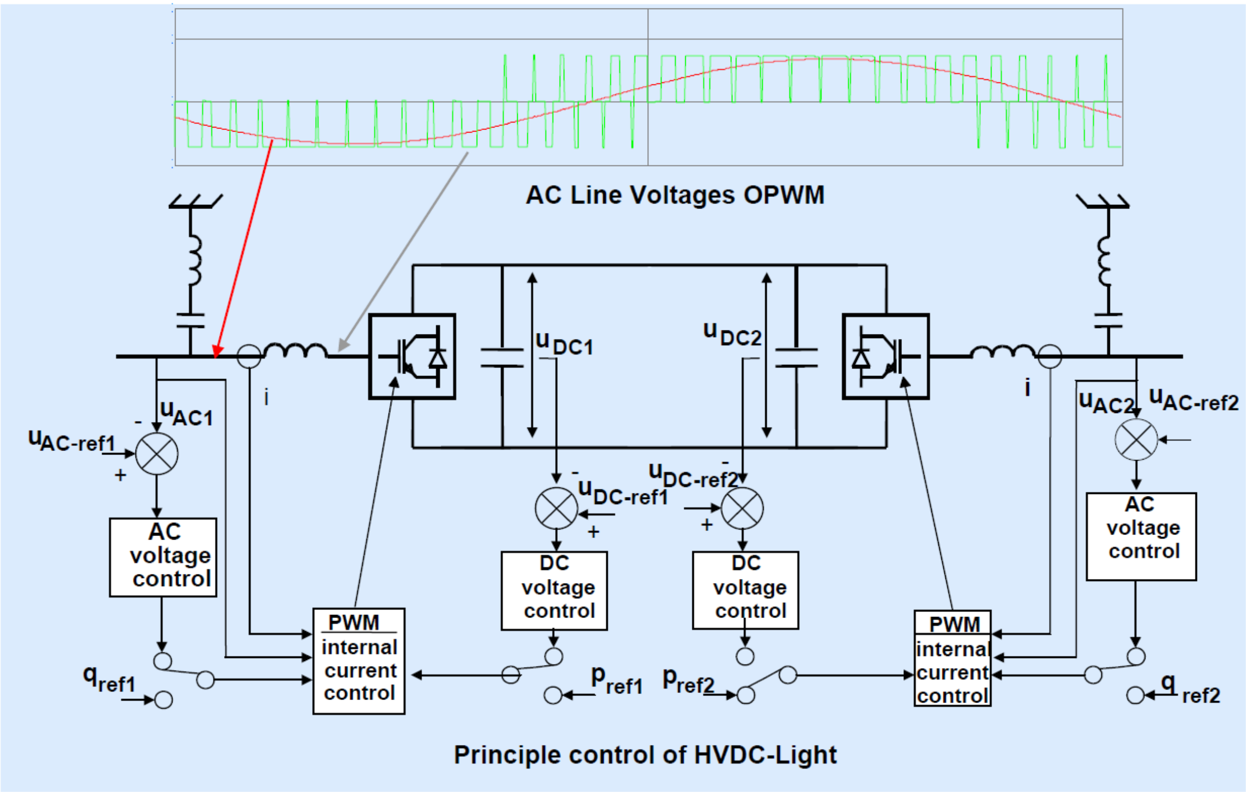


- Back-to-Back Systems

  - Interconnection of asynchronous AC grids

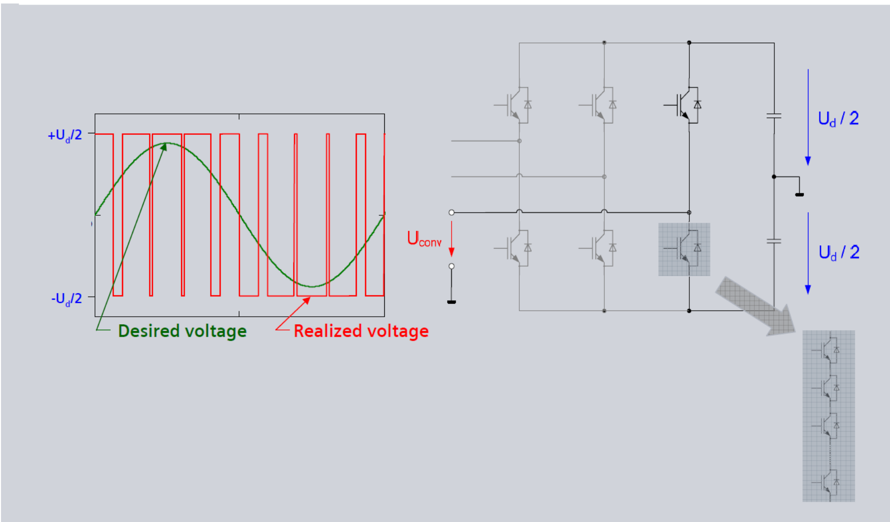
Introduction: Basics of HVDC Systems

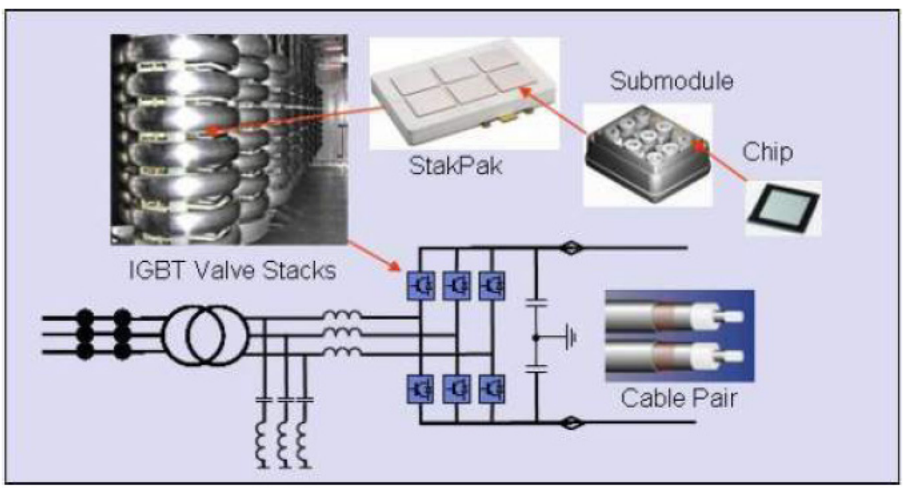




Ref: ABB

HVDC Technology: Converter Requirements



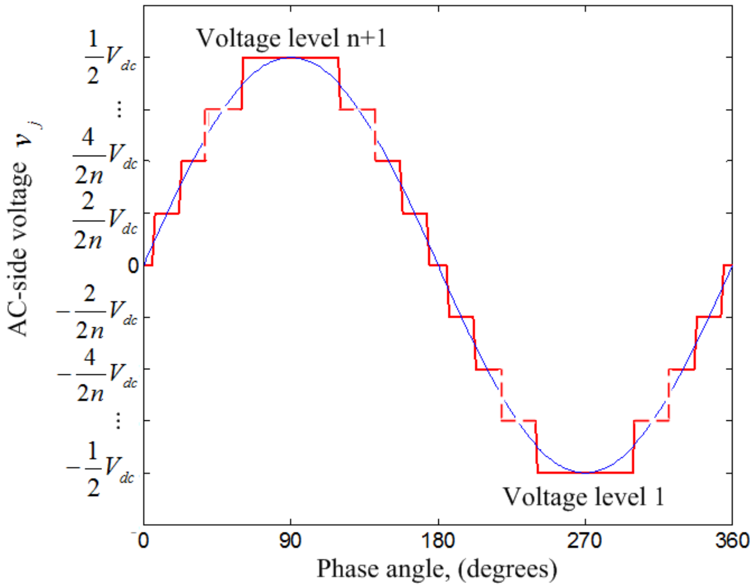


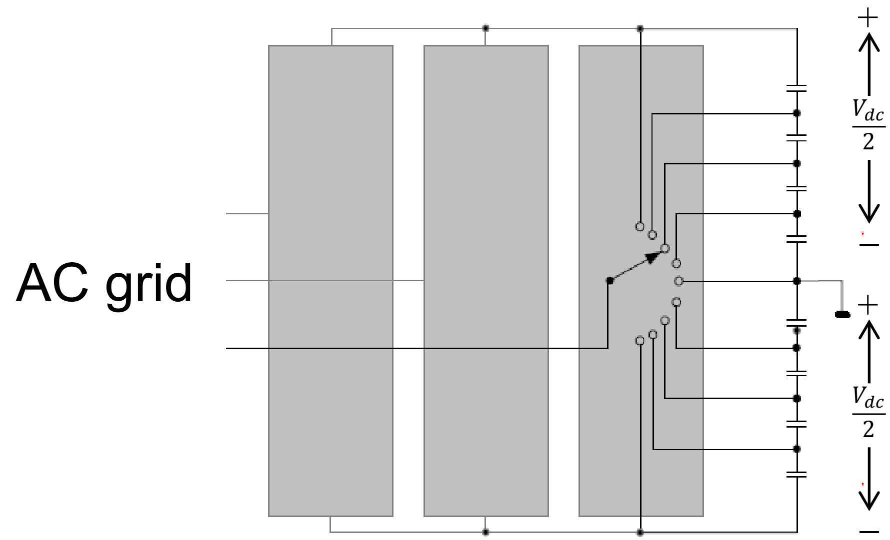
Shortcomings:

- ✕ Harmonic distortion
- ✕ Switching frequency and power losses

Ref: ABB

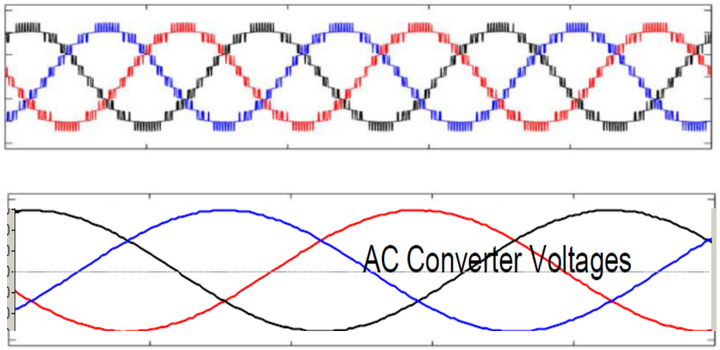
HVDC Technology: Converter Requirements

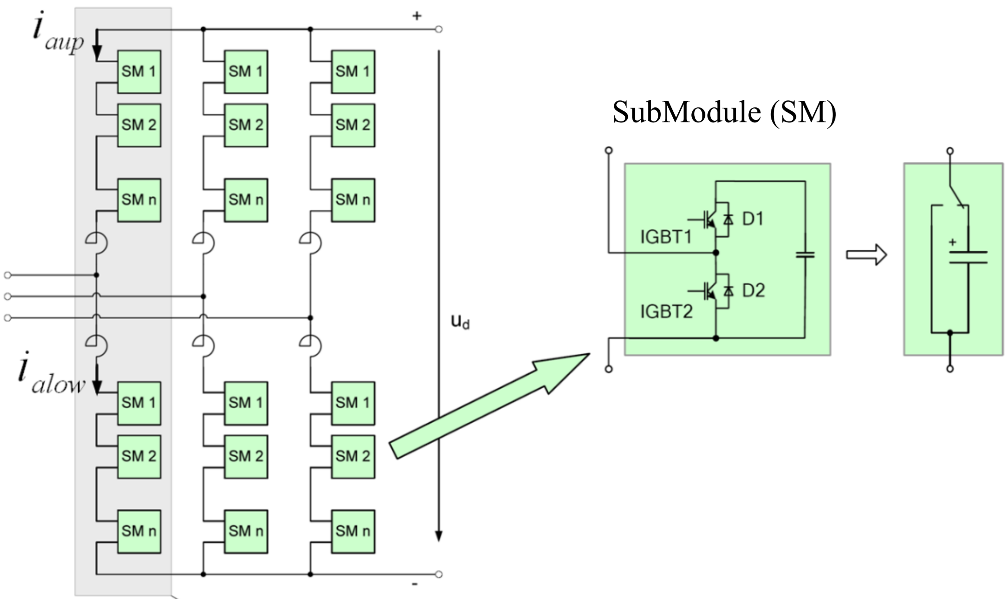




- ✓ Staircase voltage waveform ==> Reduced harmonic distortion and filtering size
- ✓ Low switching frequency ==> High efficiency

The MMC





Features:

✓ Modular and scalable design

✓ Smooth and sinusoidal waveform

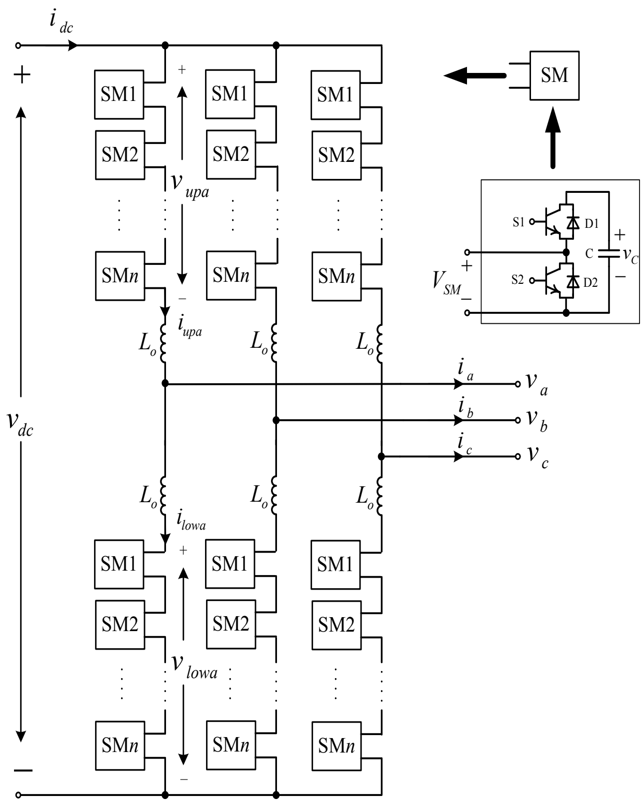
✓ Increased reliability and redundancy

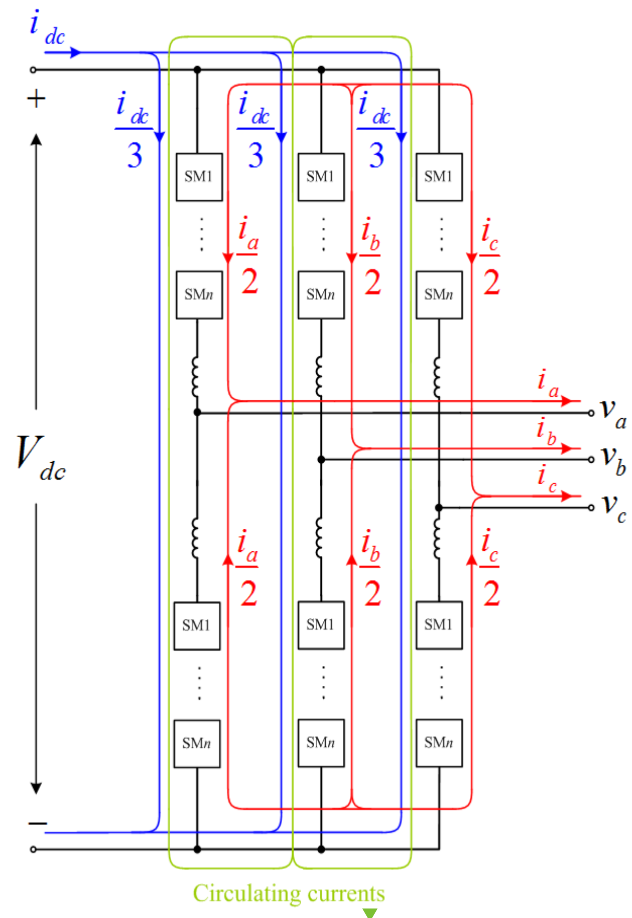
Challenges:

✗ SM capacitor voltage balancing

✗ Circulating currents

Equivalent Circuit of an MMC





$$i_j = i_{upj} - i_{lowj}.$$

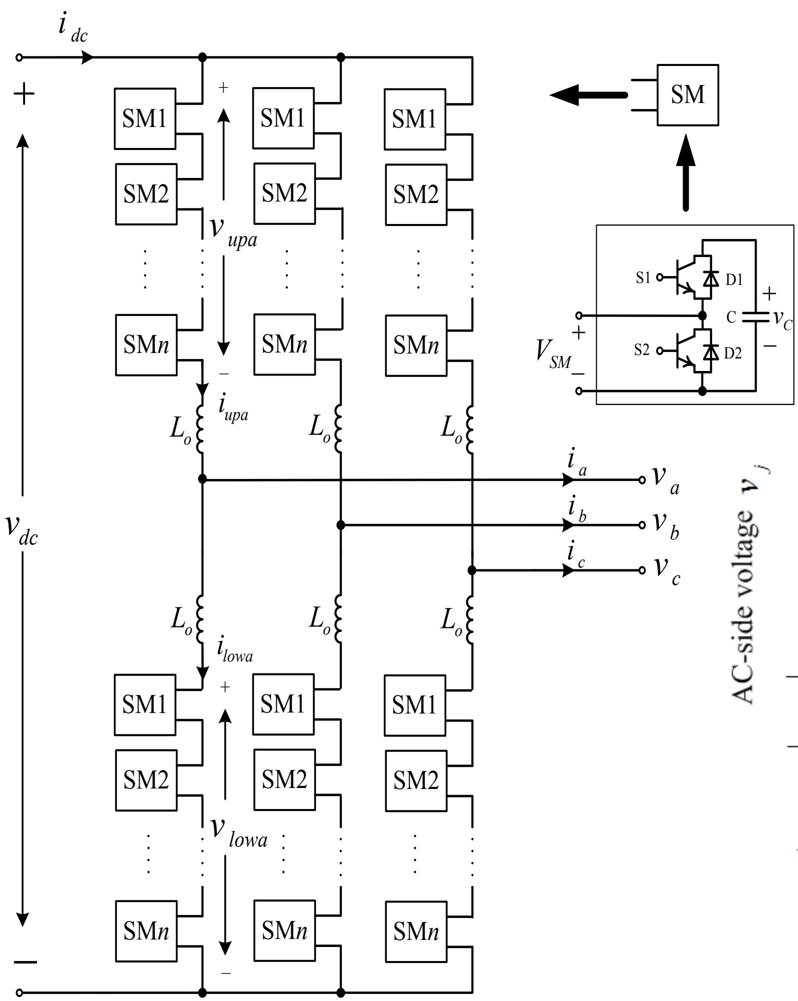
$$i_{upj} = \frac{i_j}{2} + \frac{i_{dc}}{3} + i_{zj},$$

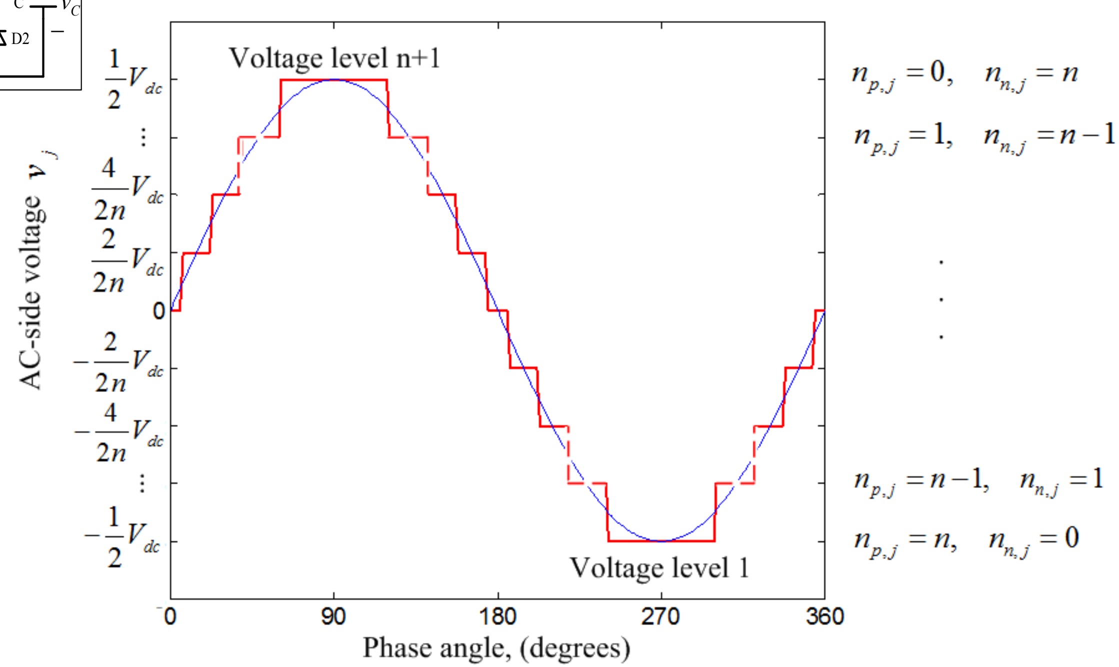
$$i_{lowj} = -\frac{i_j}{2} + \frac{i_{dc}}{3} + i_{zj},$$

$$i_{zj} = \frac{1}{2}(i_{upj} + i_{lowj}) - \frac{i_{dc}}{3},$$

$$\frac{V_{dc}}{2} - \frac{v_{lowj} + v_{upj}}{2} = l\frac{di_{zj}}{dt}.$$

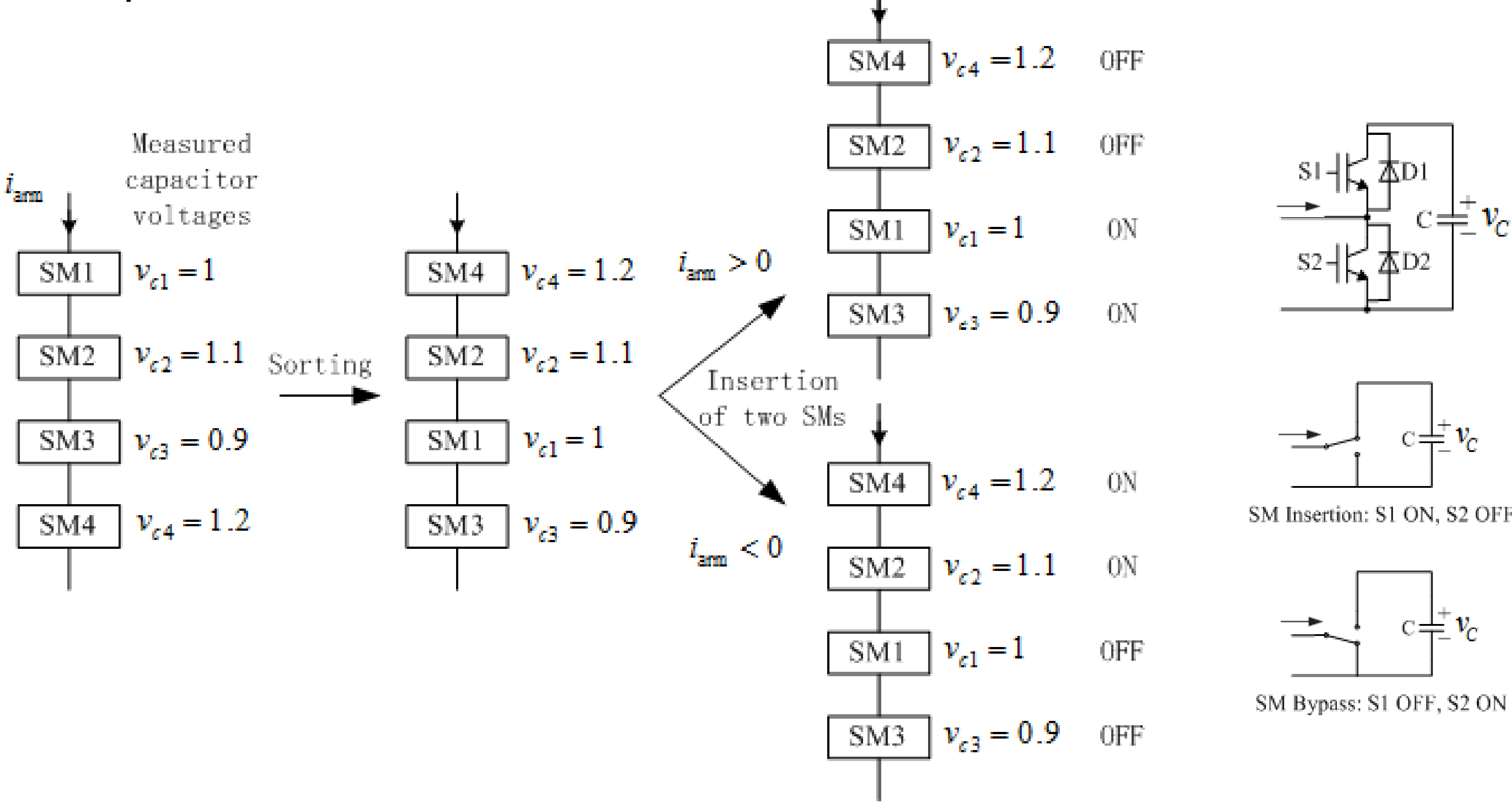
SM Capacitor Voltage Balancing



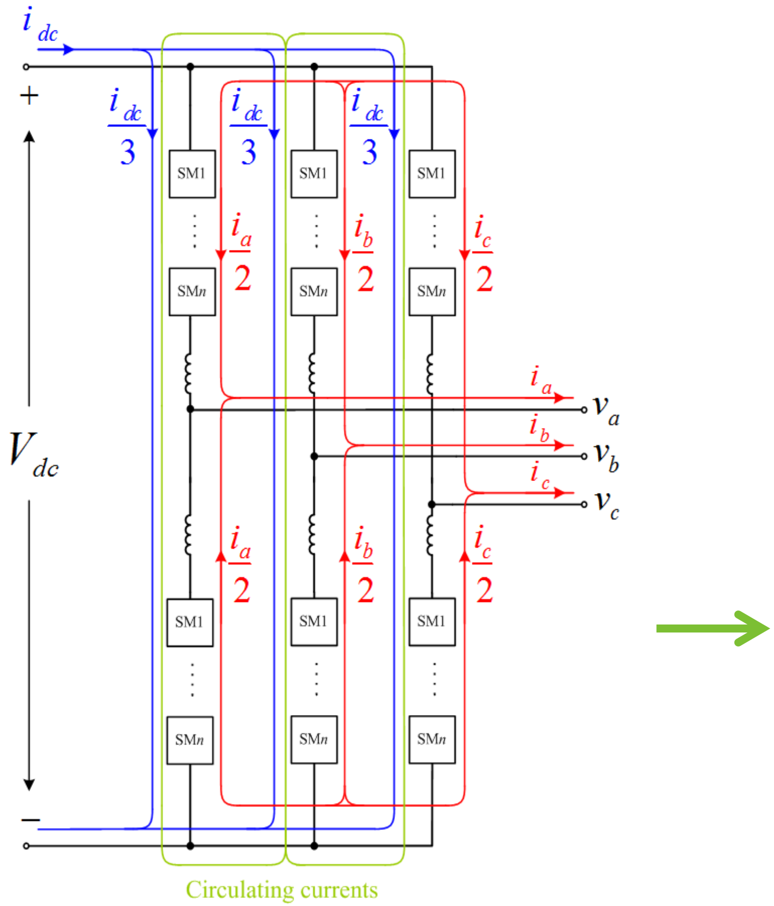


SM Capacitor Voltage Balancing

Example: Five-Level MMC



Circulating Current Control



High circulating current:

- Rating value/size of components
- SM capacitor voltage ripple
- Power losses

$$i_j = i_{upj} - i_{lowj}.$$

$$i_{zj} = \frac{1}{2}(i_{upj} + i_{lowj}) - \frac{i_{dc}}{3},$$

$$\frac{V_{dc}}{2} - \frac{v_{lowj} + v_{upj}}{2} = l\frac{di_{zj}}{dt}.$$

Circulating Current Control

- Circulating current – contains 2nd harmonic predominantly

- Controllers to eliminate circulating current:
  - Proportional Resonant (PR) Controller
  - Predictive Circulating Current Controller

Circulating Current Control: PR Controller

- Circulating current dynamics:

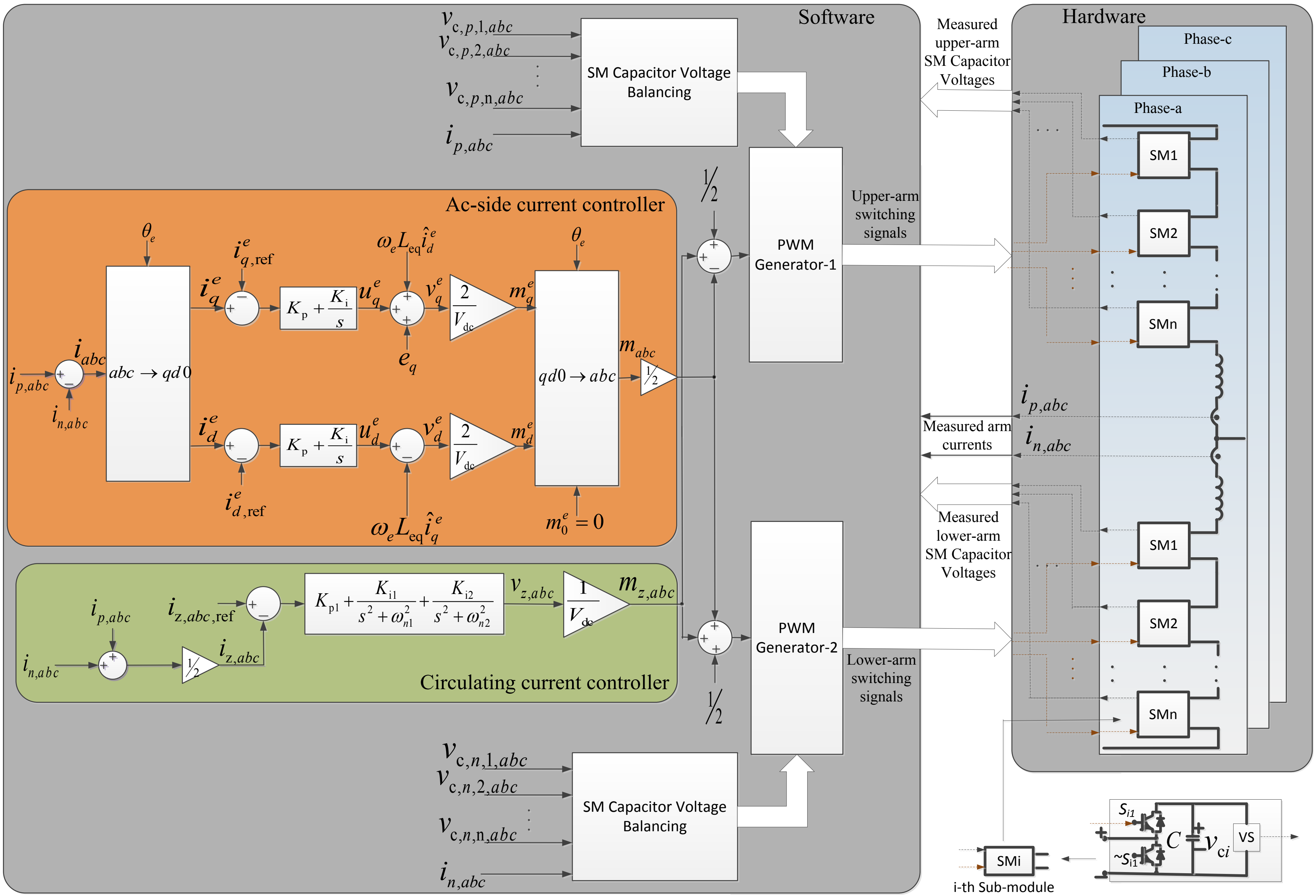
$$L_o \frac{\mathrm{d}i_{z,abc}}{\mathrm{dt}} + R_o i_{z,abc} = v_{z,abc} \approx m_{z,abc} V_{\mathrm{dc}}$$

- PR Controller:

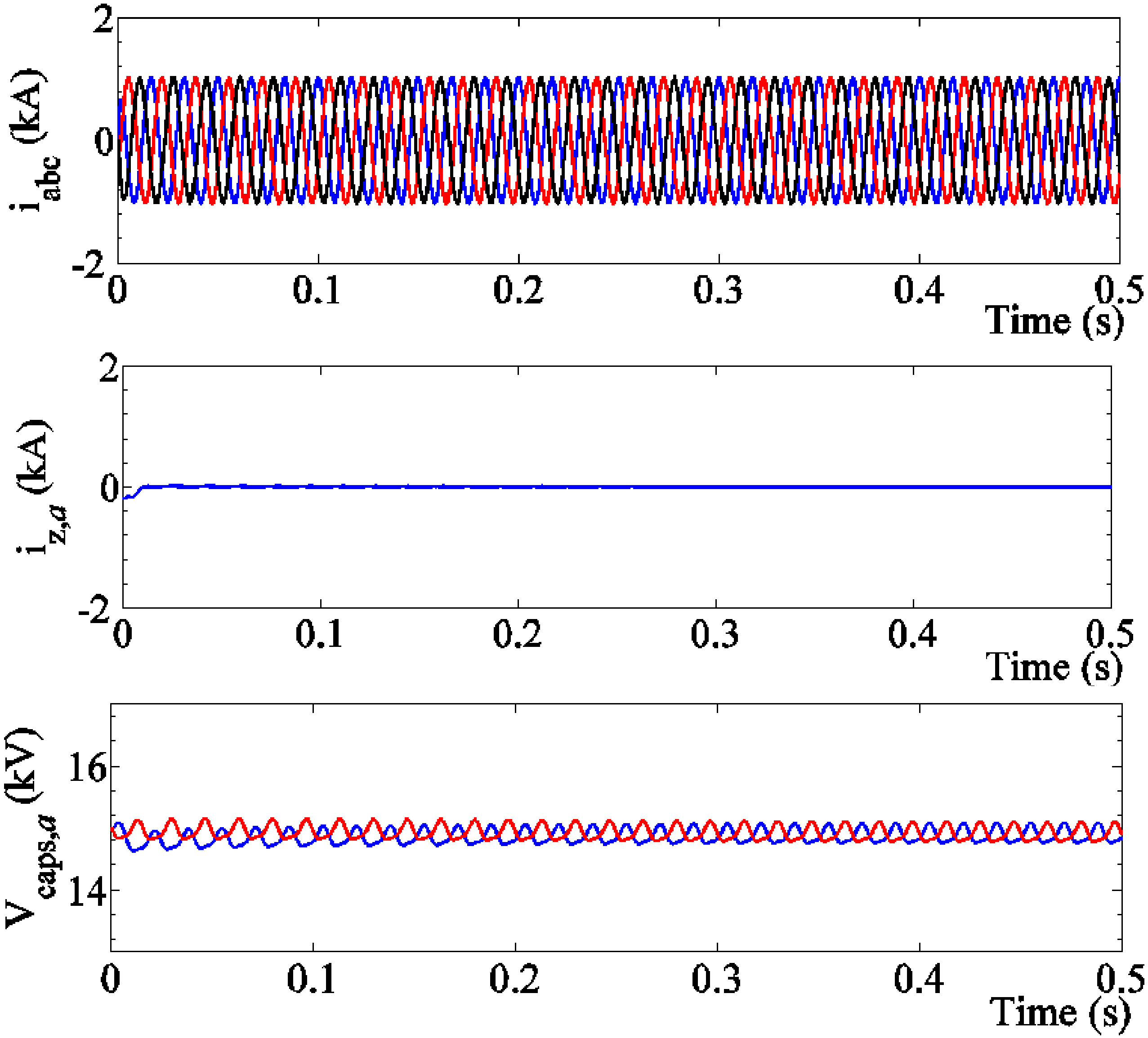
$$K_{p1} + \frac{K_{i1} s}{s^2 + \omega_{n1}^2} + \frac{K_{i2} s}{s^2 + \omega_{n2}^2}$$

  - *ω_{n1} and ω_{n2} are tuned to 2nd and 4th harmonic.*

Circulating Current Control: PR Controller



Circulating Current Control: PR Controller

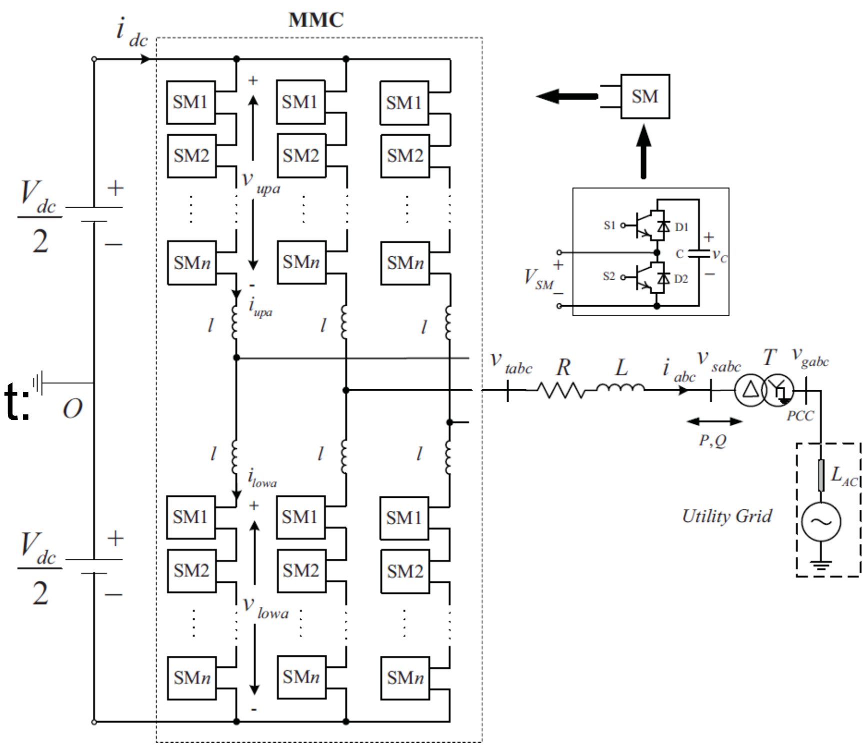


Circulating Current Control: Predictive Current Controller

From KVL:

$$\frac{V_{dc}}{2} - v_{upa} = l\frac{di_{upa}}{dt} + Ri_a + L\frac{di_a}{dt} + v_{sa},$$

$$\frac{V_{dc}}{2} - v_{lowa} = l\frac{di_{lowa}}{dt} - Ri_a - L\frac{di_a}{dt} - v_{sa}$$



Discrete model of the ac-side phase current:

$$i_a(k+1) = \frac{1}{K'}\left(\frac{v_{lowa}(k+1) - v_{upa}(k+1)}{2} - v_{sa}(k+1) + \frac{L'}{T_s}i_a(k)\right)$$

$$L' = \frac{l}{2} + L \qquad K' = \frac{L'}{T_s} + R$$

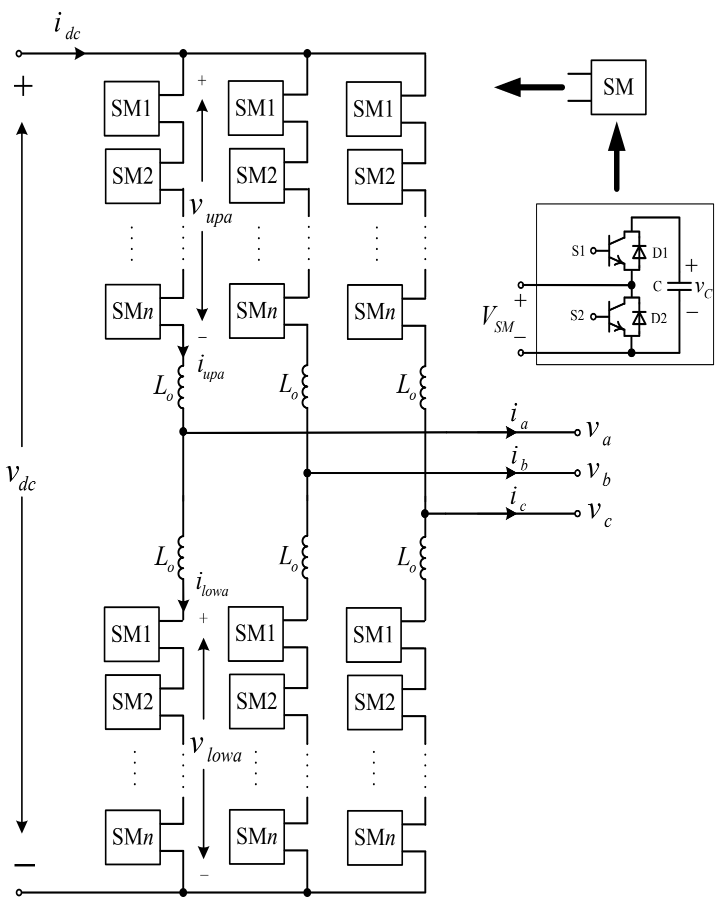
Discrete model for circulating current and SM capacitor voltages:

$$i_z(k+1) = \frac{T_s}{2l}\left(V_{dc} - v_{lowa}(k+1) - v_{upa}(k+1)\right) + i_z(k)$$

$$V_{cij}(k+1) = V_{cij}(k) + \frac{i_l(k)}{C}T_s$$

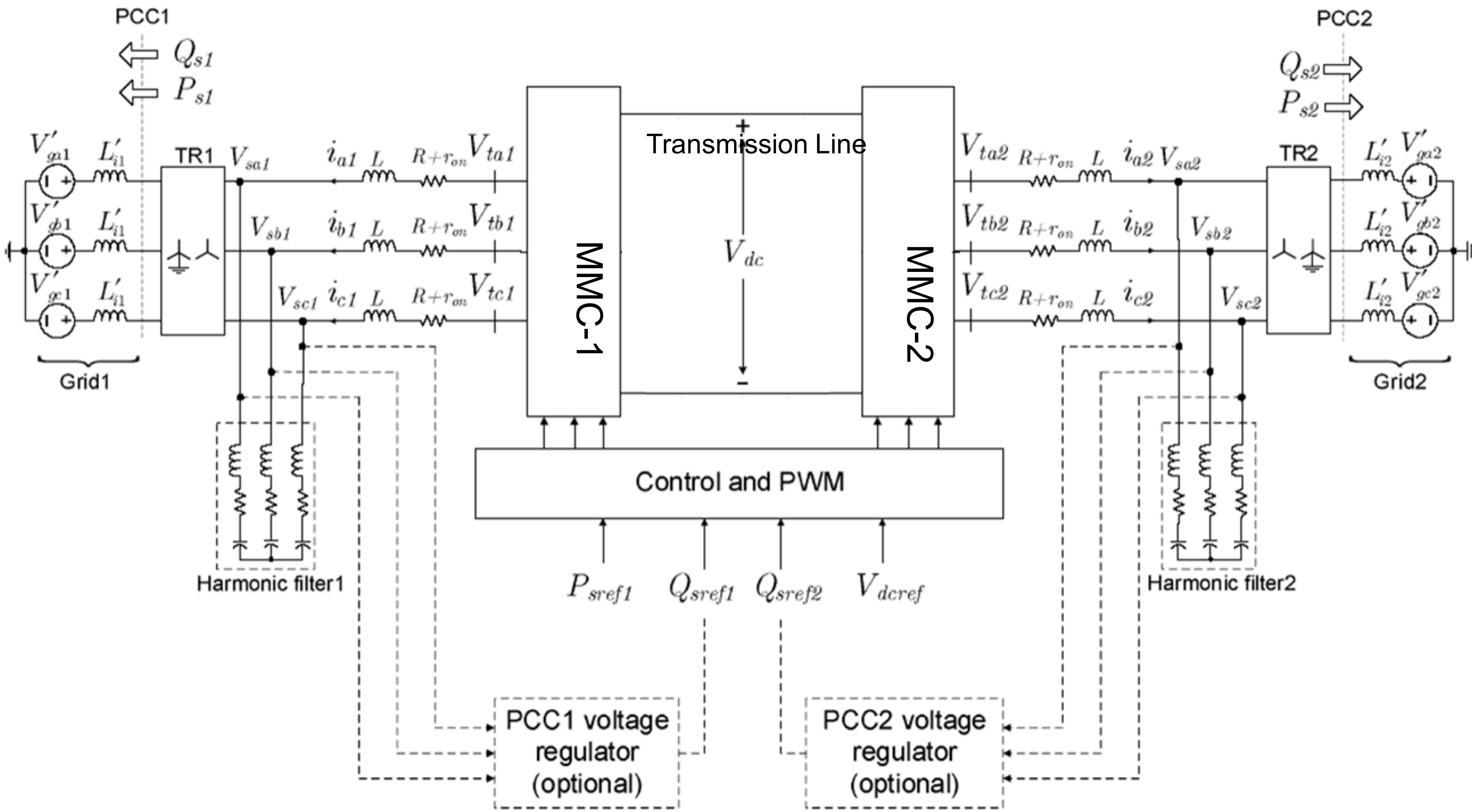
Predictive Circulating Current Control of MMC

Prediction based on cost function minimization:

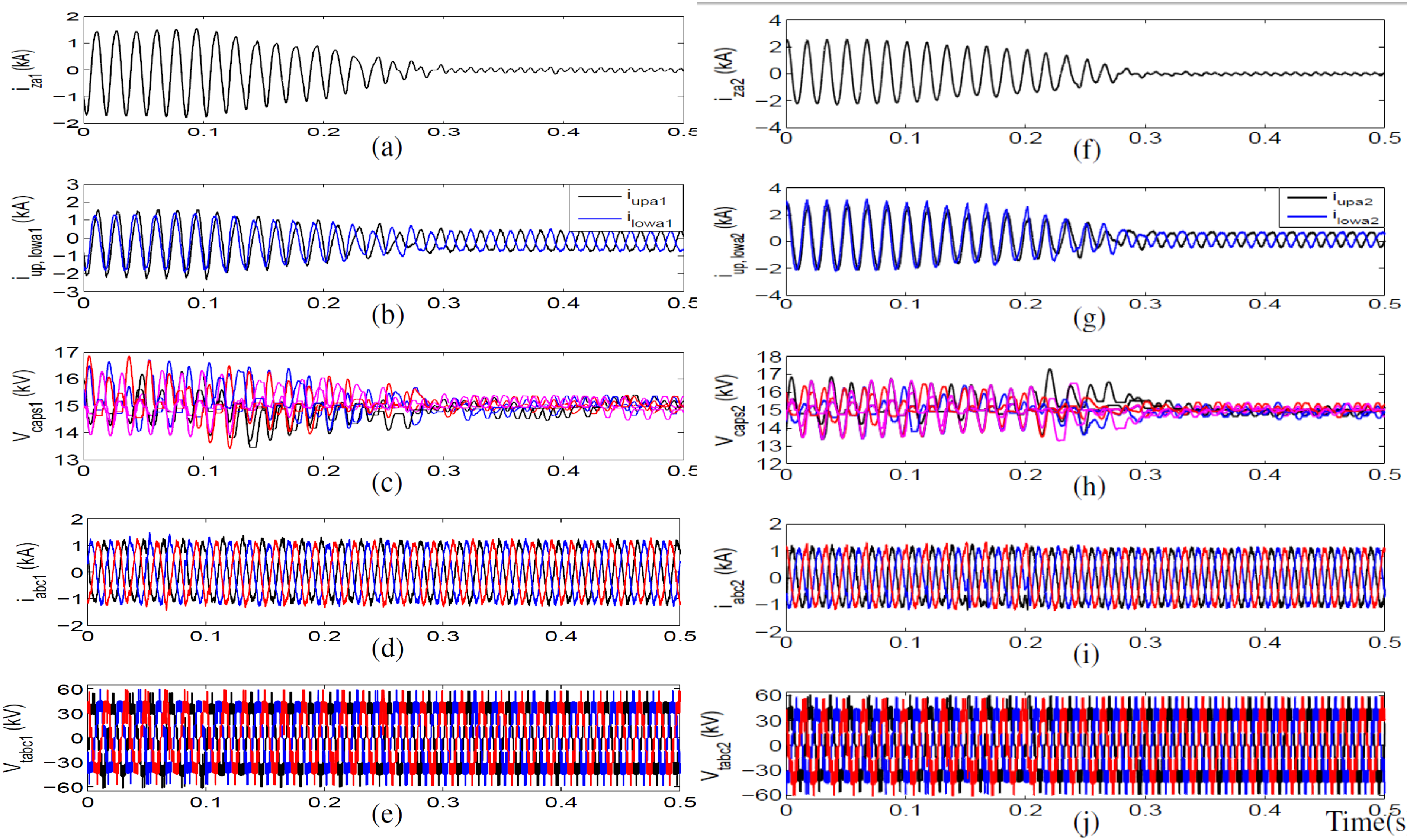


$$J = \lambda\left(\sum_i \left|V_{cij} - \frac{V_{dc}}{n}\right|\right) + \lambda_z \left|i_{zj}\right|$$

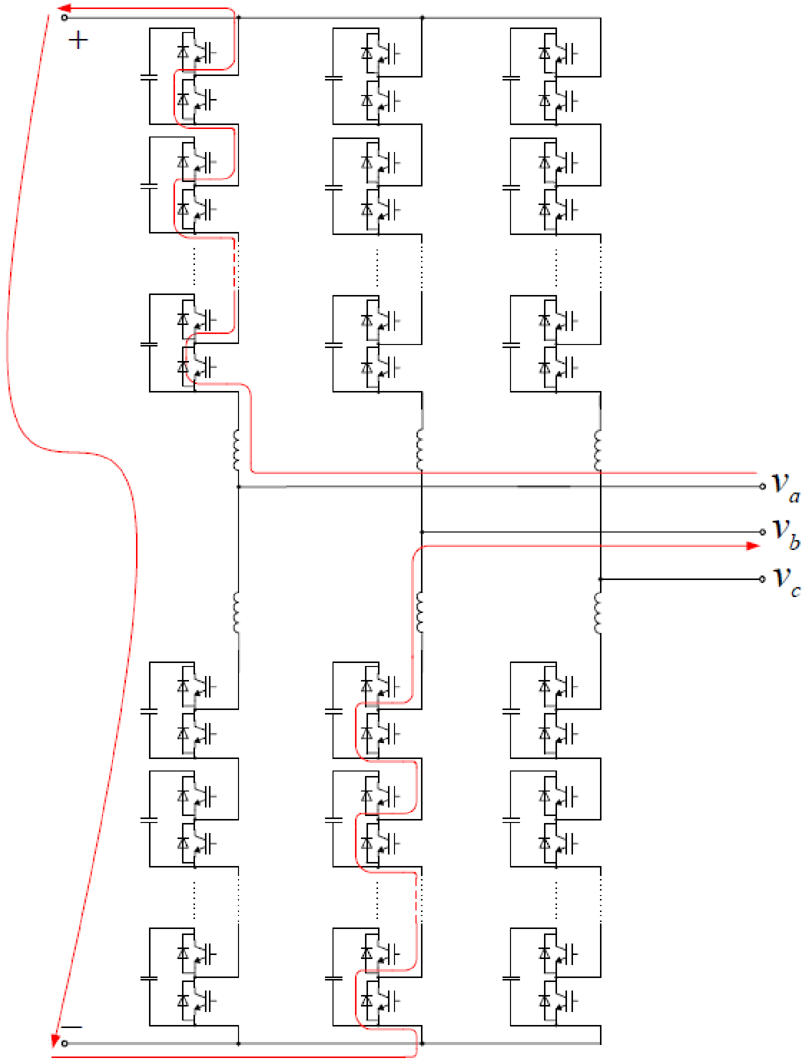
Closed-Loop Control of MMC-HVDC

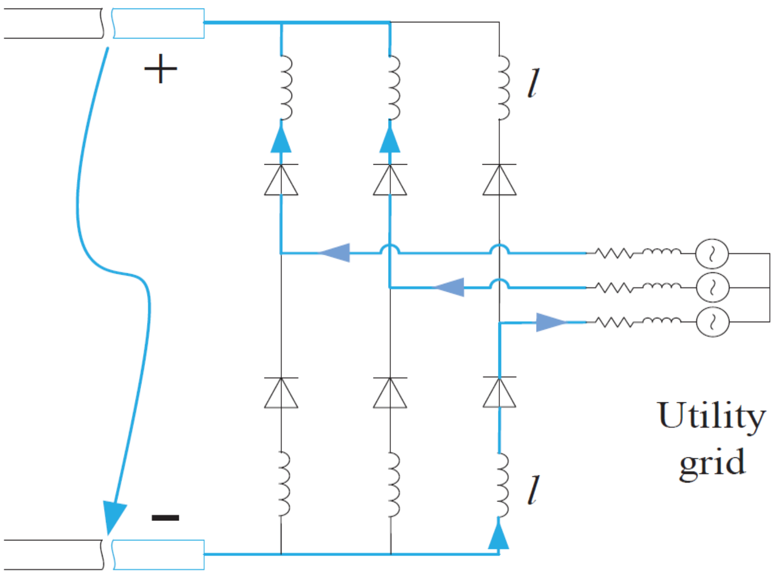


Predictive Control of MMC-HVDC



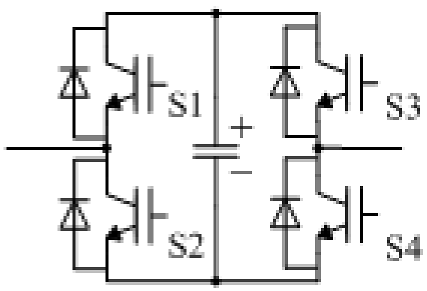
DC-Side Fault in MMC-HVDC Systems

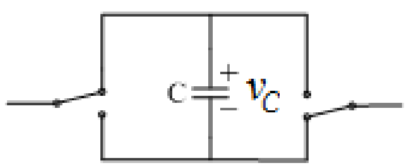




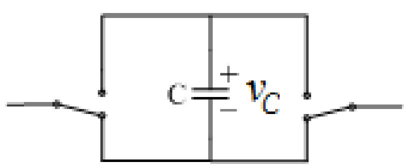
SM Technologies: Normal Operation

Full-Bridge SM

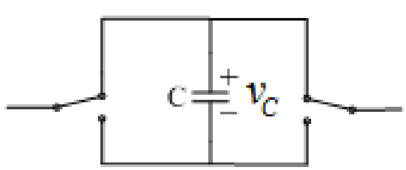




SM Insertion: S1, S4 ON; S2, S3 OFF

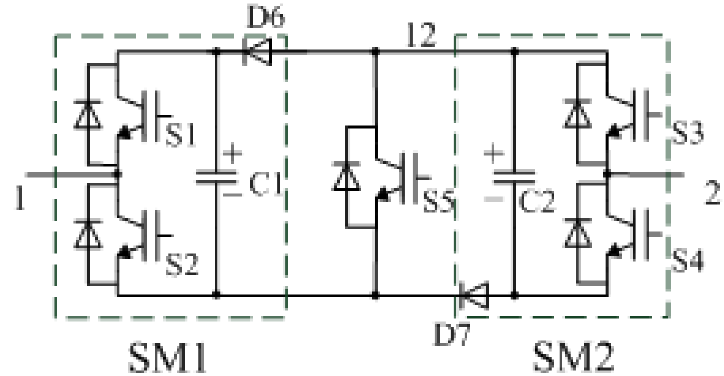


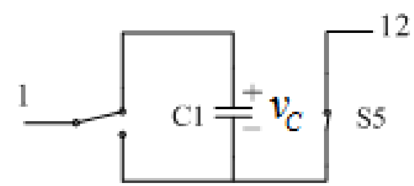
SM Bypass: S1, S3 OFF, S2, S4 ON



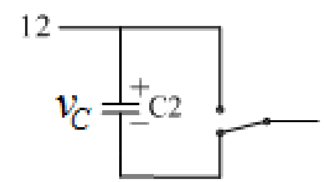
SM Bypass: S1, S3 ON, S2, S4 OFF

Clamp-Double SM

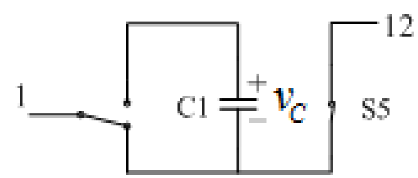




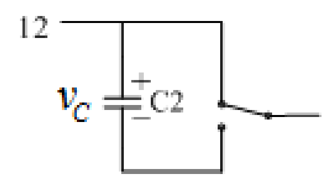
SM1 Insertion: S1 ON, S2 OFF



SM2 Insertion: S4 ON, S3 OFF

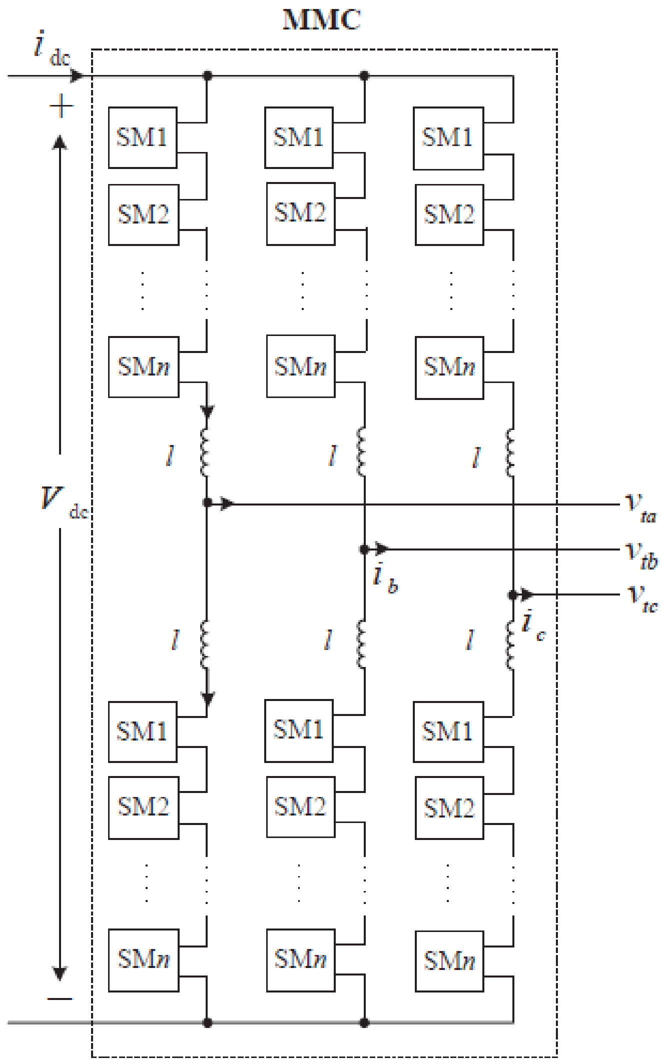


SM1 Bypass: S1 OFF, S2 ON

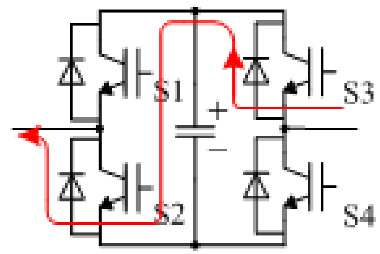


SM2 Bypass: S4 OFF, S3 ON

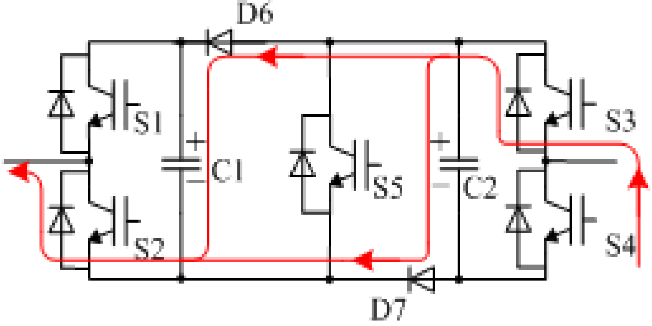
SM Technologies: DC-side Short-Circuit Fault Operation



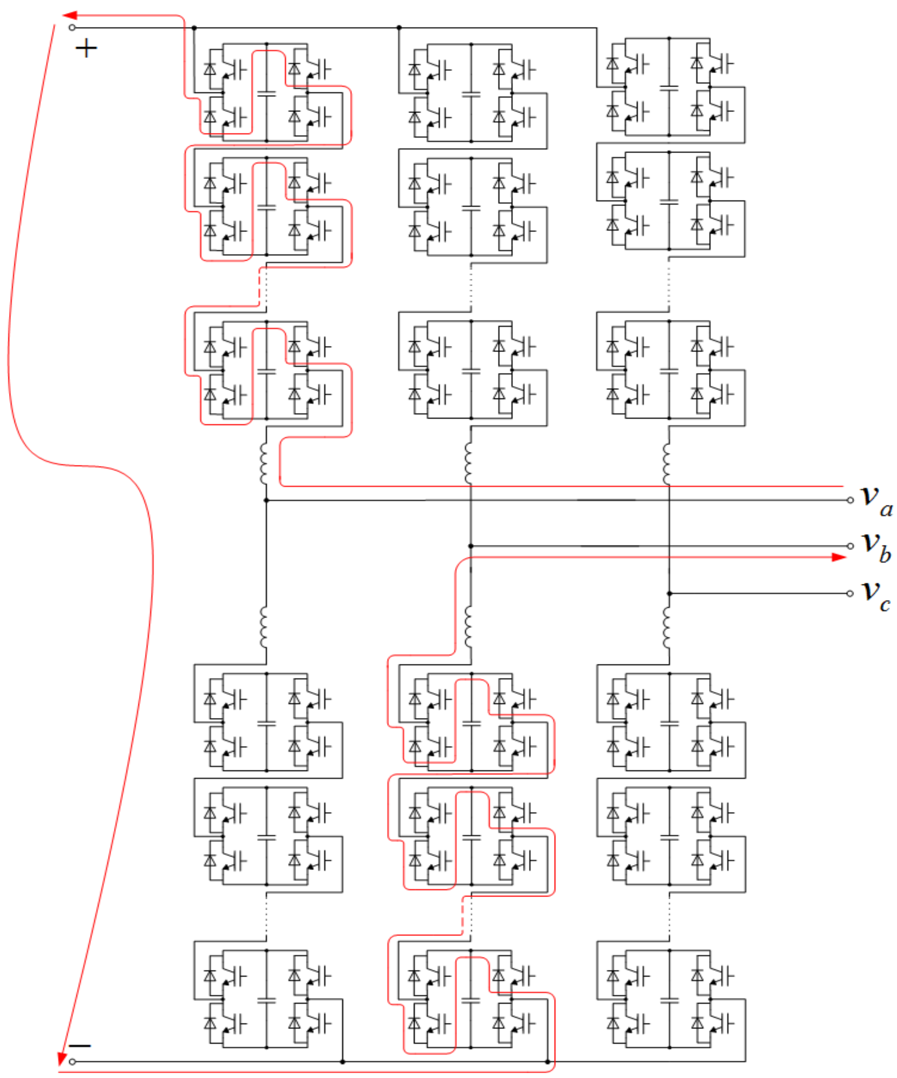
Full-Bridge SM



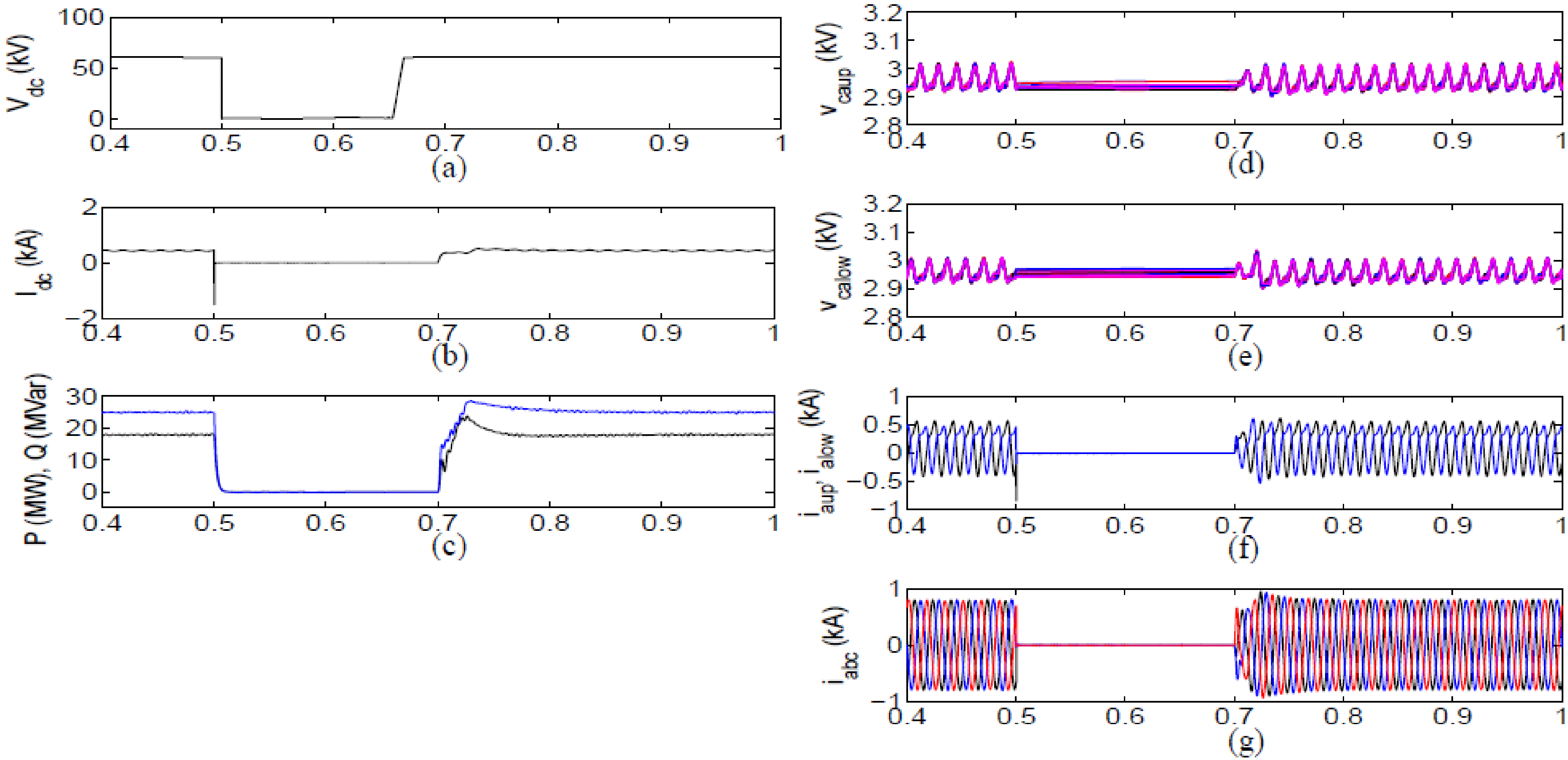
Clamp-Double SM



DC-side Short-Circuit Fault Operation of Full-Bridge MMC

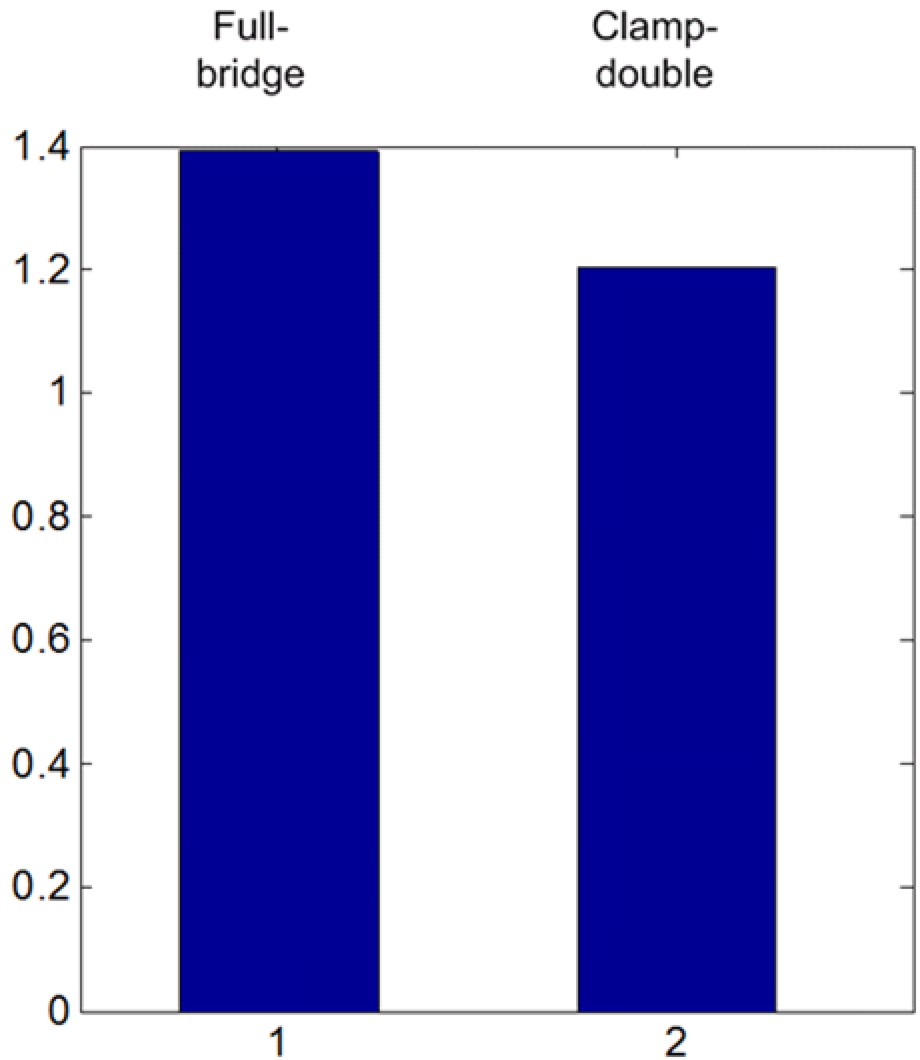


DC-Side Fault in MMC-HVDC Systems: Full-Bridge MMC Case

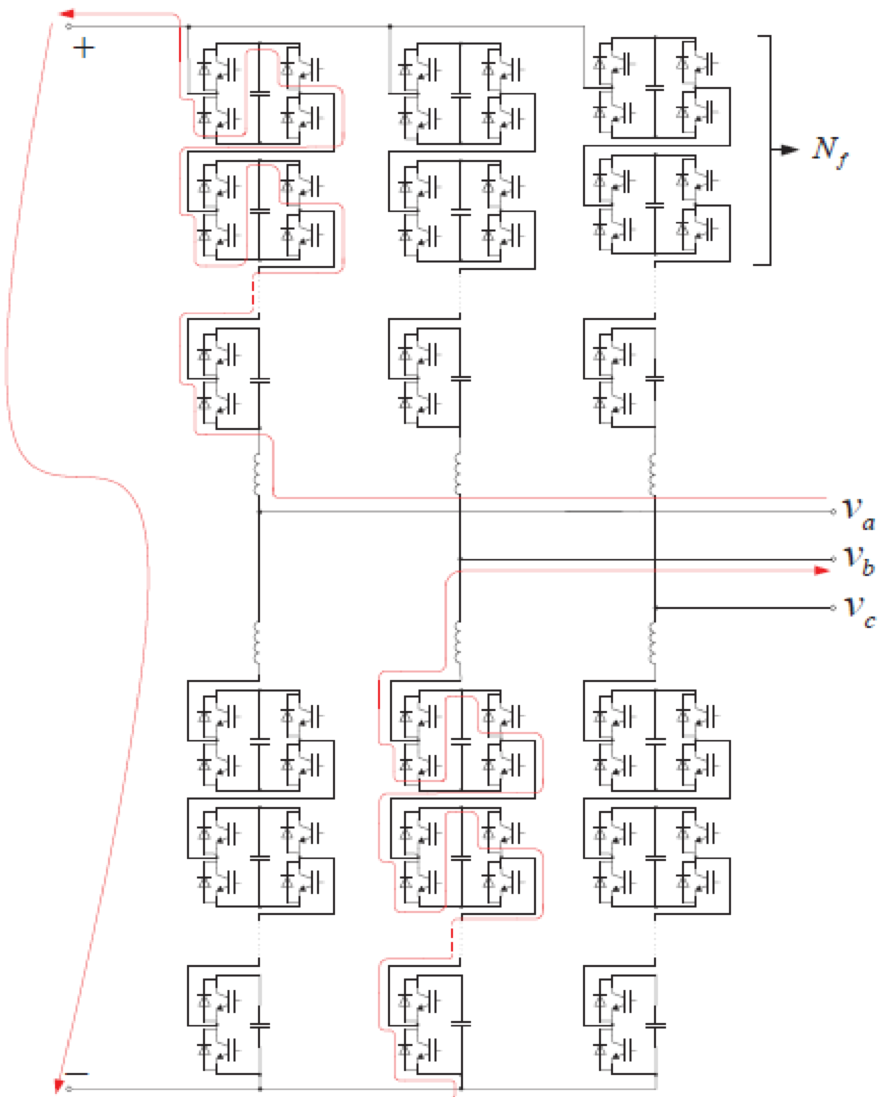


Power Losses for Various SM Circuits

Power Losses of Single SM-type MMCs Normalized with Respect to Half-Bridge MMC

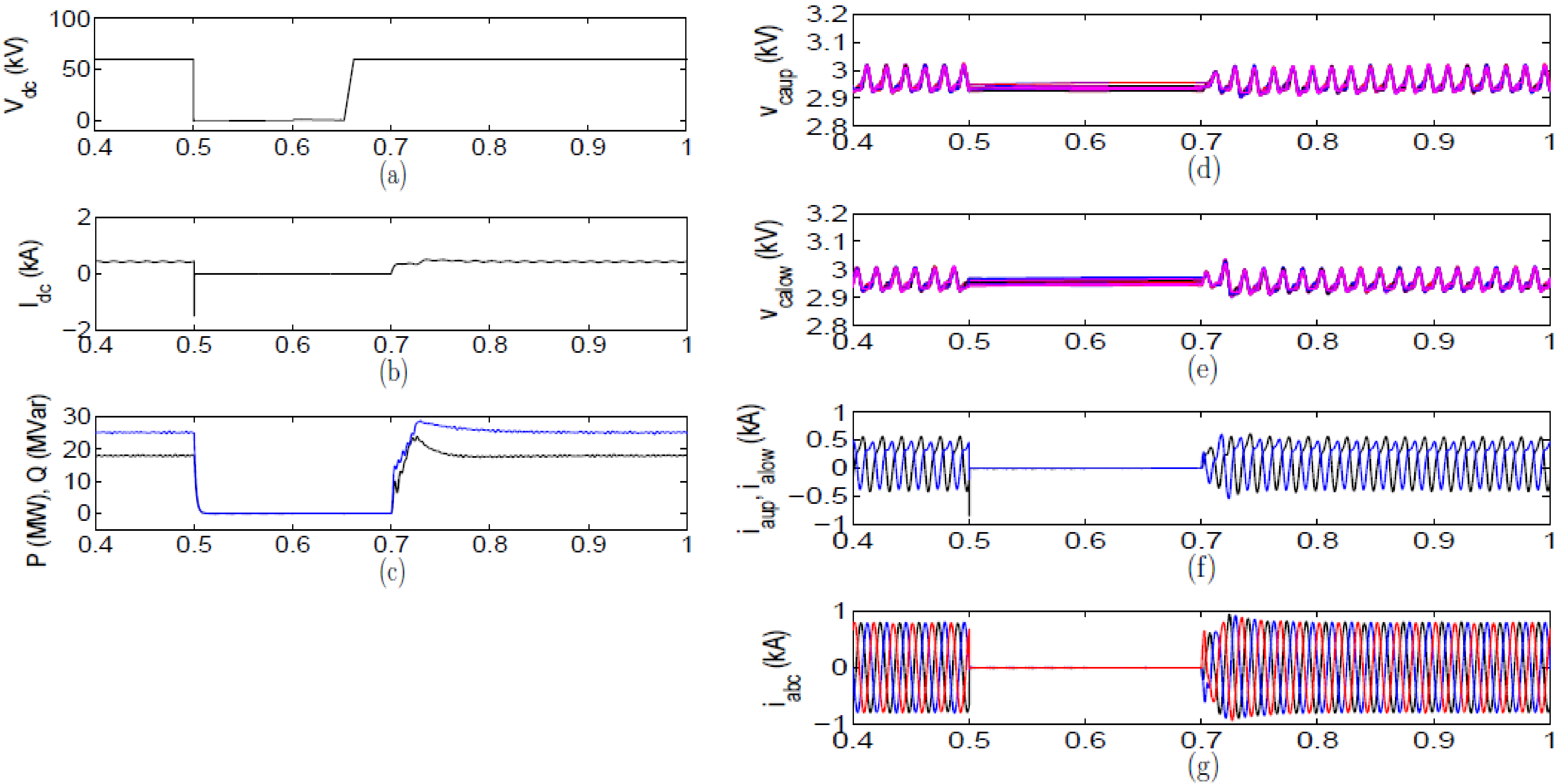


Hybrid Design of MMC-HVDC Systems



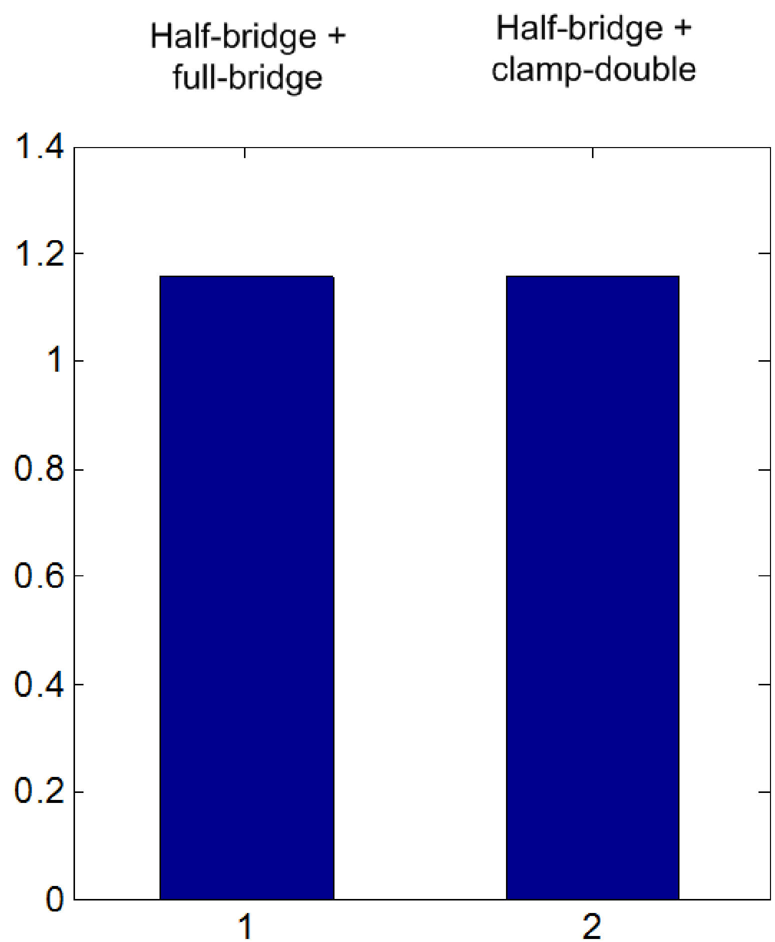
$$N_f \geq \frac{V_{\mathrm{amp\_}LL}}{2V_{\mathrm{cap\_ref}}}$$

DC-Side Fault in MMC-HVDC Systems: Hybrid MMC Case



Power Losses for Various Hybrid MMCs

Power Losses of Hybrid MMCs Normalized with Respect to Half-Bridge MMC



Future Work

- Control and protection of multi-terminal HVDC systems based on the MMC
- Accurate and efficient modeling and simulation tools for MMC-HVDC systems
- Operation of the MMC-HVDC systems under fault conditions

Acknowledgement

- This presentation contains data and graphs from ABB publications/presentations available on the public domain including:
- Mats Larsson, Corporate Research, ABB Switzerland Ltd, “HVDC and HVDC Light: An alternative power transmission system”,Symposium on Control & Modeling of Alternative Energy Systems, April 2, 2009.
- Gunnar Persson, Senior Project Manager,Power Systems - HVDC, ABB AB Sweden, “HVDC Converter Operations and Performance, Classic and VSC”, Dhaka, September 18, 2011.