Voltage-Source Converters for HVDC Systems

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Never Stand Still | Australian Energy Research Institute

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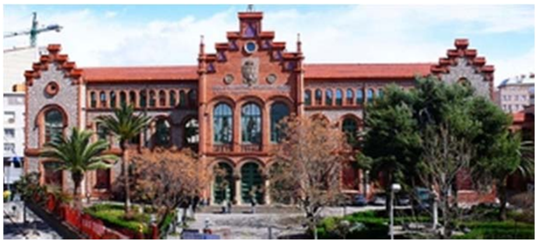

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Outline

I. HVDC Systems
II. Voltage-Source Converter (VSC)
III. Neutral-Point-Clamped (NPC) Converter
IV. Modular-Multilevel Converter (MMC)

Outline

I. HVDC Systems

Reasons for High-Voltage Direct Current (HVDC)

- AC transmission is impractical over long distances, while for DC transmission distance is not a significant restriction.
- Although rectifier/inverter stations costs and losses are higher, from long distances HVDC transmission results in lower costs and losses than AC transmission.
- HVDC can interconnect asynchronous systems and systems with different frequencies.
- HVDC can be controlled faster so that the AC system stability can be improved.

HVDC Applications

- Long distance transmission from remote energy sources.
- Interconnection between power systems.
- High power underground (submarine) distribution system feeders.
- Reconfiguration of old AC lines to DC to increase capacity, e.g. a double circuit 230 kV AC line, now limited to 400 MW transmission capacity can be used for a DC line with capacity of about 1500 MW.

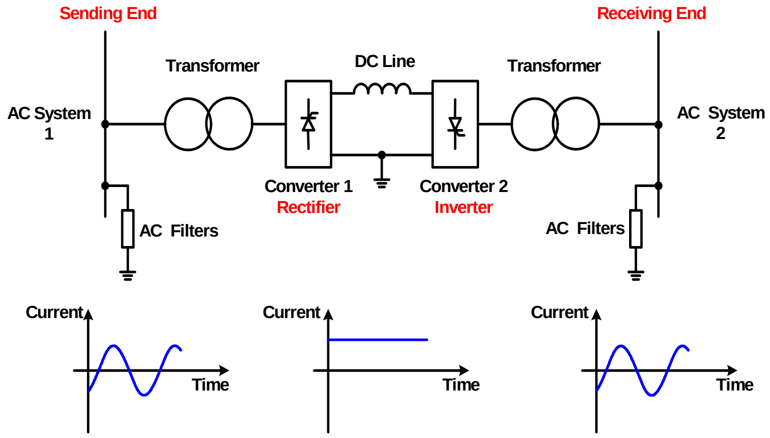
I. HVDC Systems

First HVDC Transmission Line

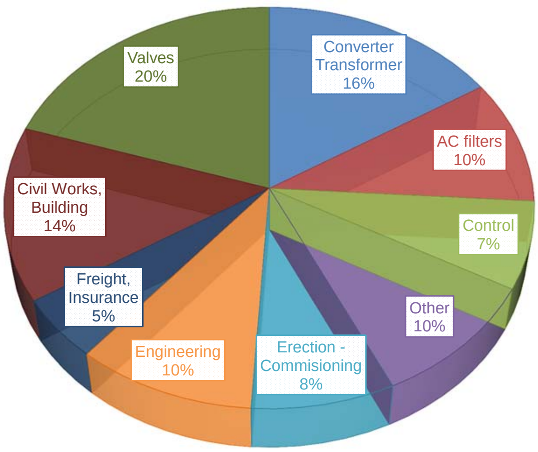
- 1954: Between Sweden and the island of Gotland in the Baltic sea, 20 MW @ 100 kV using mercury arc valves and control equipment was based on vacuum tubes (ASEA).

Conventional HVDC System

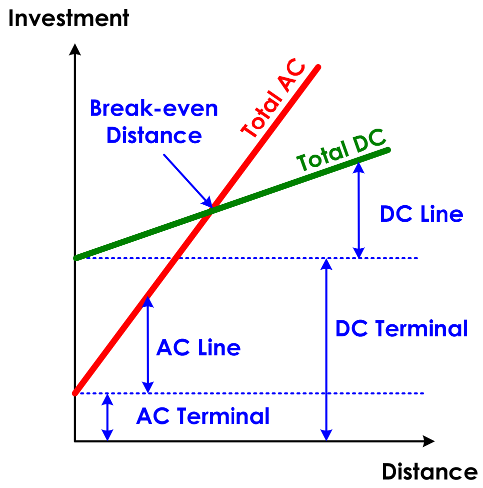
Based on thyristors - Line-commutated converters (LCCs)



Typical Cost of an HVDC Project



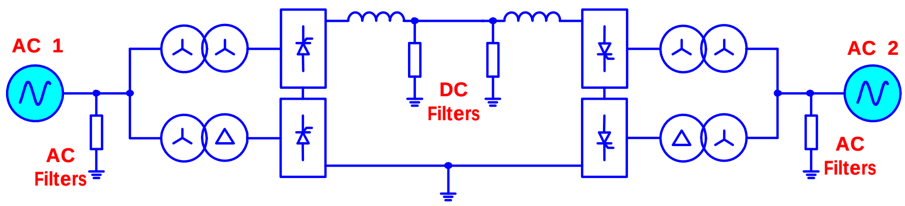
Investment Cost vs. Distance



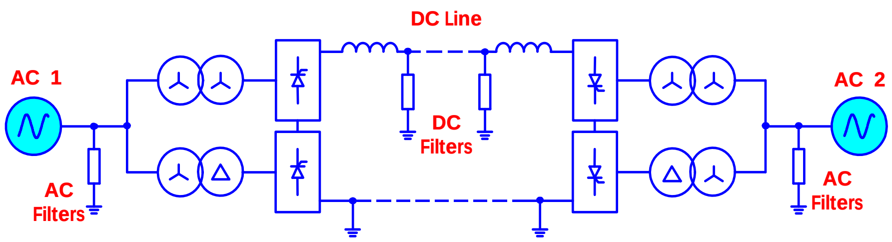
HVDC Schemes

- Depending upon the function and location of the converter stations, various schemes and configurations of HVDC systems exist as follows:
  - Back-to-Back
  - Monopolar
  - Bipolar
  - Multiterminal

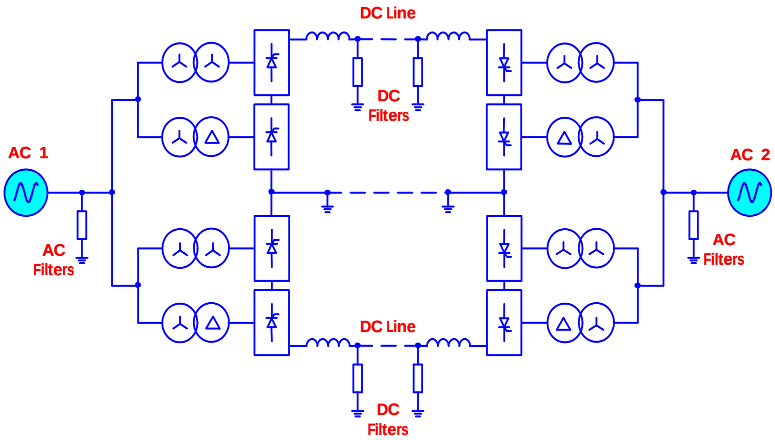
Back-to-Back HVDC Scheme



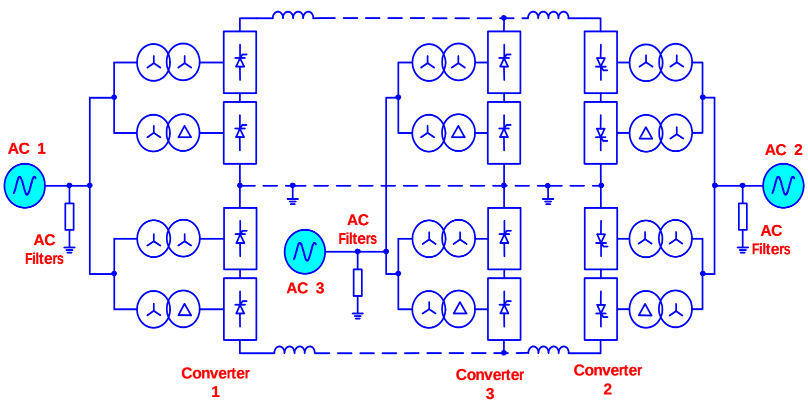
Monopolar HVDC Scheme



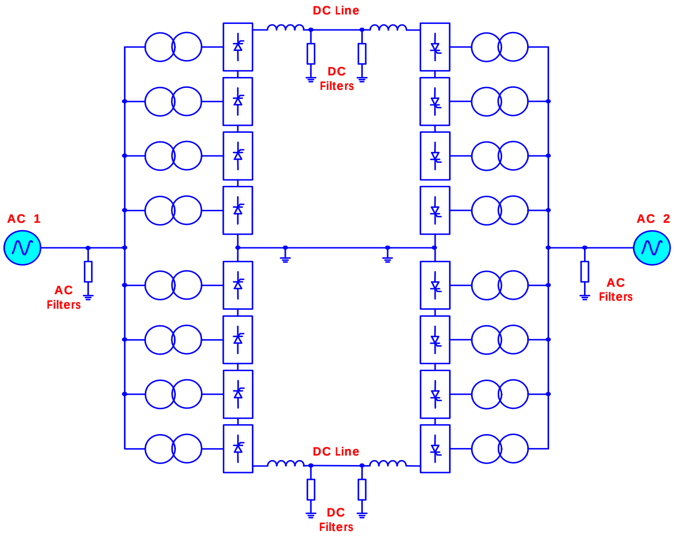
Bipolar HVDC Scheme



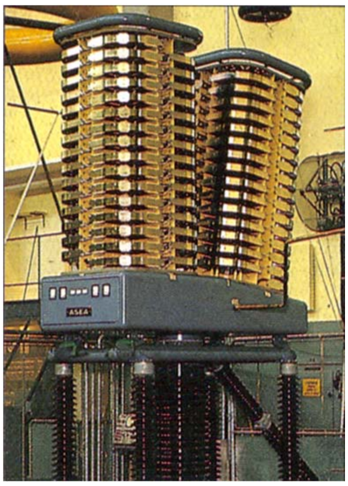
Multiterminal HVDC Scheme



Bipolar with 24-Pulse Converter HVDC



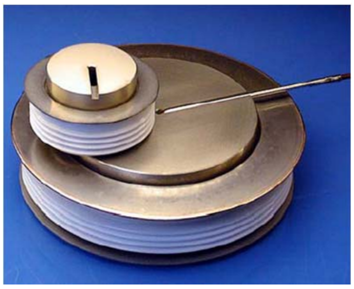
Old Thyristor Valve
50 kV, 200 A



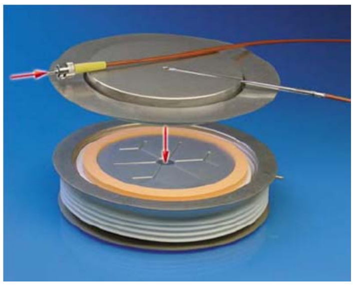
Suspended Thyristor Valve
150 kV, 914 A

Courtesy of ABB

Light triggerable thyristors (LTT) with integrated protection functions and blocking voltages between 5.2 kV to 8 kV



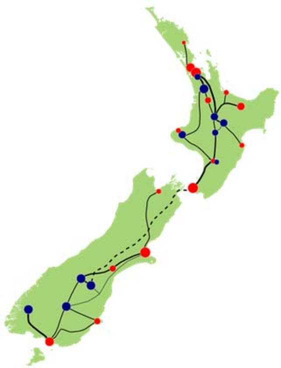
2” and 5” LTT with Light Guide

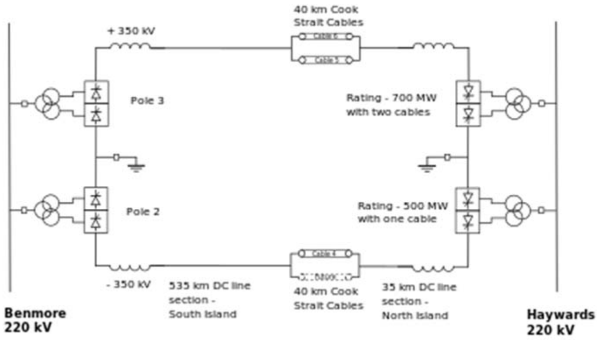


Surge current capabilities up to 100 kA for single sine half waves

New Zealand Inter-Island Link (ABB)

- Connection between the south and the north islands.
- Pole 2 and 3 combined can transfer up to 1200 MW.
- 610 km between Canterbury (south island) and Lower Hutt (north island).





New Zealand Inter-Island Link (ABB)

Valve Hall

±500kV Longquan-Zhengping HVDC Project, China (ABB)

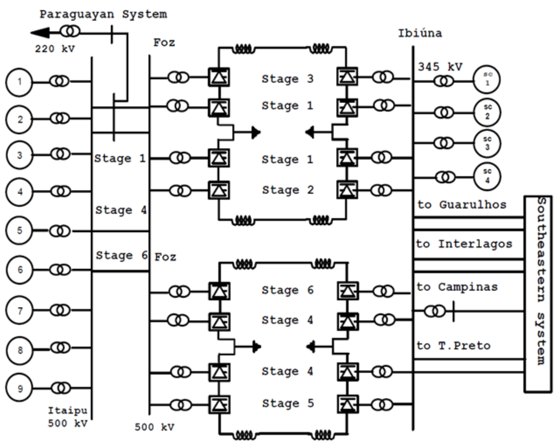
- 940 kilometers
- Commercial operation in 2004
- Power rating 3000 MW

Chandrapur Back-to-Back HVDC Link, India (Alstom)

- Two independent poles, each with a nominal power transmission rating of 500 MW.
- One quadrivalve is approximately 3.8 x 3.8 x 6.2 m and weighs 14 tonnes.

HVDC Itaipu, Brasil (ABB)

- ±600 kV bipoles, each with a rated power of 3150 MW.
- Transmit power generated at 50 Hz from the Paraguay side of the Itaipu Dam to São Paulo (aprox. 800 km).
- When completed in 1985, it became the world's largest HVDC system.



HVDC Itaipu, Brasil (ABB)

Foz do Iguaçu converter station

HVDC Transformer

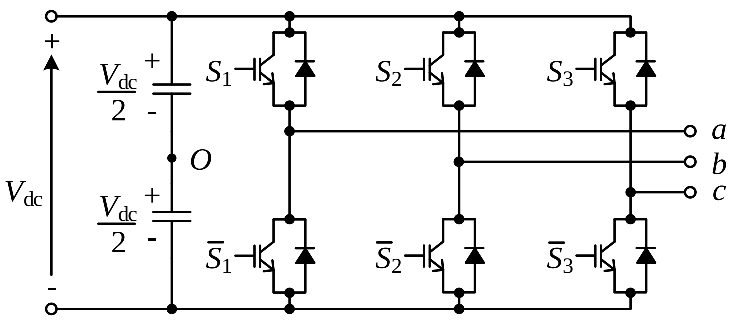
Discussion on Using Thyristors (LCC Technology)

- LCC technology requires existing AC grids for proper commutation of the thyristors. Auxiliary diesel generators may be needed at the generation side of the transmission line.
- Reactive power compensation should be provided.
- The size of the thyristor valve hall and auxiliary filters, and the need of auxiliary generation systems make HVDC LCC stations bulky and difficult to install in offshore platforms.
- Reversing the flux of power requires changing the DC polarity.

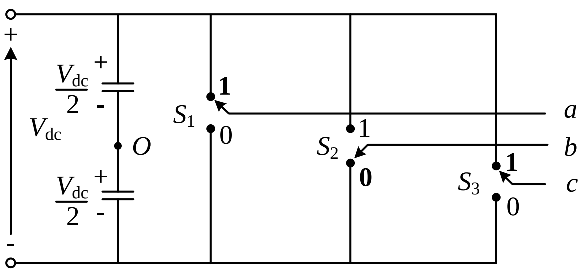
Outline

II. Voltage-Source Converter (VSC)

Three-phase two-level voltage source converter (VSC)

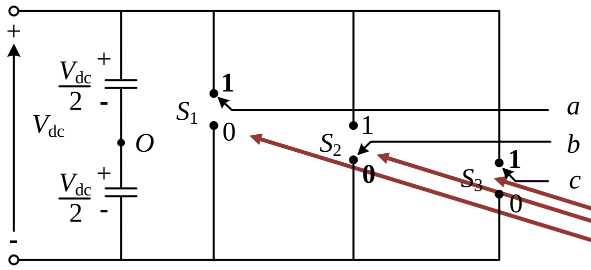


Three-Phase Two-Level VSC



2L VSC		Switches		
		S_1	S_2	S_3
Switching States	ST_0	0	0	0
	ST_1	1	0	0
	ST_2	1	1	0
	ST_3	0	1	0
	ST_4	0	1	1
	ST_5	0	0	1
	ST_6	1	0	1
	ST_7	1	1	1

Three-Phase Two-Level VSC



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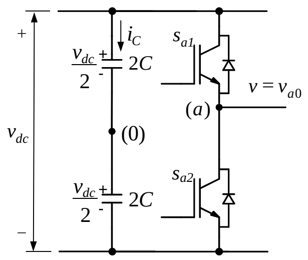
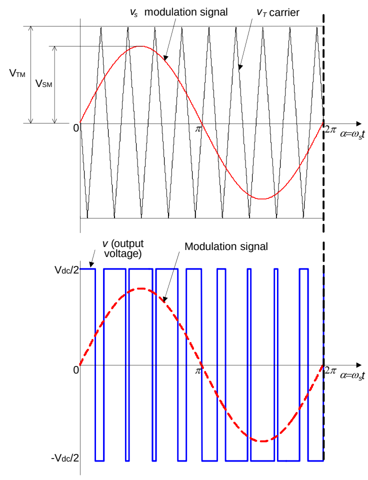
	ST_5	0	0	1
	ST_6	1	0	1
	ST_7	1	1	1

Pulse-Width Modulation (PWM)





Modulation signal:

$v_s(t)=V_{SM}\sin\omega_s t$

Output voltage:

If $v_s \geq v_T \rightarrow s_{a1}$ ON s_{a2} OFF $\rightarrow v=v_{a0}=V_{dc}/2$

If $v_s < v_T \rightarrow s_{a1}$ OFF s_{a2} ON $\rightarrow v=v_{a0}=-V_{dc}/2$

Series-Connected Semiconductors

- Typical IGBT ratings

Trench IGBT Modules

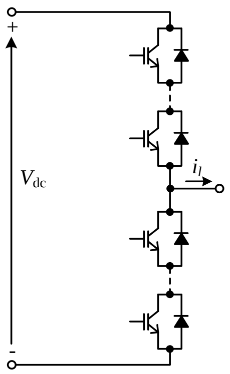
SKM 800GA176D

Absolute Maximum Ratings — T_c = 25 °C, unless otherwise specified

Symbol	Conditions		Values	Units
IGBT				
V_{CES}	T_j = 25 °C		1700	V
I_C	T_j = 150 °C	T_c = 25 °C	830	A
		T_c = 80 °C	590	A
I_{CRM}	I_{CRM}=2xI_{Cnom}		1200	A
V_{GES}			± 20	V
t_{psc}	V_{CC} = 1200 V; $V_{GE} \leq$ 20 V; V_{CES} < 1700 V	T_j = 125 °C	10	µs
Inverse Diode				
I_F	T_j = 150 °C	T_c = 25 °C	630	A
		T_c = 80 °C	440	A
I_{FRM}	I_{FRM}=2xI_{Fnom}		1200	A
I_{FSM}	t_p = 10 ms; sin.	T_j = 150 °C	3600	A
Module				
$I_{t(RMS)}$			500	A

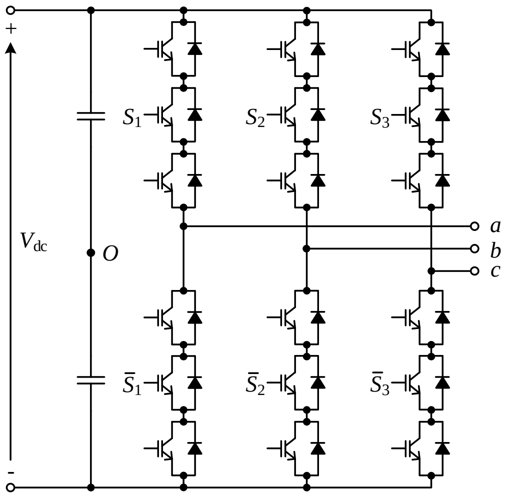
Three-Phase Two-Level VSC

- ❑ Operation of the converter beyond the voltage rating of existing semiconductor devices requires additional devices to be connected in series.



- The voltages across the power devices have to be limited.
- The quality of the waveform is poor (only two levels).

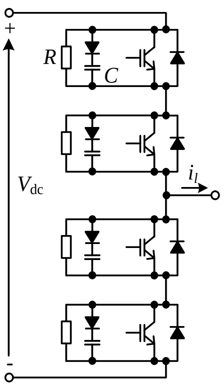
Series Connected Semiconductors



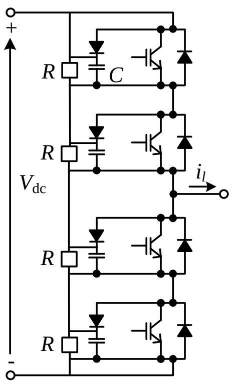
II. Voltage-Source Converter (VSC)

Series Connected Semiconductors

- Challenge: Voltage distribution across the series-connected semiconductors.



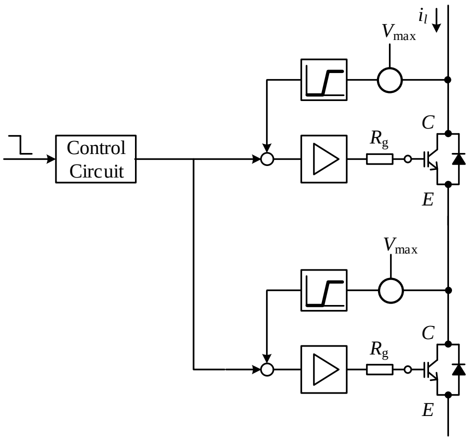
Passive snubbers



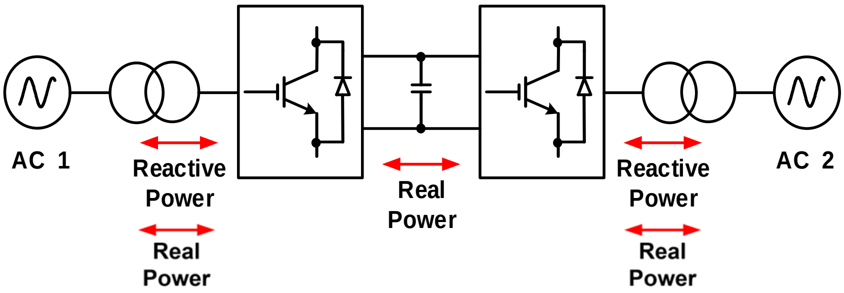
Regenerative snubbers

Active Clamping

- An active overvoltage clamping scheme can be implemented to limit the collector–emitter voltage during switching transients.
- It provides protection of the device from overvoltage at the expense of device switching losses.

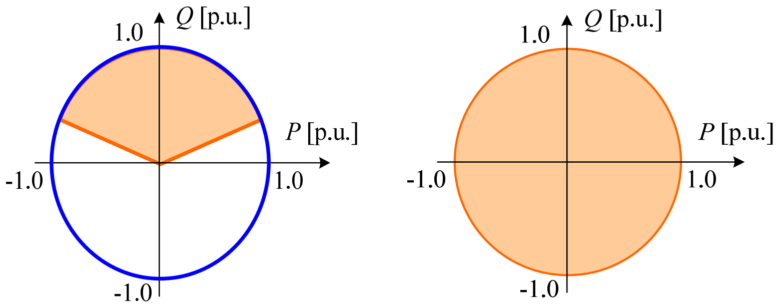


VSC-Based HVDC Transmission



Active-Reactive (PQ) Locus Diagram of Power Transmission System

LCC (Thyristors) **VSC (Transistors)**



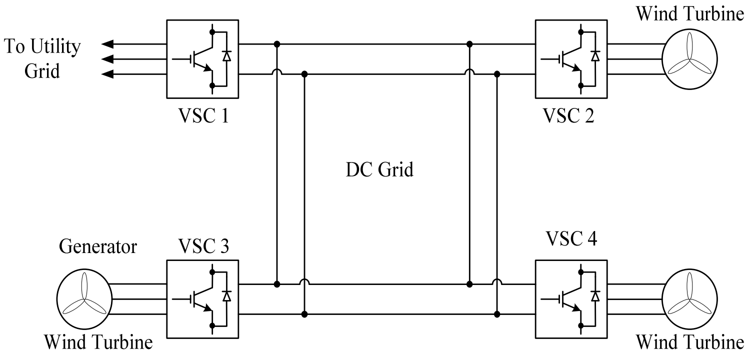
VSC HVDC Systems - Advantages

- Can operate when the grid voltages are reduced or distorted.
- No need for generators, which makes it suitable for weak networks and long distances.
- Low order harmonics are greatly reduced and harmonic filters can be smaller.
- No reactive power compensation is required. Real and reactive power independently controlled.
- Faster response owing to the increased switching frequency of the PWM.
- Reversing of power is achieved by changing the direction of the DC current (while keeping the voltage polarity).

II. Voltage-Source Converter (VSC)

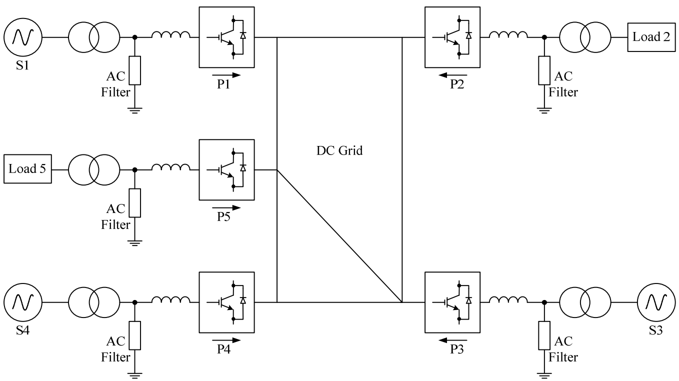
Multi-Terminal HVDC Systems

Four-terminal PWM VSC-based HVDC system for wind turbines/wind parks



II. Voltage-Source Converter (VSC)

Five-Terminal VSC-HVDC System



DC Cable Technology

- Triple extruded polymer insulation system (XLPE)
- Same polarity (can be used in VSC-based HVDC systems)

Directlink - A Power Trading Machine, Australia

Technical Data

Commissioning year: 2000
Power rating: 180 MW (3 x 60)
AC Voltage: 132/110 kV
DC Voltage: ± 80 kV
DC current 342 A
Length of DC cable: 6 x 59 km

Main reasons for choosing HVDC system:
Controlled asynchronous connection for trading.
Easy to get permission for underground cables.

Directlink

Bungalora converter station

Troll A HVDC Light® link

The HVDC Light® installation between the Norwegian main land and the Troll A oil platform consists of two circuits, each feeding a 40 MW compressor motor

Technical Data

Commissioning year:2004/2005

Power rating: 2 x 42 MW

AC Voltage: 132 kV/56 kV

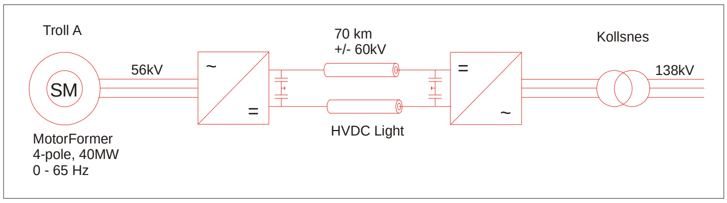
DC Voltage: ± 60 kV

DC current 350 A

Length of DC cable: 4 x 70 km

Main reasons for choosing HVDC Light® system:
Environmental improvement by elimination of gas turbines on platform. Low weight and small space on platform. Ability to feed and black-start motors, without local generation.

Troll A HVDC Light® link



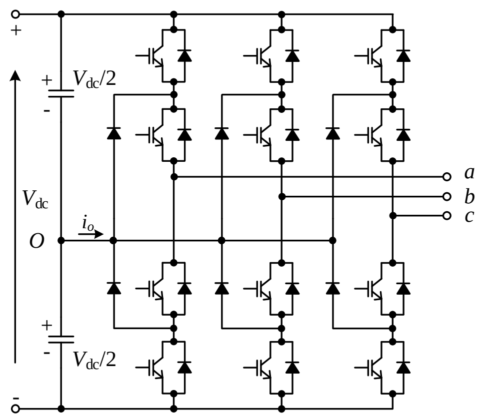
Troll A, Converters on the Platform

- The converters are housed in a pre-fabricated module, shipped and lifted onto the platform.

Outline

IV. Neutral-Point-Clamped (NPC) Converter

- Split DC-link with capacitors and clamping diodes to generate three voltage levels.
- Voltage across the capacitors should equal half the DC-link voltage.



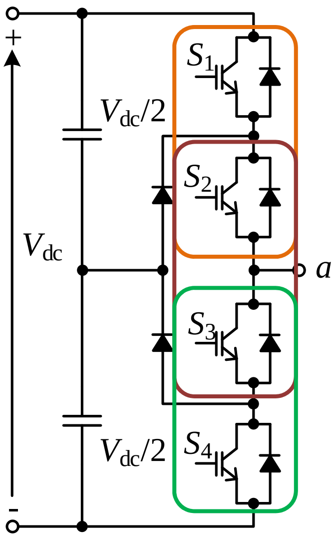
The NPC Converter

- The NPC can provide three voltage levels at the outputs.
- Higher quality of the output voltages compared to the two-level case imply:

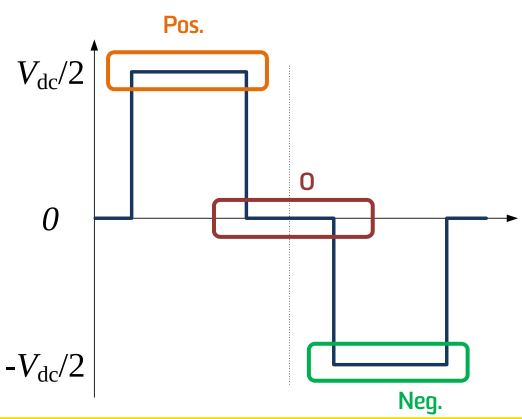
  (1) smaller reactive components needed to filter, and

  (2) lower switching frequency and power losses.
- Still series connection of power devices is needed for HVDC applications.

Three-Level Voltage Waveforms



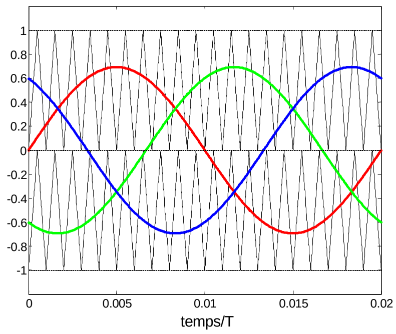
	S_1	S_2	S_3	S_4	V_{aO}
Pos.	1	1	0	0	$+V_{dc}/2$
0	0	1	1	0	0
Neg.	0	0	1	1	$-V_{dc}/2$

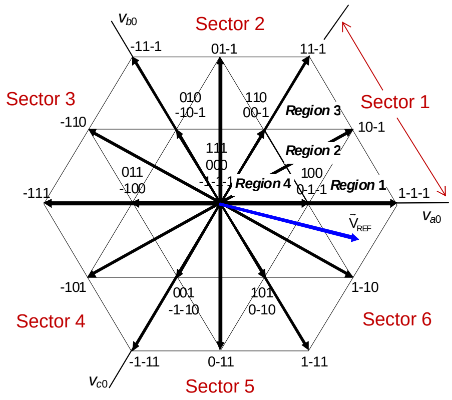


Pulse-Width Modulation (PWM) Strategies

Carrier-based PWM (CB-PWM)

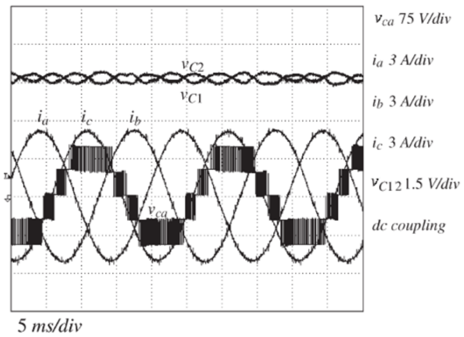
Space-vector PWM (SV-PWM)





Pulse-Width Modulation (PWM)

Line-to-line output voltage (v_{ab}), output currents (i_a, i_b and i_c), and capacitor voltages (v_{C1} and v_{C2})



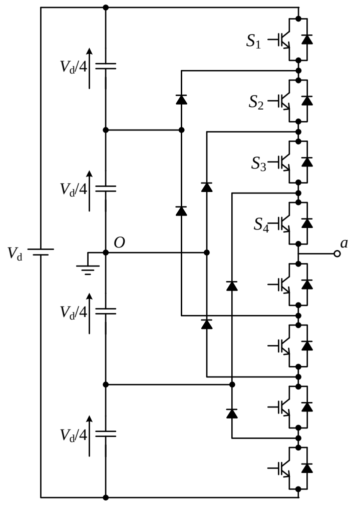
➢ The line-to-line voltages can produce up to five levels.

Extension of the NPC Concept

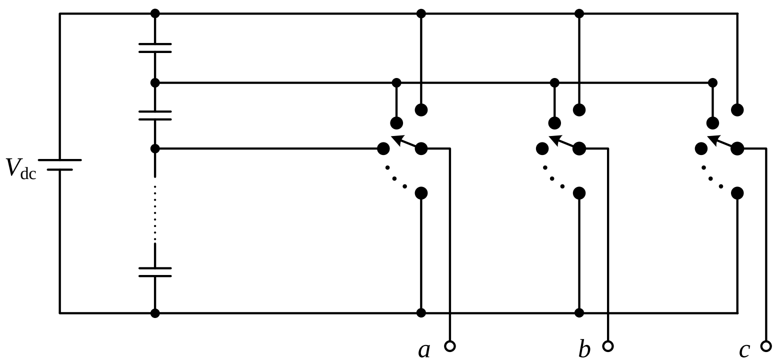
- Extension to higher number of levels. Multiple capacitors in the DC-link provide multiple “neutral points”.

Five-level NPC converter

	S_1	S_2	S_3	S_4	V_{aO}
State 1	1	1	1	1	$+V_{dc}/2$
State 2	0	1	1	1	$+V_{dc}/4$
State 3	0	0	1	1	0
State 4	0	0	0	1	$-V_{dc}/4$
State 5	0	0	0	0	$-V_{dc}/2$



Generalized *n*-Level NPC Converter Model



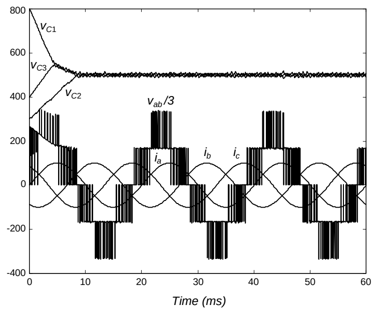
Issues with High Order (n>3) NPC Converters

- Voltage balancing **cannot be always achieved** and depends on the operating point and load connected to the converter.
- The clamping diodes on the different NPs **support different reverse voltages**.
- The central switches of the topology conduct current longer than the outer switches resulting in **unbalanced distribution of the losses**.

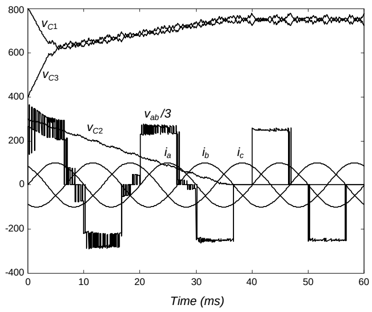
Capacitors Voltage Balance

Example: four-level NPC converter

m=0.4, Unity Power factor



m=0.6, Unity Power Factor

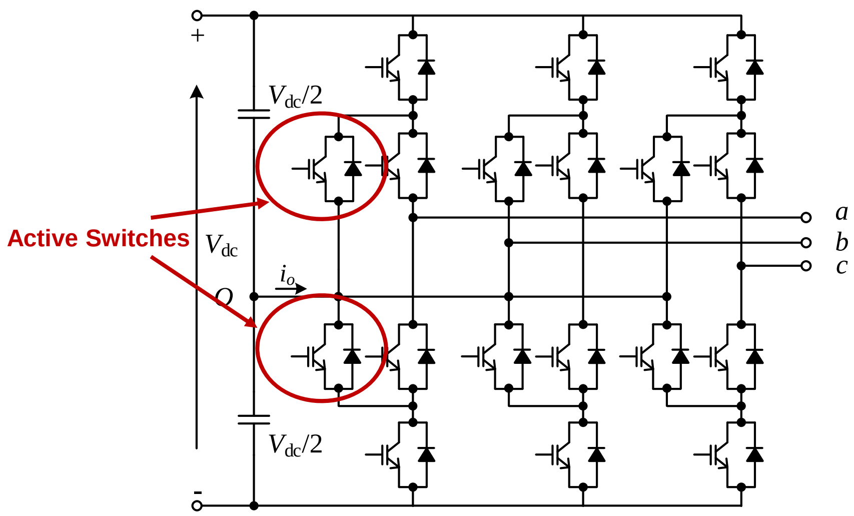


- Voltage balancing **might not be always achieved** for large modulation indices and high power factors.

Active NPC (ANPC) Converter

- The NPC converter produces unequal distribution of losses among the semiconductors.
- A solution to overcome these problems is derived from the concept of active neutral-point clamping.
- Clamping diodes on the neutral-point are replaced with active switches.
- Zero voltage states and commutations can be selected actively and are not defined by the direction of the phase current.

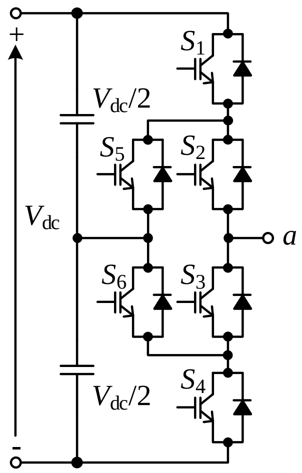
Three-Level ANPC Converter



Three-Level ANPC Converter

	S_1	S_2	S_3	S_4	S_5	S_6	
Pos.	1	1	0	0	0	1	$+V_{dc}/2$
0	0	1	0	0	1	0	0
0	0	1	0	1	1	0	0
0	1	0	1	0	0	1	0
0	0	0	1	0	0	1	0
Neg.	0	0	1	1	1	0	$-V_{dc}/2$

- In the case of NP connection, the state of the switches S_5 and S_6 will define the path of the current.

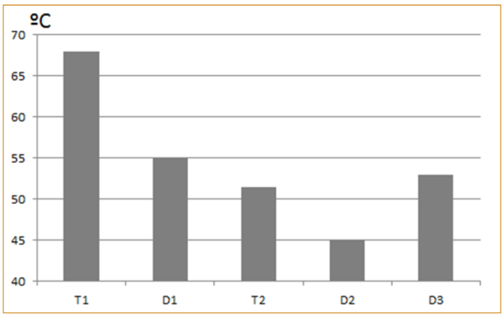


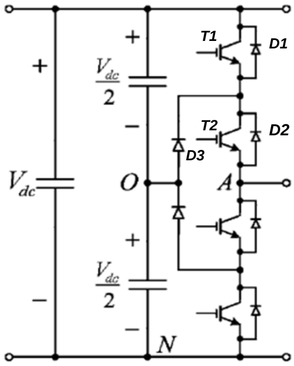
Three-Level ANPC Converter

- The commutations to or from the zero states determine the distribution of the switching losses. All commutations take place between one active switch and one diode.
- Even if more than two devices turn on or off, only one active switch and one diode essentially experience switching losses.

NPC Converter with Series-Connected IGBTs

- Losses distribution

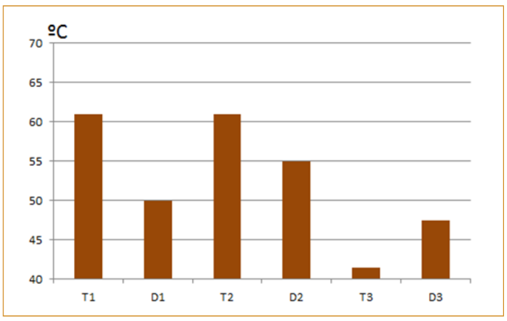


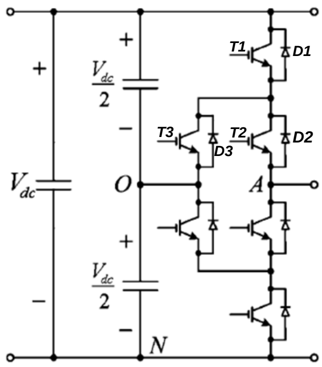


Uneven loss distribution between the switching devices. The converter needs to be overrated.

ANPC Converter with Series-Connected IGBTs

- Losses distribution





The ANPC introduces additional switching states that can be used to balance the power losses between semiconductor devices. Better converter use is achieved.

Remarks

- ABB adopted the ANPC converter technology for HVDC applications but came back to the two-level converter (less expensive).
- Two and three level converters can facilitate AC/DC conversion in HVDC applications. However:
  - High switching frequency is mandatory due to the reduced number of levels.
  - Poor efficiency.
  - Direct connection of switching devices required.
  - Not easy scalable to higher power/voltage levels.

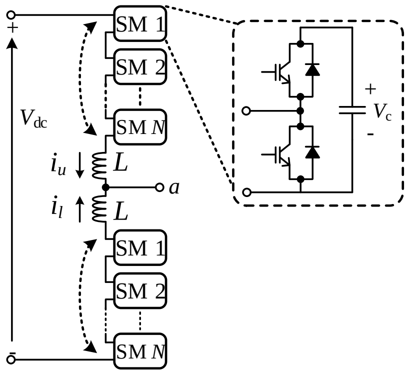
⇩

Modular Multilevel Converters (MMCs)

Outline

IV. Modular Multilevel Converters (MMCs)

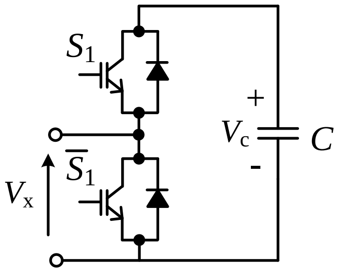
- Cascaded connection of sub-modules (SMs) or cells.
- The SMs are connected in series to create arms.
- A phase-leg comprises two arms (upper and lower).
- It is structurally scalable and can theoretically meet any voltage level requirements.



Half-Bridge Sub-Modules (SMs)

- Operation of switches within a SM is complementary.

SM States	S_1	$\overline{S}_1$	v_x
Activated	1	0	v_c
Deactivated	0	1	0



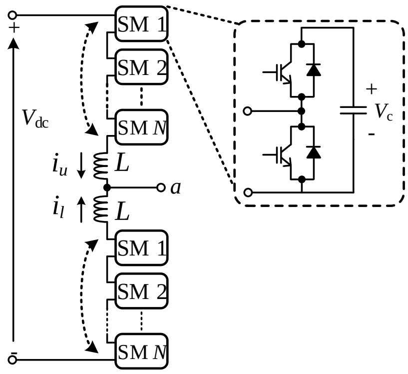
Half-bridge SM

MMC Arms

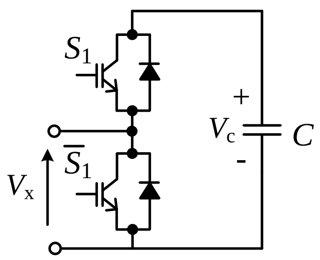
- Number of SMs per arm: *N*
- Reference voltage for the SM capacitors:

$$V_C^* = \frac{V_{dc}}{N}$$

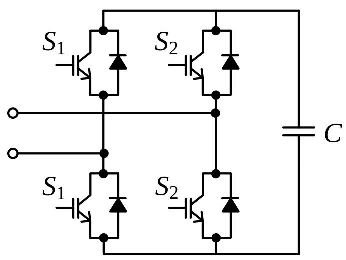
- Reactors *L* are inserted in the circuit to control the circulating currents and to limit the fault currents.



SM Configurations



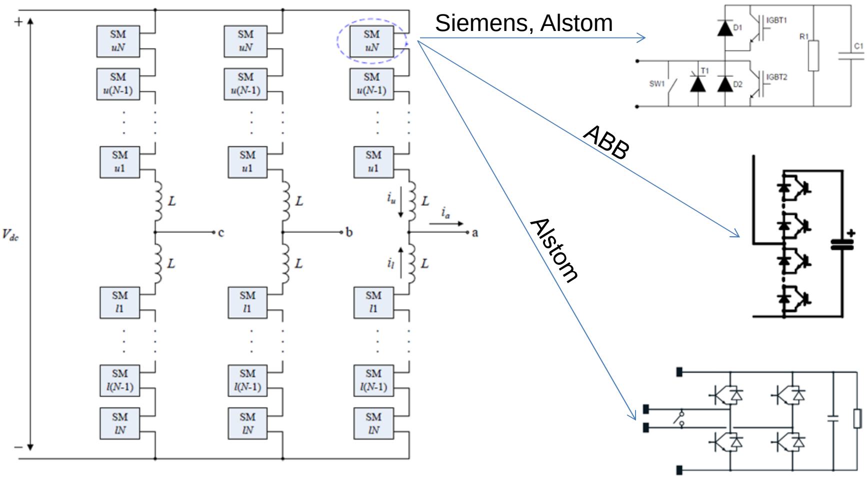
Half-bridge: v_x={0, v_C}



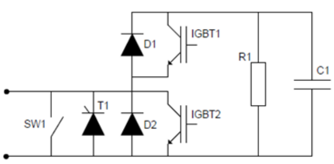
Full-bridge: v_x={v_C, 0, -v_C}

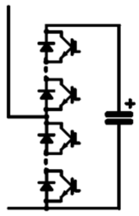
SM Configurations

- Modular multilevel converters: Manufacturers' implementation



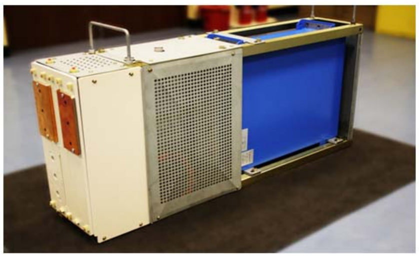
Modular multilevel converters: Manufacturers implementations

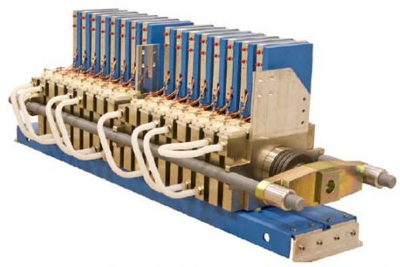




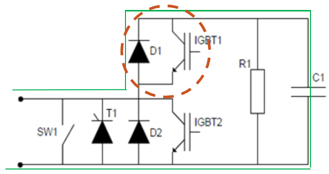
ALSTOM

ABB

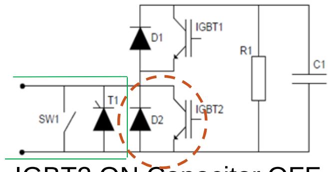




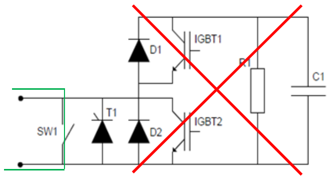
Switching States



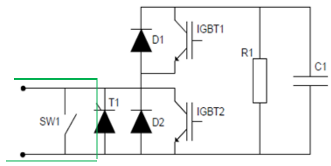
IGBT1 ON Capacitor ON



IGBT2 ON Capacitor OFF



Submodule failure SW1 ON



DC short-circuit T1 ON

Alstom Implementation

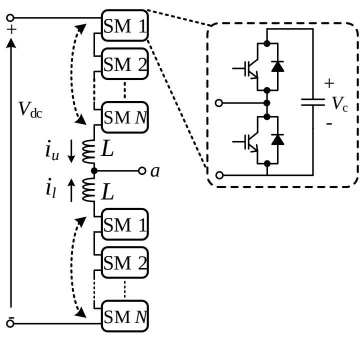
MMC Features

- The MMC offers salient features such as:
  - It is structurally scalable and can theoretically meet any voltage level requirements.
  - The capacitor voltage balancing task is relatively simple and there is no requirement for isolated dc sources.
  - A DC-link capacitor is not required (only a small one is connected to attenuate switching-frequency ripples).

Operation of the MMC

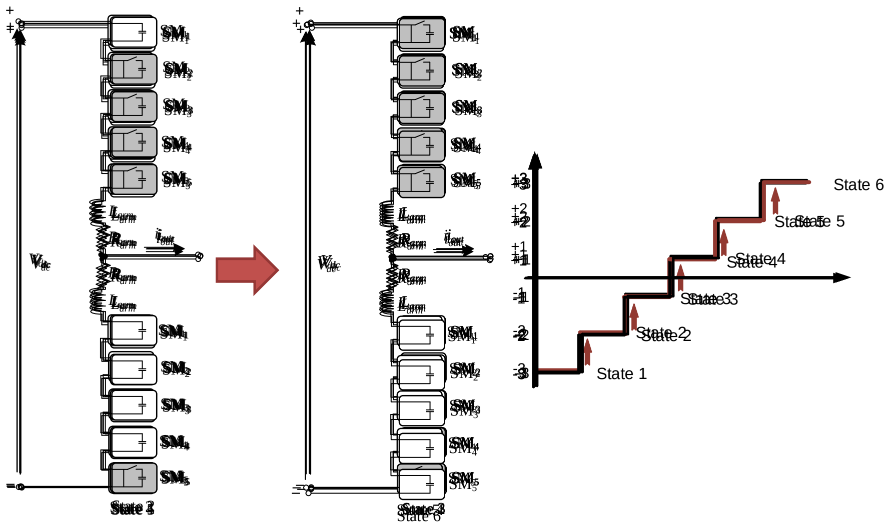
- On average, the number of SMs activated in a phase-leg is equal to *N*. Deviations from that number can be due to interleaving between the upper and lower arm carriers or due to external control actions.
- Ideally, the DC voltage is distributed equally across the SMs:

$$V_C = \frac{V_{dc}}{N}$$



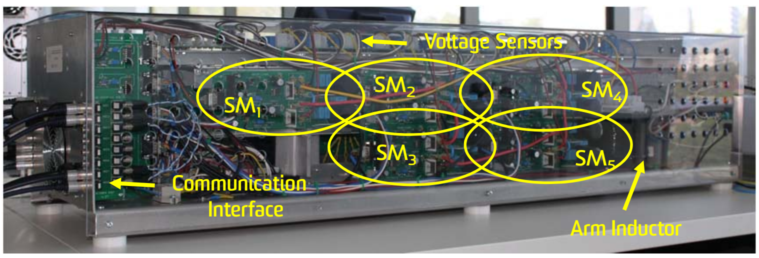
- The output voltage level is defined by the number of SMs that are connected in the upper and lower arm of the converter.

States of the MMC. Example

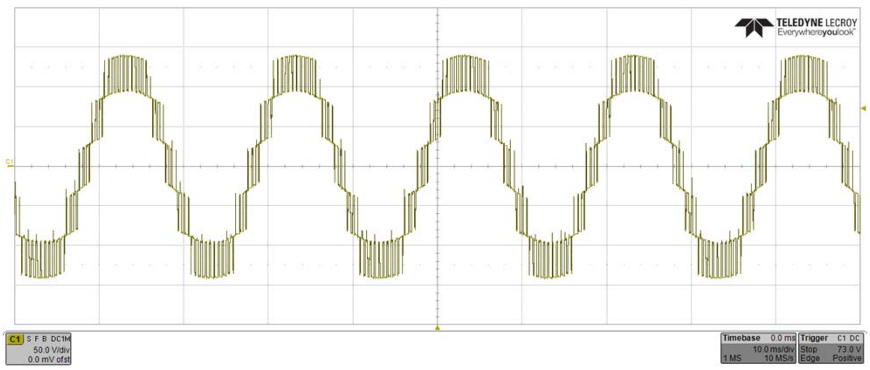


Experimental Setup

- Single-phase laboratory prototype a the Australian Energy Research Institute (AERI), the University of New South Wales (UNSW), Sydney, Australia
- Number of SMs per arm: 5



Output Voltage



SM Capacitor Voltage Balancing

- During the operation of the MMC, the arm current flows though the SM capacitors, which charge and discharge the capacitors.
- In order to ensure the proper operation of the converter, the SM capacitor voltages have to be regulated to the reference value of

$$V_C^* = \frac{V_{dc}}{N}$$

- An active voltage balancing method is essential for the operation of the MMC.

SM Capacitor Voltage Balancing

- The voltage balancing algorithm uses measurements from the SM capacitor voltages and arm currents to select the next SM that will be connected or bypassed.

- If the arm current is in the charging direction:
  - and the PWM method requires the **addition** of one SM in the arm, the SM with the **lowest** voltage that is not connected to the arm will be selected and added to the arm.
  - and the PWM method requires the **removal** of one SM in the arm, the SM with the **highest** voltage that is connected to the arm will be selected and removed from the arm.

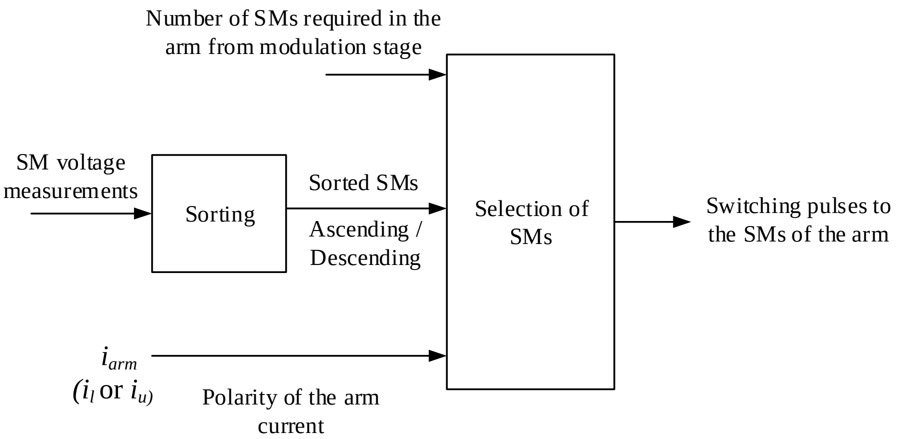
IV. Modular Multilevel Converters (MMCs)

SM Capacitor Voltage Balancing

- The voltage balancing algorithm uses measurements from the SM capacitor voltages and arm currents to select the next SM that will be connected or bypassed.

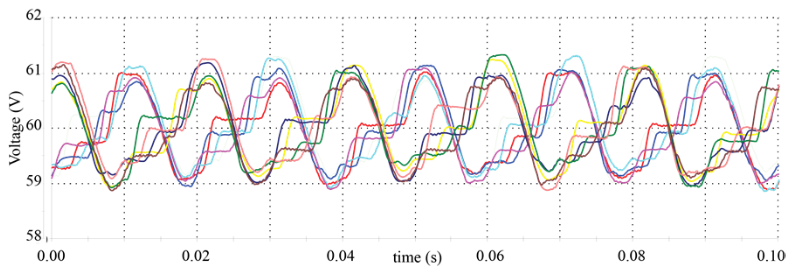
- If the arm current is in the discharging direction:
  - and the PWM method requires the **addition** of one SM in the arm, the SM with the **highest** voltage that is not connected to the arm will be selected and added to the arm.
  - and the PWM method requires the **removal** of one SM in the arm, the SM with the **lowest** voltage that is connected to the arm will be selected and removed from the arm.

SM Capacitor Voltage Balancing



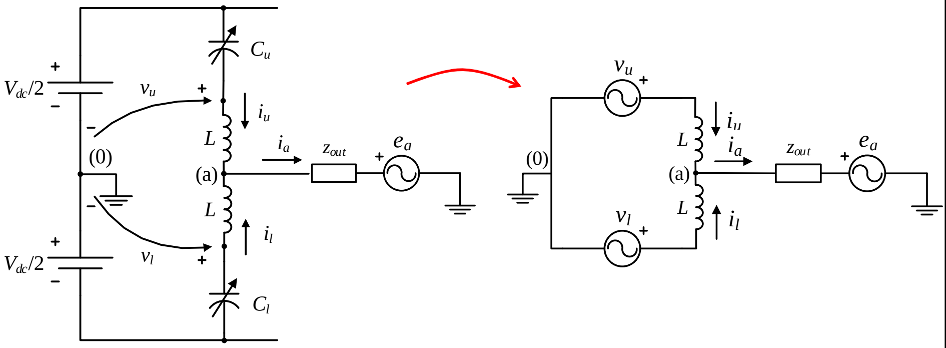
Experimental Results

SM Capacitor voltages (V_{dc}= 300V, N = 5)



Circulating Current Control

- From the equivalent circuit:

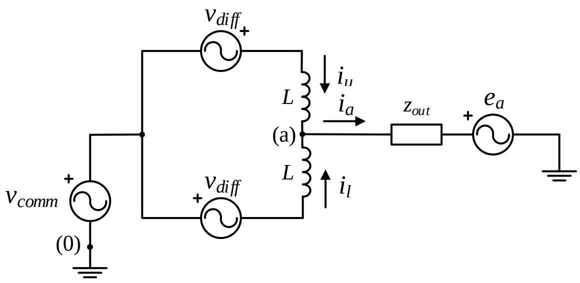


Common and Differential Voltages

- Two distinct voltages in the phase-leg can be identified; the common voltage (v_{comm}) and the differential voltage (v_{diff}):

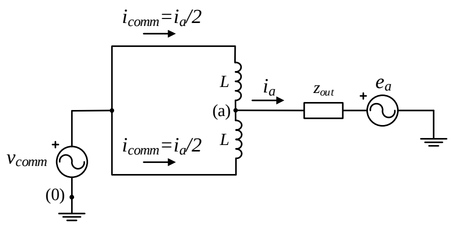
$$v_{comm} = \frac{v_u + v_l}{2}$$

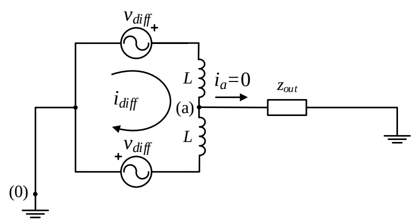
$$v_{diff} = \frac{v_u - v_l}{2}$$



Common and Differential Circuits

- Based on the superposition theorem, two circuits can be distinguished:





Common Mode

$$v_{comm} = \frac{v_u + v_l}{2}$$

$$i_{comm} = \frac{i_u + i_l}{2} = \frac{i_a}{2}$$

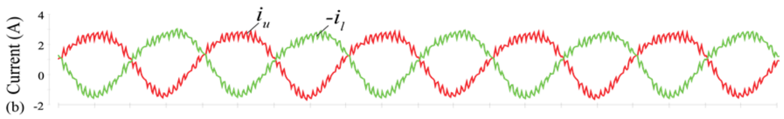
Differential Mode

$$v_{diff} = \frac{v_u - v_l}{2}$$

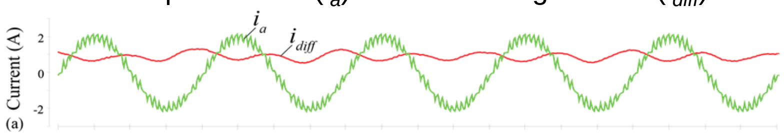
$$i_{diff} = \frac{i_u - i_l}{2} \Rightarrow$$ Circulating Current

Currents of the MMC

Arm currents



Output current (i_a) and circulating current (i_{diff})



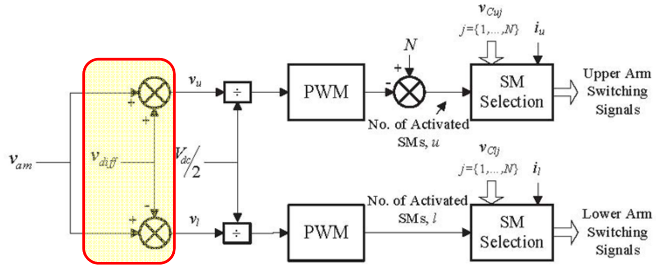
- The circulating current contains a DC component that is essential to keep the phase-leg energized, i.e. maintain the capacitor voltages at the reference values.
- It also contains some AC components (not essential).

Control of the Circulating Current

- The common and differential circuits can be analyzed independently. The differential voltage defines the differential/circulating current:

$$i_{diff} = \frac{1}{L}\int_0^t v_{diff}\,dt + I_{diff\,0}$$

- A differential voltage can be introduced to control the circulating current without affecting the output current.



Discussion on the Circulating Current Components

- If the only reference for the circulating current is the DC component, the arm currents are minimized and this reduces power losses in the MMC.

$$i_{diff} = I_{DC}$$

- A second order harmonic can be added to the DC component to reduce the capacitor voltage ripples.

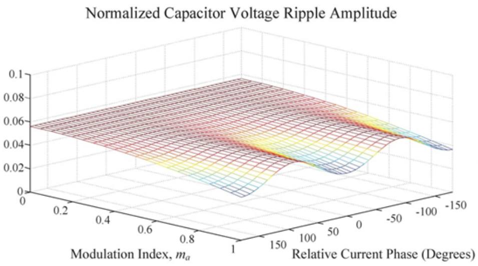
$$i_{diff} = I_{DC} + \hat{I}_2 \cos(2\omega t + \varphi_2)$$

Normalized Capacitor Voltage Ripple Amplitudes

$$\frac{\Delta v_{NPn}}{2} = \frac{\Delta v_{NP}/2}{I_{arms}/fC}$$

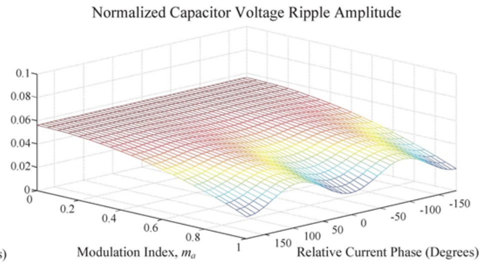
Case 1:

$i_{diff} = I_{DC}$



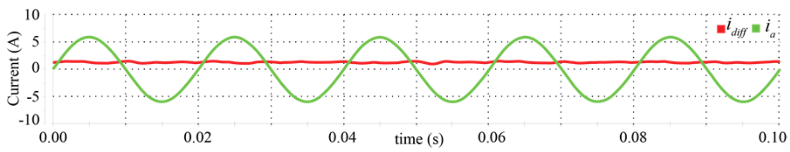
Case 2:

$i_{diff} = I_{DC} + \hat{I}_2 \cos(2\omega t + \varphi_2)$

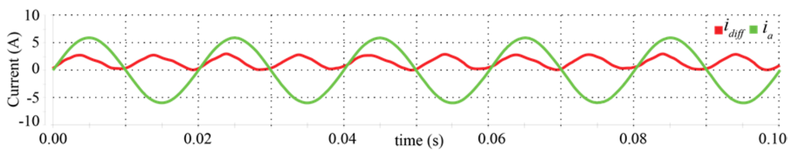


Circulating Current and Output Current

Case 1: $i_{diff} = I_{DC}$

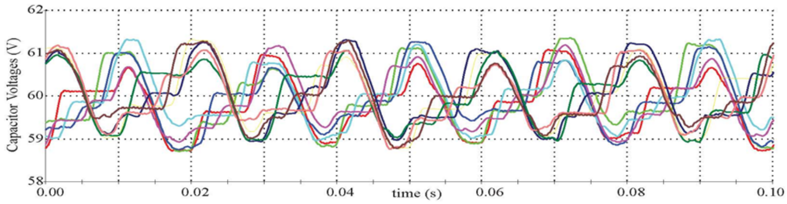


Case 2: $i_{diff} = I_{DC} + \hat{I}_2 \cos(2\omega t + \varphi_2)$

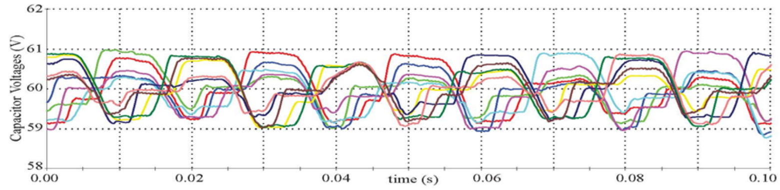


Capacitor Voltages

Case 1: $i_{diff} = I_{DC}$



Case 2: $i_{diff} = I_{DC} + \hat{I}_2 \cos(2\omega t + \varphi_2)$

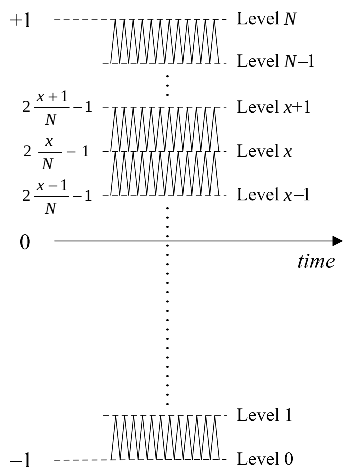


Modulation Techniques

- Level-shifted phase-disposition PWM (PD-PWM) is normally applied to the MMC.
- Other modulation strategies such as phase-shifted PWM (PS-PWM) can also be applied(*)

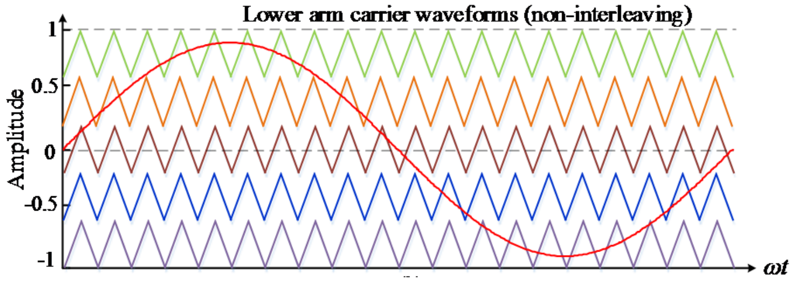
(*) M. Hagiwara and H. Akagi, "Control and experiment of pulsewidth-modulated modular multilevel converters," IEEE Trans. Power Electron., vol. 24, no. 7, pp. 1737-1746, Jul. 2009.

PD-PWM

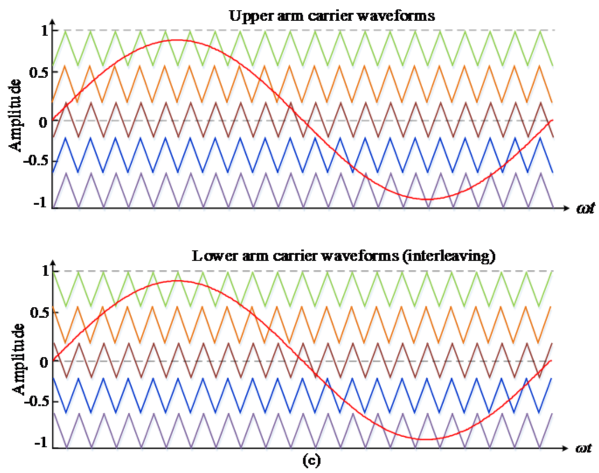


PD-PWM

- A number *N* of carriers is needed for the modulation.
- The reference signal is compared with the carriers.
- The output voltage level of the phase-leg, which ranges from 0 to *N,* is defined by the number of carriers that have an instantaneous value lower than the reference signal.

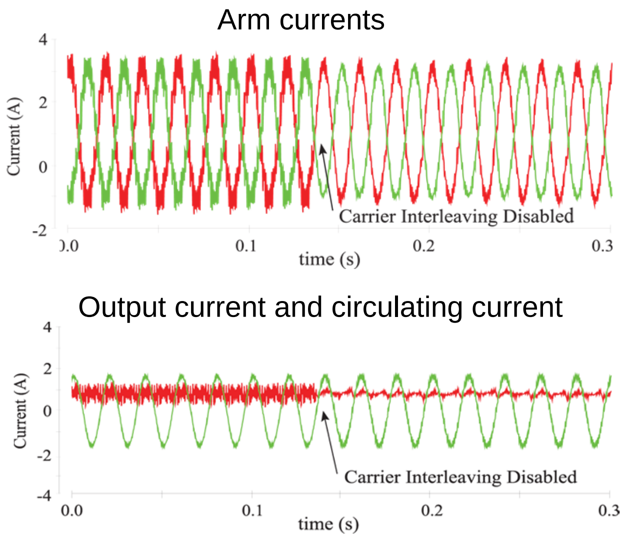


Interleaving between Upper and Lower Arms

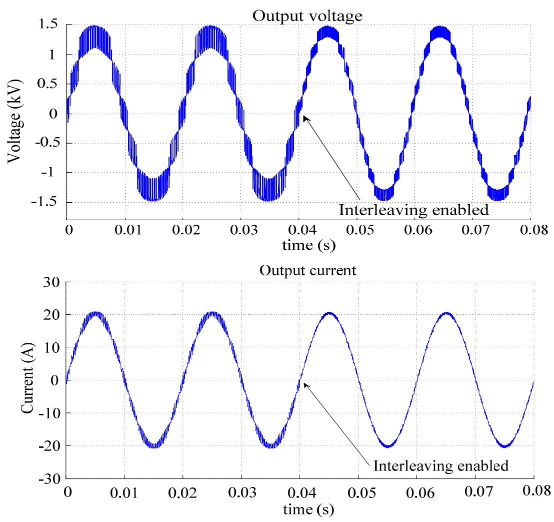


(c)

Interleaving between Upper and Lower Arms



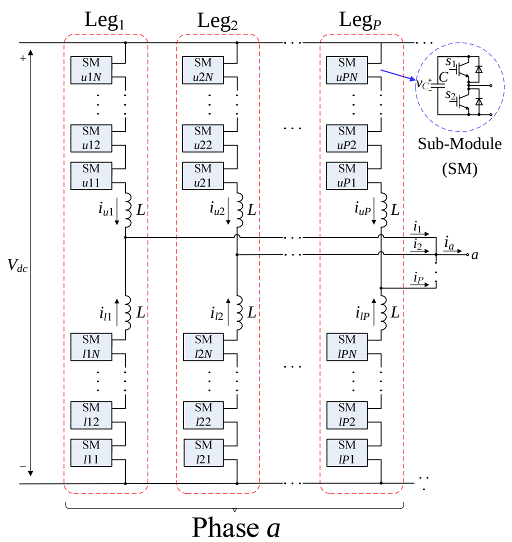
Interleaving between Upper and Lower Arms



Effects of Interleaving

- When applying interleaving between the upper and lower arms the ripple in the arm currents increases.
- In order to reduce the current ripples the value of the inductors should be increased.
- The quality of the output voltage (common voltage) improves because of the increased number of levels provided by the MMC (from *N*+1 to 2*N*+1).

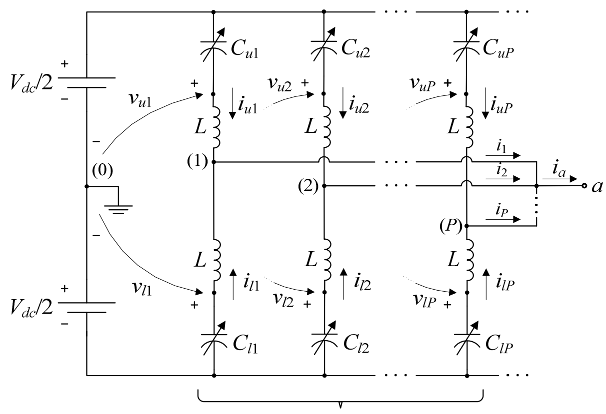
MMC Legs Connected in Parallel



- Each leg is integrated by two arms (the upper and lower arms)
- *P* legs build up a phase of the MMC (e.g. Phase *a*)
- The output currents of the legs have to be balanced ($i_1 \approx i_2 \ldots \approx i_P \approx i_a/P$)

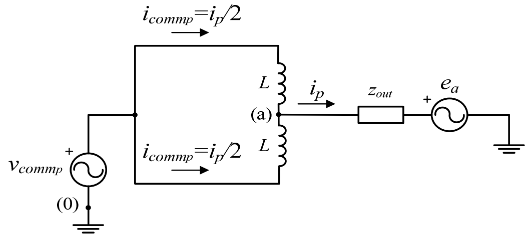
Equivalent Circuit

Model of an MMC phase (Phase *a*) with *P* legs connected in parallel

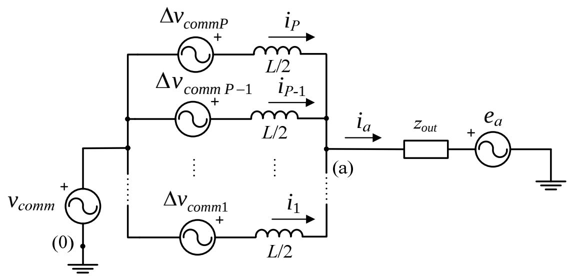


Control of the Currents

- Each leg has its independent circulating current control.
- The legs should share the output current evenly.
- The common voltage of each leg will be modified to achieve balanced output currents.



Current Balance Among the Legs (Phase a)



Control magnitude:

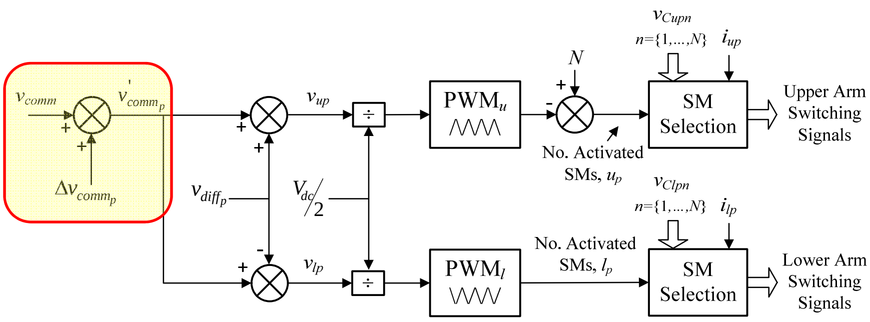
$$\Delta v_{comm_p} = -\frac{L}{2T_s}\Delta i_p$$

with: $\Delta i_p = i_p - \frac{i_a}{P}$

Restriction to avoid distorting the output voltage (v_{comm}):

$$\sum_{p=1}^{P} \Delta v_{comm_p} = 0$$

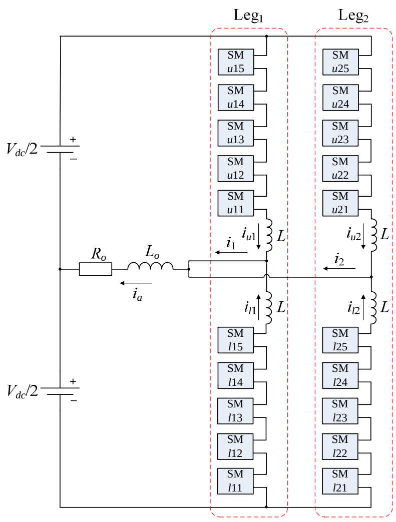
Modulation Scheme (Leg p)



- Δv_{commp} is injected into the reference signal of each leg to achieve equal current sharing.

IV. Modular Multilevel Converters (MMCs)

Simulation Results



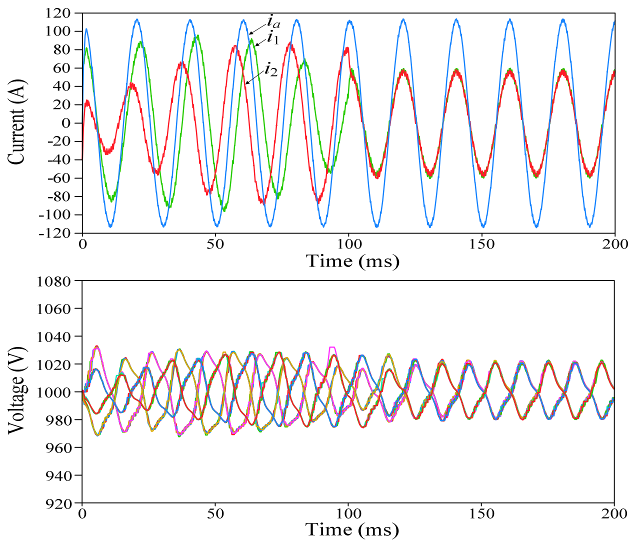
- Single-phase MMC with two legs connected in parallel

Data:

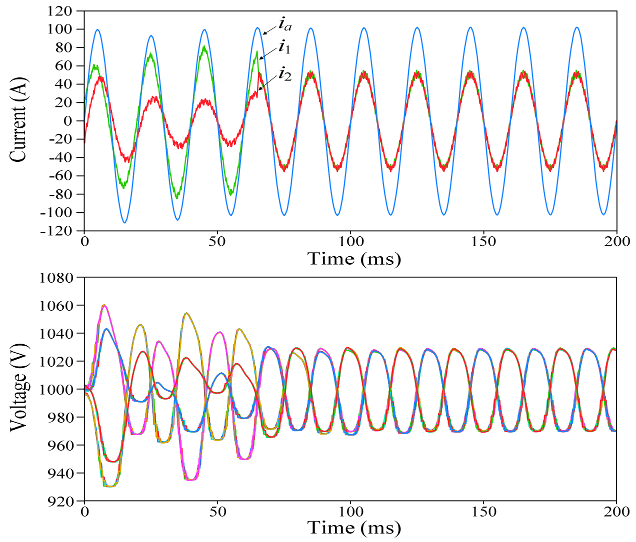
Parameter	Value
Number of SMs per Arm, N	5
Number of Legs in Parallel, P	2
SM Capacitors, C	1 mF
Arm Inductors, L	10 mH
Load 1	R_o= 20 Ω, L_o= 5 mH
Load 2	R_o= 0 Ω, L_o= 70 mH
DC-Link Voltage, V_{dc}	5 kV
SM Voltage, V_C	1 kV
Modulation Index, m_a	0.9
Carrier Frequency, f_s	5 kHz

IV. Modular Multilevel Converters (MMCs)

Simulation Results: Load 1



Simulation Results: Load 2



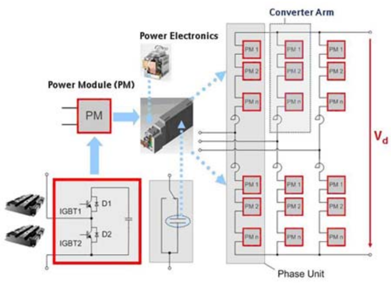
Discussion

- The rated current/power of an MMC can be increased by connecting legs in parallel.
- The circulating current of each leg is controlled independently from the other legs.
- The proposed current balancing strategy is able to achieve equal current sharing among the legs.
- None of the current control actions applied affects the output voltages of the MMC.
- The proposed strategy is general and applicable to MMCs with any number of voltage levels and legs connected in parallel.

Future Research on HVDC Systems

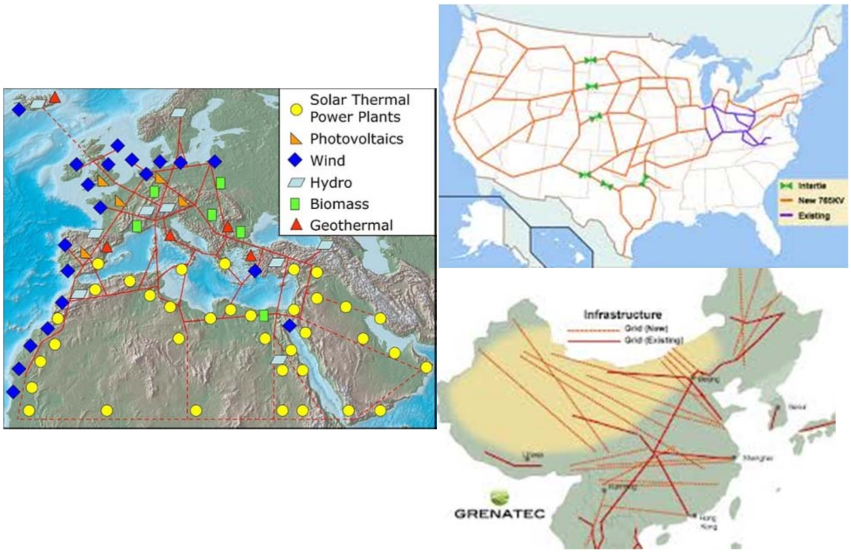
- The MMC represents an important milestone in the evolution of the HVDC transmission links.
- Research topics
  - New energy transmission layouts with MVDC collector systems.
  - Development of control algorithms for multiterminal HVDC links.
  - DC short-circuit handling.

Trans Bay's Underwater HVDC Plus (Siemens)



Courtesy of Siemens

Super Grids



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Thank you!

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