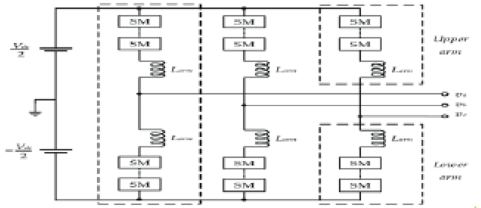
HVDC LEARN



Modules for Maturing HVDC Electric Transmission Knowledge

Funded by the US Department of Energy (DOE)
within the Office of Energy Efficiency & Renewable Energy (EERE)

HVDC-Learn Short Course

Thursday, May 22, 2025

Module 3d: Modular Multilevel Converter Design for HVDC Interface

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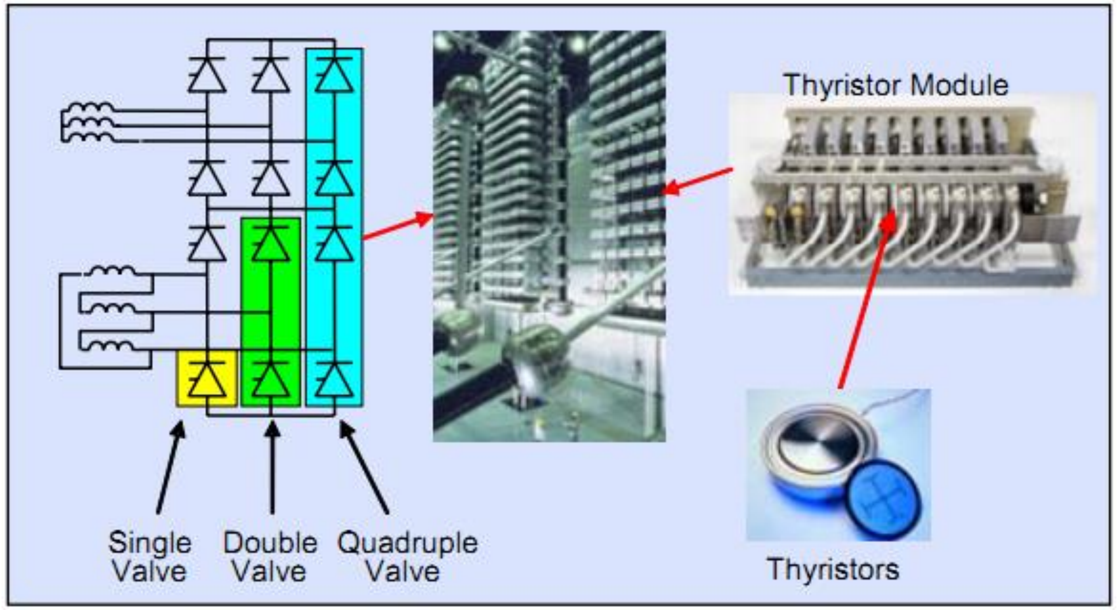
Modular Multilevel Converter (MMC) Outline

- ***Introduction***
- Modular multilevel converter structure & operation principles
- Multilevel modulation methods
- Arm inductance impact & circulating current suppression
- Capacitor voltage balancing
- MMC-based HVDC system

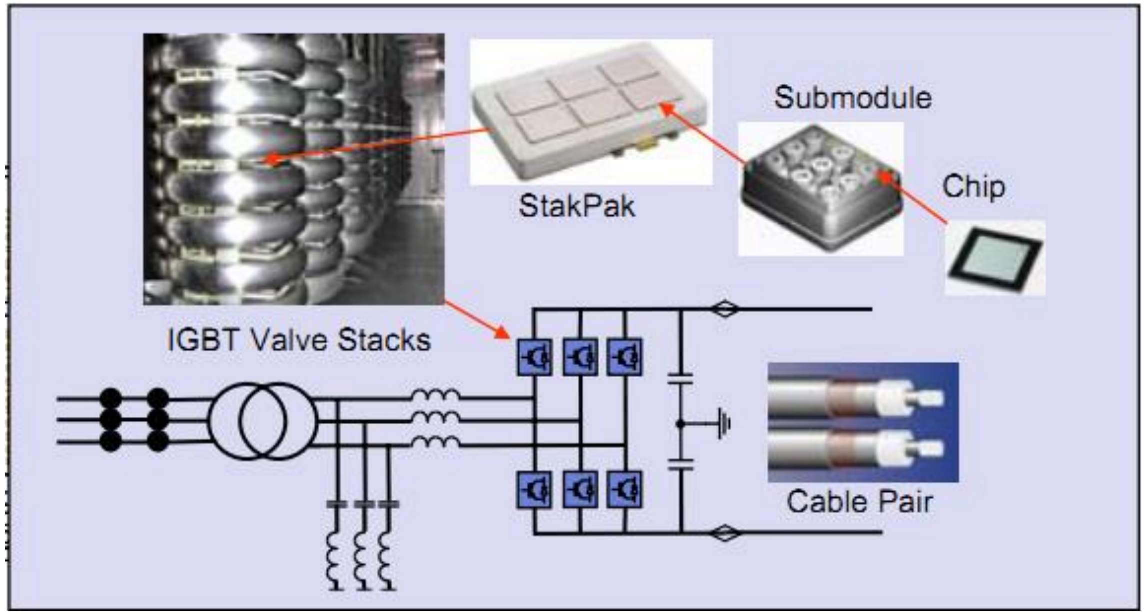
Two Main HVDC Transmission Systems

- **HVDC Classic or Line Commutated Converters (LCC) HVDC**
  Current source converters (CSCs) using controllable thyristor switches.

- **Voltage source converters (VSC) HVDC**
  Pulse width modulated converters comprised of fully controllable switches like IGBTs or IGCTs.
  (In future, may be MMCs with SiC MOSFETs)



LCC HVDC Interface (Hitachi Energy)



VSC HVDC Interface (Hitachi Energy)

Ref: K. Johnson, "The ABCs of HVDC transmission technologies," *IEEE Power and Energy Magazine*, Mar. 2007.

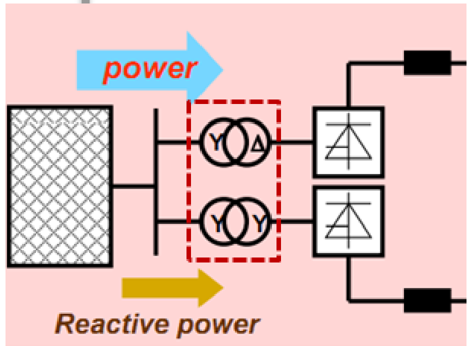
HVDC Converter Topologies

HVDC

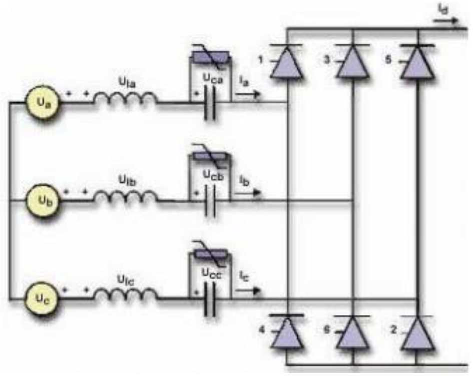
CSC

❖High power rating, low cost
❖DC fault current controllability

LCC



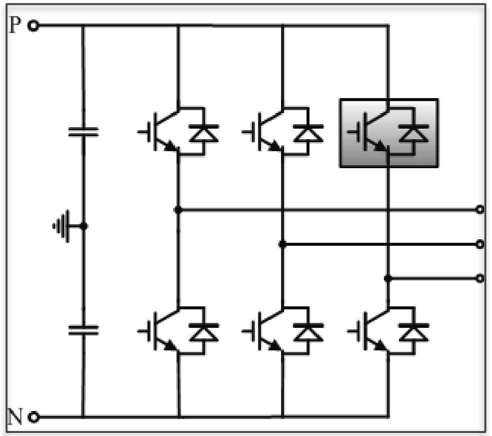
CCC



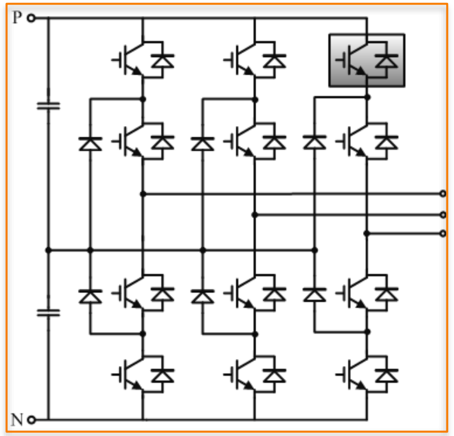
VSC

❖Independent active and reactive power control
❖Black start capability
❖Power reversal without reversing DC link voltage polarity
❖Compact converter station footprint
❖Improved AC fault ride-through capability

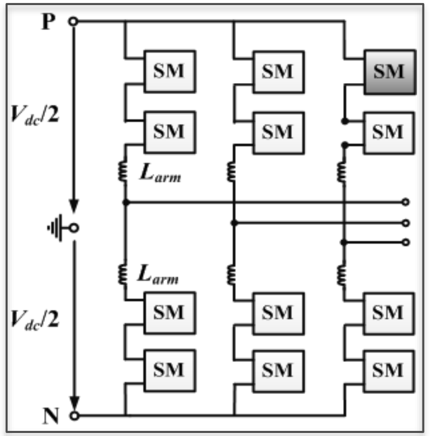
Two Level VSC

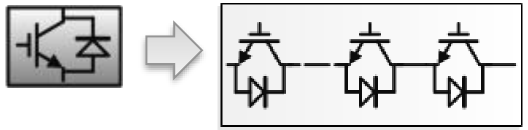


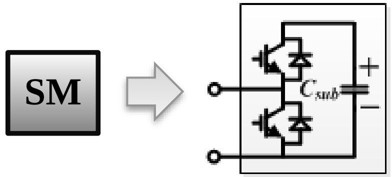
Three level VSC



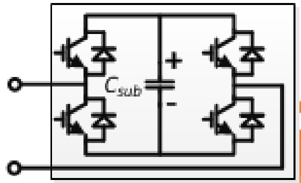
Modular Multilevel Converter (MMC)



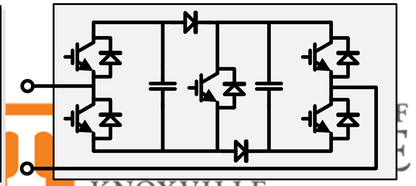




half-bridge



full-bridge

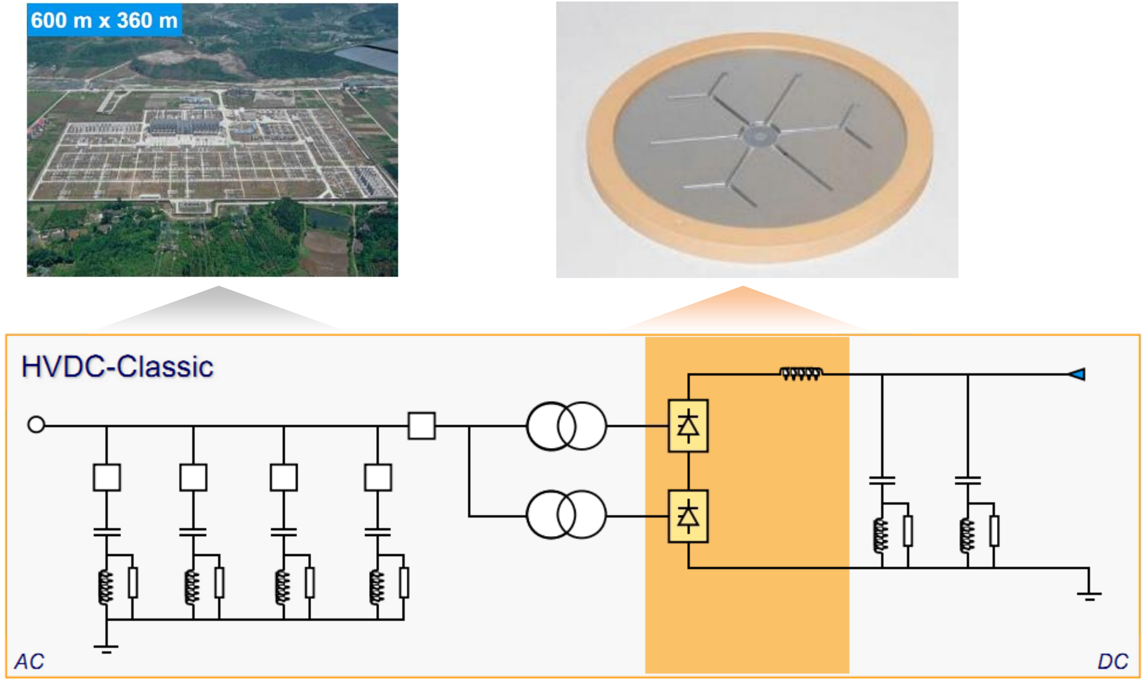


clamp-double

Ref: [1] Cigre report, 2012
[2] B. Gemmell, 2008

HVDC Converters

Current Source Converter based HVDC

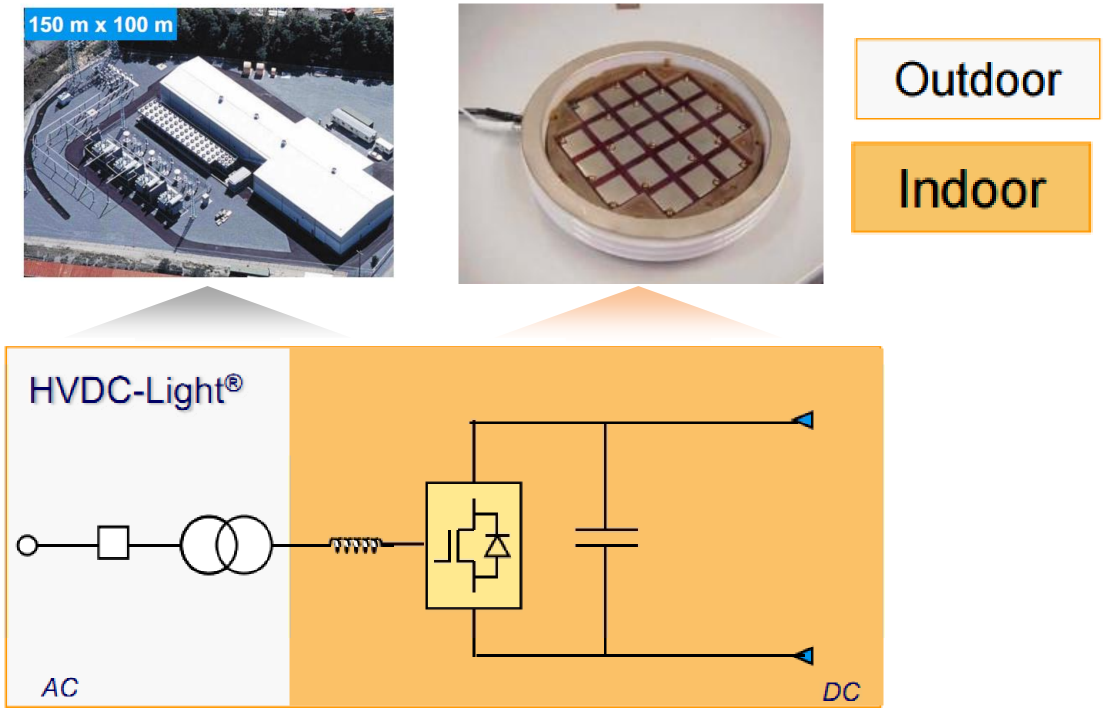


- Line-commutated thyristor valves
- Power levels up to 6,400 MW
- Requires reactive power compensation
- Minimum short circuit capacity > 2X converter rating
- Power reversal with reversed DC link voltage polarity

Ref: [1] K. Johnson, “The ABCs of HVDC transmission technologies,” *IEEE Power and Energy Magazine*, 2007.
[2] J. G. Johansson, “HVDC converter technology.” [Online]. Available: https://new.abb.com/docs/librariesprovider51/till-evenemang/jan-johansson_hvdc-converter-technology.pdf?sfvrsn=2

HVDC Converters

Voltage Source Converter based HVDC



- Self-commutated IGBT valves
- Power levels up to 2000 MW
- Needs no reactive power compensation
- No minimum short circuit capacity
- Black start and improved AC fault ride-through capability
- Power reversal with reversed dc current polarity
- Fewer components; most equipment indoors

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Ref: [1] K. Johnson, "The ABCs of HVDC transmission technologies," *IEEE Power and Energy Magazine*, 2007.
[2] J. G. Johansson, "HVDC converter technology." [Online]. Available: https://new.abb.com/docs/librariesprovider51/till-evenemang/jan-johansson_hvdc-converter-technology.pdf?sfvrsn=2

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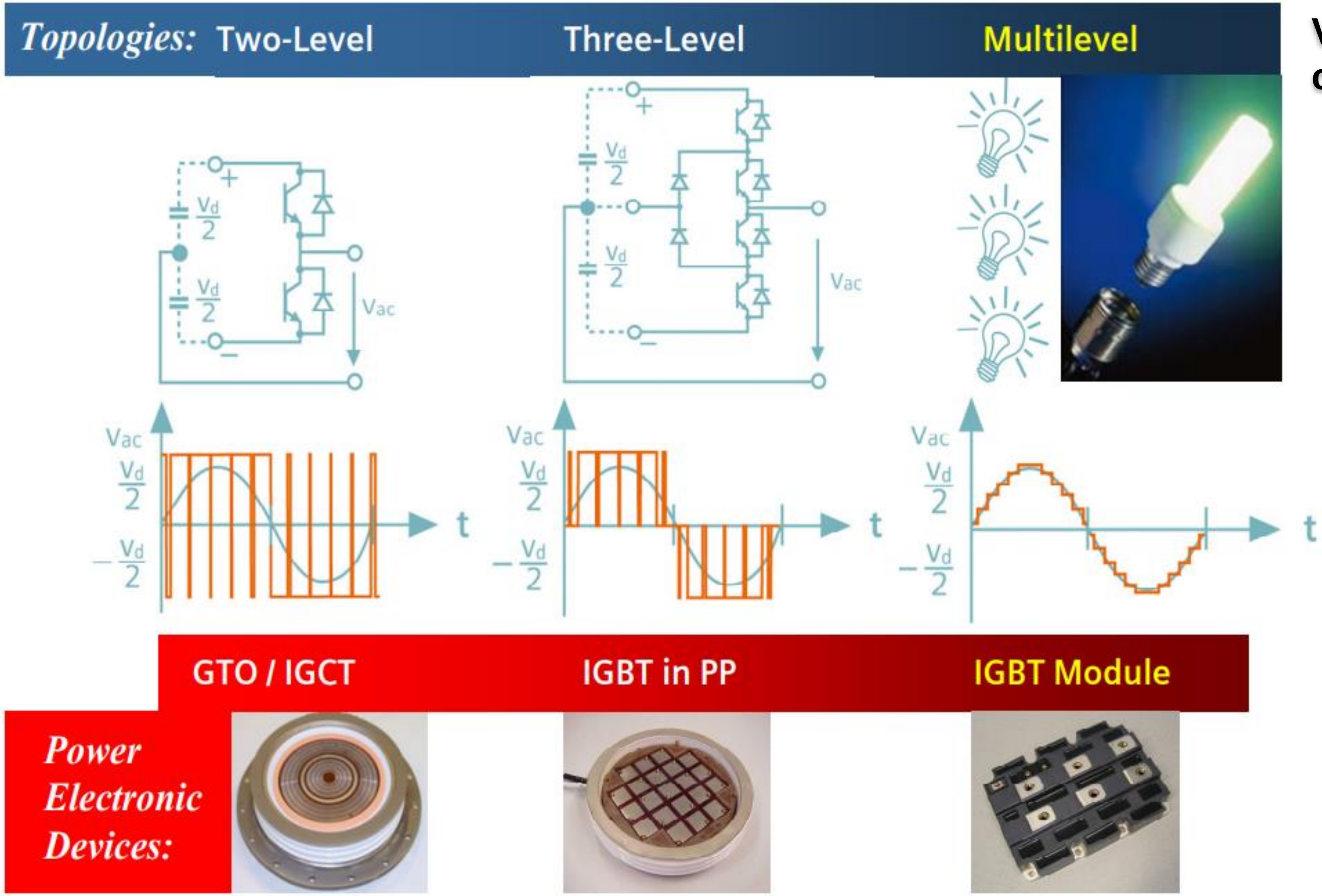
Comparison between Two Level VSC and MMC



VSC based HVDC converter topologies

Ref: B. Gemmell, J. Dorn, D. Retzmann and D. Soerangr, "Prospects of multilevel VSC technologies for power transmission," 2008 *IEEE/PES Transmission and Distribution Conference and Exposition*, Chicago, IL, USA, 2008.

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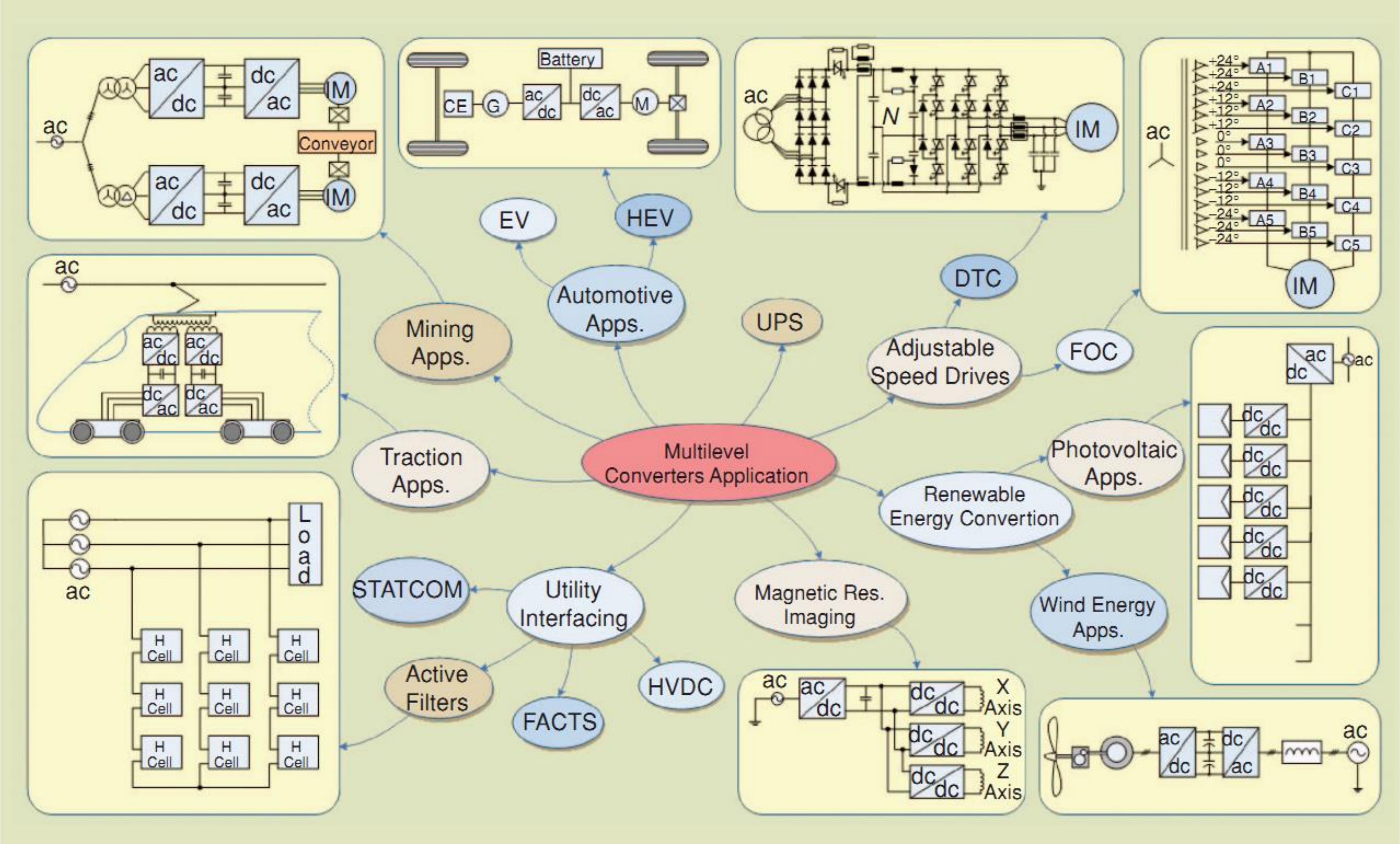
Multilevel Converter Applications



Ref: Franquelo, L.G., J.Rodriguez, J.I. Leon, S. Kouro, R. Portillo, and M.A.M. Prats, "The Age of Multilevel Converters Arrives," *IEEE Industrial Electronics Magazine*, pp. 28-39, June 2008.

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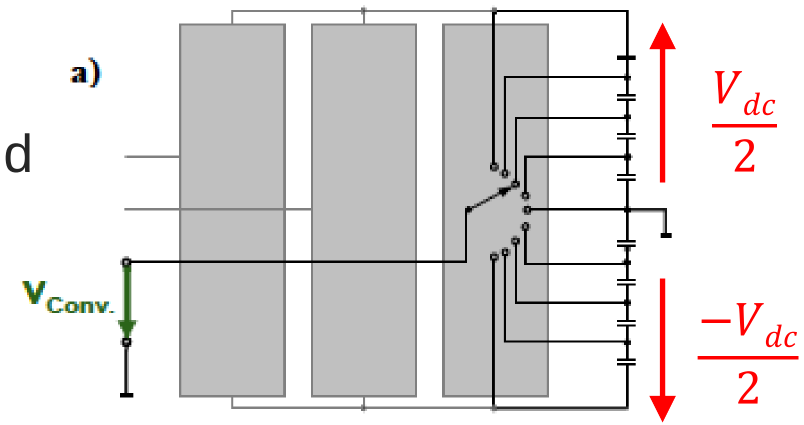
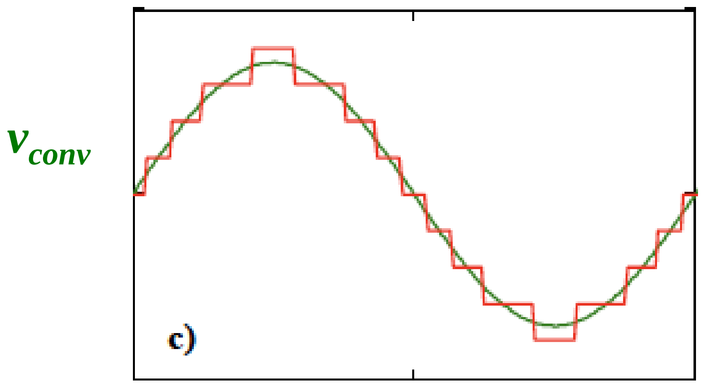
Multilevel Converter Topologies

- **General structure**
  - Synthesize desired ac voltage from several levels of dc voltages
  - More levels produce a staircase waveform that approaches a sinusoid
  - Harmonic distortion of output waveform decreases with more levels
  - No voltage sharing problems with series connected devices
  - Low dv/dt reduces switching losses and EMI

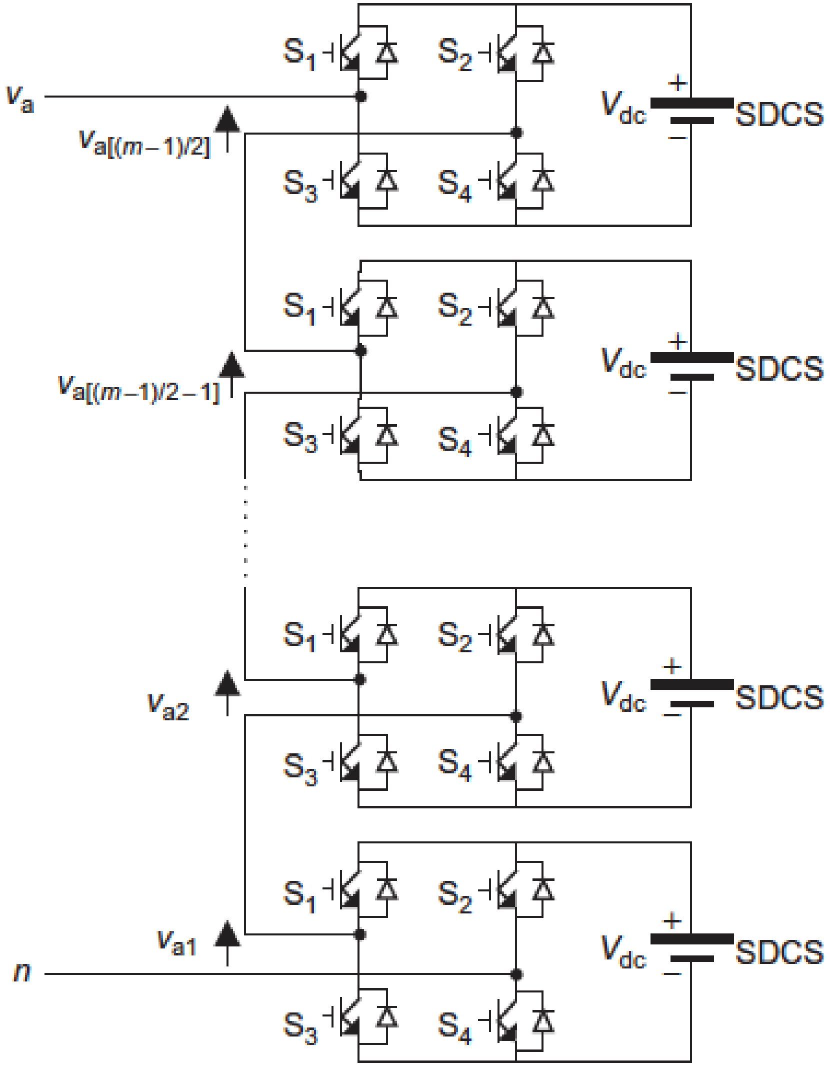


- **Four structures**
  - Diode clamped converter
  - Flying-capacitor converter
  - Cascaded H-bridges inverter with separate dc sources
  - **Modular multilevel converter (MMC)**

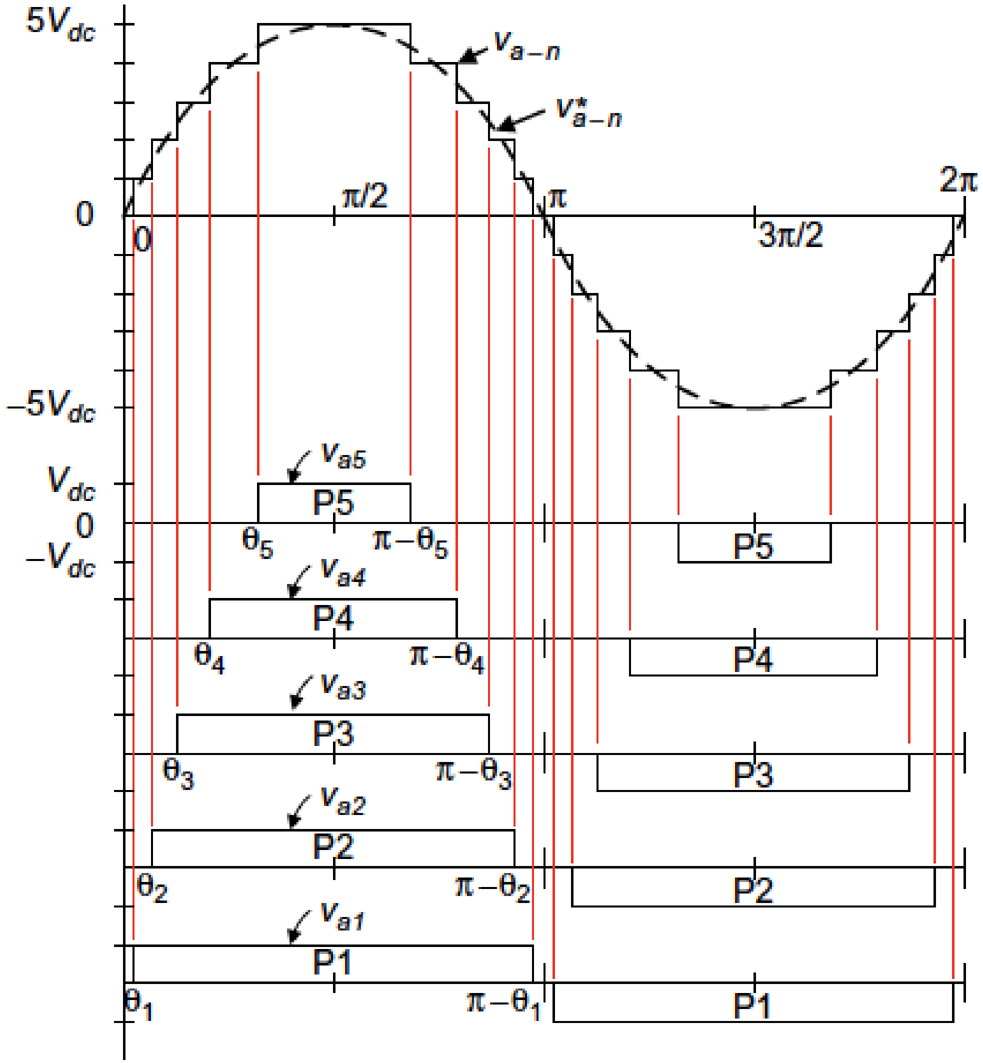


Ref: B. Gemmell, J. Dorn, D. Retzmann and D. Soerangr, "Prospects of multilevel VSC technologies for power transmission," 2008 *IEEE/PES Transmission and Distribution Conference and Exposition*, Chicago, IL, USA, 2008.

Cascaded H-Bridges Multilevel Inverter

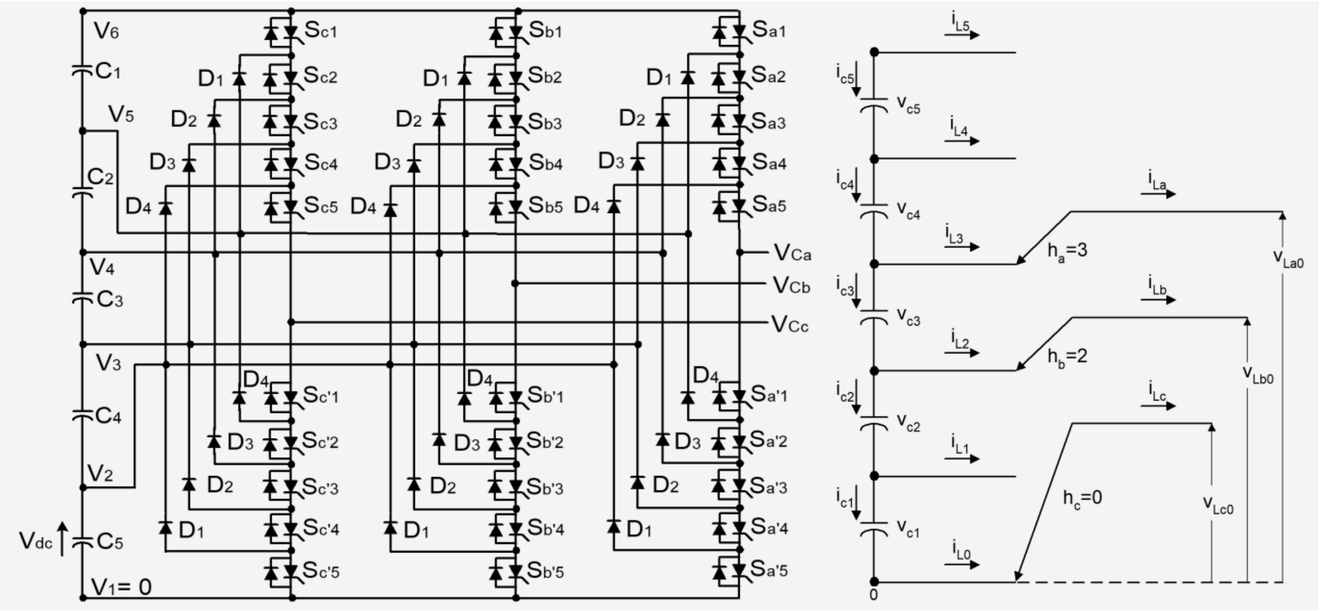


Single phase m-level structure

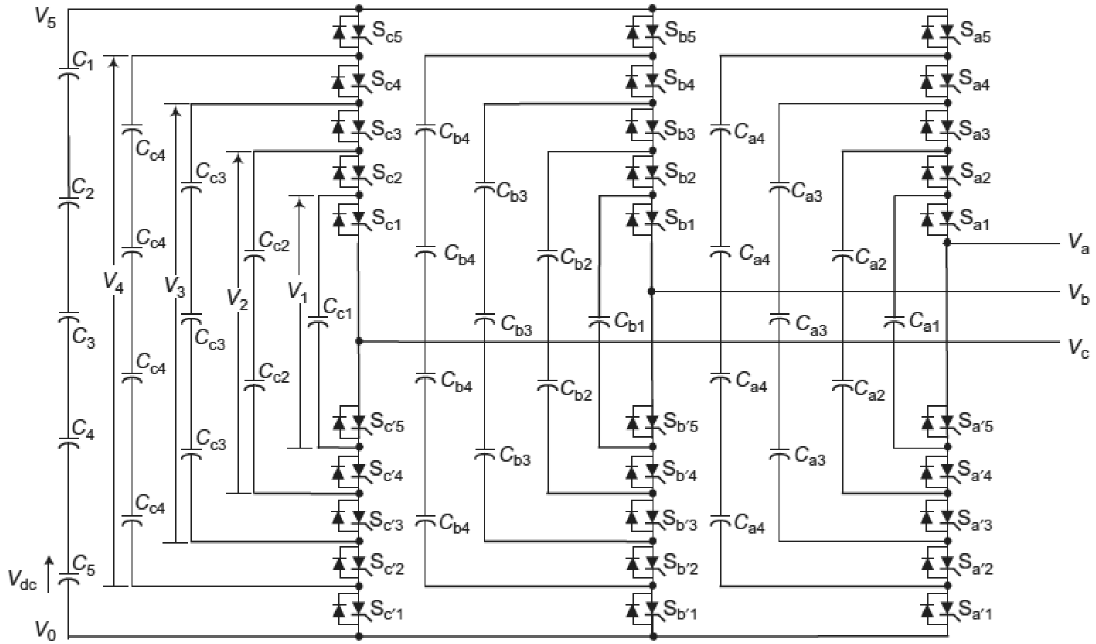


Ref. L. M. Tolbert, X. Shi, Y. Liu, "Multilevel Power Converters," *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

Multilevel Converter Topologies – Clamping based



Three phase 6-level **diode-clamped inverter** with its multiplexer model



Three-phase 6-level **flying capacitor inverter**

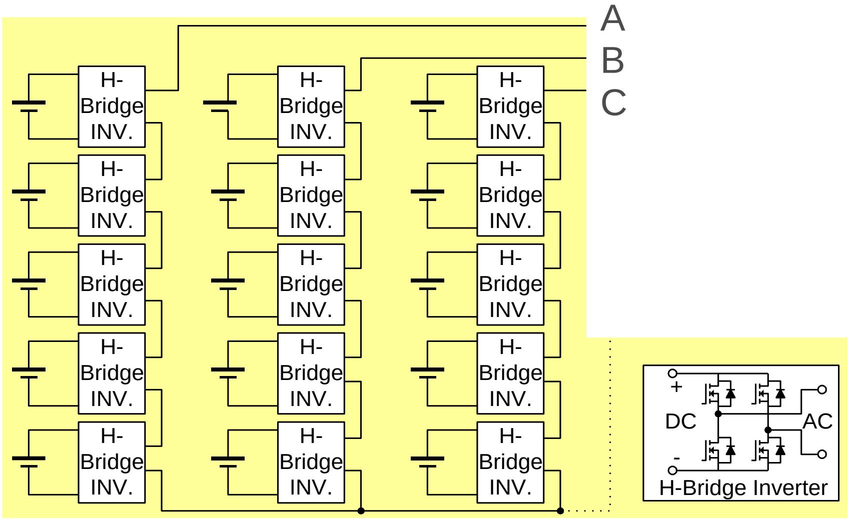
Typical Applications:

- Static Var Compensation
- FACTs/UPC Applications
- Back-to-Back Intertie of Asynchronous AC Utilities

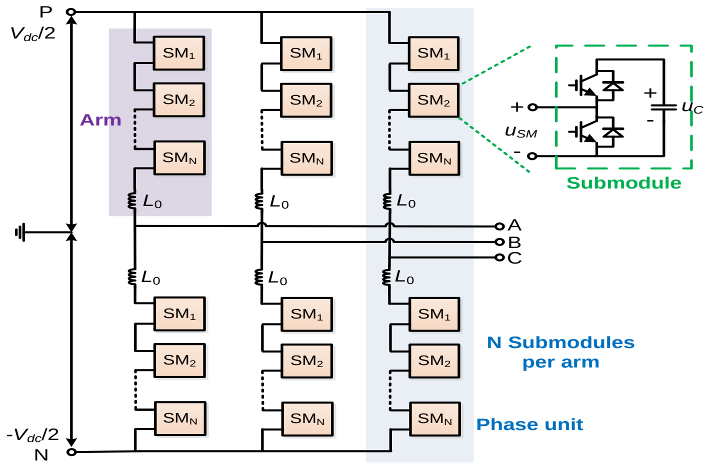
- Interface between DC and AC
- Interface between distributed generation sources and utility
- Medium voltage motor drives

Ref. L. M. Tolbert, X. Shi, Y. Liu, "Multilevel Power Converters," *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

Multilevel Converter Topologies – Modular



Three phase wye connected **cascaded inverter**



Modular multilevel converter (MMC)

Typical Applications:

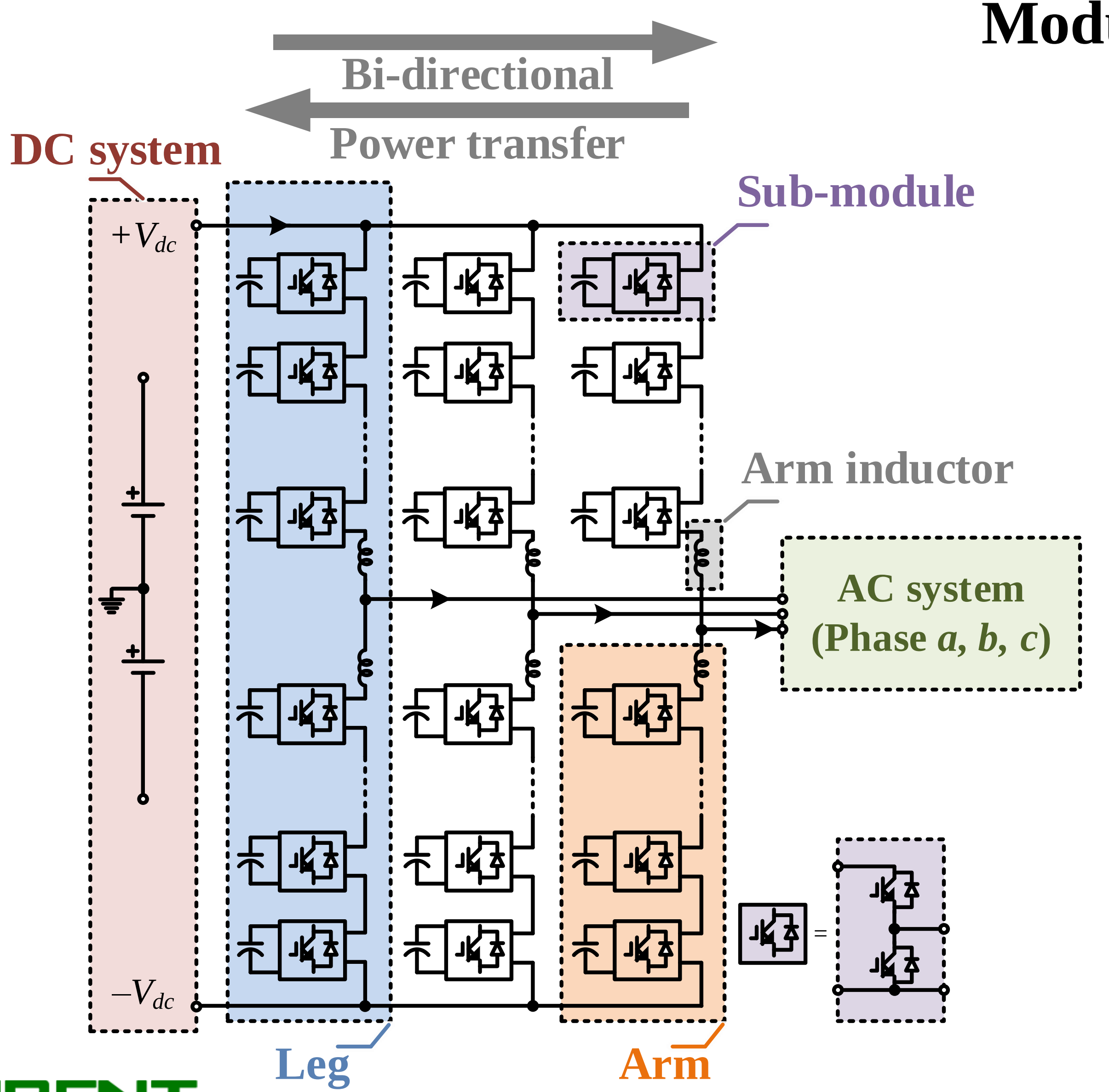
- HVDC
- Static Var Compensator (SVC)
- STATCOM
- FACTS/UPFC Applications
- Active Power Filter
- Sag Compensation
- Interface with Distributed Generation Resources
  - Photovoltaics (Solar Panels)
  - Fuel Cells
  - Wind Turbines (rectified)
  - Energy Storage (Batteries, Ultracapacitors)

Ref. L. M. Tolbert, X. Shi, Y. Liu, "Multilevel Power Converters," *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

Modular Multilevel Converter (MMC) Outline

- Introduction
- ***Modular multilevel converter structure and operation principles***
- Multilevel modulation methods
- Arm inductance impact and circulating current suppression
- Capacitor voltage balancing
- MMC-based HVDC system

MMC Structure



Modular Multilevel Converter (MMC)

Applications:

(a) **High-Voltage DC (HVDC) Transmission Systems**

High-Voltage DC ↕ High-Voltage AC — Hundreds-level MMC

(b) **Variable-Speed Drives**

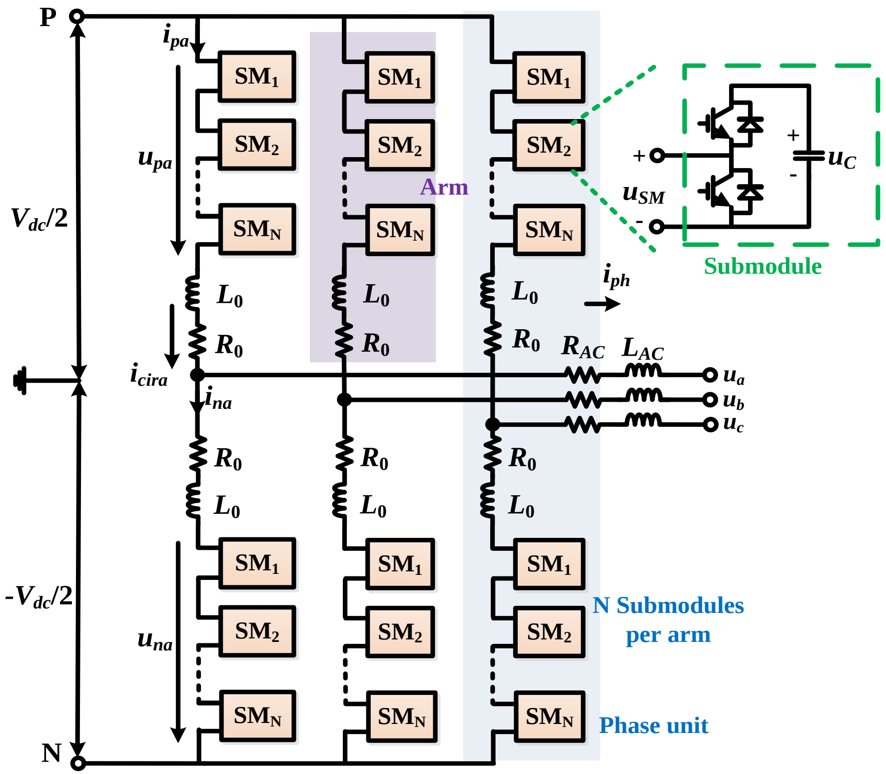
Medium-Voltage DC ↕ Medium-Voltage AC — Tens-level MMC

➡ Nearest level modulation

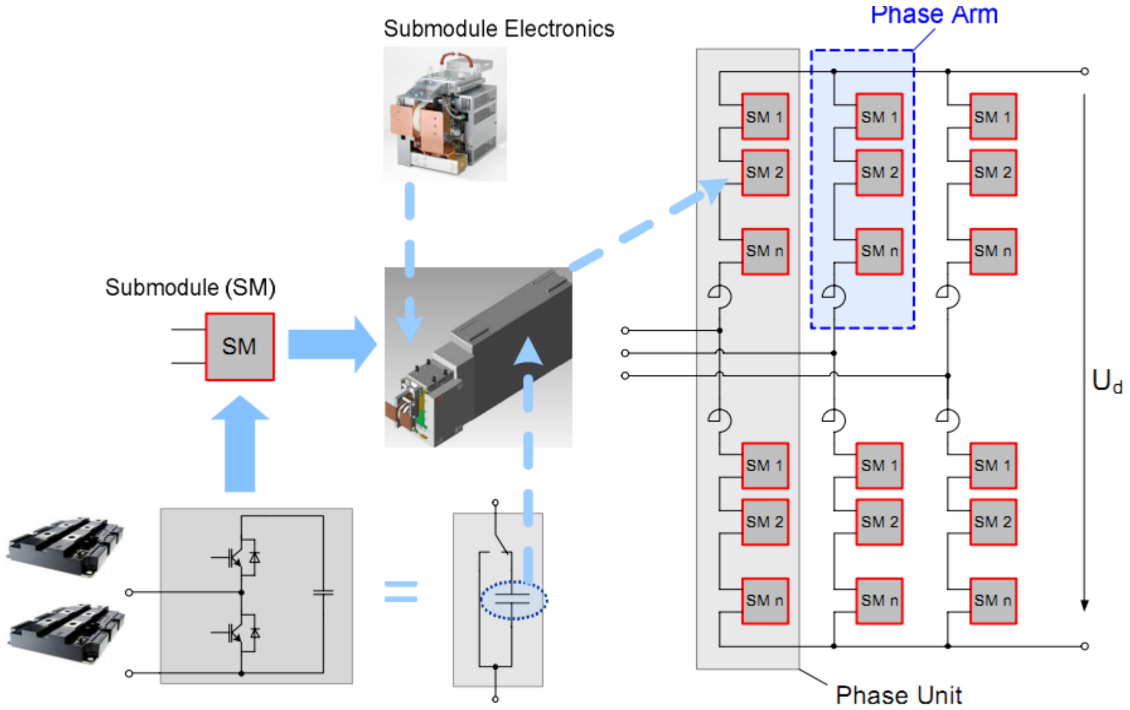
➡ PWM modulation

MMC Configuration and Merits

MMC Configuration [1]



Siemens HVDC PLUS [2]



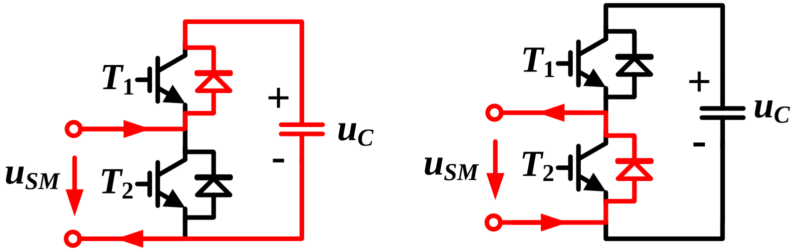
Ref: [1] X. Shi, et al, *IEEE Transactions on Power Electronics*, 2015.
[2] Ref: https://site.ieee.org/winnipeg/files/2012/12/2012-12-18-pes-presentation.pdf

Merits:

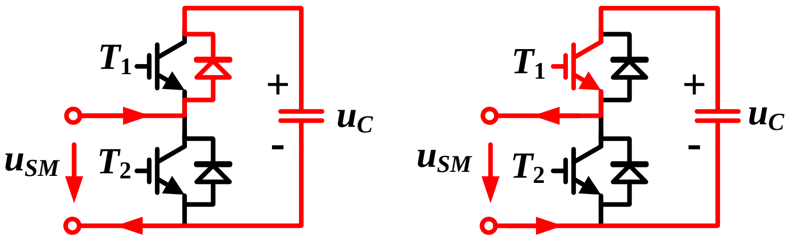
- Modular design enables simple voltage scaling by a series connection of cells
- Filterless configuration
- High equivalent switching frequency for output voltage with relatively low individual device switching frequency
- Simple realization of redundancy

MMC Sub-module Operation States

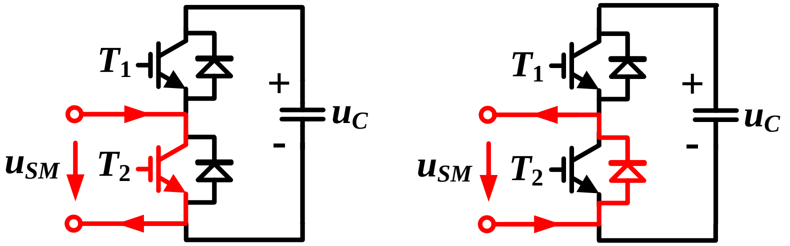
State 1. Both IGBTs are switched off, often occurs during startup or fault condition.



State 2. IGBT T_1 is switched ON, IGBT T_2 is switched OFF, and the output voltage equals to the capacitor voltage u_c.

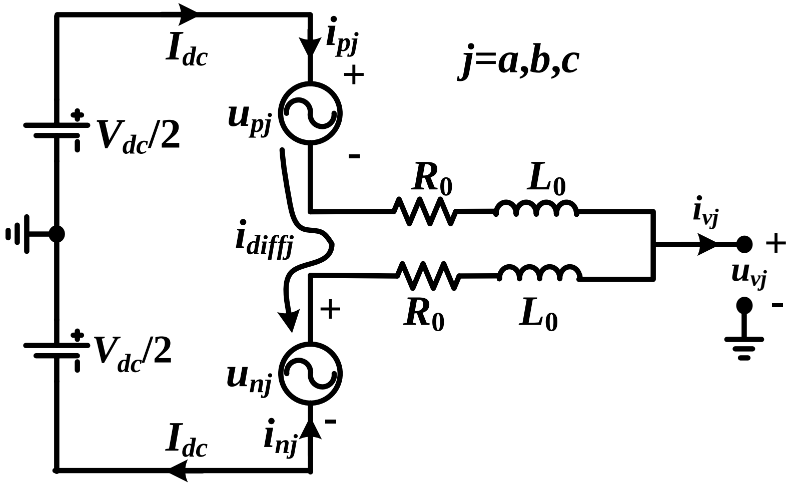


State 3. IGBT T_1 is switched OFF, IGBT T_2 is switched ON, and the output voltage is zero.



By adjusting the ON and OFF states of each switch, the desired sinusoidal voltage at the AC terminal can be achieved.

MMC basic structure and operation principle



The inner difference current of phase j, i_{diffj} is:

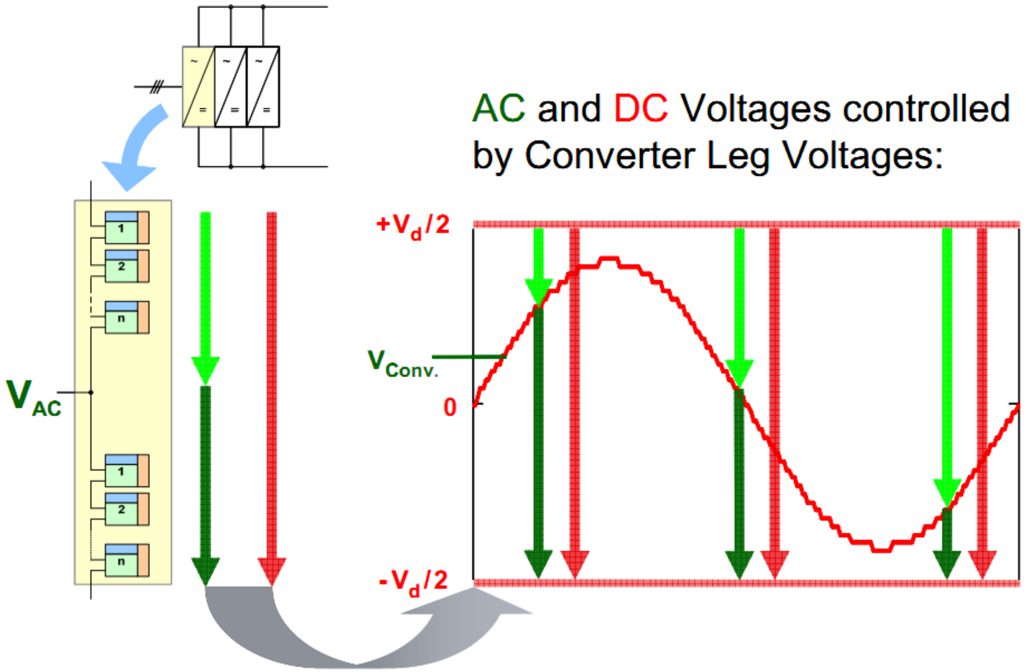
$$\left.\begin{aligned} i_{pj} &= \frac{i_{vj}}{2} + i_{diffj} \\ i_{nj} &= \frac{i_{vj}}{2} - i_{diffj} \end{aligned}\right\} \Rightarrow i_{diffj} = \frac{i_{pj} - i_{nj}}{2}$$

The output voltage is:

$$u_{vj} = \frac{u_{nj} - u_{pj}}{2} - \frac{R_0}{2} \cdot i_{vj} - \frac{L_0}{2} \cdot \frac{di_{vj}}{dt} \qquad (j = a, b, c)$$

$$R_0 \cdot i_{diffj} + L_0 \cdot \frac{di_{diffj}}{dt} = \frac{V_{dc}}{2} - \frac{u_{nj} + u_{pj}}{2} \qquad (j = a, b, c)$$

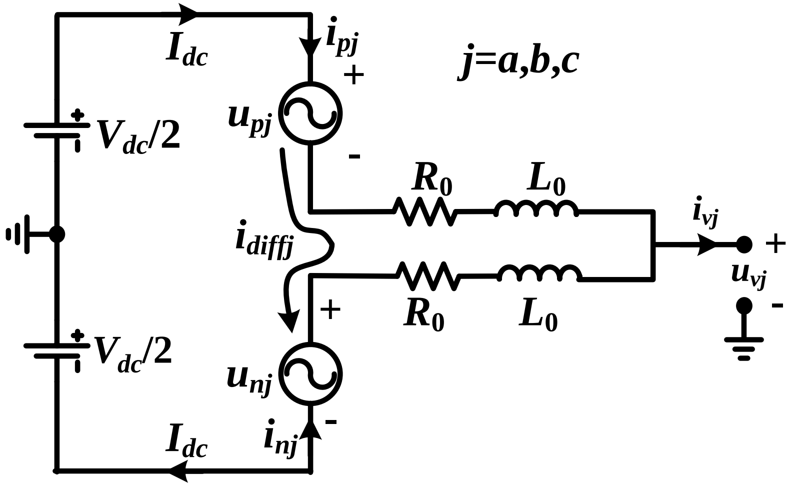
- L_0 and R_0 are the arm inductance and equivalent arm resistance.
- V_{dc} and I_{dc} are the total dc bus voltage and dc current.
- u_{vj} is the converter output voltage of j phase at point v *and* i_{vj} is the corresponding line current.
- The arm voltages generated by the cascaded SMs are expressed as u_{pj} and u_{nj} where the subscripts p and n denote the upper (positive) and lower (negative) arms, respectively.



Ref: A. Antonopoulos, L. Angquist, and H. P. Nee, "On dynamics and voltage control of the modular multilevel converter," *in Proc. Eur. Conf. Power Electron. Appl.* , Barcelona, Spain, 2009, pp. 1–10.

Operation Principle

Single phase equivalent circuit

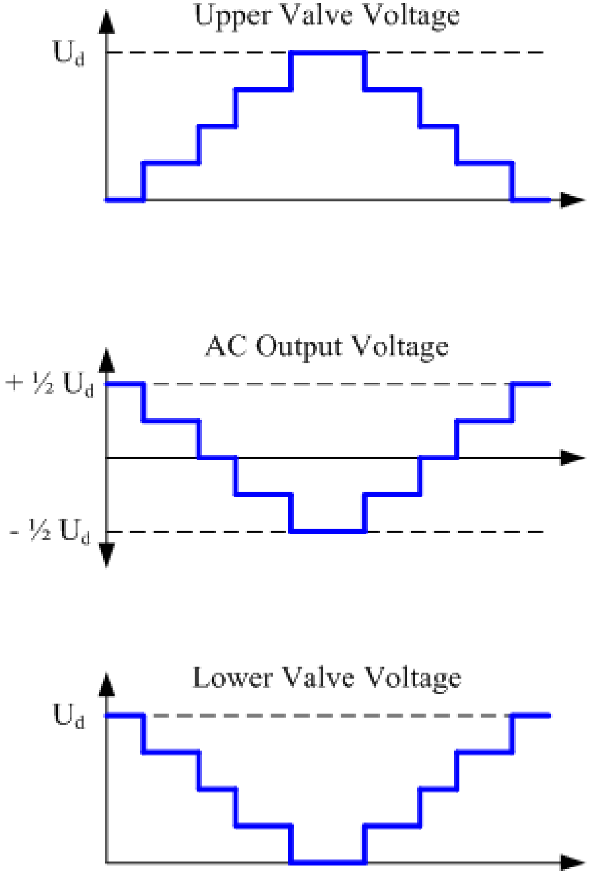


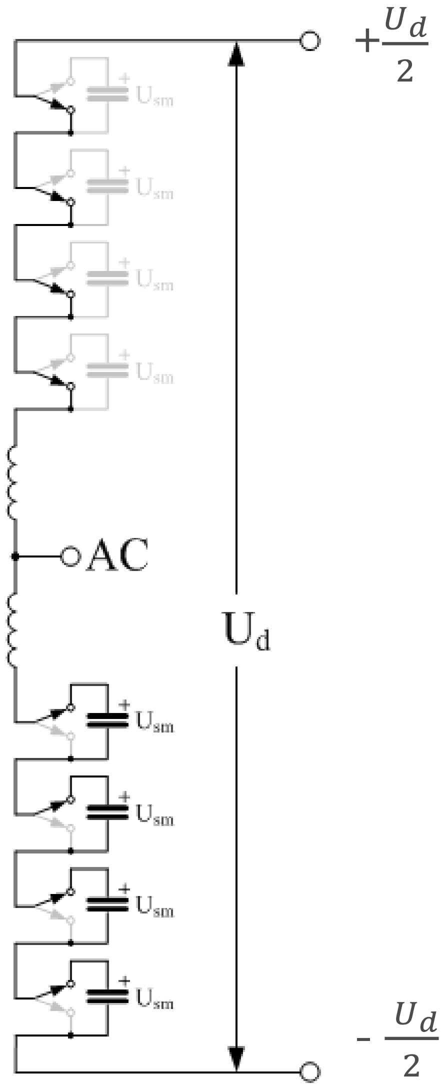
$$i_{pj} = \frac{i_{vj}}{2} + i_{diffj} \qquad i_{nj} = \frac{i_{vj}}{2} - i_{diffj}$$

$$u_{vj} = \frac{u_{nj} - u_{pj}}{2} - \frac{R_0}{2} \cdot i_{vj} - \frac{L_0}{2} \cdot \frac{di_{vj}}{dt} \qquad (j = a,b,c)$$

$$R_0 \cdot i_{diffj} + L_0 \cdot \frac{di_{diffj}}{dt} = \frac{V_{dc}}{2} - \frac{u_{nj} + u_{pj}}{2} \qquad (j = a,b,c)$$

Operation Status





- ❑ Issues
  - Circulating current
  - Capacitor voltage balancing

Ref. L. M. Tolbert, X. Shi, Y. Liu, “Multilevel Power Converters,” *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

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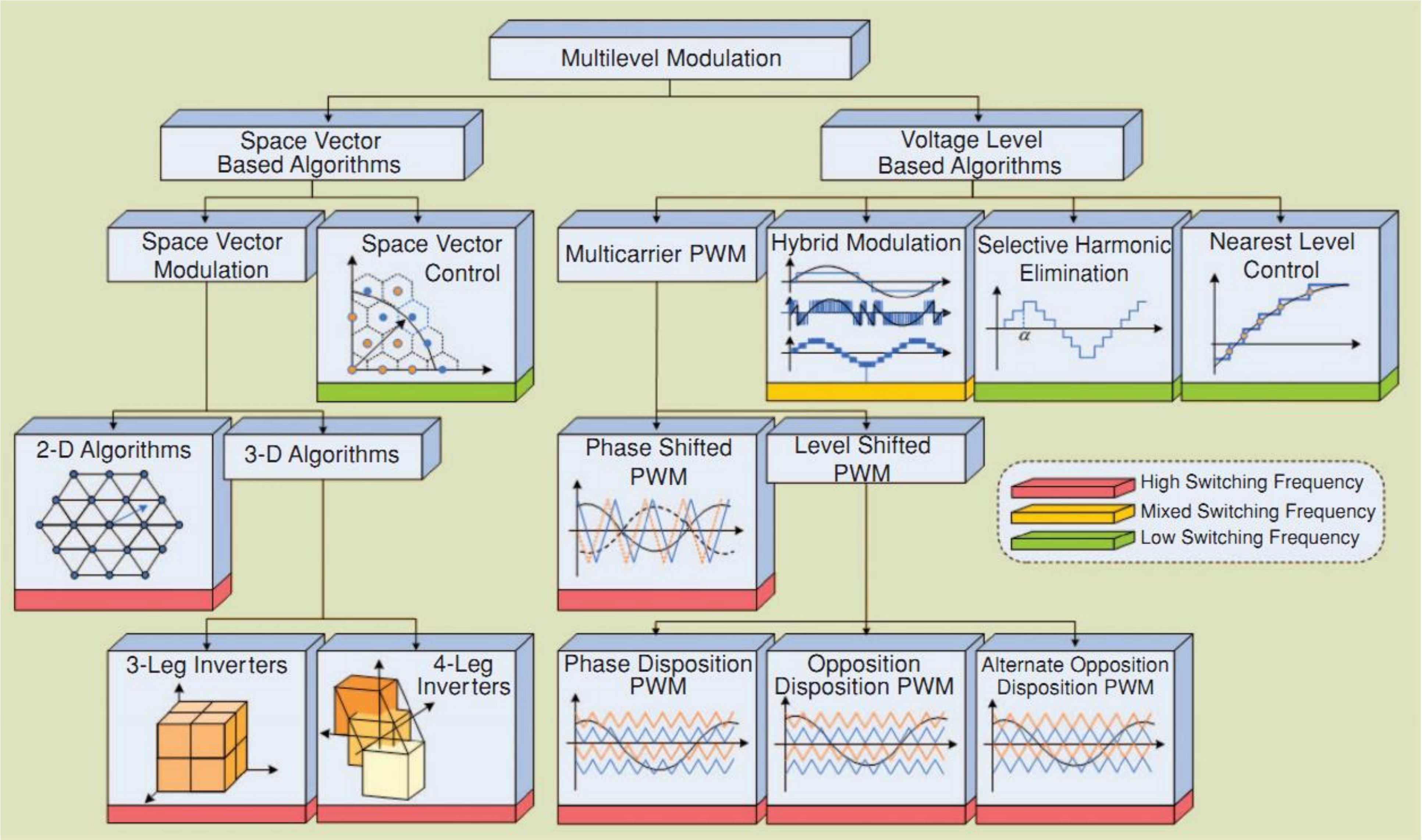
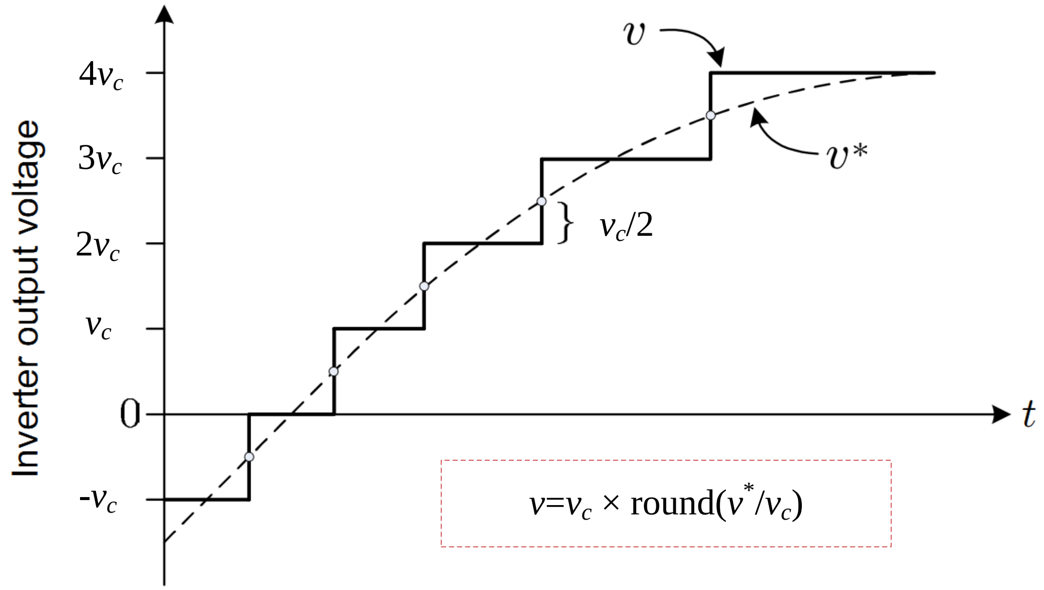
Multilevel Modulation Methods



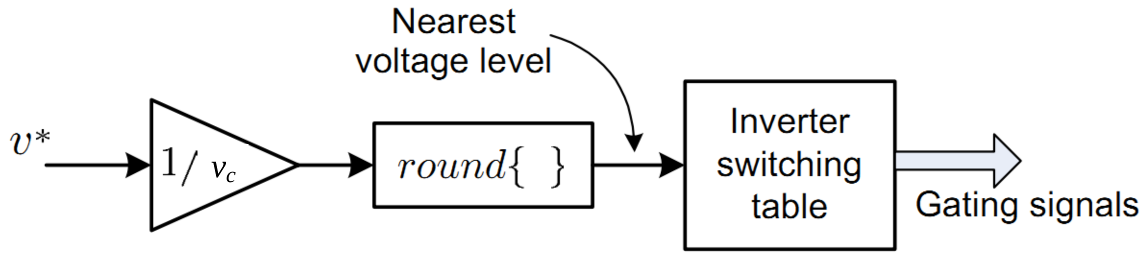
Ref: Franquelo, L.G., J.Rodriguez, J.I. Leon, S. Kouro, R. Portillo, and M.A.M. Prats, "The Age of Multilevel Converters Arrives," *IEEE Industrial Electronics Magazine*, pp. 28-39, June 2008.

Nearest Level Control (NLC)

- The core idea of NLC is to first calculate how many sub-modules should be put into action.
- Capacitors' voltage sorting and final working sequence should be determined by the direction of the arm current.



Waveform synthesis



Control diagram

Advantage:

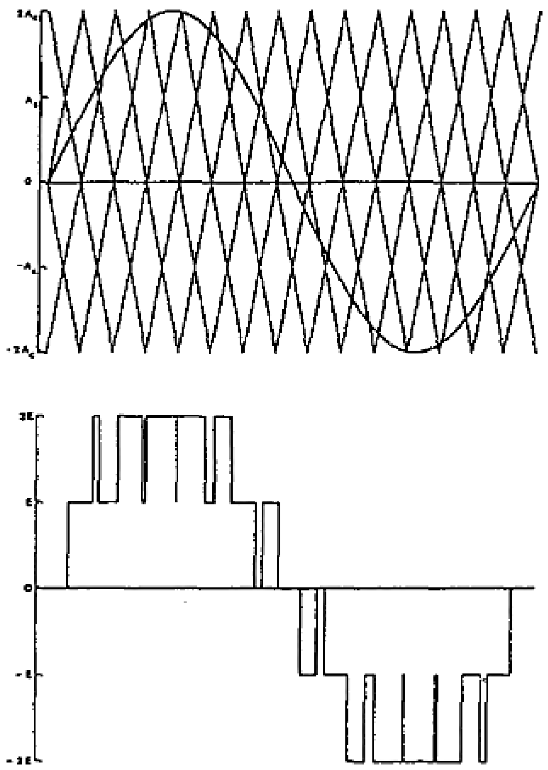
Simple and using a low switching frequency.

Disadvantage:

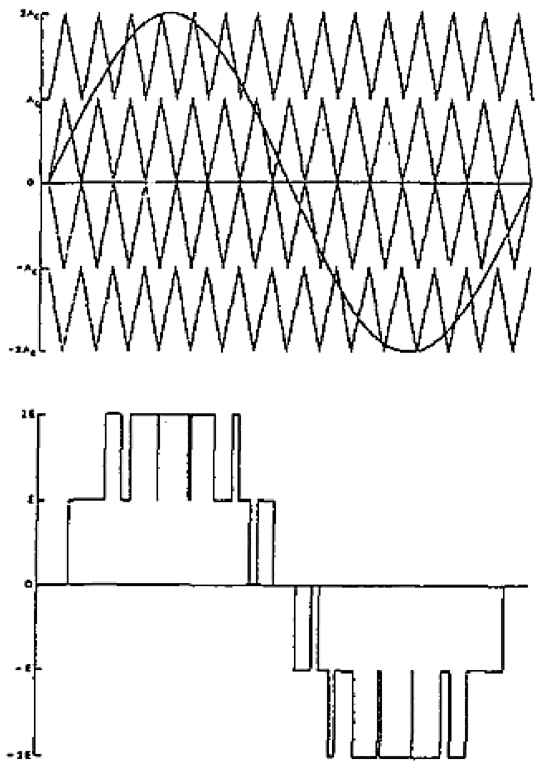
There are frequent sorting issues with the capacitor voltage (sort from highest voltage to lowest voltage) which would be a burden to the controller if the number of sub-modules is large.

Ref: https://e2e.ti.com/support/microcontrollers/c2000-microcontrollers-group/c2000/f/c2000-microcontrollers-forum/680649/tms320f28335-f28335

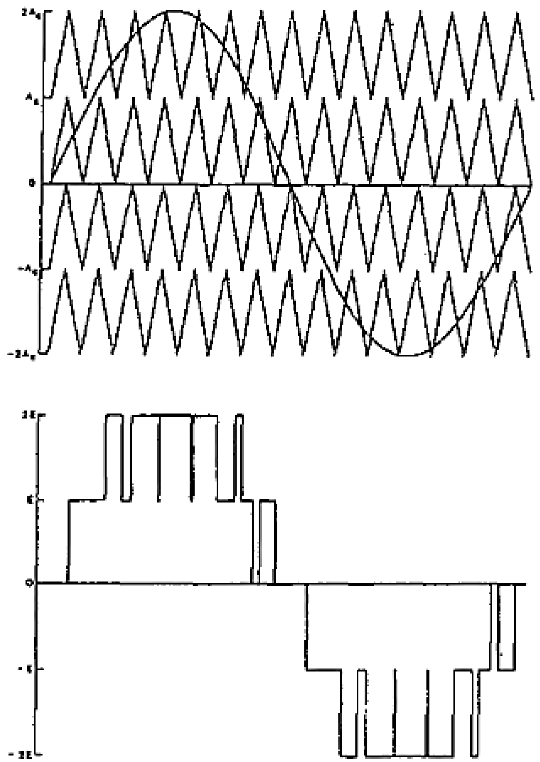
Carrier Level Shift PWM (CLS-PWM)



Alternative Phase Opposition Disposition (APOD)



Phase Opposition Disposition (POD)



Phase Disposition (PD)

- PD has the lowest line-to-line harmonic voltage distortion, while that of POD is the highest (APOD has the same harmonic components as CPS-PWM).
- Produces an uneven distribution of power among cells, which can produce a high harmonic content in the input current (especially when the modulation index is small).

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Ref. L. M. Tolbert, X. Shi, Y. Liu, "Multilevel Power Converters," *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

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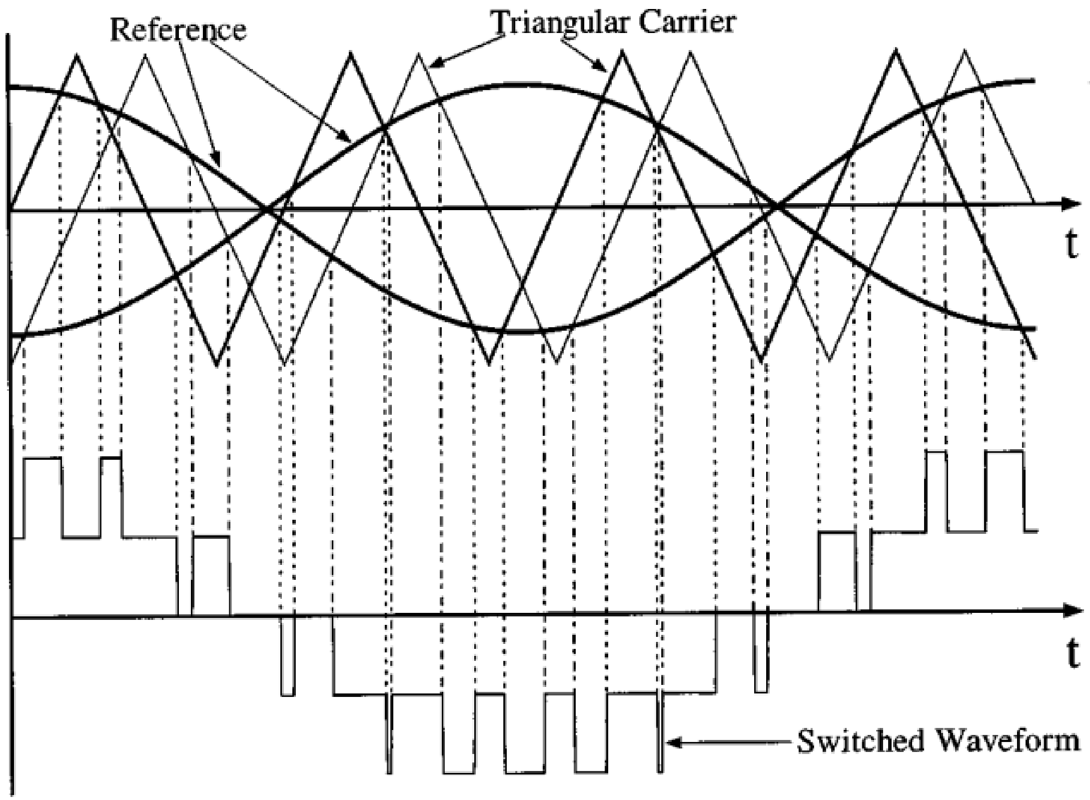
Carrier Phase Shift PWM (CPS-PWM)



N+1 level modulation
Shifted angle: 360°/N

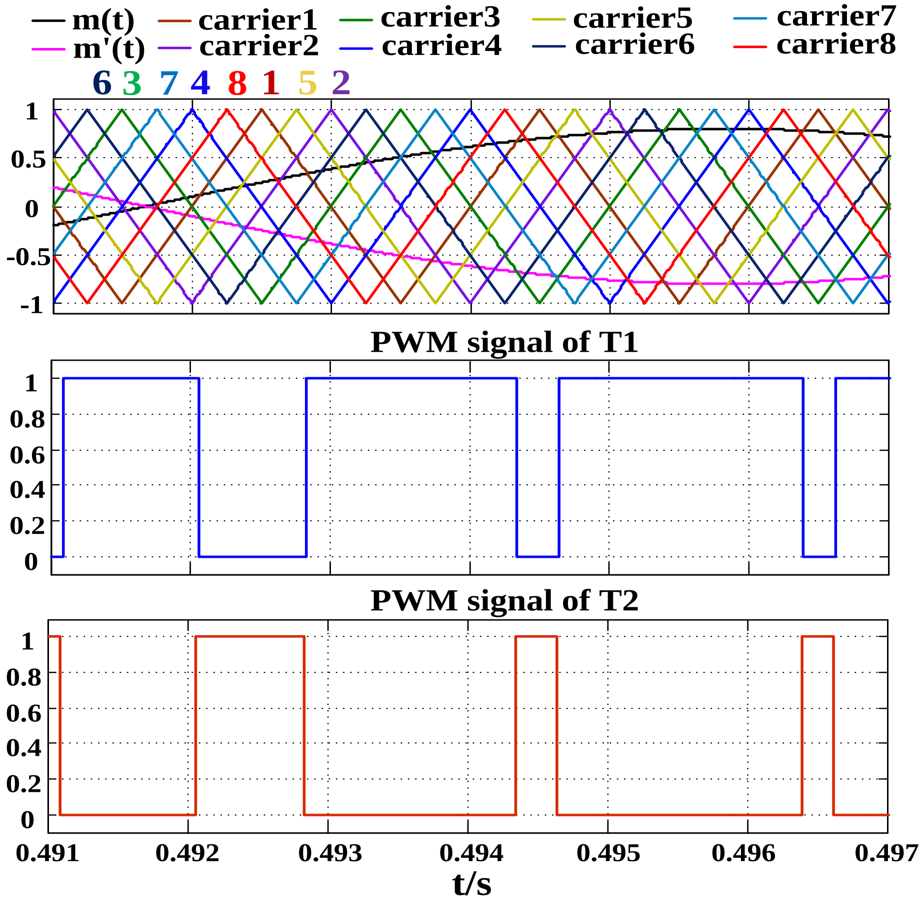
2N+1level modulation
Shifted angle: 180°/N

- Effective switching frequency of the load voltage is N times of the carrier wave, contributing to low switching losses
- Low harmonics contained in the output voltage enables smaller filter
- Offers an even power distribution among cells
- Easy to be implemented independently between number of inverters
- Works in the over-modulation region when a common-mode term is added to the reference

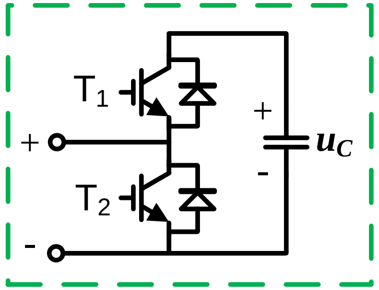
Ref: B. P. McGrath and D. G. Holmes, “Multicarrier PWM strategies for multilevel inverters,” *IEEE Transactions on Industrial Electronics,* vol. 49, no. 4, pp. 858–867, Aug. 2002.

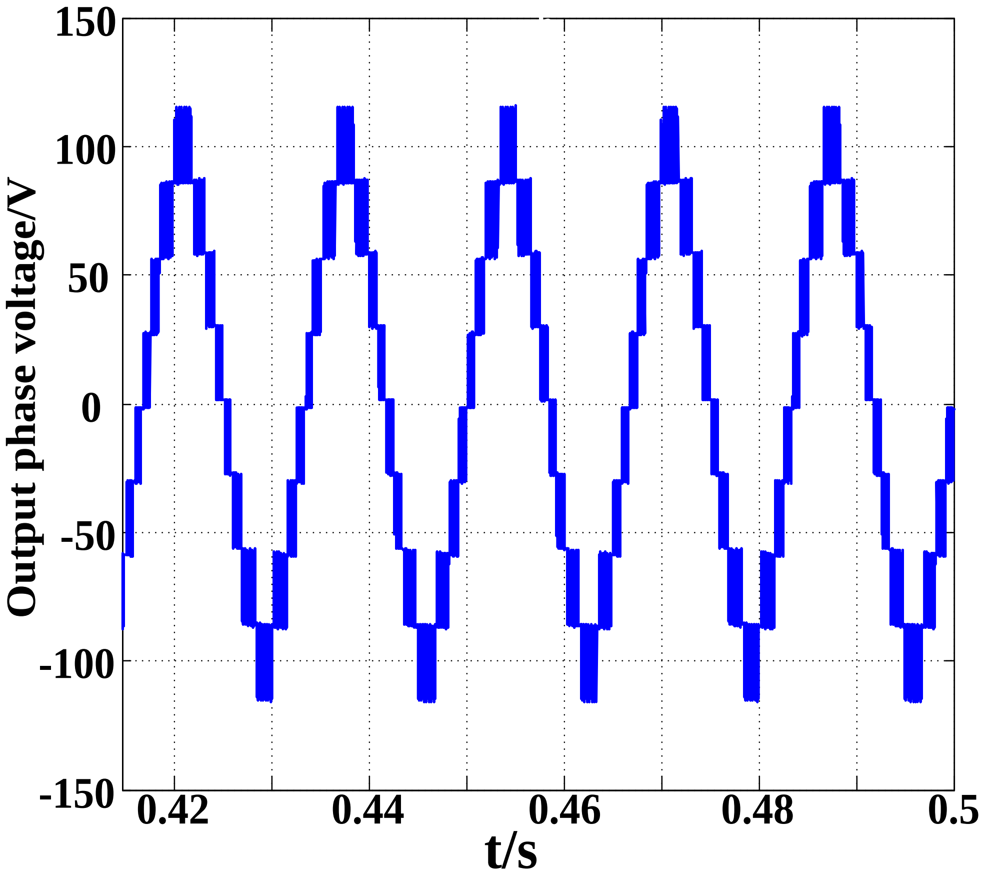
CPS-PWM Modulation (2N+1 level)

***N*=4 submodules, V_{dc}=240 V, arm inductance L_0=0 mH, f_c=1 kHz, amplitude modulation index =1, phase shift angle between carrier waveforms is 180°/8=22.5°, with resistive load and R_{load}=10 Ω .**



Modulation and carrier waves



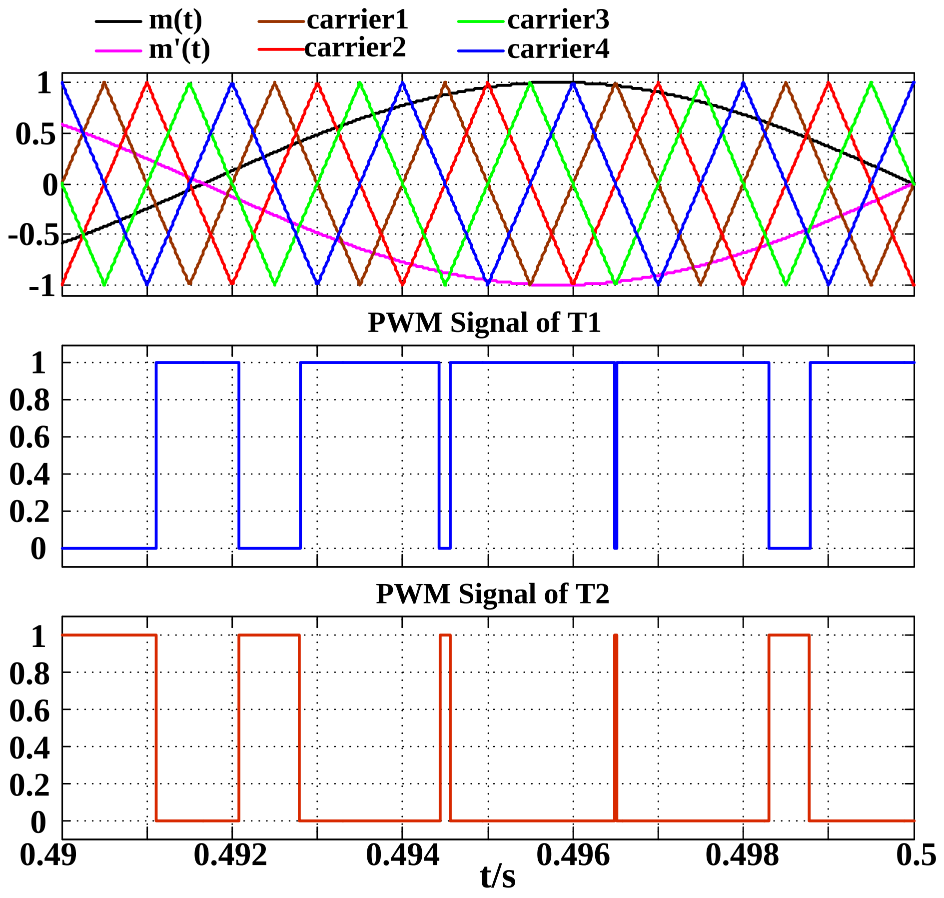


Output phase voltage

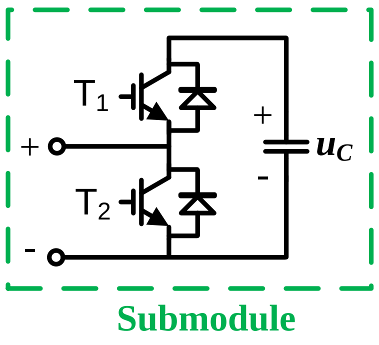
Ref. L. M. Tolbert, X. Shi, Y. Liu, "Multilevel Power Converters," *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

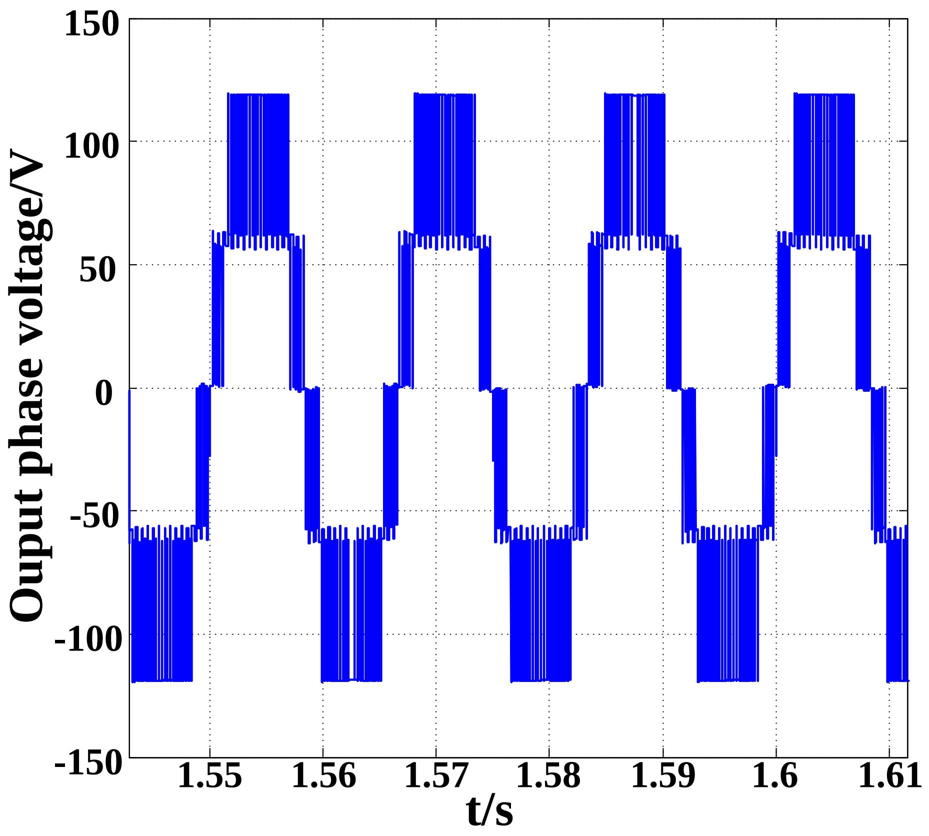
CPS-PWM Modulation (N+1 level)

***N*=4 submodules, V_{dc}=240 V, arm inductance L_0=0 mH, f_c=1 kHz, amplitude modulation index =1, phase shift angle between carrier waveforms is 180°/4=45°, with resistive load and R_{load}=10 Ω .**



Modulation and carrier waves





Output phase voltage

Ref. L. M. Tolbert, X. Shi, Y. Liu, "Multilevel Power Converters," *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

Modulation Methods Used in MMC

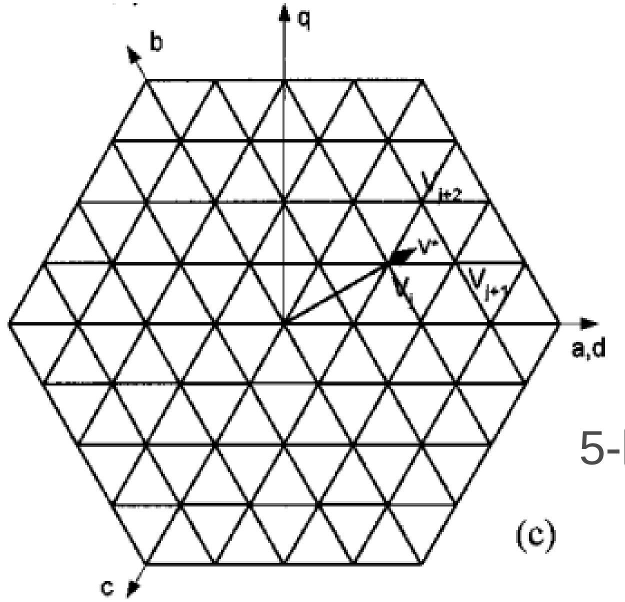
Space-vector PWM (SVPWM)

Advantages:

1. Good utilization of dc-link voltage
2. Low switching frequency with reduced switching losses
3. Relatively easy hardware implementation by a digital signal processor (DSP)

Disadvantage:

1. As the number of levels increases, redundant switching states and the complexity of selecting switching states increase dramatically.



5-level

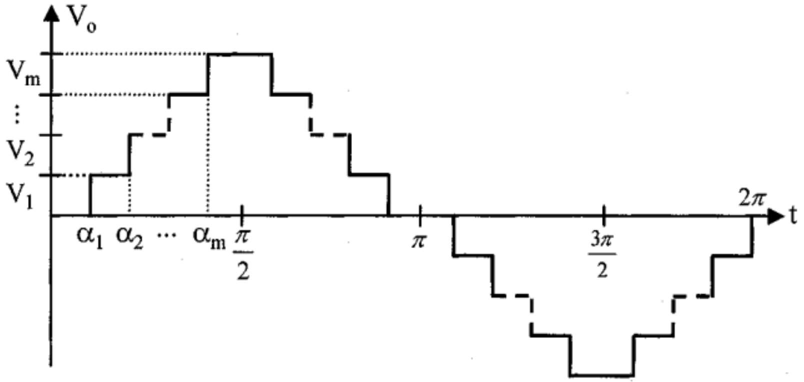
Selective Harmonic Elimination (SHE-PWM)

Advantage:

1. Up to N-1 harmonic contents can be removed from the voltage waveform.

Disadvantages:

1. If switching angles are computed offline and stored in tables, which are then interpolated according to the operating conditions, then can be used in open-loop or low-bandwidth applications.
2. Become very complex to design and implement for converters with a high number of levels (above five).



Ref: José Rodríguez, Jih-Sheng Lai, and Fang Zheng Peng, "Multilevel Inverters: A Survey of Topologies, Controls, and Applications", *IEEE Trans. Ind. Electron.*,vol. 49, no. 4, pp. 724-738, August. 2002.

Comparison Between Modulation Methods

Modulation methods	Advantages	Disadvantages	Application
Nearest Level Control	Simplest; High voltage quality; Low switching losses	When modulation index and voltage levels are low, the THD increase significantly	High voltage level
CPS-PWM	Low voltage distortion, easy to be modularized	Leads to circulating current between phases	Low and medium level
CLS-PWM	Each carrier signal can be easily related to each power semiconductor	The vertical shifts produces an uneven power distribution among the cells	Low and medium level
SVM	Simple, low voltage distortion;	High control complexity	Low voltage level
SHE-PWM	Low voltage distortion	Poor dynamic response	Low voltage level

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Modular Multilevel Converter (MMC) Outline

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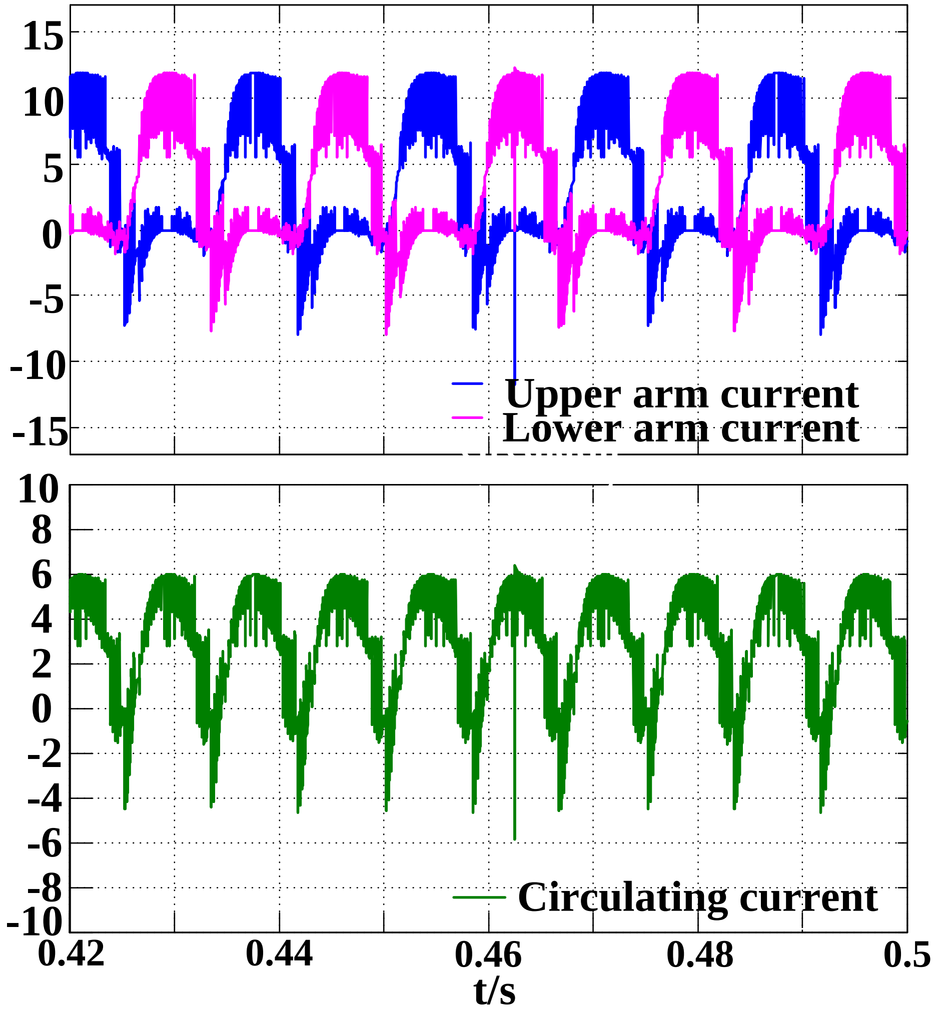
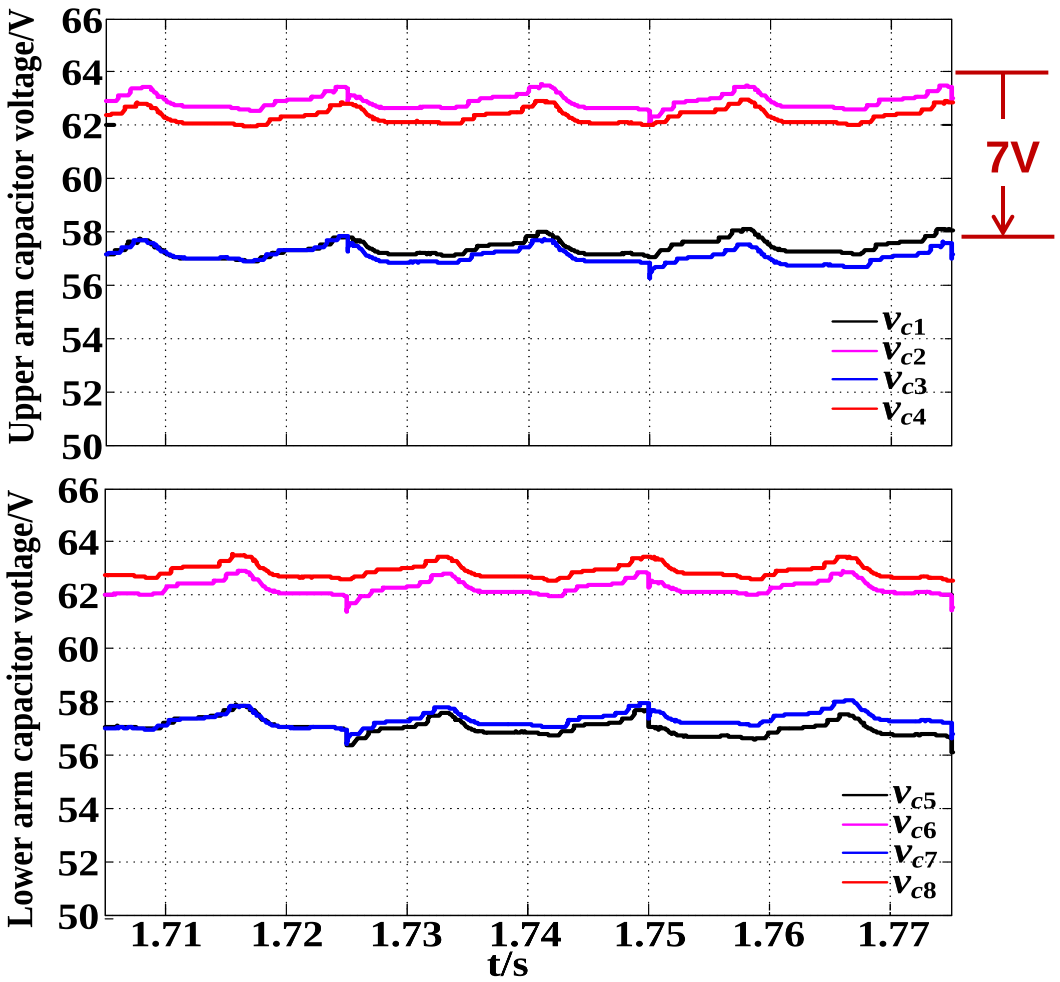
- MMC-based HVDC system

Circulating Current & Capacitor Voltages

N+1 level modulation

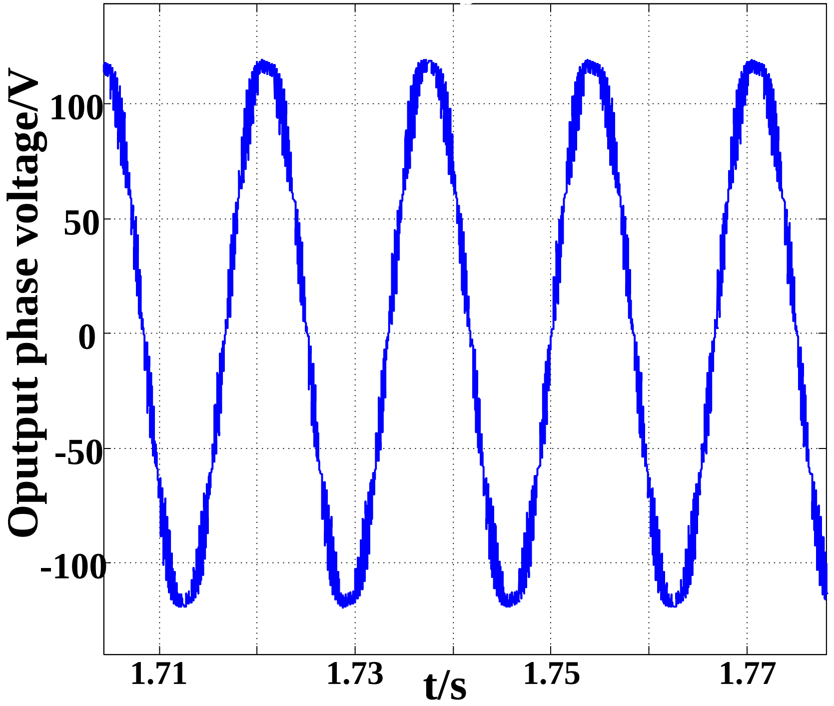




Ref: Y. Li, "Arm Inductance and Sub-module Capacitance Selection in Modular Multilevel Converter," 2013.

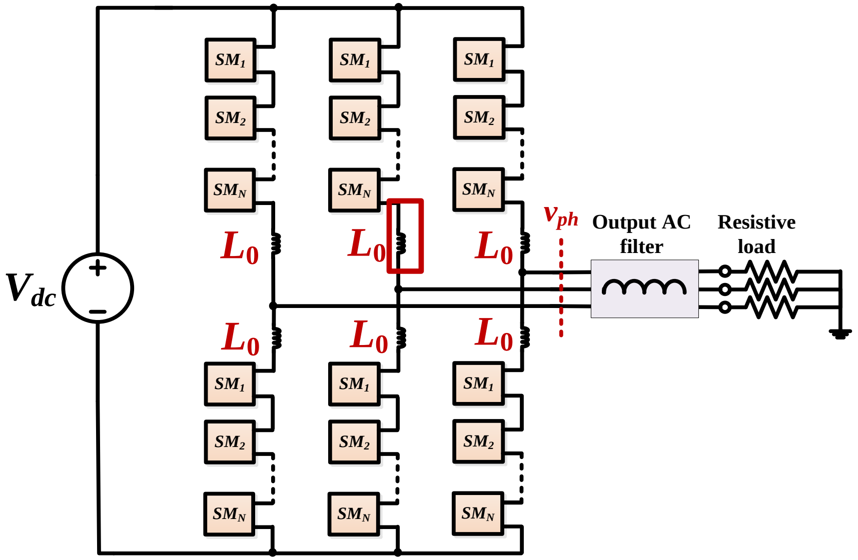
Impact of Arm Inductors, L_0

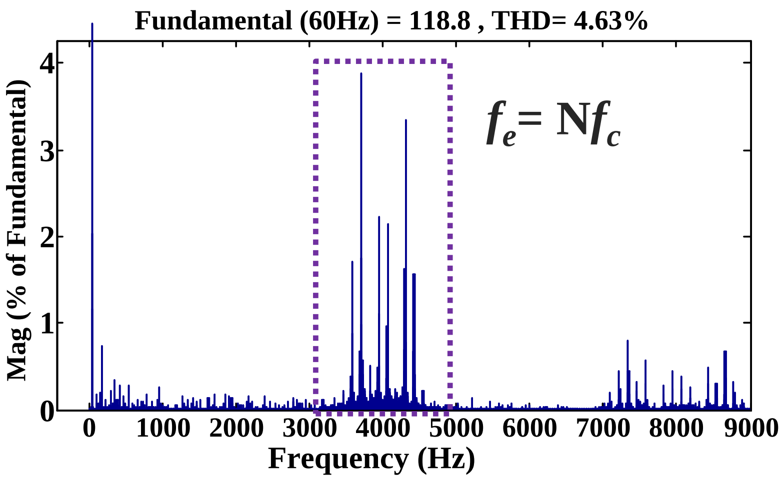
N=4, V_{dc}=240 V, arm inductance L_0=2 mH, f_c=1 kHz, modulation index =1, phase shift angle between carrier waveforms is 360°/4=90°, with resistive load and R_{load}=10 Ω .



Output phase voltage

Arm inductor aids in filtering the phase voltage switching ripple





Spectrum analysis of the output voltage

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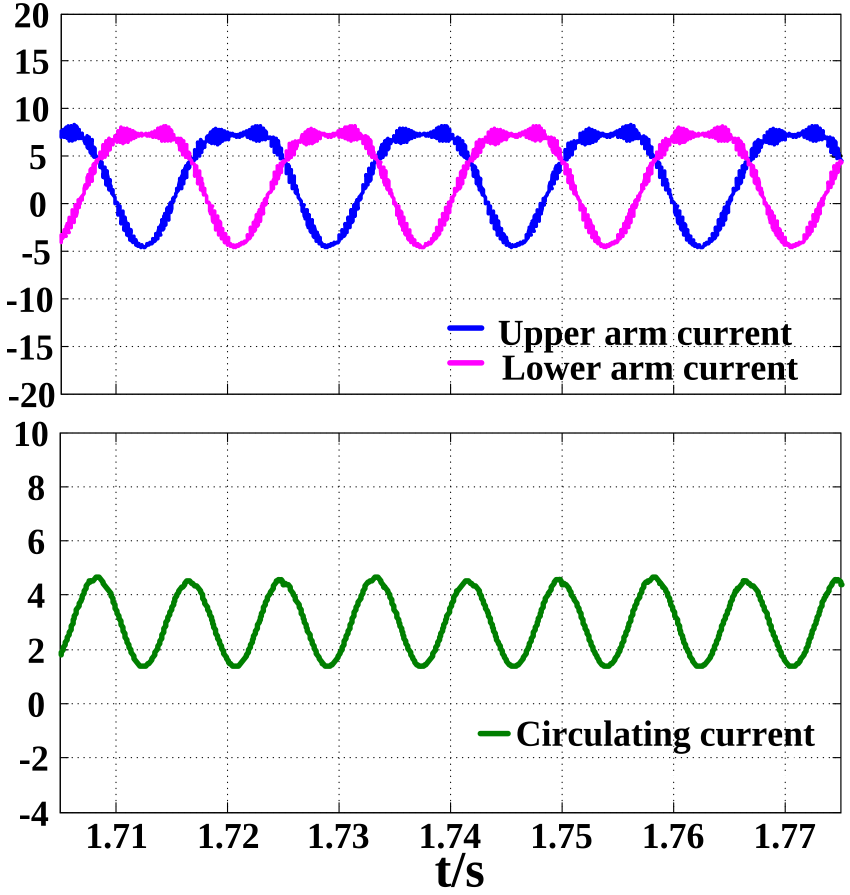
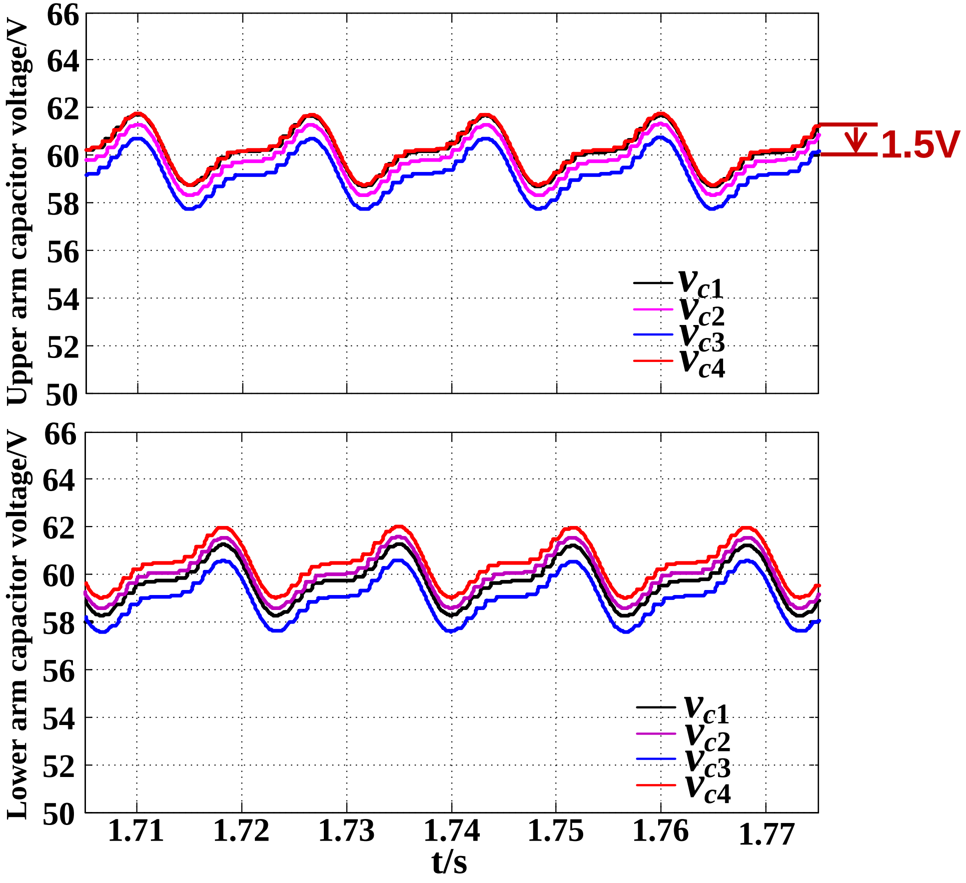
Ref. X. Shi, Z. Wang, L. M. Tolbert, and F. Wang, “A comparison of phase disposition and phase shift PWM strategies for modular multilevel converters,” in 2013 IEEE Energy Conversion Congress and Exposition, Sep. 2013, pp. 4089–4096.

Impact of Arm Inductors

With 2 mH arm inductors

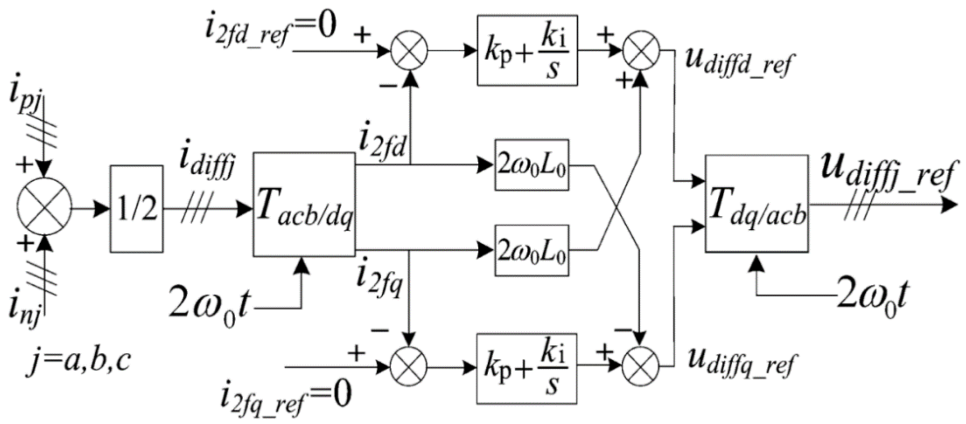




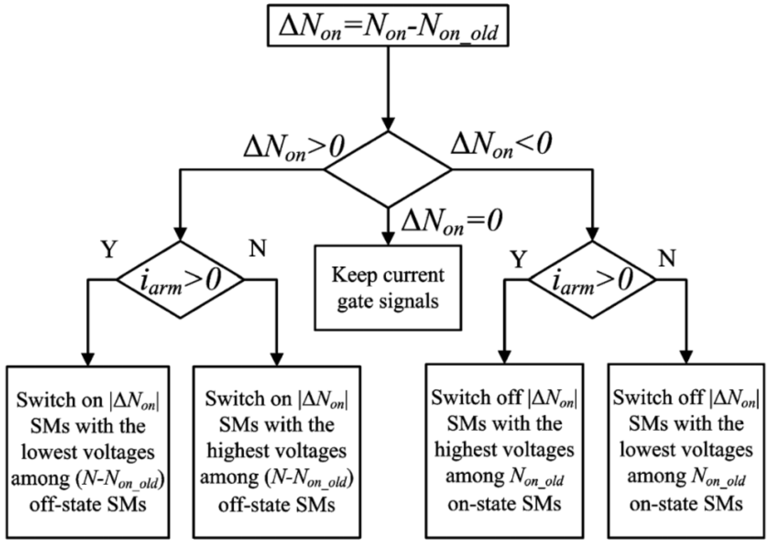
Larger arm inductance also helps to reduce the capacitor voltage unbalance and circulating current, but it increases system size, weight and cost.

Ref: Y. Li, “Arm Inductance and Sub-module Capacitance Selection in Modular Multilevel Converter,” 2013.

Active Control Schemes

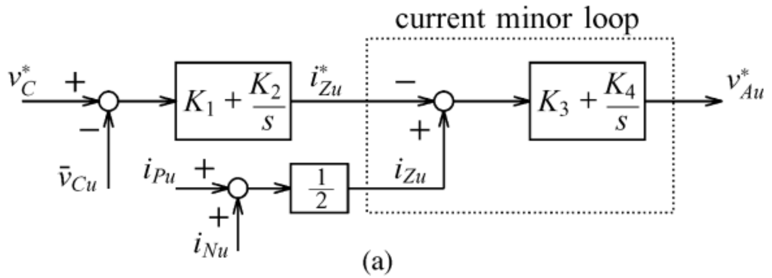


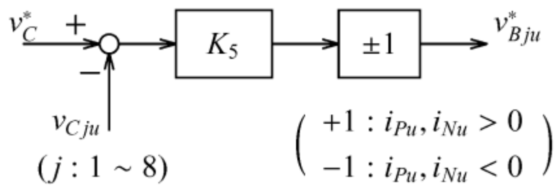
Circulating current suppressing controller



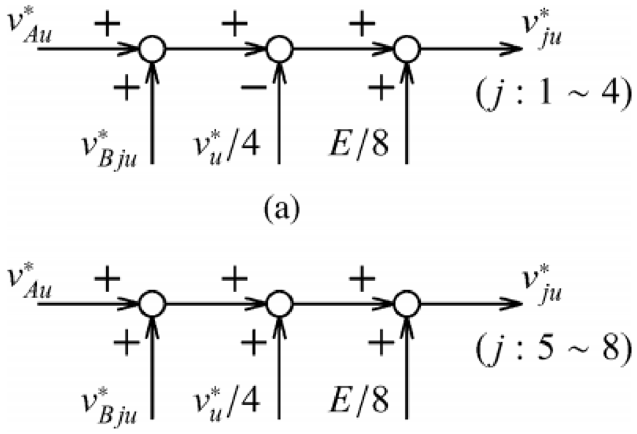
Capacitor voltage control

Ref: Q. Tu, Z. Xu, and L. Xu, "Reduced Switching-Frequency Modulation and Circulating Current Suppression for Modular Multilevel Converters," IEEE Trans. Power Del., vol. 26, no. 3, pp. 2009 – 2017, July 2011.





Average control

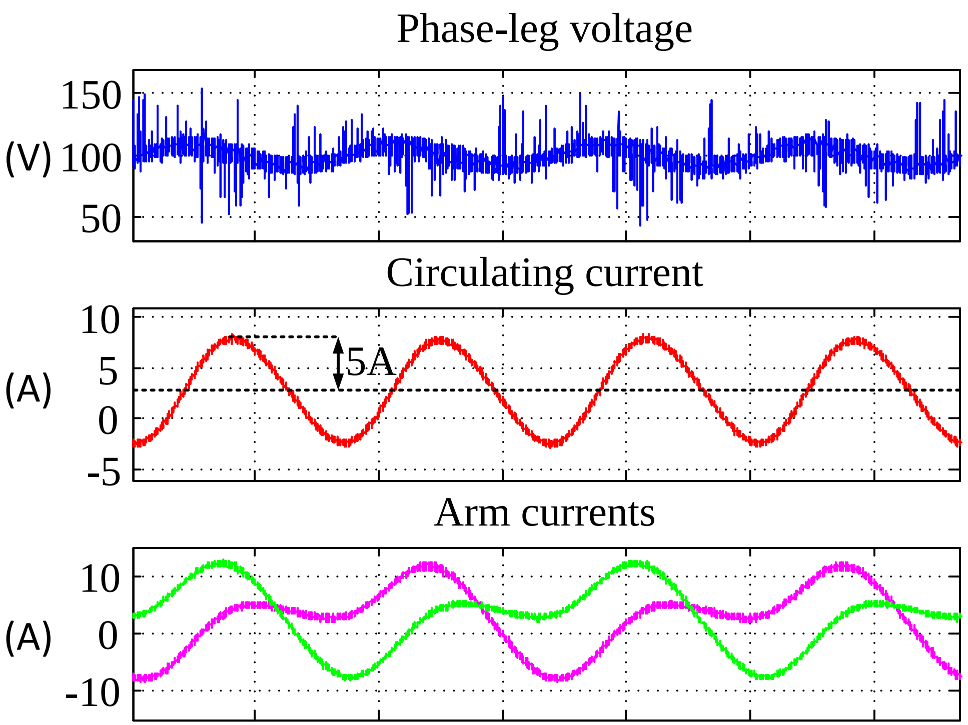


Balancing control

Ref: M. Hagiwara and H. Akagi, "Control and Experiment of Pulsewidth-Modulated Modular Multilevel Converters," IEEE Trans. Power Electron., vol. 24, no. 7, pp. 1737 –1746, July 2009.

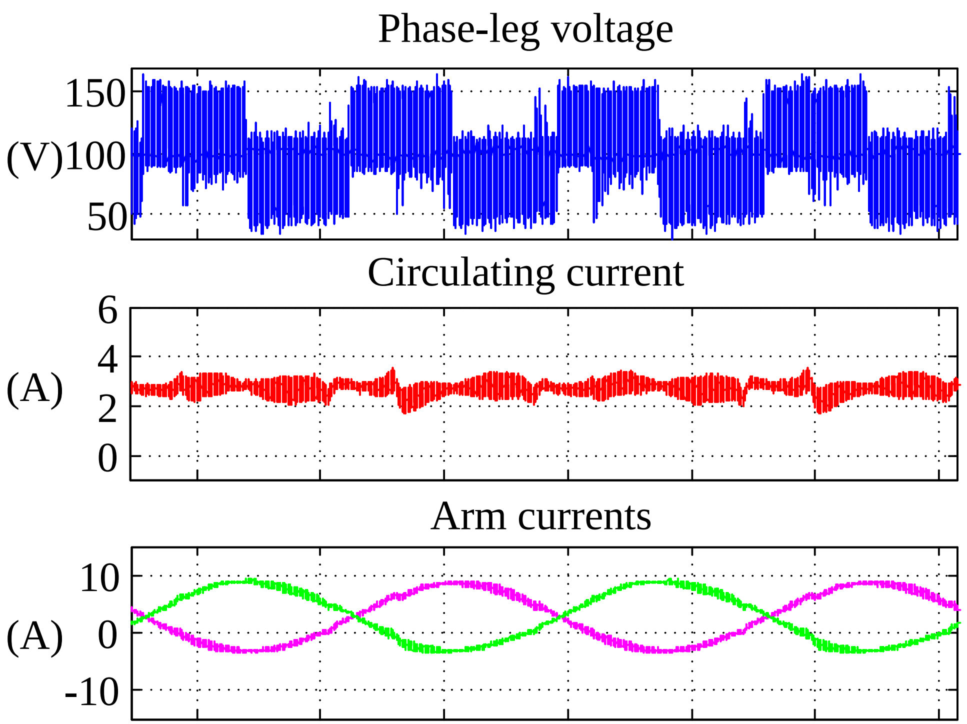
Circulating Current Control

Large inductor (L=1 mH)
&
Controller disabled



Second-order circulating current

Reduced inductor (L=0.1 mH)
&
Controller enabled



High frequency circulating current

- ✓ **Enabling sinusoidal arm currents with small inductance**
- ✓ **No additional hardware cost**

Ref. L. M. Tolbert, X. Shi, Y. Liu, "Multilevel Power Converters," *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

Modular Multilevel Converter (MMC) Outline

- Introduction
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- MMC-based HVDC system

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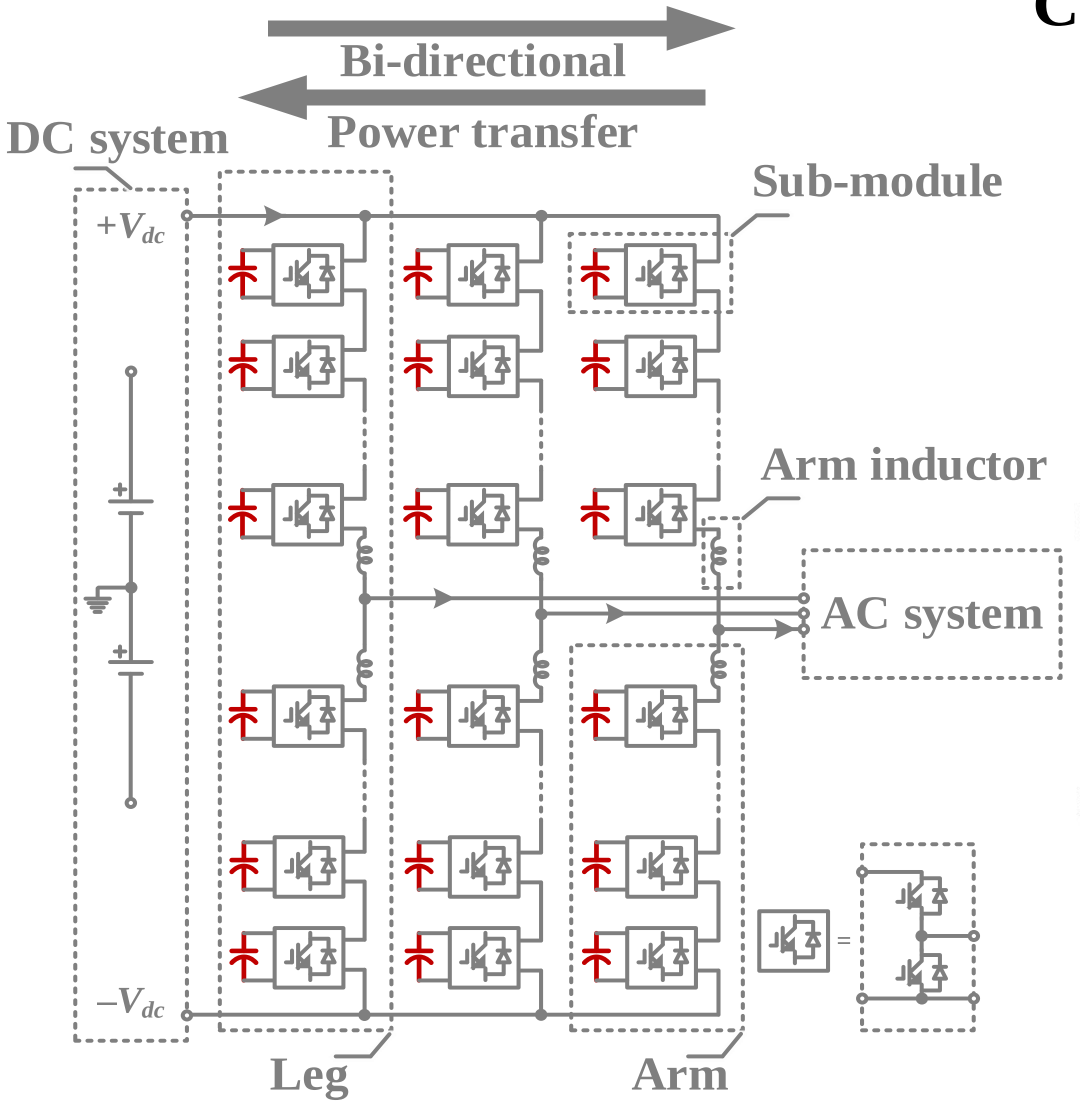
Capacitor Voltage Unbalance



Capacitor Voltage Unbalance

Capacitor voltage is NOT self balanced with existing open-loop modulations.

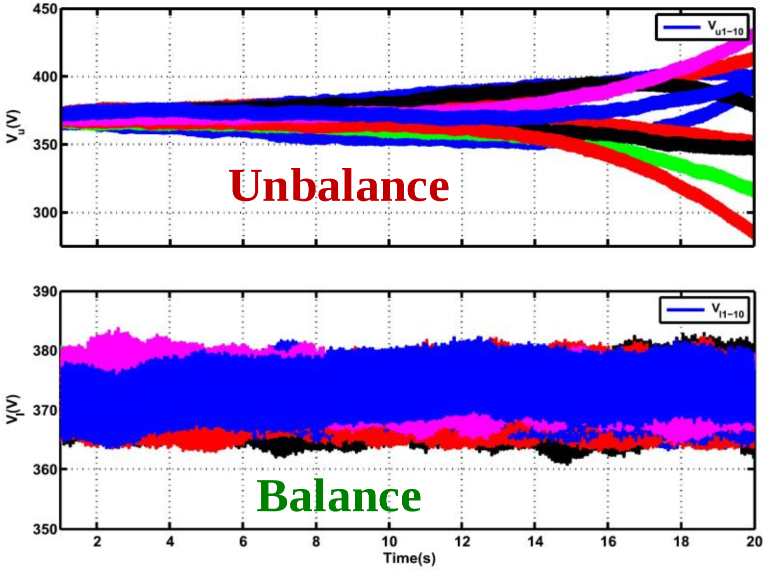
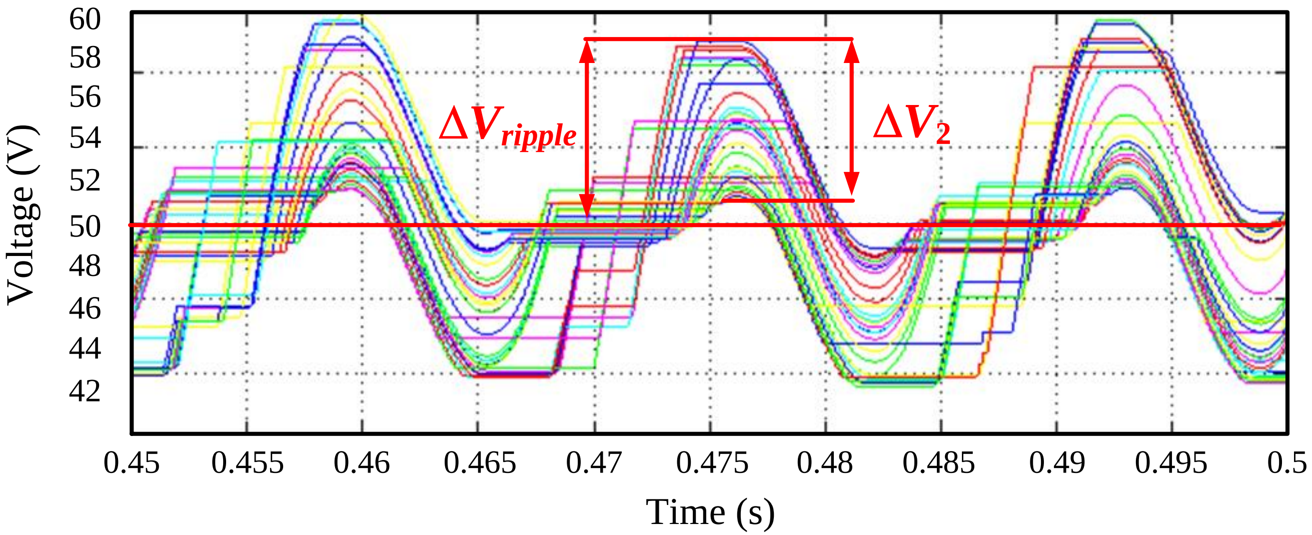


Fig. Examples of capacitor voltage trajectories [1].

Ref: A. Ghazanfari and Y. A. R. I. Mohamed, "A Hierarchical Permutation Cyclic Coding Strategy for Sensorless Capacitor Voltage Balancing in Modular Multilevel Converters," IEEE J. Emerg. Sel. Top. Power Electron., vol. 4, no. 2, pp. 576–588, 2016.

Capacitor Voltage Balancing

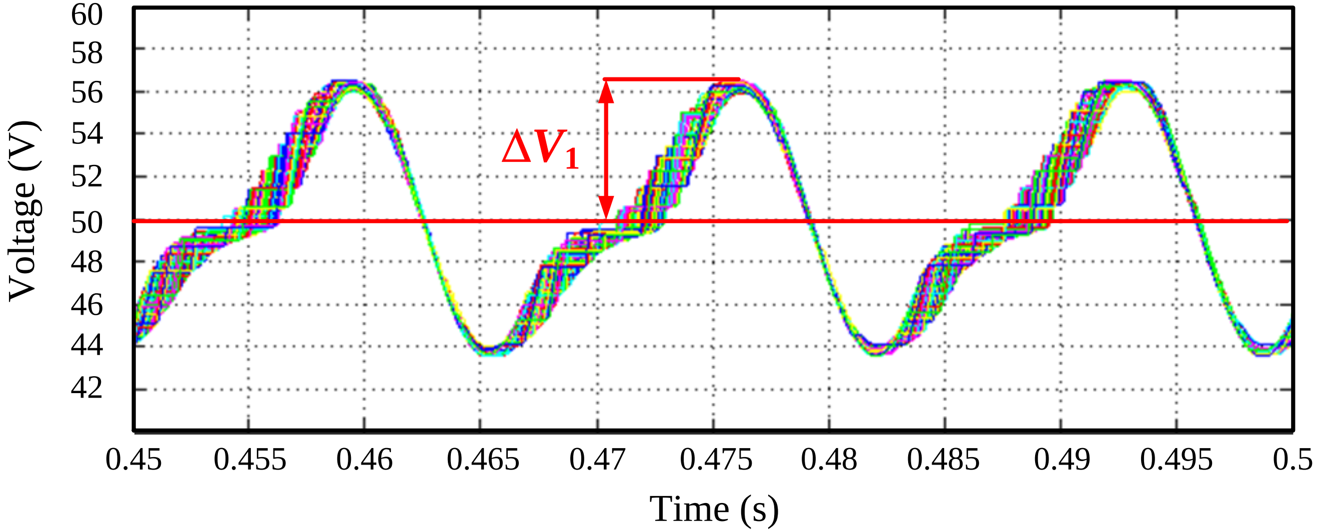
- **Not well-balanced case**



✓ **Enabling balanced capacitor voltages with small individual level capacitors**

✓ **No additional hardware cost**

- **Well-balanced case**



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Ref. L. M. Tolbert, X. Shi, Y. Liu, "Multilevel Power Converters," *Power Electronics Handbook*, 5th Edition, 2023, ISBN 9780323992169, Chapter 12, pp. 407-435.

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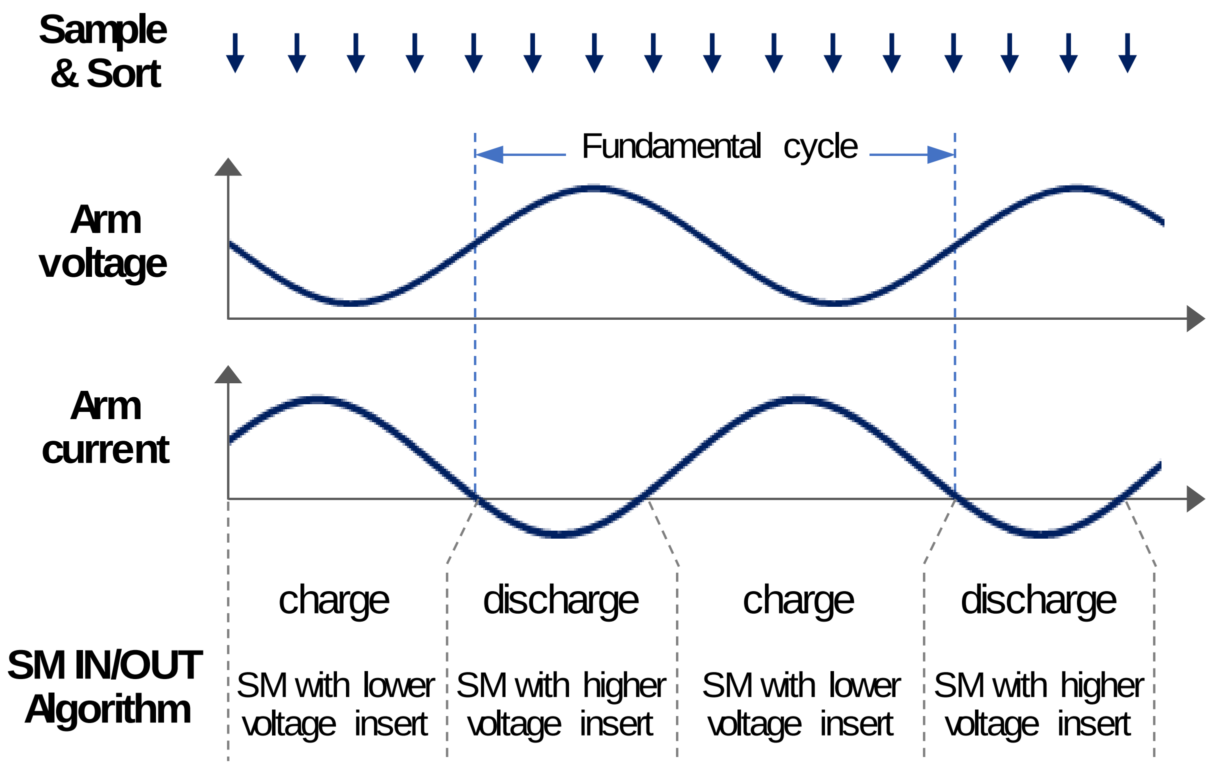
Classic Capacitor Voltage Balancing Methods



Classic closed-loop SM balancing method

Access real-time SM voltage
- Real-time SM voltage sampling
- Model-based estimation

Identify charging/ discharging
- Real-time arm current sampling
- Model-based arm current direction
- Offline net-charge change prediction

Switching pattern allocation
- Reverse correspondence of SM voltages & switching pattern charging capability
- Non-global sorting and non-global pattern update
- Variable frequency switching
- Optimization of sorting process
- Model predictive control

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Ref. S. Fan, L. M. Tolbert, X. Xiang, and W. Li, "Submodule Voltage Balancing Methods in Modular Multilevel Converters – A Review," *in 2024 IEEE Energy Conversion Congress and Exposition (ECCE),* Oct. 2024, pp. 2775–2782.

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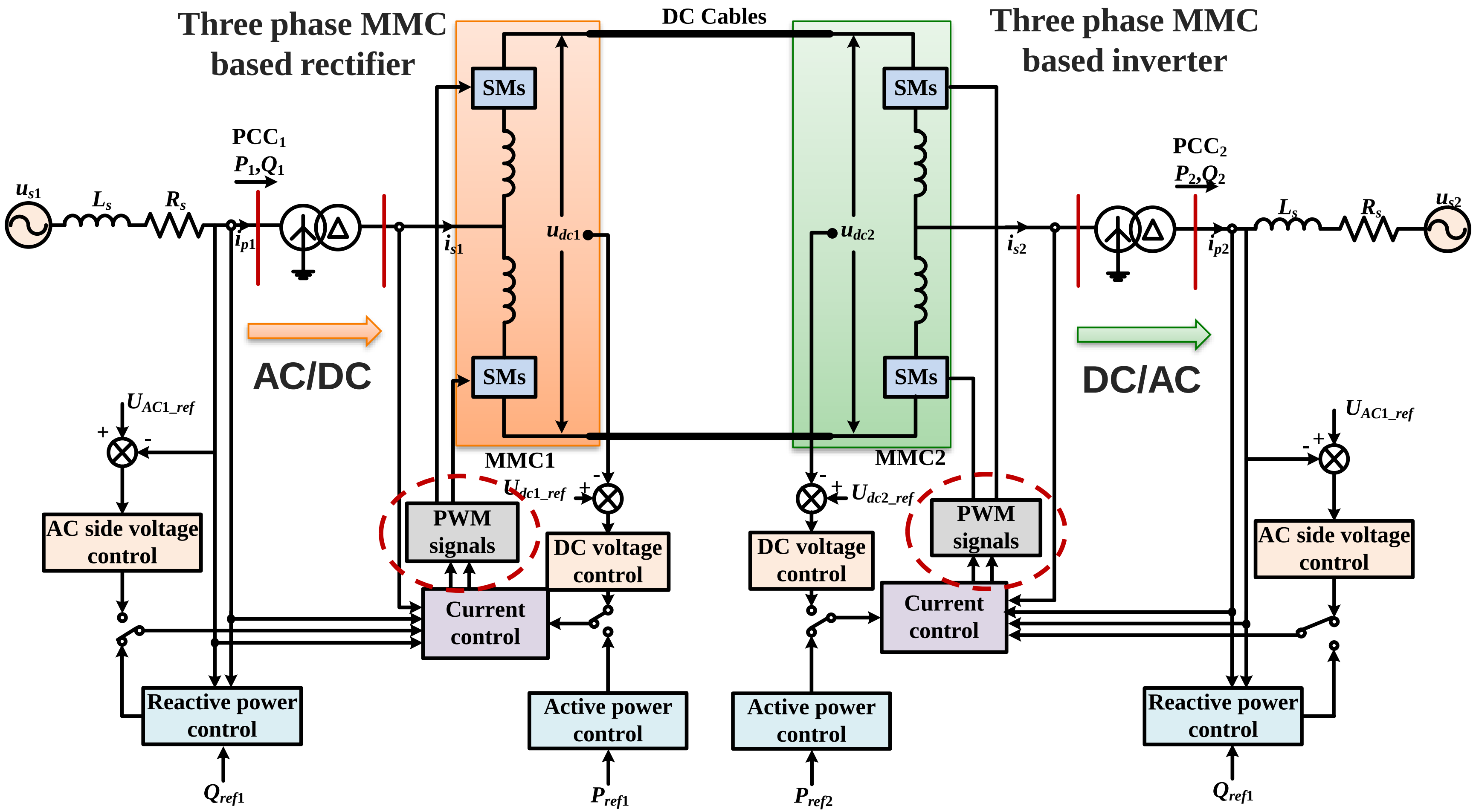
MMC Based HVDC Transmission System

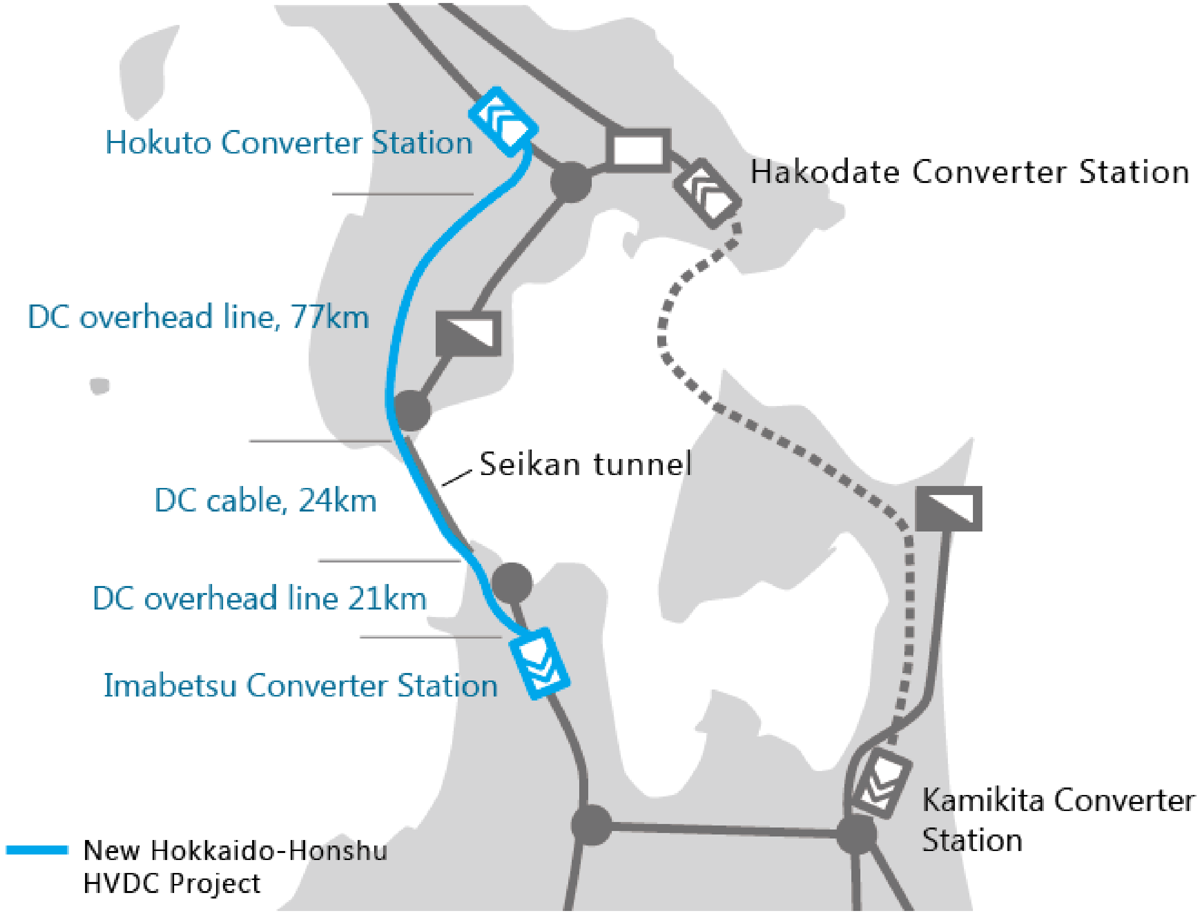


Differences from control of two level VSCs

- PWM signal generation
- Circulating current control
- Capacitor voltage balancing control

Toshiba MMC-Based VSC for HVDC

Toshiba MMC-based Converter Valve



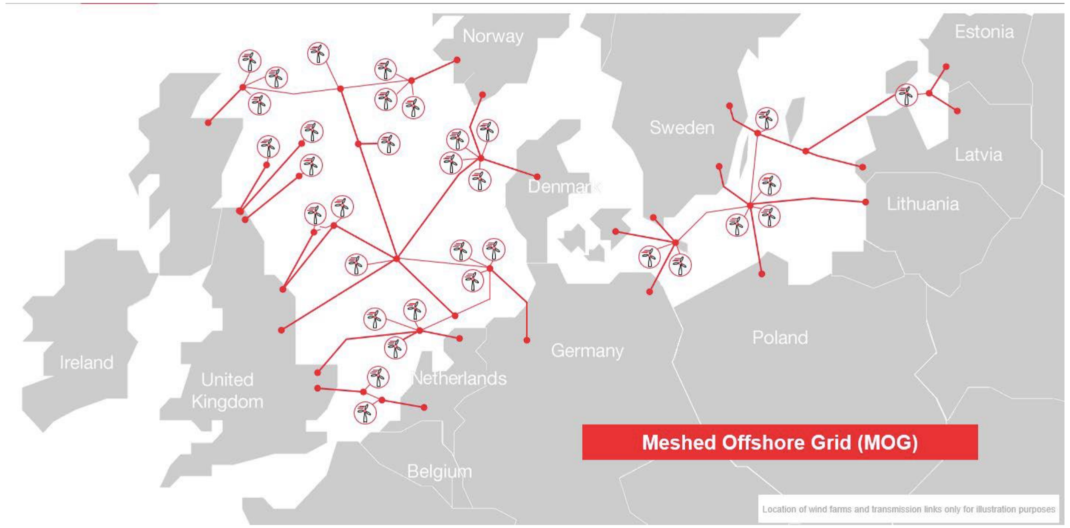
Hokkaido-Honshu Japan HVDC Link (300MW, DC 250kV, DC 1200A)

Ref: https://www.global.toshiba/ww/products-solutions/transmission/products-technical-services/power-conversion.html/1000

Hitachi Energy (ABB) HVDC Light

Power from Shore for Offshore Platforms

Hitachi Energy HVDC Light Valve Hall

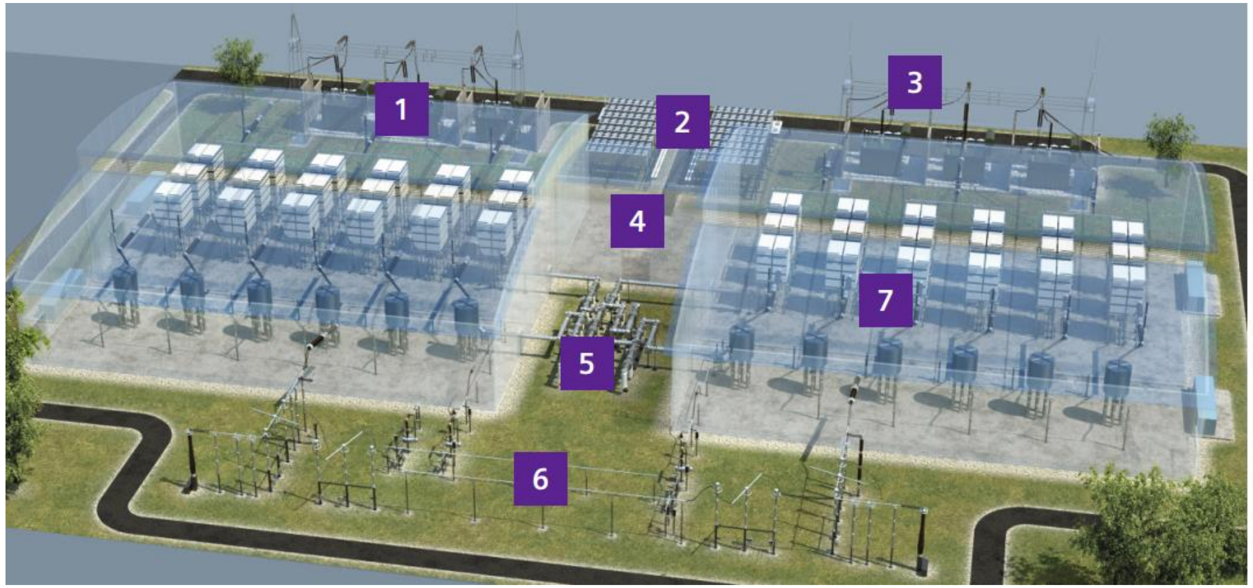


Proposed Meshed Offshore HVDC Grid in Europe

Ref: https://www.hitachienergy.com/us/en/products-and-solutions/hvdc/hvdc-light

Siemens Energy HVDC Plus (MMC-based)

2kA DC current
6.5kV voltage
Half-bridge submodule

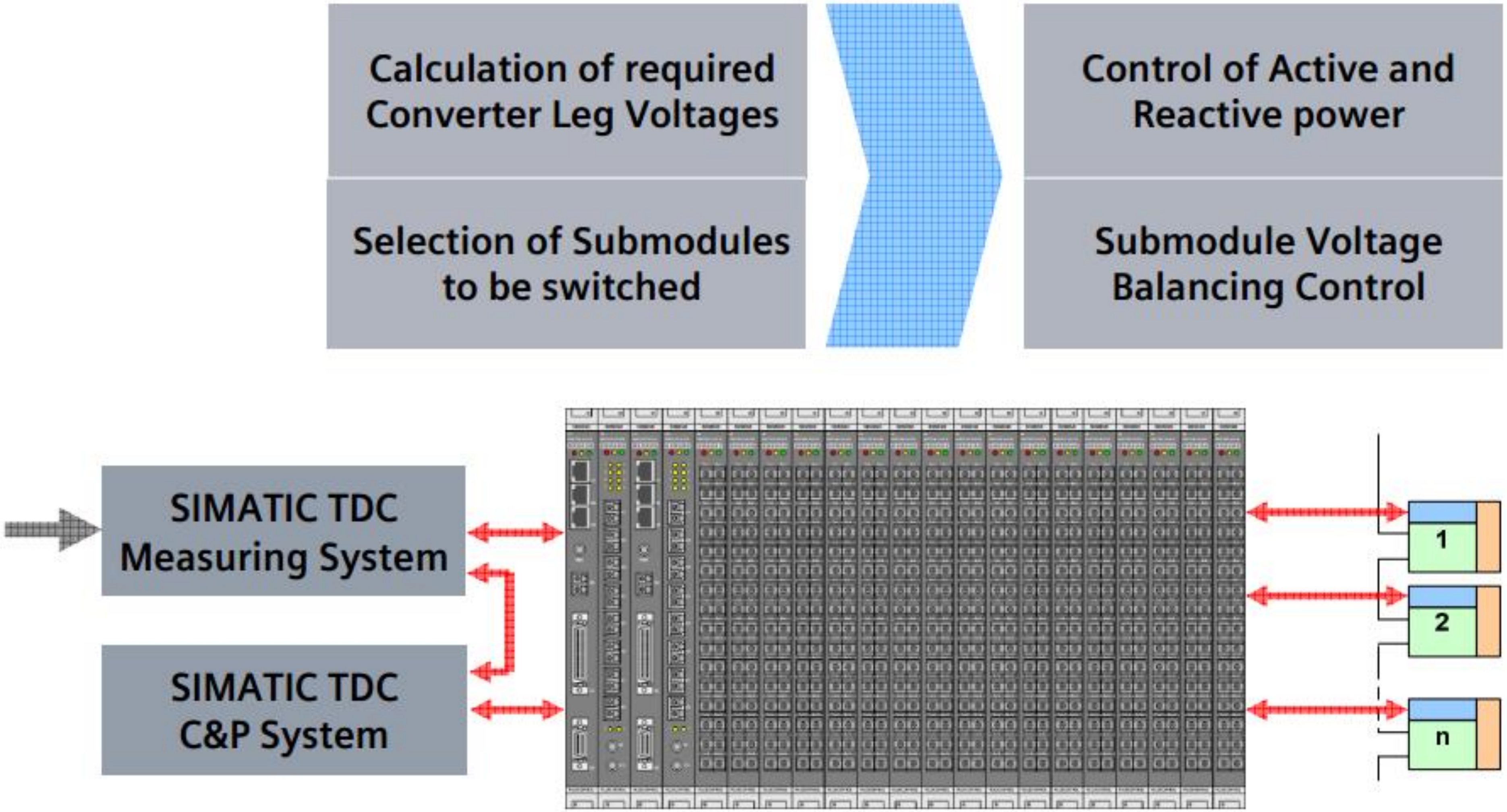


1 Converter transformers
2 Cooling
3 AC switchyard
4 Control and protection
5 DC compact switchgear
6 DC yard
7 Converter hall

BorWin3 (2019) project with float-over platform installation concept

Ref: https://www.siemens-energy.com/us/en/home/products-services/product/hvdc-plus.html

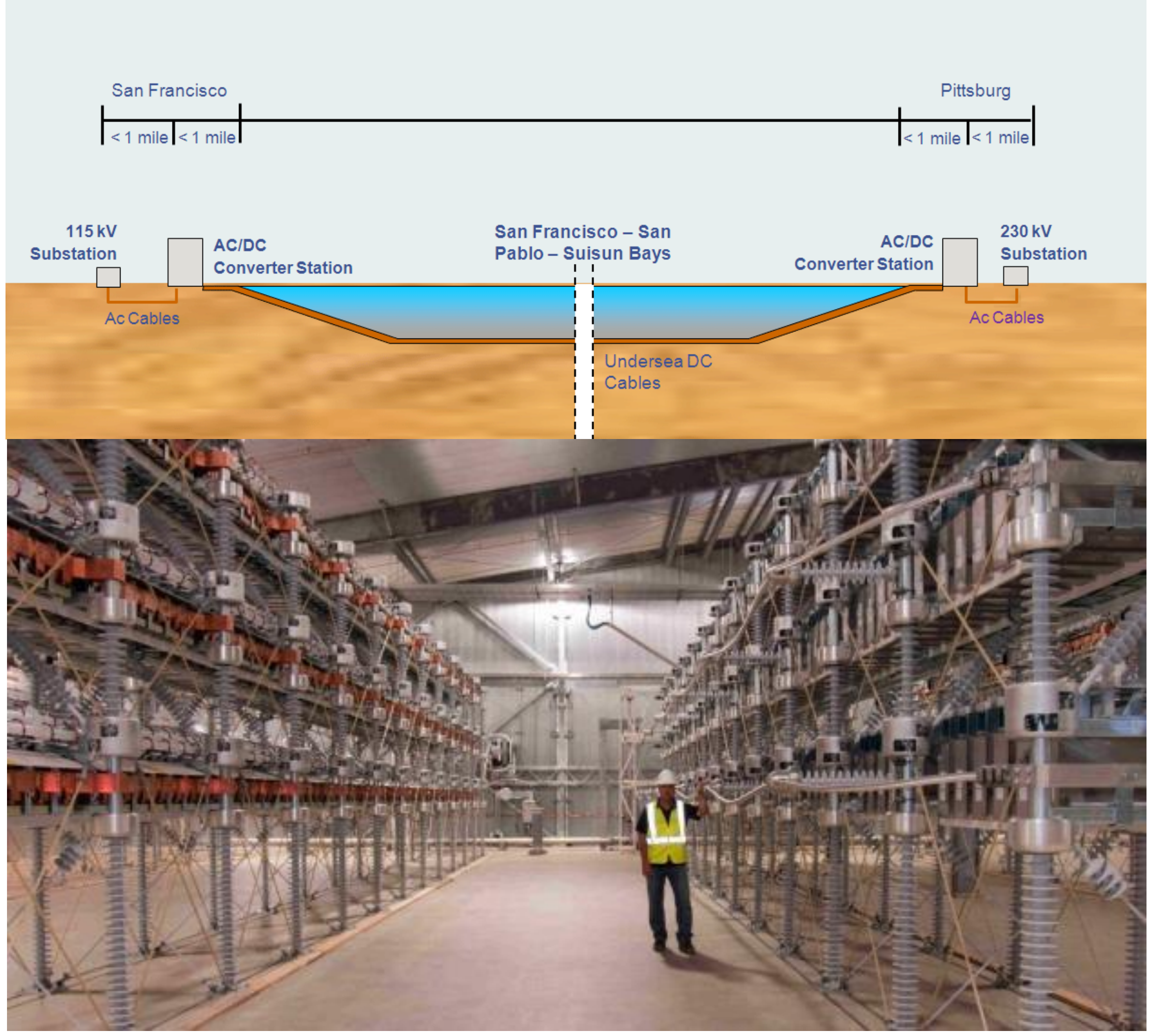
Control System for HVDC PLUS



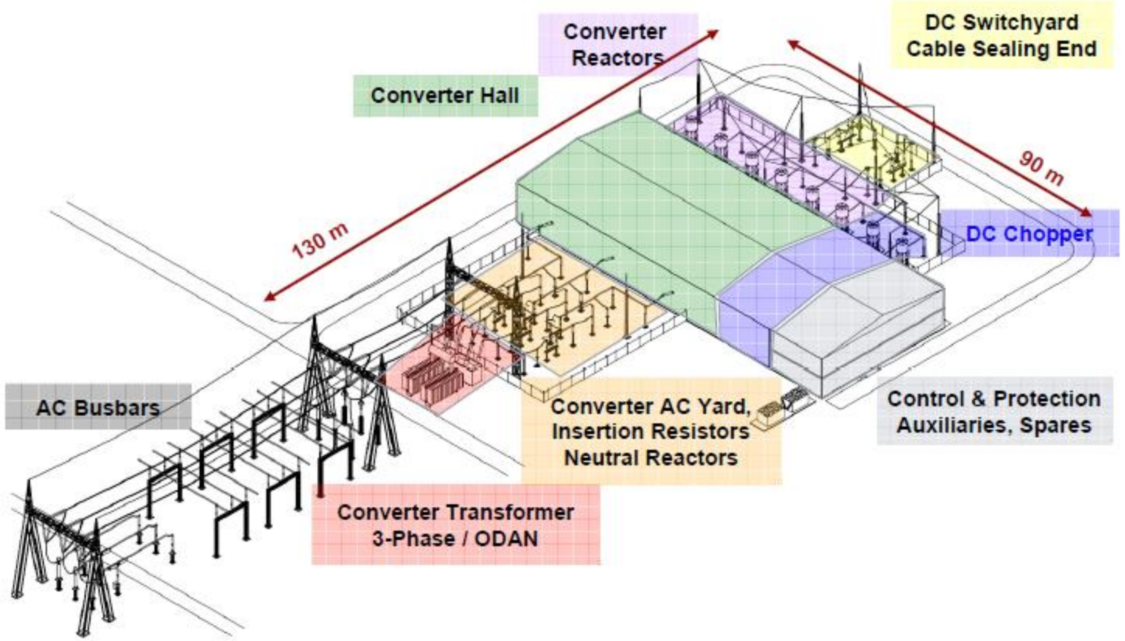
Ref: B. Gemmell, J. Dorn, D. Retzmann and D. Soerangr, “Prospects of multilevel VSC technologies for power transmission, ” *IEEE PES Transmission and Distribution Conference and Exposition*, 2008, pp.1-16.

Technology Evolution – Projects

- **First HVDC PLUS System (MMC): Trans Bay Cable Link, San Francisco**



- Rated power: 400 MW
- Reactive power: ± 300MVar
- DC voltage: ± 200 kV
- AC voltage: 230kV/138kV, 60Hz
- Transmission: 85 km submarine cable
- Commissioned: 2010



Ref：[1] H.-J. Knaak, “Modular multilevel converters and HVDC/FACTS: A success story,” in *Proceedings of the 2011 14th European Conference on Power Electronics and Applications*, 2011.
[2] A. Allerhand, “A Contrarian History of Early Electric Power Distribution [Scanning Our Past],” *Proceedings of the IEEE*, 2017.

Technology Evolution – Projects

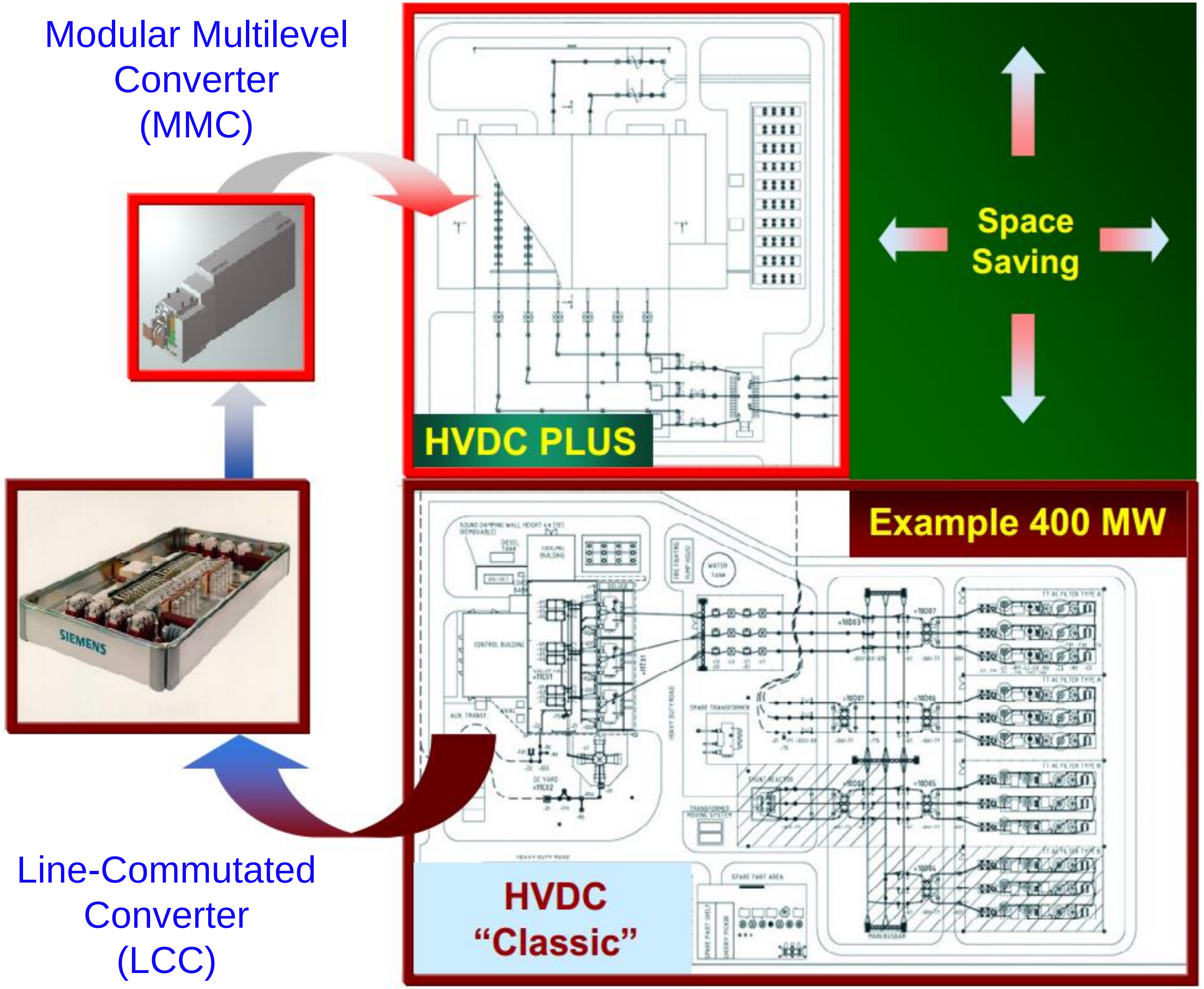
- **First VSC Project (MMC) with 1000 MW Capacity: INELFE (two links)**

- Rated power: 2*1000 MW
- Reactive power: ± 300MVar
- DC voltage: ± 320 kV
- AC voltage: 400 kV, 50 Hz
- Transmission: 60 km underground cable
- Scheduled commission: 2014

Ref: https://www.energy.gov/sites/prod/files/2013/05/f0/HVDC2013-Kohnstam_0.pdf

Space Savings in Comparison with HVDC "Classic"

Modular Multilevel Converter (MMC)



Line-Commutated Converter (LCC)

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Ref: B. Gemmell, J. Dorn, D. Retzmann and D. Soerangr, "Prospects of multilevel VSC technologies for power transmission, " *IEEE PES Transmission and Distribution Conference and Exposition*, 2008, pp.1-16.

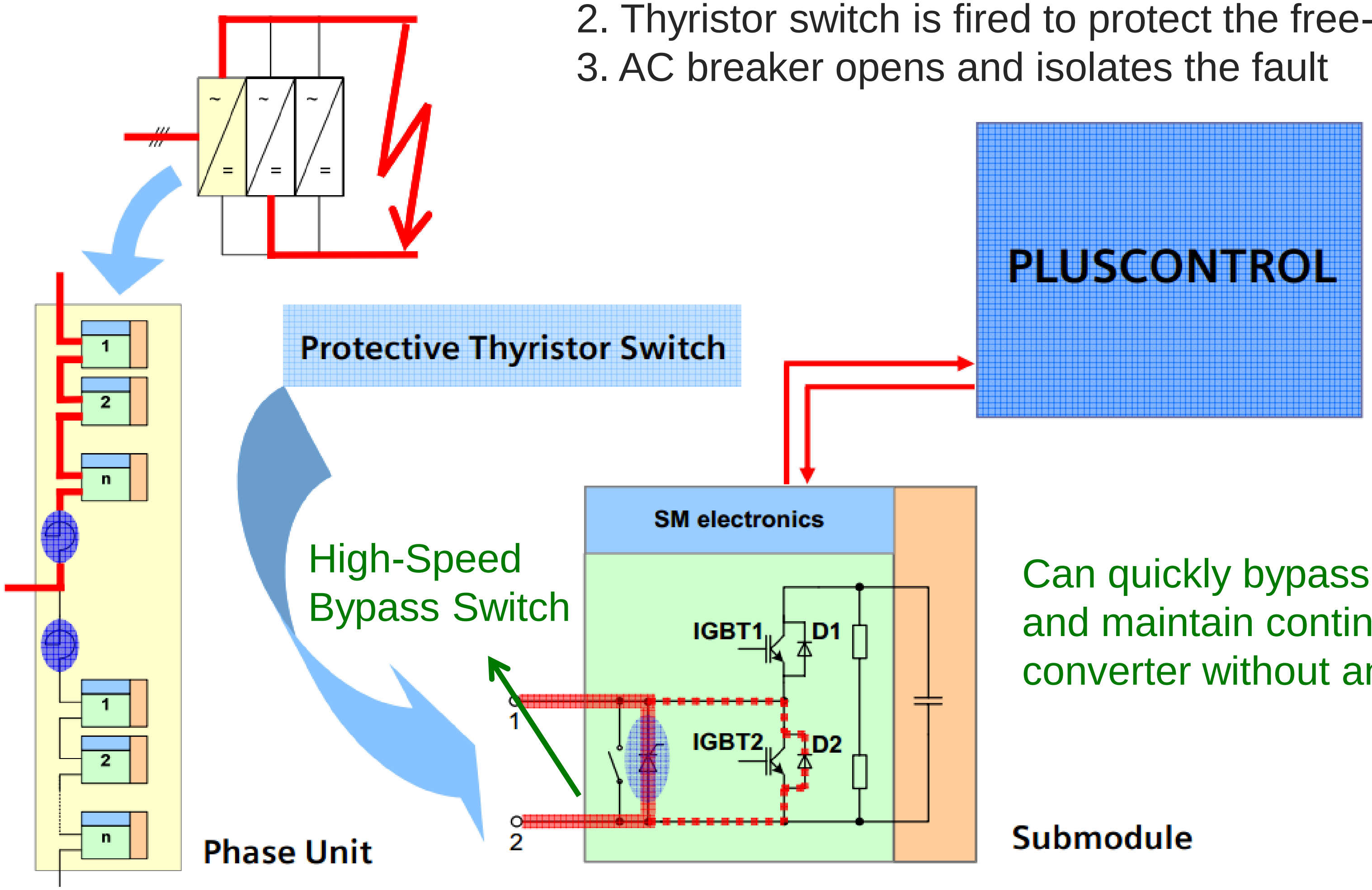
Comparison of Three Generations of HVDC

Application	Site footprint	Site area (%)	Max building height (%)	Converter building footprint	Converter building area (%)	Converter building volume (%)
LCC-HVDC (reference)	225 m × 120 m	27,000 m^2 (100%)	20 m (100%)	35 m × 20 m	700 m^2 (100%)	14,000 m^2 (100%)
Two-level VSC	180 m × 115 m	20,700 m^2 (77%)	24 m (120%)	38 m × 35 m	1330 m^2 (190%)	25,000 m^2 (179%)
Half-bridge MMC-HVDC	165 m × 95 m	15,675 m^2 (58%)	15 m (75%)	70 m × 45 m	2730 m^2 (390%)	29,500 m^2 (211%)

* This comparison is made for comparable power and voltage ratings: for LCC-HVDC (Grita project, 500 MW and 400 kV), two-level VSC-HVDC (500 MW and 400 kV), and half-bridge MMC-HVDC (EWIC project, 500 MW and ± 200 kV)

Ref: R. L. Sellick and M. Åkerberg, "Comparison of HVDC light (VSC) and HVDC classic (LCC) site aspects, for a 500MW 400kV HVDC transmission scheme," in *Proc. IET AC and DC Power Transmission*, 2012, pp. 1–6.

Fault tolerant capacity



Fault protection:
1. Turn off IGBTs
2. Thyristor switch is fired to protect the free-wheeling diodes
3. AC breaker opens and isolates the fault

Can quickly bypass failed sub-modules and maintain continuous operation of converter without any interruption.

Ref: B. Gemmell, J. Dorn, D. Retzmann and D. Soerangr, "Prospects of multilevel VSC technologies for power transmission, " *IEEE PES Transmission and Distribution Conference and Exposition*, 2008, pp.1-16.

Summary

- As power electronic switch ratings (IGBTs and SiC MOSFETs) increase, VSC-converter based HVDC interfaces are becoming more common.
- MMC-based converters have the advantages of modularity, redundancy, and low switching frequency.
- Need to consider switching (PWM) control method, capacitor voltage balancing, and circulating current suppression in design.
- Several companies offering MMC options for their VSC HVDC, SVC, and STATCOM products.

Acknowledgements

This work was supported primarily by the U.S. Department of Energy under DE-EE0011075.