3-Φ AC/AC Matrix & Current Source Converter Modulation & Control

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Part 3 — Tutorial

Emerging Bidirectional Switches and Their Impact on Future AC Power Converter Applications

Oct. 10, 2021

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Emerging Bidirectional Switches and Their Impact on Future AC Power Converter Applications

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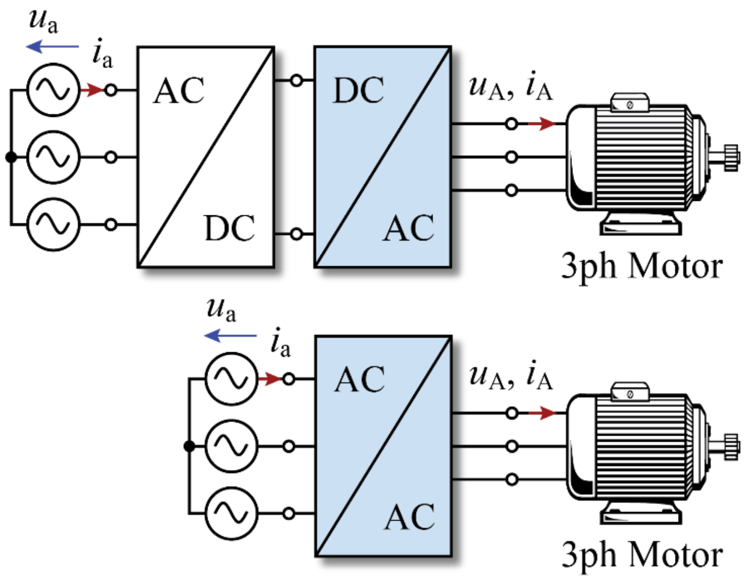
Outline

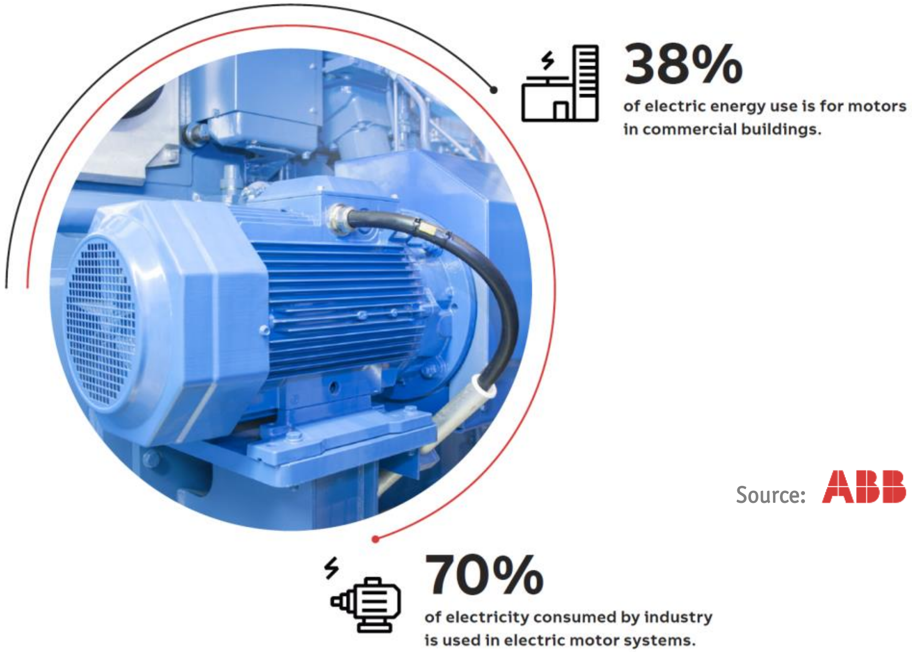
- Introduction
- Indirect & Direct Matrix Converter
- I-DC Link AC/AC Converter
- Comparative Evaluation
- Conclusions

Acknowledgement
T. Friedli
F. Krismer
F. Schafmeister

Variable Speed Drive Inverter Concepts

- *Voltage OR Current DC-Link AC/AC Converters*
- *Indirect OR Direct AC/AC Matrix Converters*



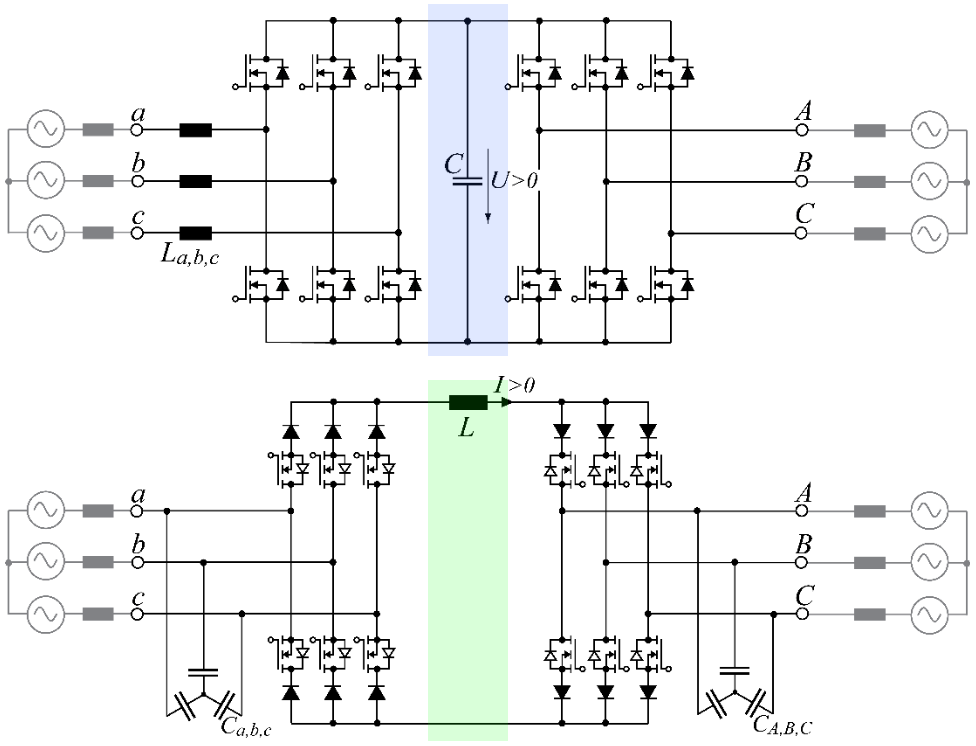


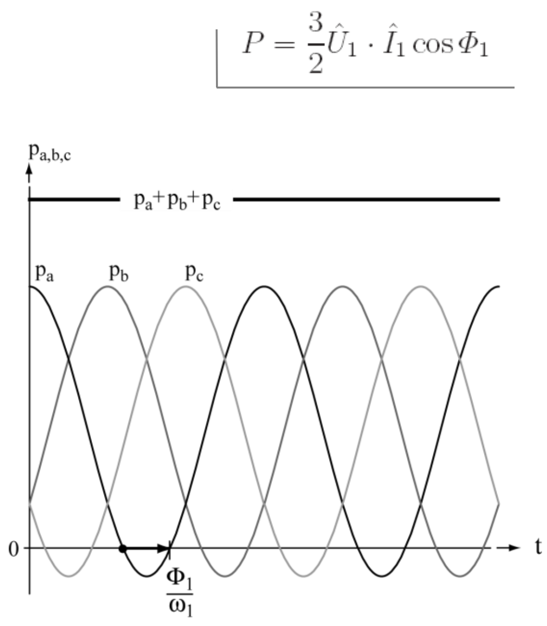
Source: ABB

- *45% of World's Electricity Used to Power Motors in Buildings & Industrial Applications*

DC-Link AC/AC Converter Topologies

- *Front-End PFC Rectifier Stage | Load-Side PWM Inverter Stage*





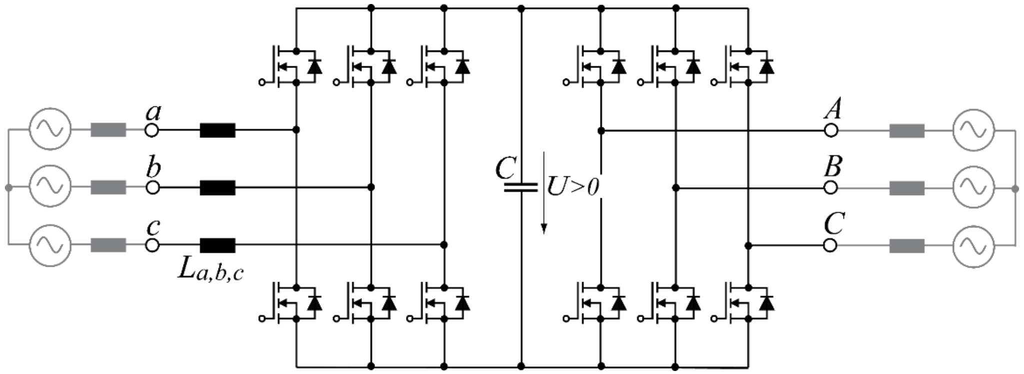
- *Constant 3-Φ Instantaneous Power Flow → No Low-Frequency Power Buffer Requirement*

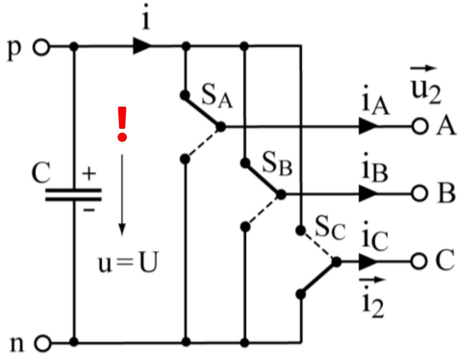
Voltage Source Converter

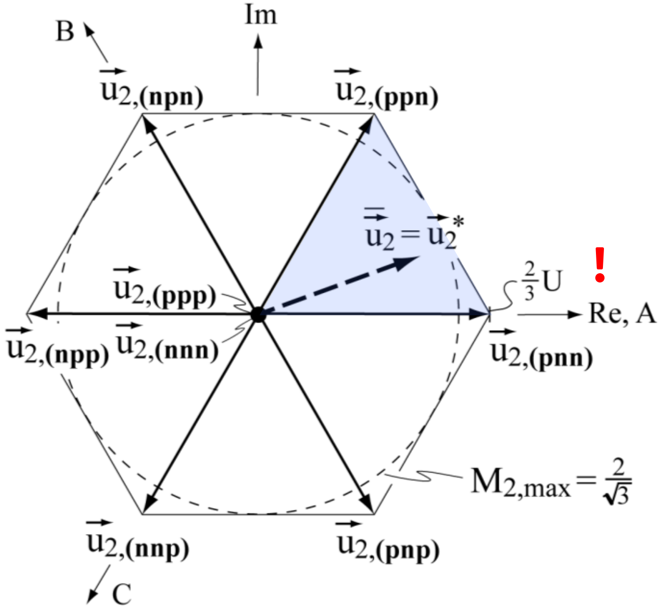
VSC Space Vector Modulation (1)

- *Switching Considering Interlock Delay Times*
- *2^3 = 8 Switching States*

$$\vec{u}_{2,j} = \frac{2}{3}\left(u_{A,j} + \underline{a}u_{B,j} + \underline{a}^2 u_{C,j}\right) \qquad \vec{u}_2^* = \hat{U}_2^* e^{j\varphi_{\vec{u}_2^*}} = \hat{U}_2^* e^{j\omega_2^* t}$$



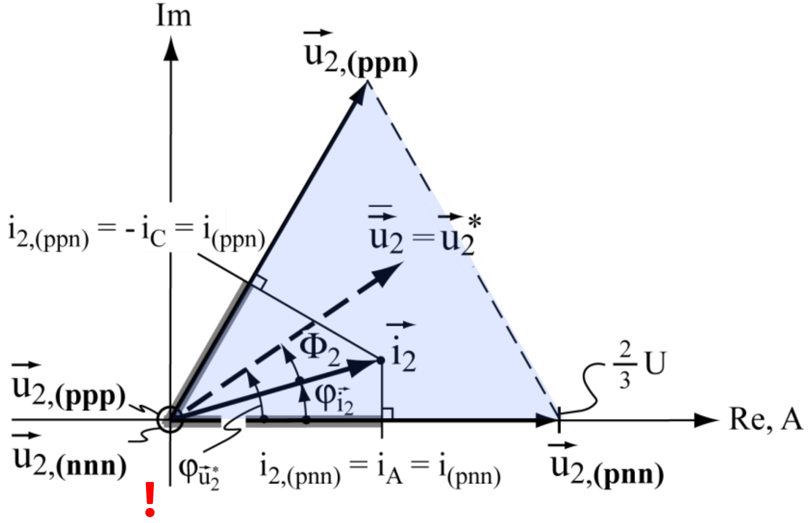




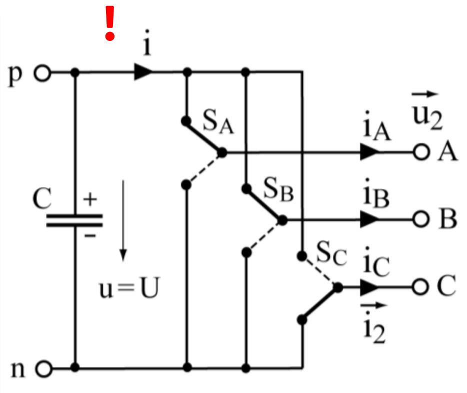
- *Continuous OR Discontinuous Modulation → (nnn)-(pnn)-(ppn)-(ppp) OR (nnn)-(pnn)-(ppn)*

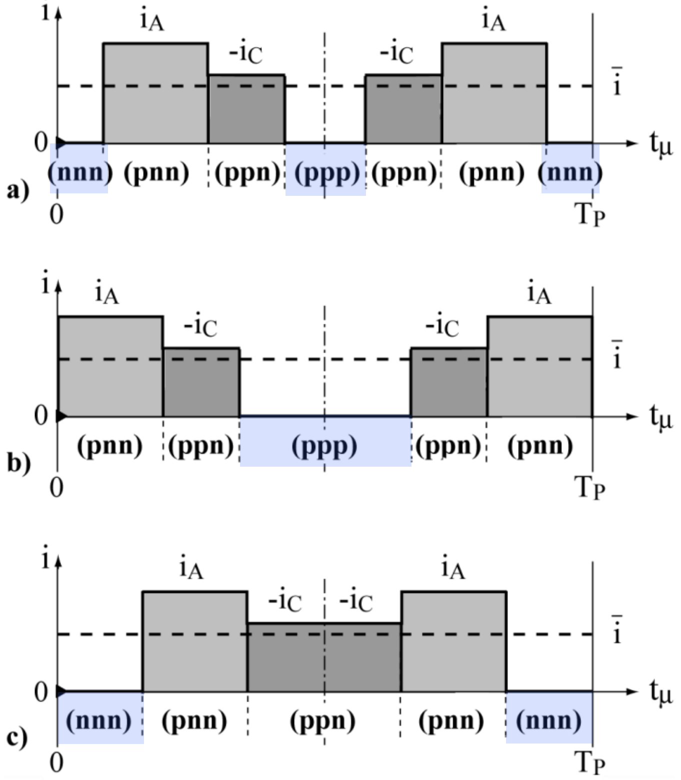
VSC Space Vector Modulation (2)

- *Switching Considering Interlock Delay Times*
- *2^3 = 8 Switching States*



$$\bar{i} = I = \frac{3}{4} M_2 \hat{I}_2 \cos \Phi_2$$





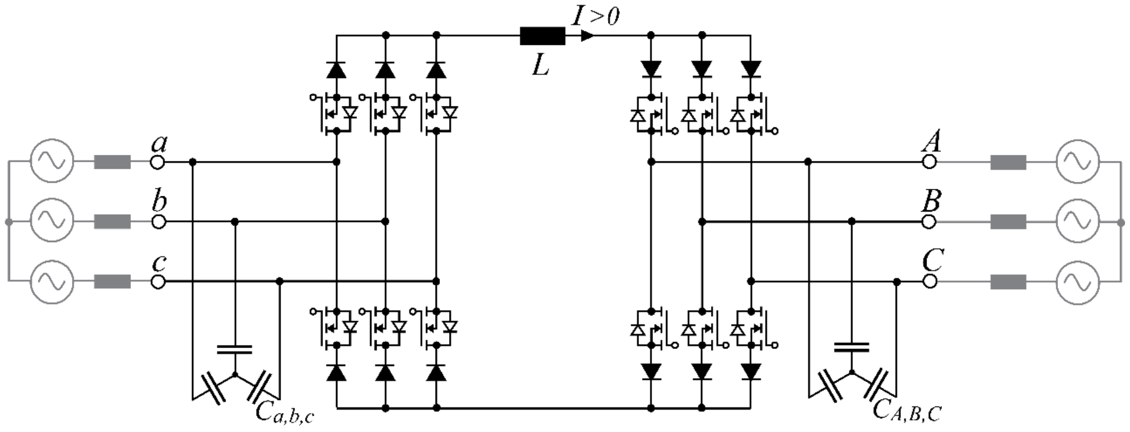
- *Continuous OR Discontinuous Modulation → (nnn)-(pnn)-(ppn)-(ppp) OR (nnn)-(pnn)-(ppn)*

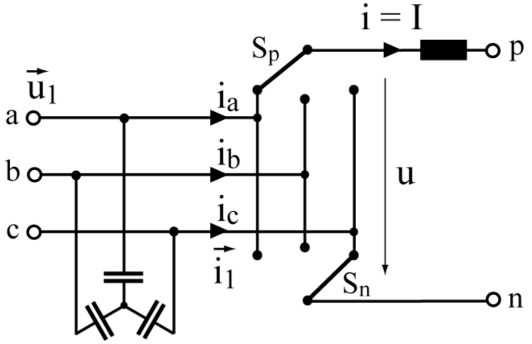
Current Source Converter

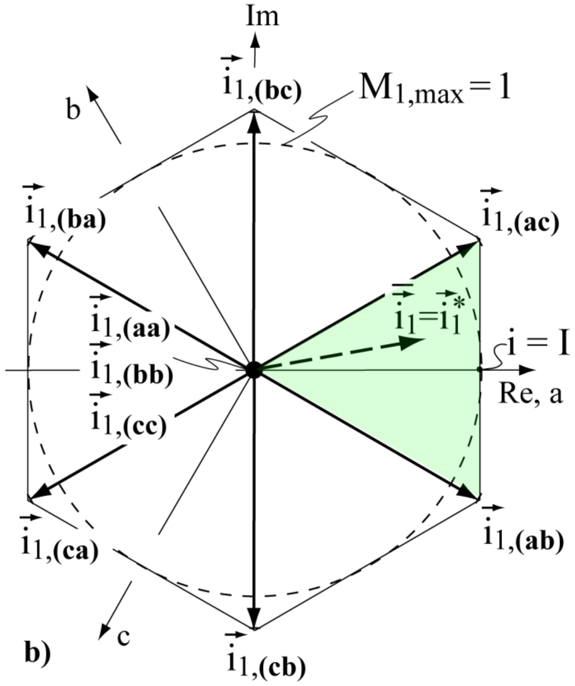
CSC Space Vector Modulation (1)

- *Overlapping Switching → Natural or Forced Commutation*
- *3^2 = 9 Switching States*

$$\vec{i}_k = \frac{2}{3}\left(i_{a,k} + \underline{a}\, i_{b,k} + \underline{a}^2\, i_{c,k}\right) \qquad \vec{i}_1^{\,*} = \hat{I}_1^* e^{j\varphi_{\vec{i}_1^*}} = \hat{I}_1^* e^{j(\omega_1 t - \Phi_1^*)}$$



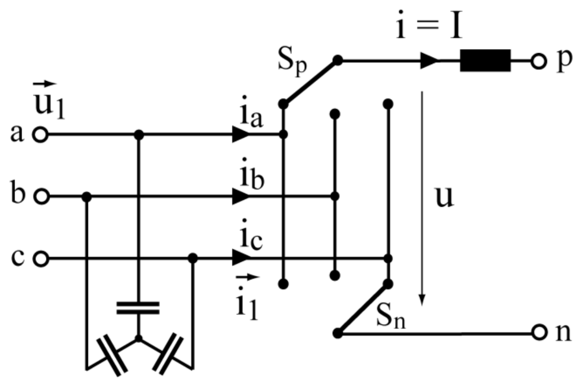




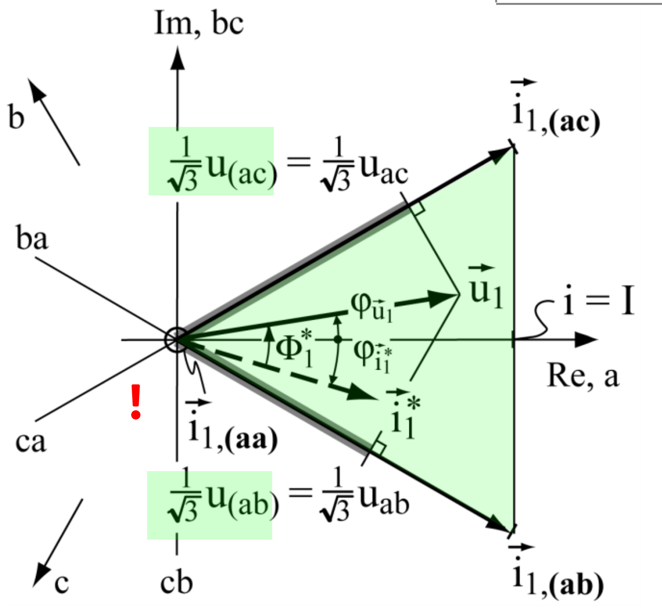
- *Shoot-Trough Free-Wheeling States (aa), (bb), (cc) → $i_a=i_b=i_c=0$*

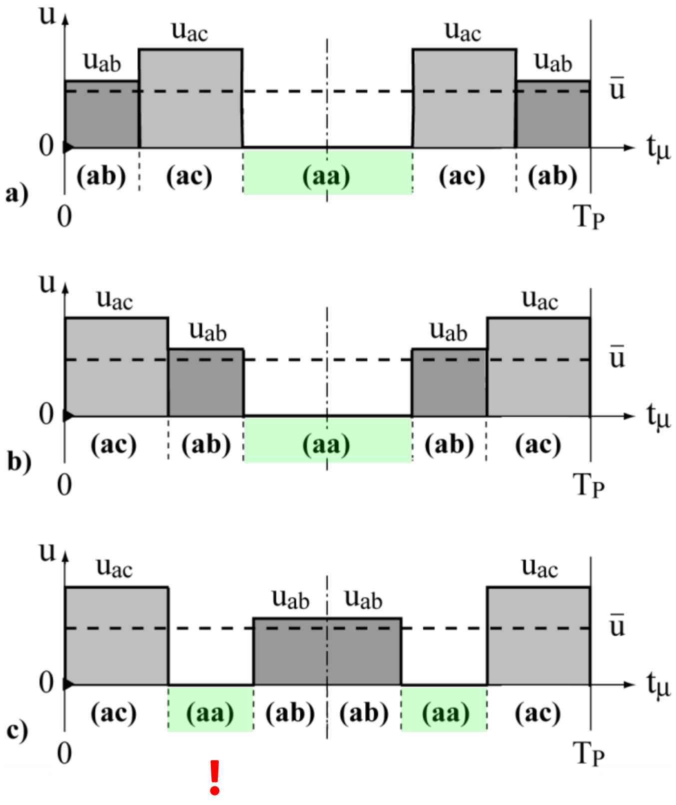
CSC Space Vector Modulation (2)

- *Overlapping Switching → Natural or Forced Commutation*
- *3^2 = 9 Switching States*



$$\bar{u} = \frac{3}{2} M_1 \hat{U}_1 \cos \Phi_1^*$$





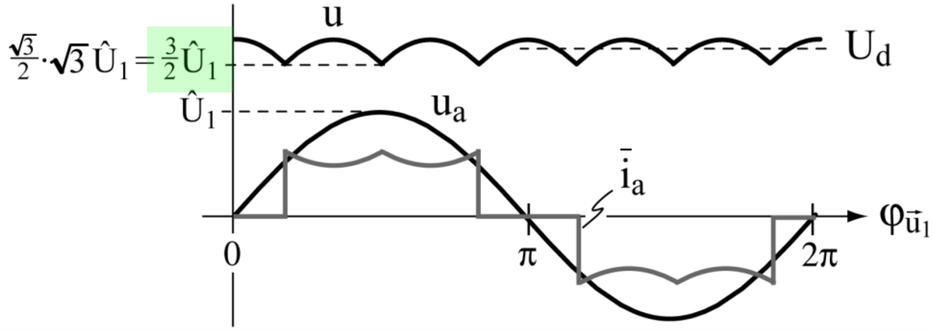
- *Shoot-Trough Free-Wheeling States (aa), (bb), (cc) → $i_a = i_b = i_c = 0$*

Indirect Matrix Converter

Topology Derivation
Space Vector Modulation
Waveforms

Fundamental Frequency Front-End (F³E)

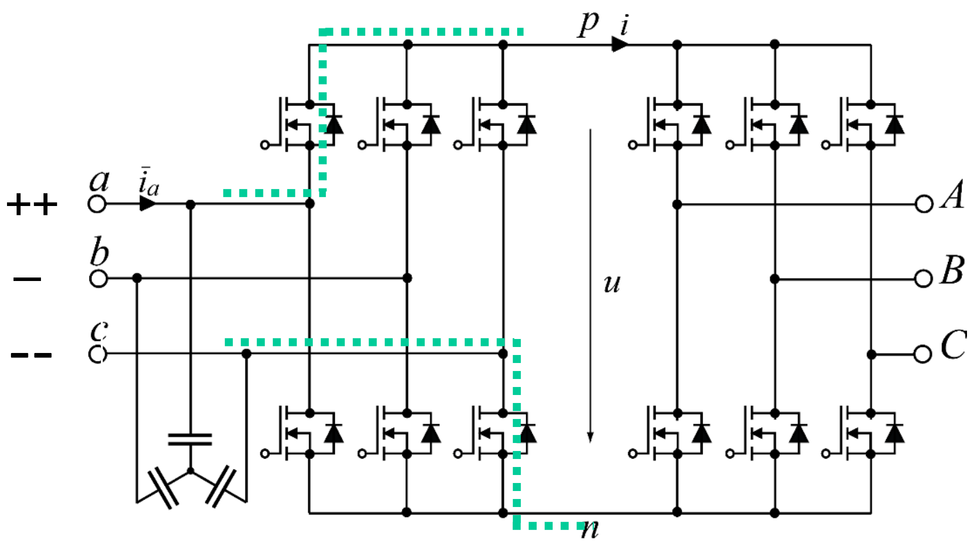
- *Voltage DC-Link AC/AC Converter w/o Energy Storage*
- *Input Diode Bridge w/ Antiparallel Transistors → Regenerative Braking*



$$u_{min} = \frac{3}{2}\hat{U}_1$$

!

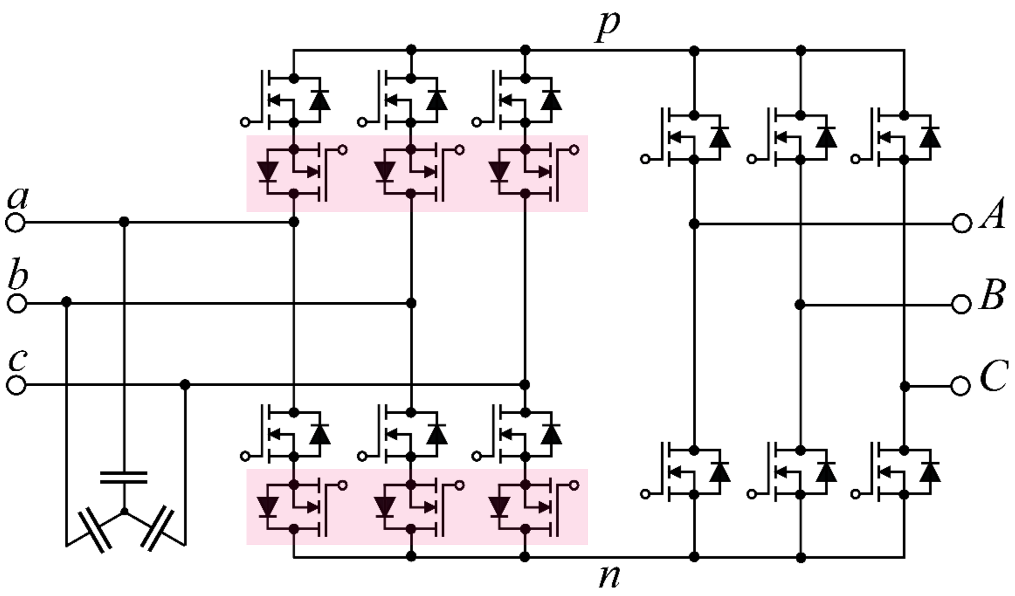
$$\hat{U}_2^* < \frac{\sqrt{3}}{2}\cdot\hat{U}_1 \approx 0.86\,\hat{U}_1$$



- *Limited Output Voltage Range*
- *Diodes Determine Switching State of Mains Interface → Block-Shaped Mains Current*

Indirect Matrix Converter (IMC)

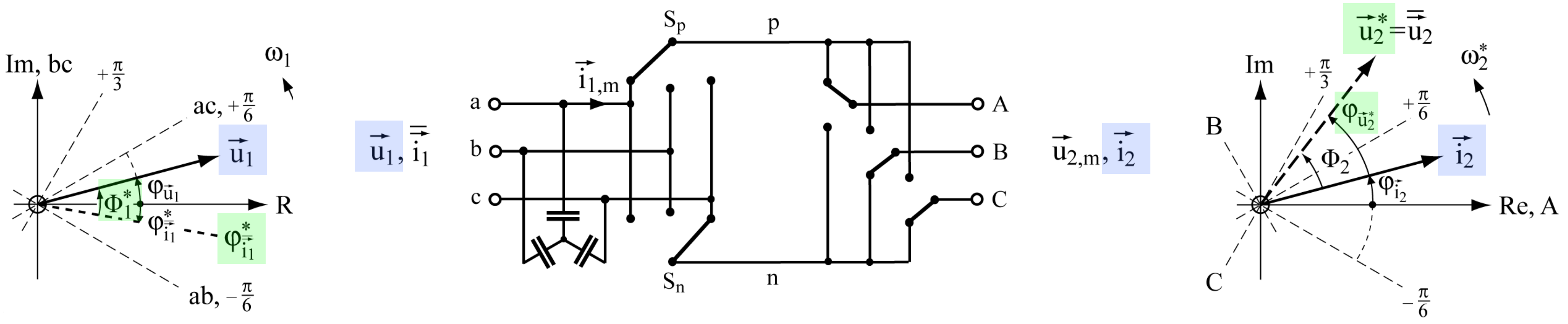
- *Extension of the F^3E-Topology → AC Switches / Full Controllability of Mains Interface*
- *Sinusoidal Mains Current*



- *Positive DC-Link Voltage Mandatory !*
- *Coordinated PWM of Input & Output Stage*

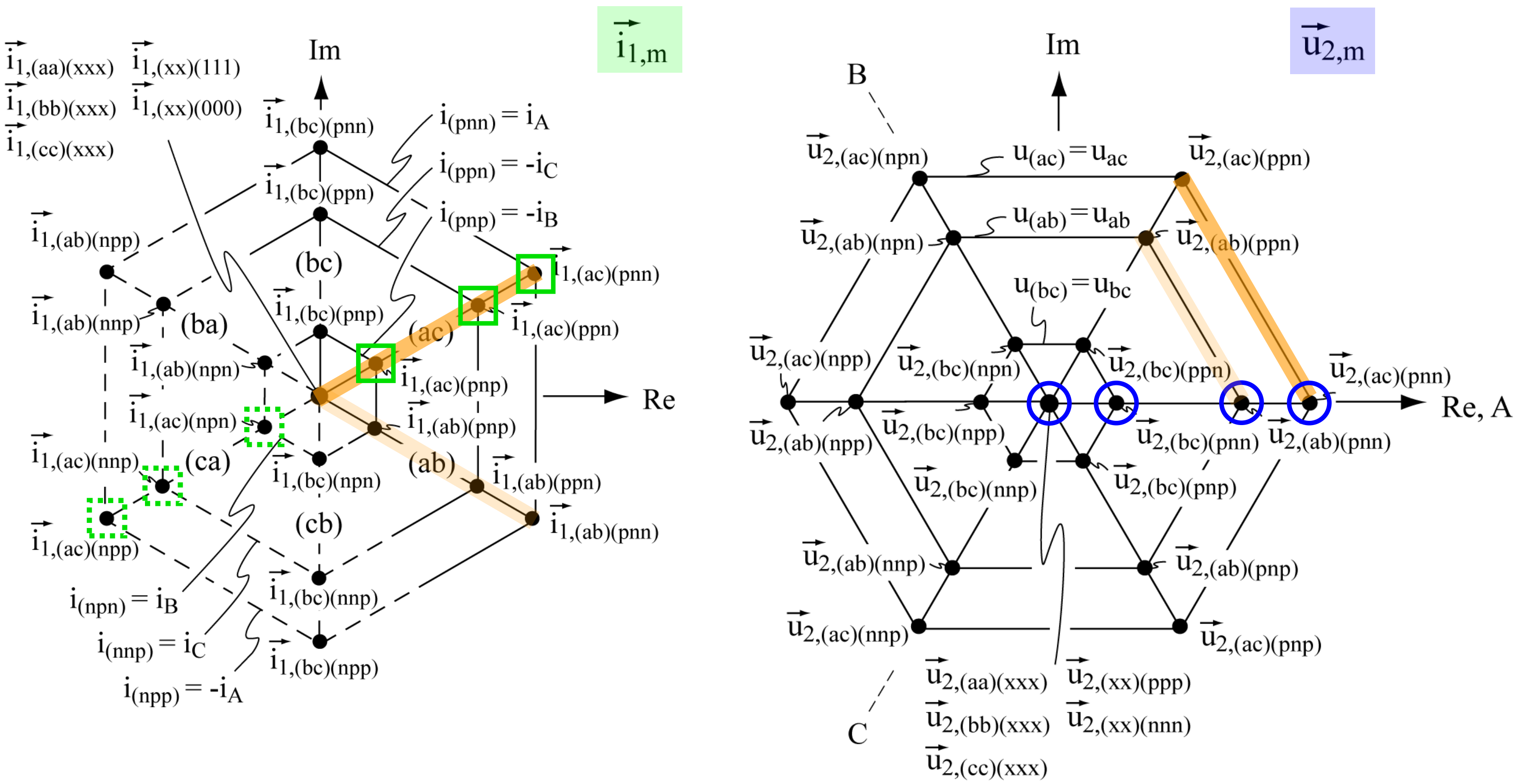
IMC Space Vector Modulation

- *Hybrid Voltage DC-Link / Current DC-Link Converter*
- *Positive DC-Link Voltage Mandatory !*



- *DC-Link Voltage → Defined by Mains Line-to-Line Voltage Sections*
- *DC-Link Current → Defined by Load Current Sections*

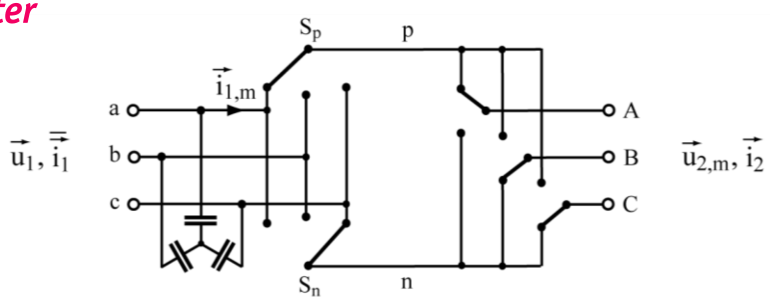
IMC Voltage & Current Space Vectors

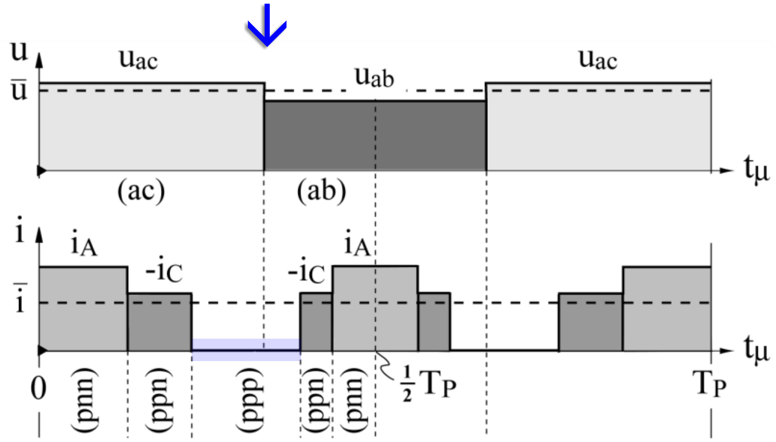


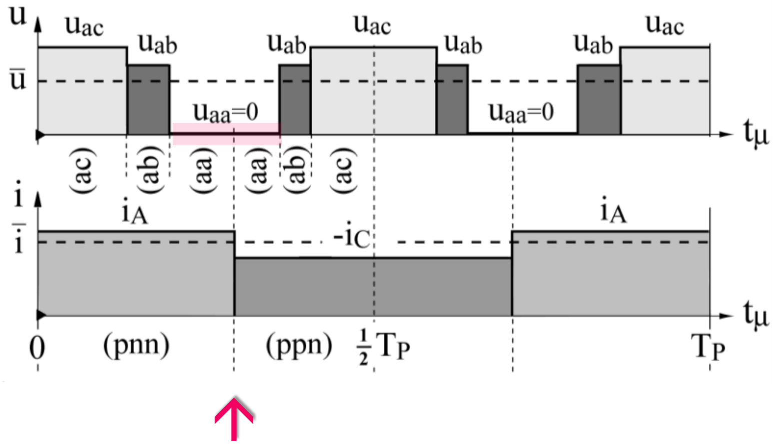
- *Positive DC-Link Voltage Mandatory !*
- *Coordinated PWM of Input & Output Stage*

IMC Commutation / Modulation

- *Hybrid Voltage DC-Link / Current DC-Link Converter*
- *Positive DC-Link Voltage Mandatory !*



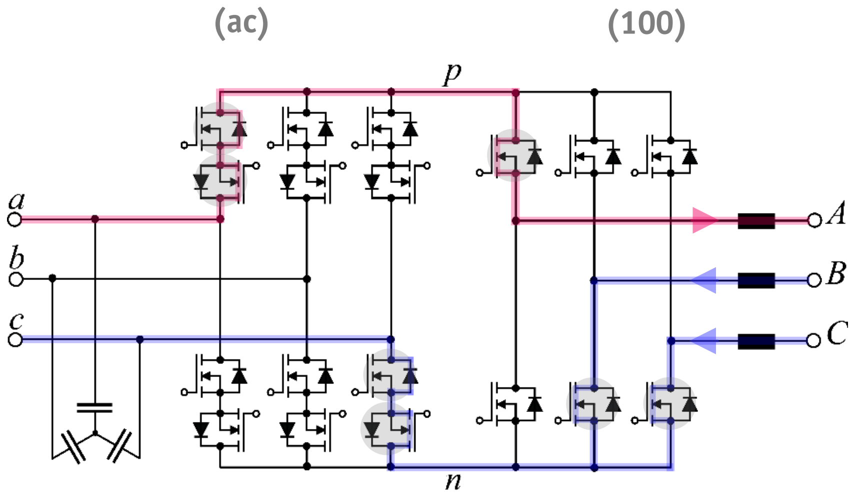


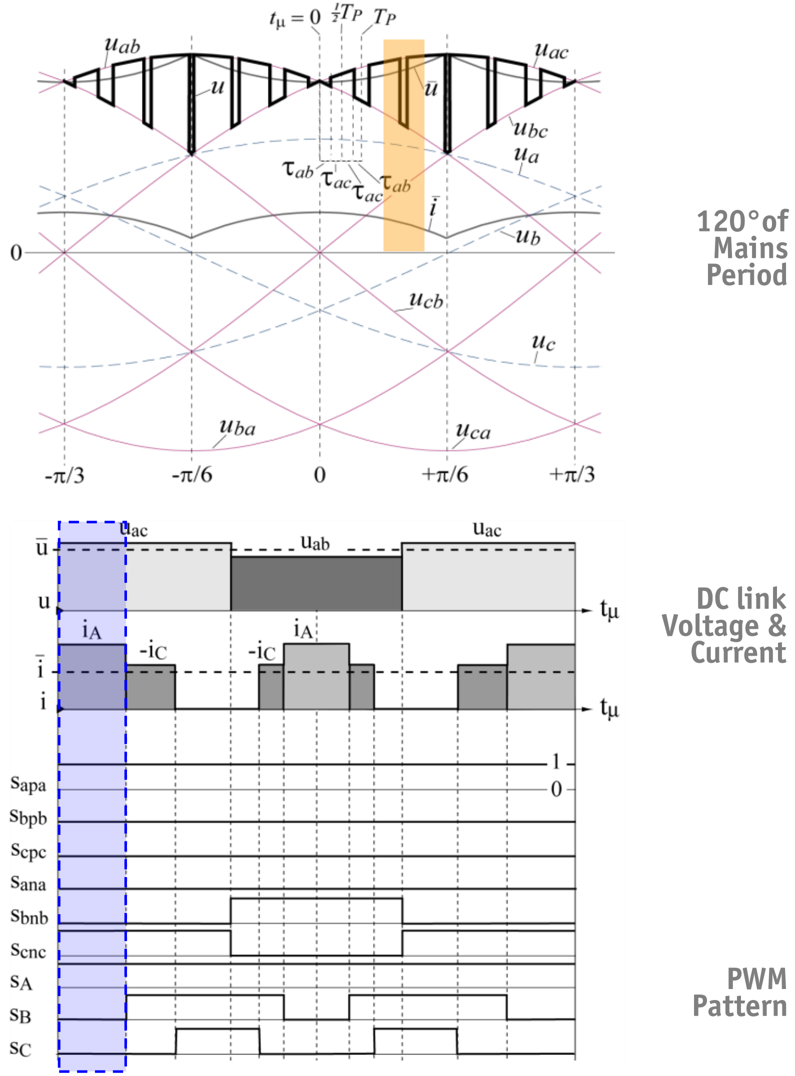


- *Zero Current Commutation of Input Stage*
- *Zero Voltage Commutation of Output Stage*

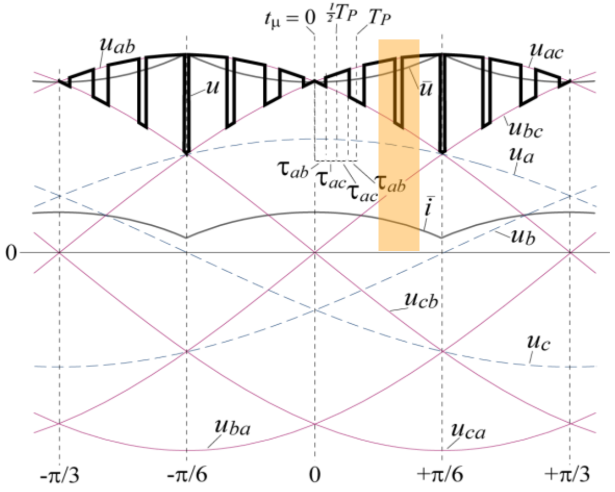
IMC Modulation (1)

DC-link Voltage $u = u_{ac}$
DC-link Current $i = i_A$





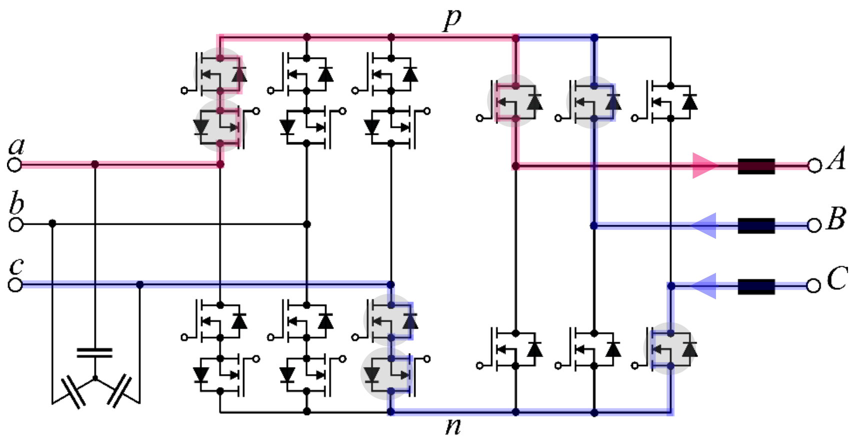
IMC Modulation (2)

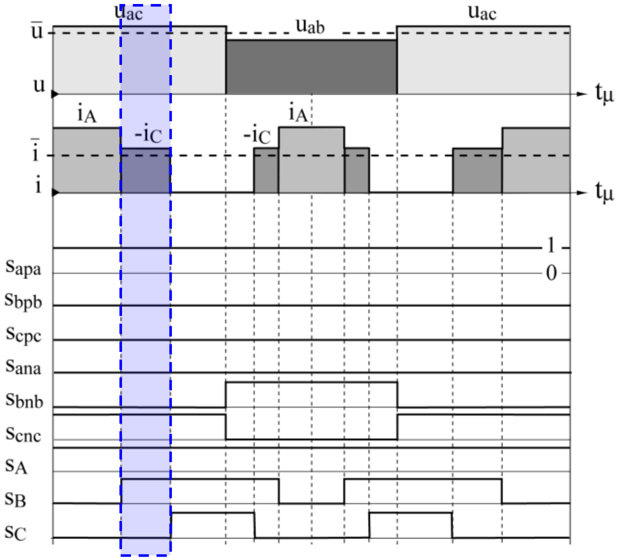


120° of Mains Period

DC-link Voltage $u = u_{ac}$

DC-link Current $i = -i_C$

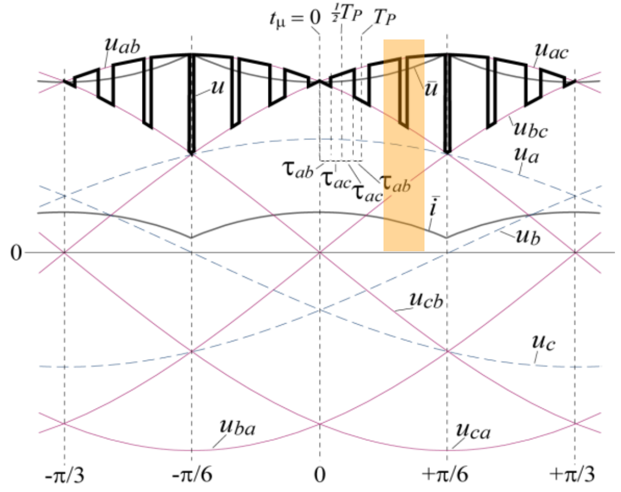




DC-Link Voltage & Current

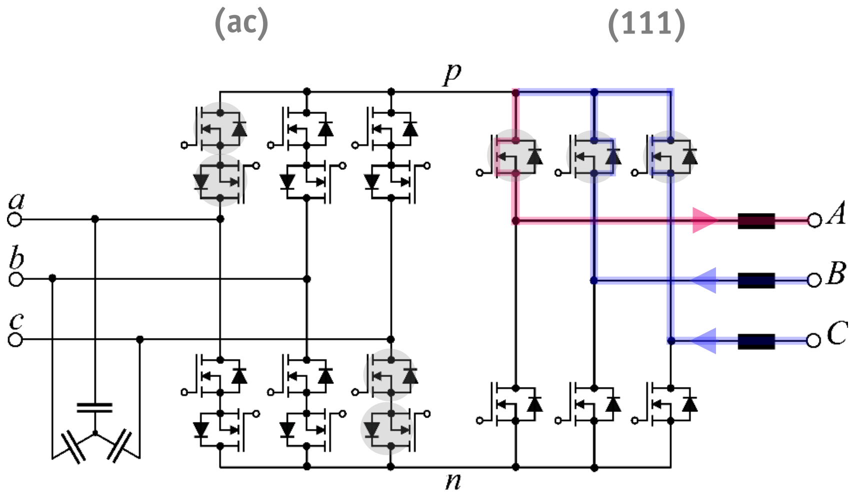
PWM Pattern

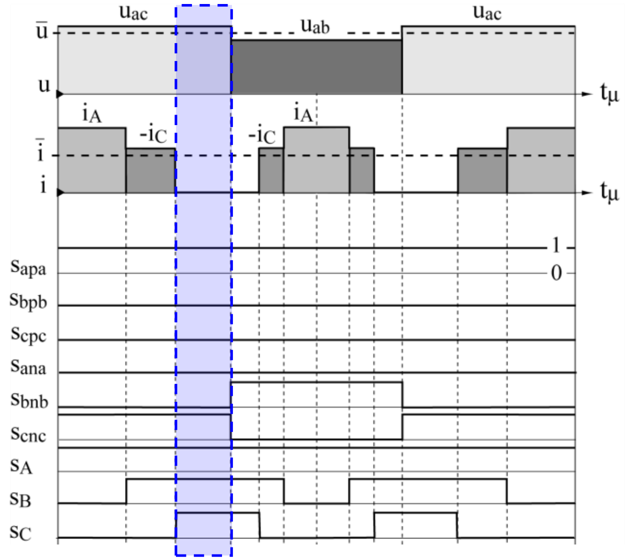
IMC Modulation (3)



120° of Mains Period

DC-link Voltage $u = u_{ac}$
DC-link Current $i = 0$ **!**

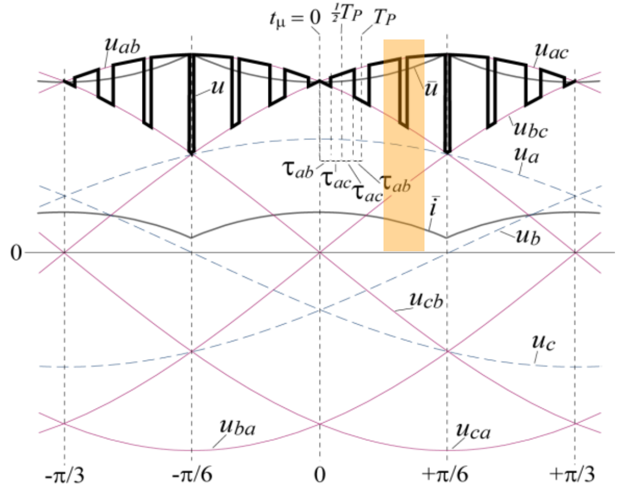




DC-Link Voltage & Current

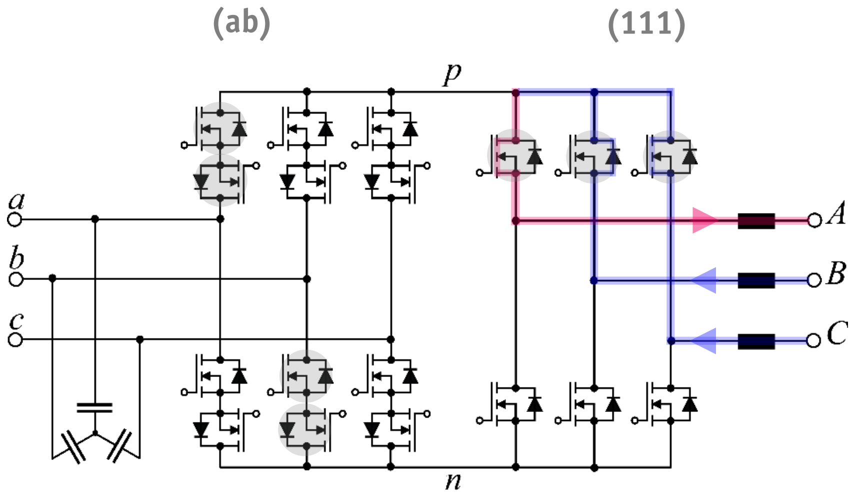
PWM Pattern

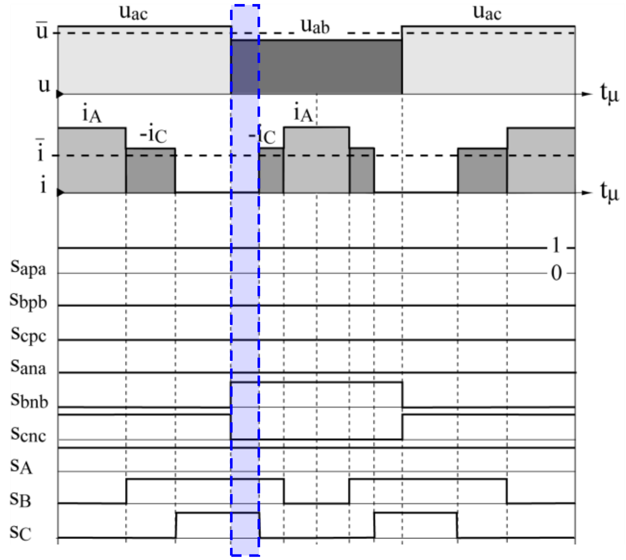
IMC Modulation (3)



120° of Mains Period

DC-link Voltage $u = u_{ab}$
DC-link Current $i = 0$!

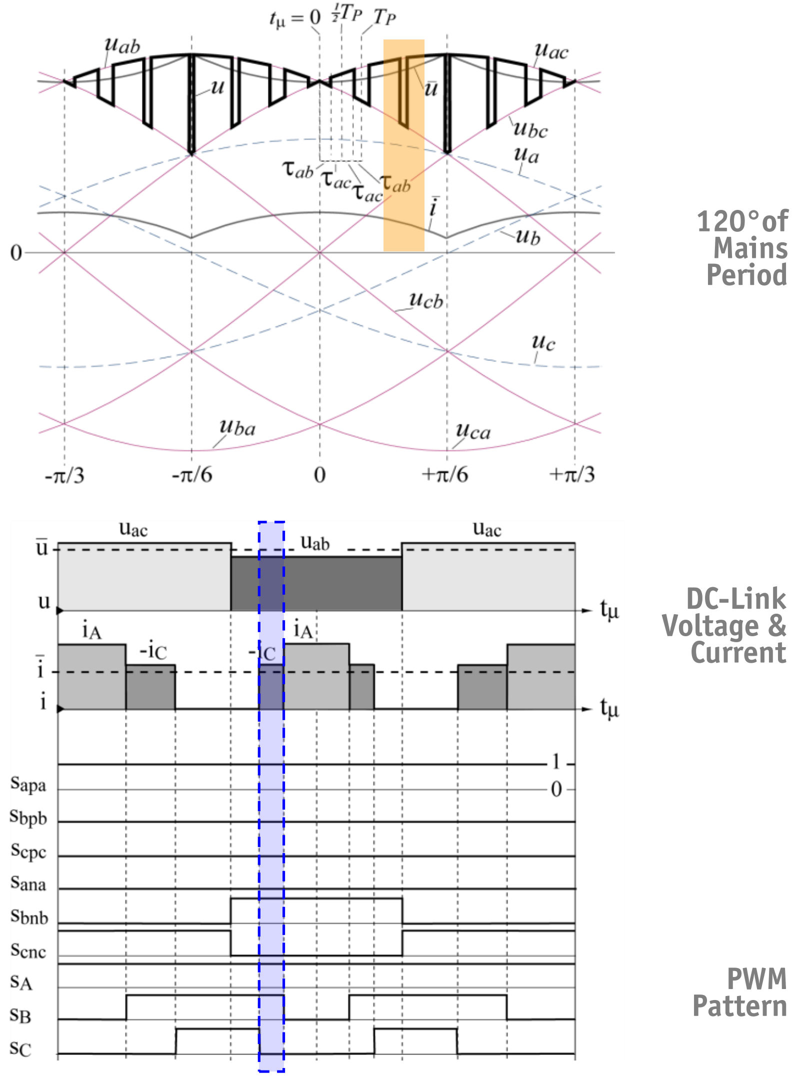




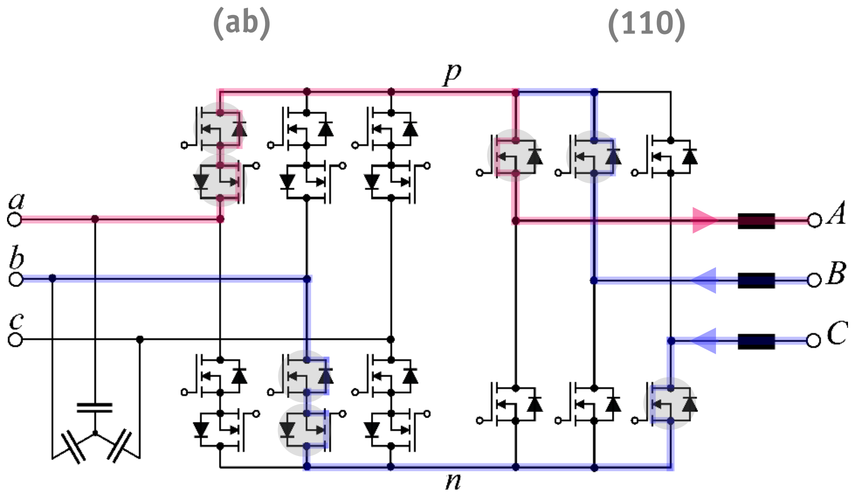
DC-Link Voltage & Current

PWM Pattern

IMC Modulation (5)

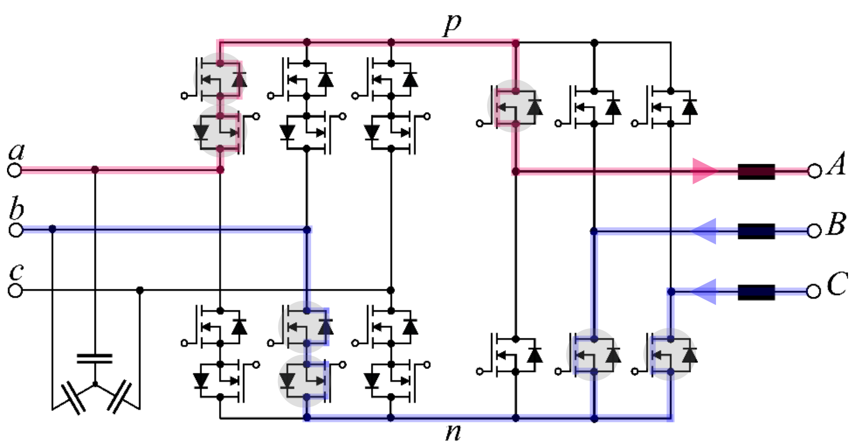


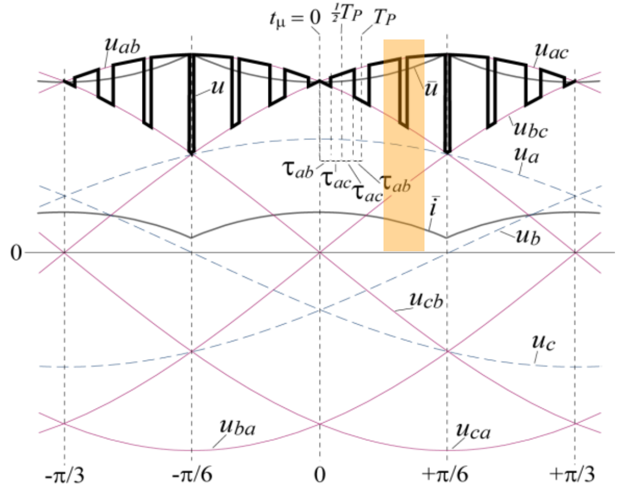
DC-link Voltage $u = u_{ab}$
DC-link Current $i = -i_C$



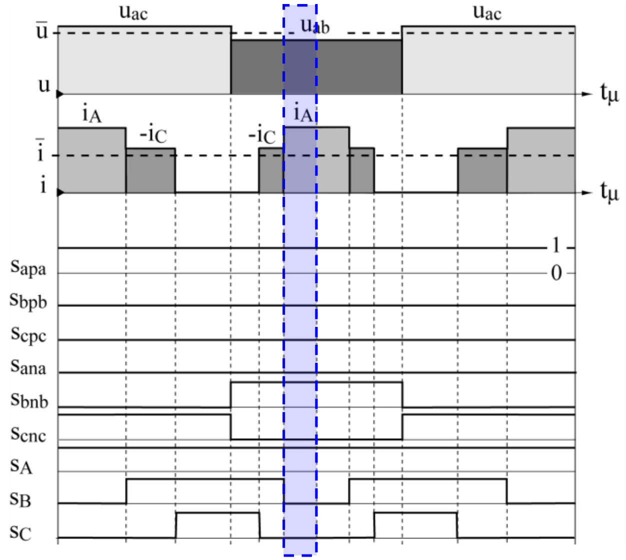
IMC Modulation (6)

DC-link Voltage $u = u_{ab}$
DC-link Current $i = i_A$





120° of Mains Period



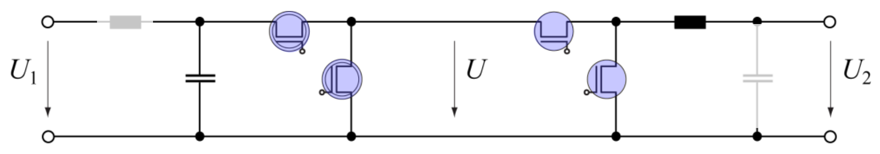
DC-Link Voltage & Current

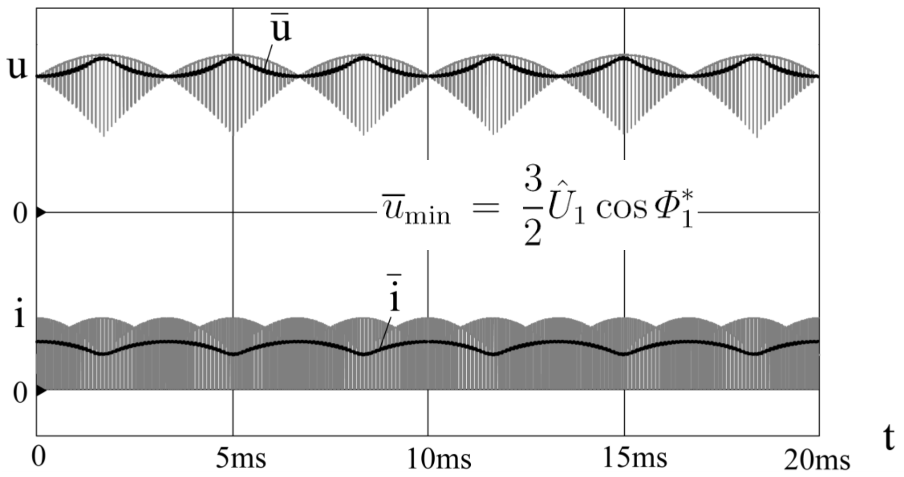
PWM Pattern

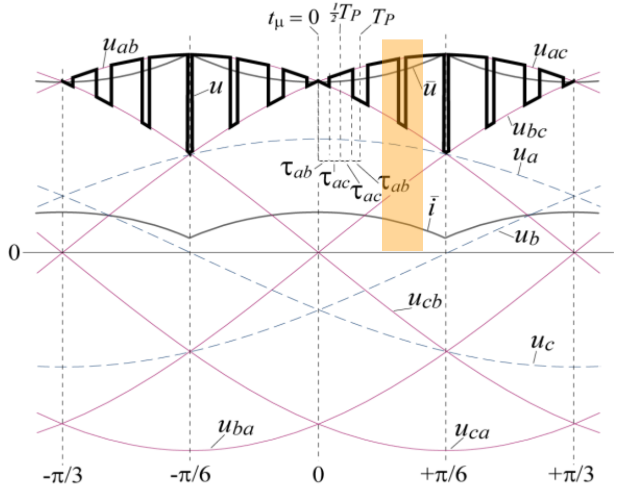
IMC Output Voltage Limit

- *IMC — Cascaded Buck-Type Structure*
- *Input-Stage Output Voltage Reduces with cos Φ_1*
- *Analogous to Thyristor AC/DC Converter*

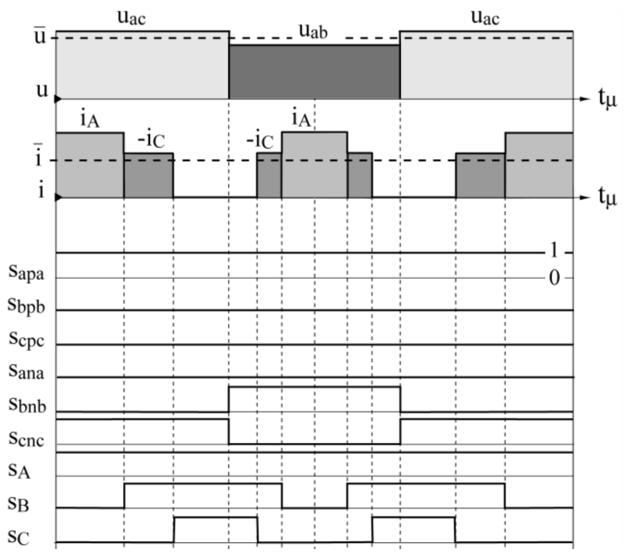
$$\hat{U}^*_{2,\max} \leq \frac{\sqrt{3}}{2} \cdot \hat{U}_1 \cos\Phi^*_1 \quad !$$







120° of Mains Period



DC-Link Voltage & Current

PWM Pattern

Alternative Modulation Schemes (1)

- *LV vs. HV Modulation*
  - *Lower Sw. Losses (40%) & Lower CM Voltage (25%)*
  - *Slightly Lower Load Current Ripple*
  - *Input Voltage Ripple Doubles (!)*
  - *Higher Conduction Losses*

- *High Output Voltage Modulation (HVM)*

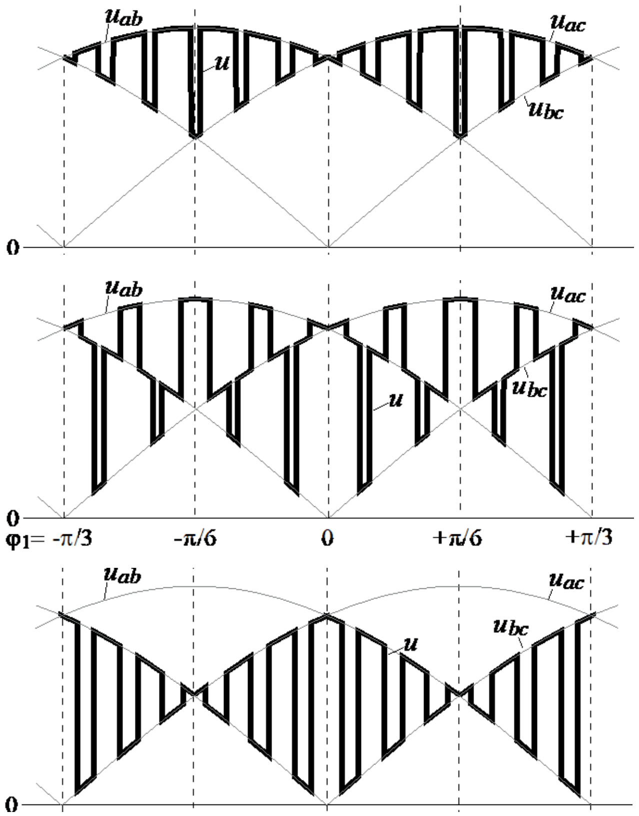
$$\hat{U}_2 = 0 \ldots \frac{\sqrt{3}}{2} \cdot \hat{U}_1$$

- *Three-Level Modulation*

$$\hat{U}_2 = \frac{1}{2} \ldots \frac{\sqrt{3}}{2} \cdot \hat{U}_1$$

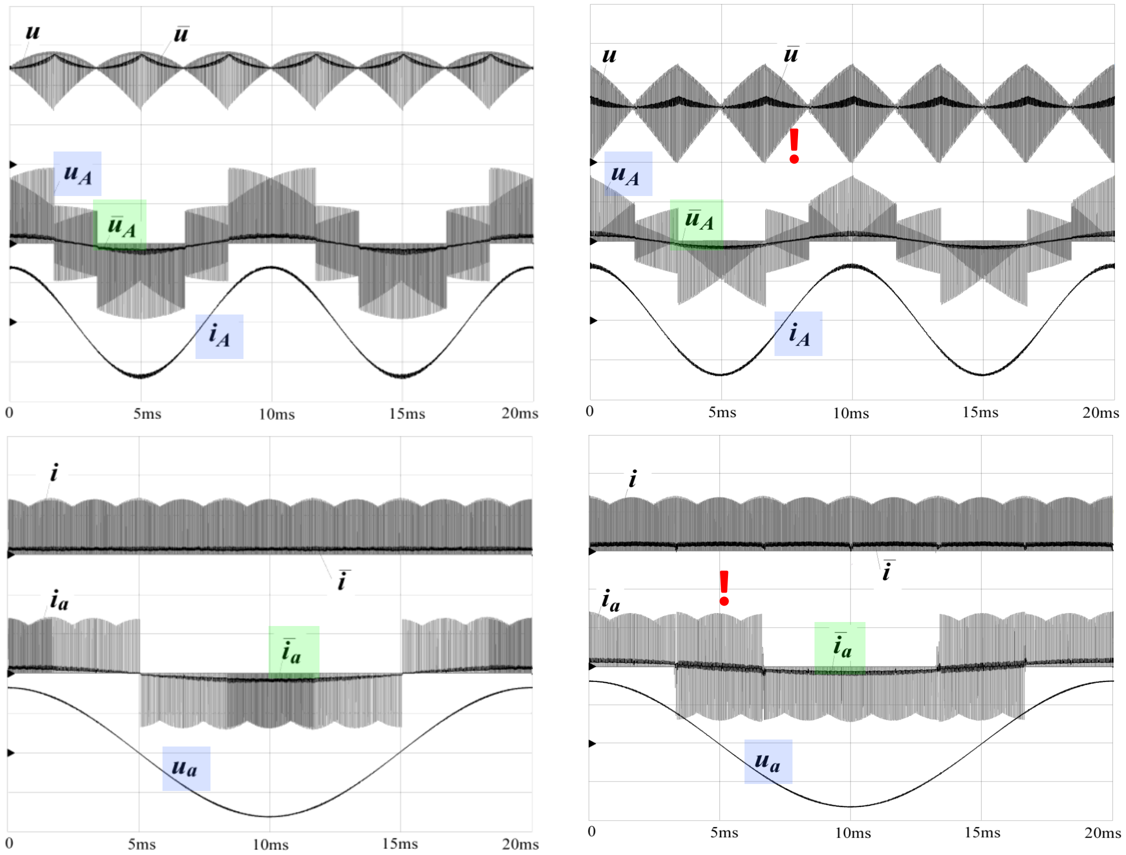
- *Low Output Voltage Modulation (LVM)*

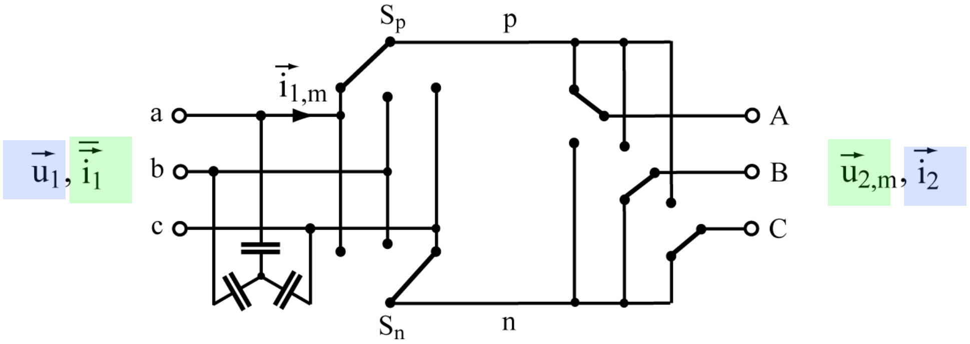
$$\hat{U}_2 = 0 \ldots \frac{1}{2} \cdot \hat{U}_1$$



Alternative Modulation Schemes (2)

- *HV vs. LV Output Modulation*
- *Voltage & Current Time Behavior*

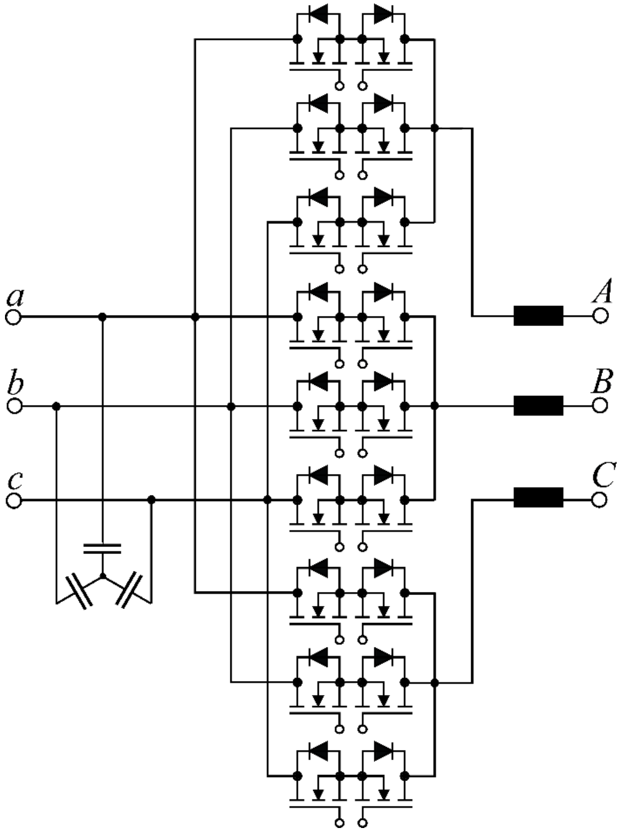




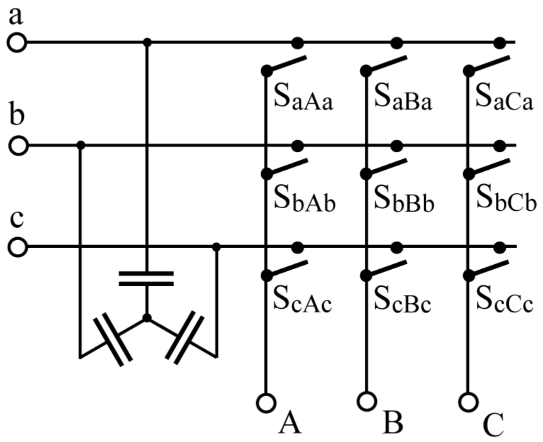
Direct Matrix Converter

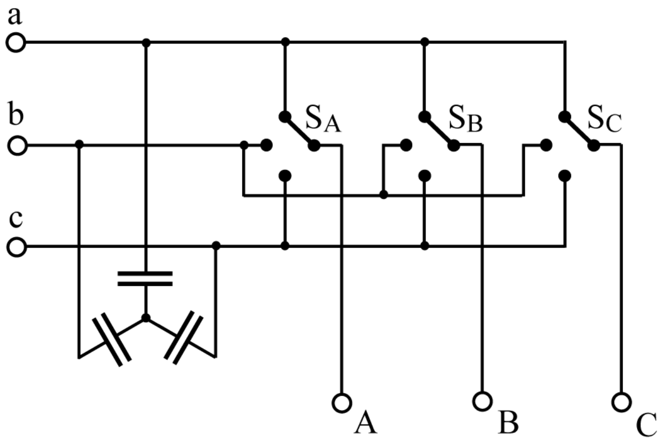
Multi-Step Commutation
Space Vector Modulation
Waveforms

Direct Matrix Converter (DMC)



- *Direct AC/AC Conversion → 4-Quadrant (AC) Switches*
- *Quasi Three-Level Output Characteristic*



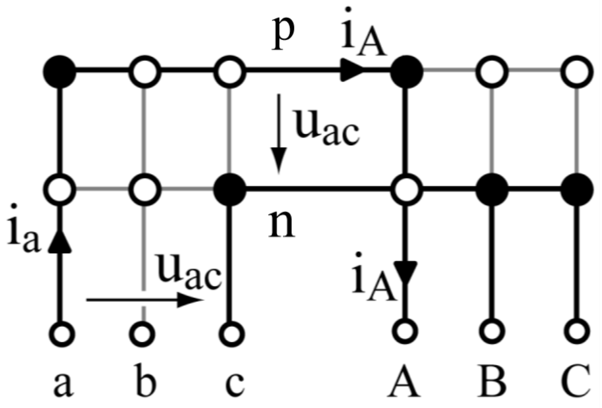


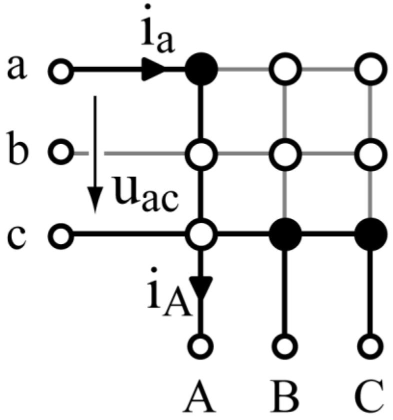
- *Multi-Step Commutation (!)*
- *Prevent Mains Short Circuit & Interruption of Load Current*

DMC / IMC Relation

- *"Indirect" Space Vector Modulation*
- *Equivalence / Re-Coding of Switching States*
- *Buck-Type Voltage Conversion*

$$\vec{u}_{2,(acc)} = \vec{u}_{2,(ac)(pnn)}$$
$$\vec{i}_{1,(acc)} = \vec{i}_{1,(ac)(pnn)}$$



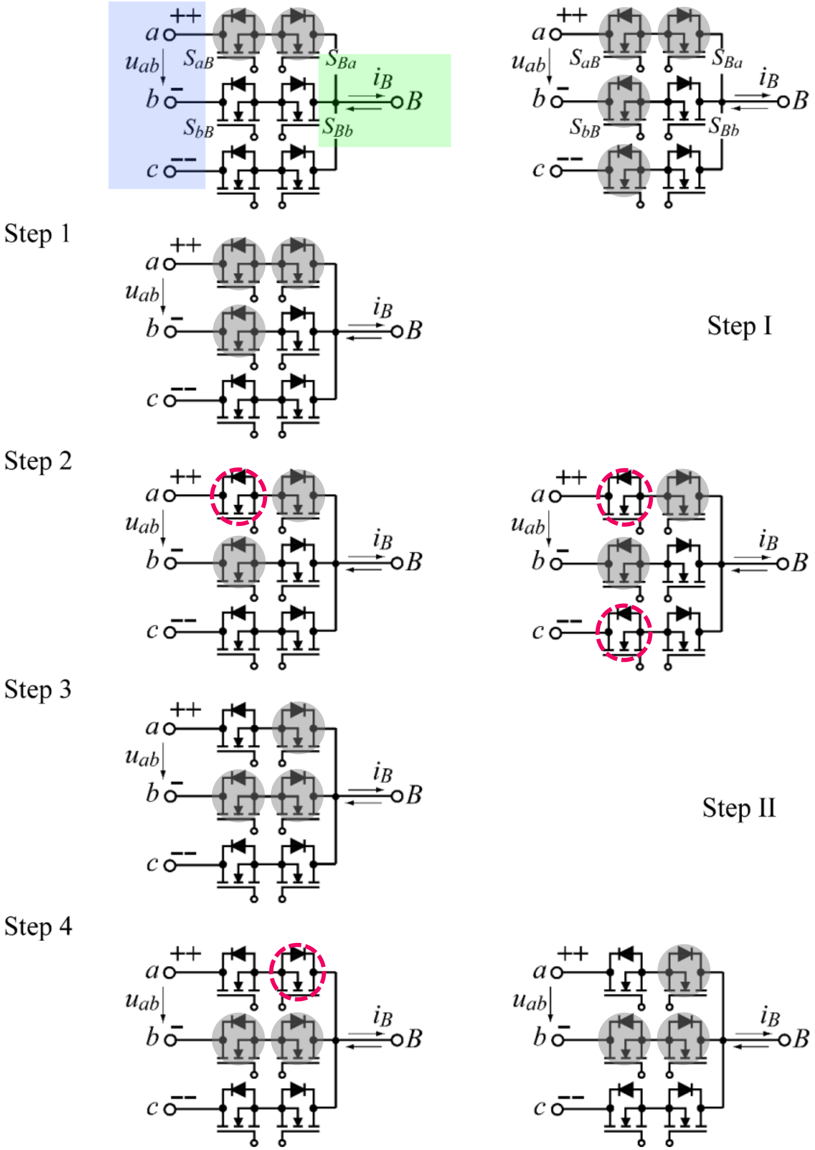


$$\ldots|_{t_\mu=0} \quad (ac)(pnn) - (ac)(ppn) - (ac)(ppp)$$
$$- (ab)(ppp) - (ab)(ppn) - (ab)(pnn)|_{t_\mu = T_P/2}$$
$$(ab)(pnn) - (ab)(ppn) - (ab)(ppp)$$
$$- (ac)(ppp) - (ac)(ppn) - (ac)(pnn)|_{t_\mu = T_P} \quad \ldots$$

$$\ldots|_{t_\mu=0} \quad (acc) - (aac) - (aaa) - (aaa) - (aab) - (abb)|_{t_\mu = T_P/2}$$
$$(abb) - (aab) - (aaa) - (aaa) - (aac) - (acc)|_{t_\mu = T_P} \quad \ldots$$

$$\varphi_{\vec{u}_2^*} \in [0, \pi/6]$$

CMC Multi-Step Commutation

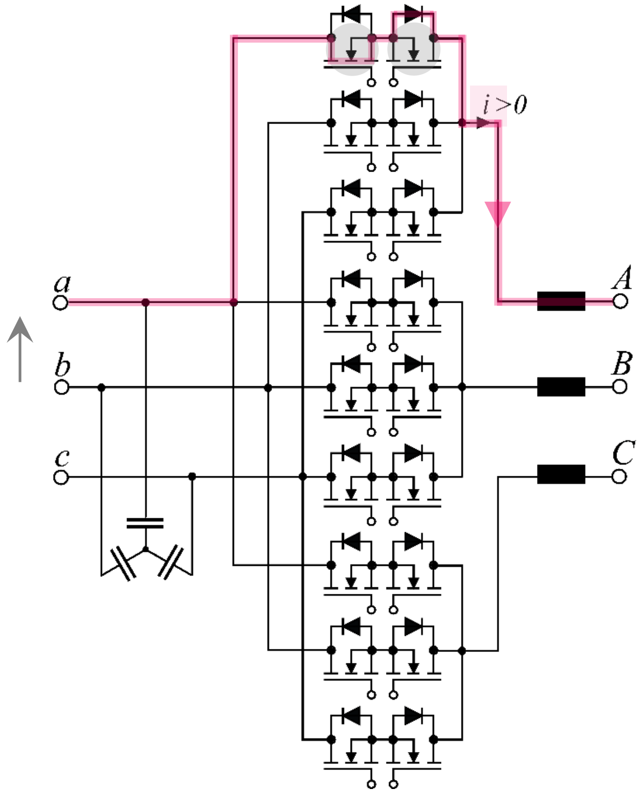


Example ***u-Dependent Commutation aB → bB @ u_{ab} > 0***

- ***Four-Step Commutation***
- ***Two-Step Commutation***

4-Step Commutation of CMC (1)

- *Example* *i-Dependent Commutation*
  aA → bA @ i > 0



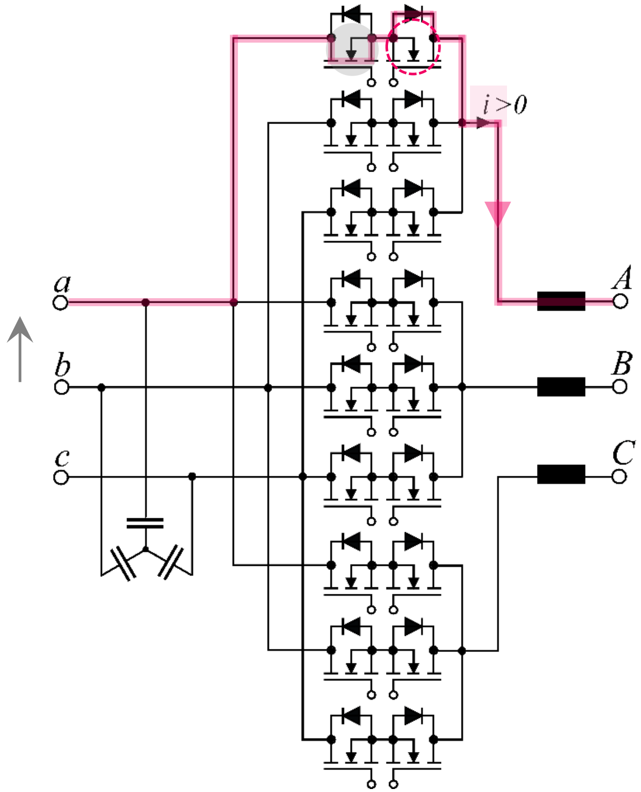
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of CMC (1)

- *Example* *i-Dependent Commutation*
  aA → bA @ i > 0

1st Step: Off



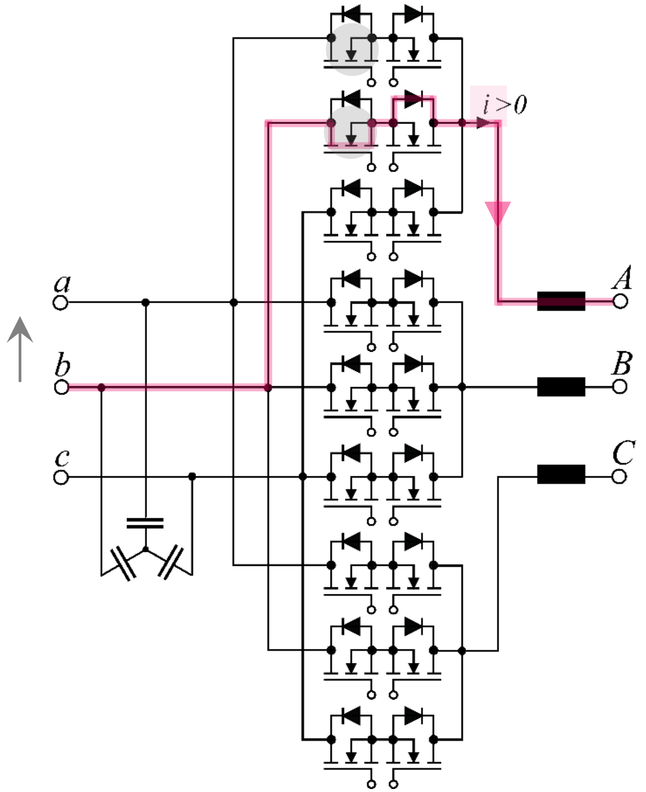
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of CMC (2)

- *Example* *i-Dependent Commutation*
  aA → bA @ i > 0

1^{st} Step: Off
2^{nd} Step: On



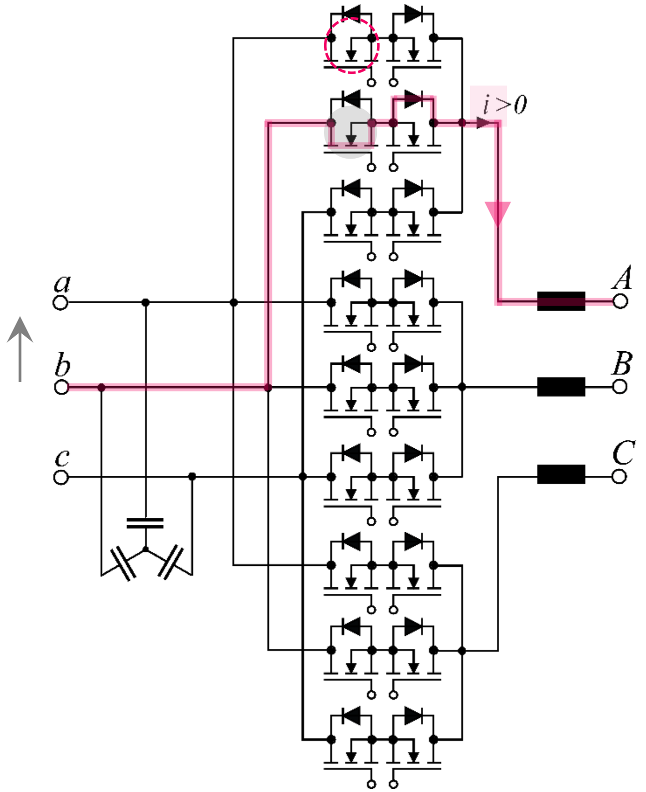
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of CMC (3)

- *Example* *i-Dependent Commutation*
  $aA \rightarrow bA$ @ $i > 0$

1st Step: Off
2nd Step: On
3rd Step: Off

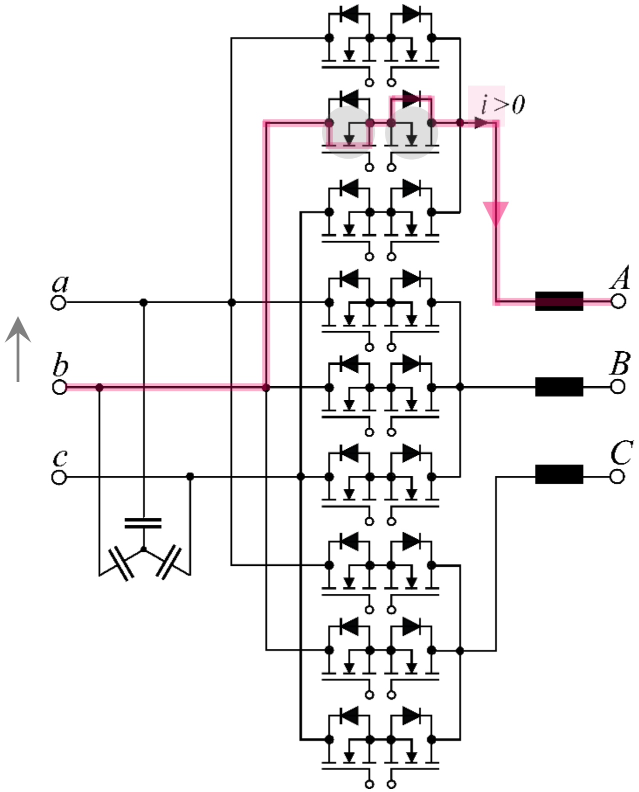


- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of CMC (4)

- *Example* *i-Dependent Commutation*
  aA → bA @ i > 0



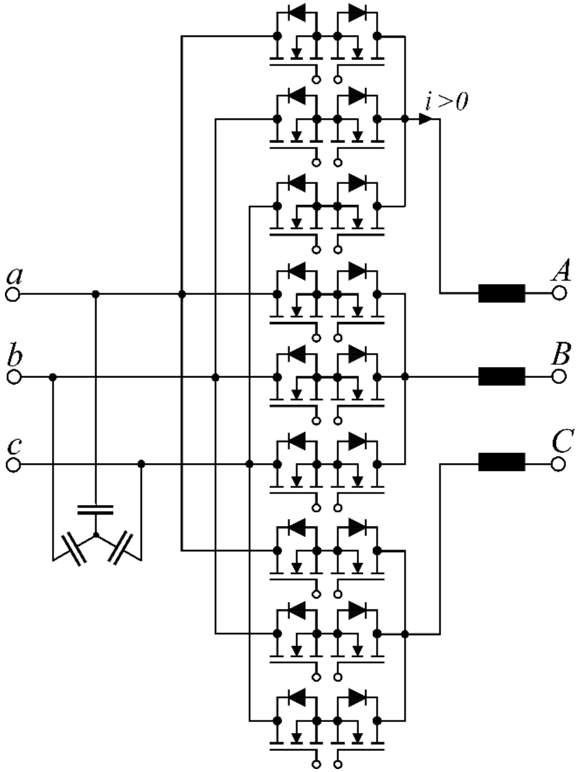
1st Step:	Off
2nd Step:	On
3rd Step:	Off
4th Step:	On

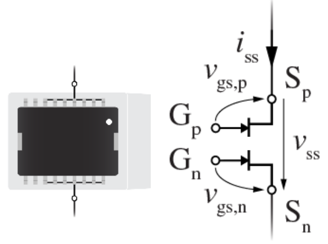
- *No Mains Short Circuit*
- *No Load Current Interruption*

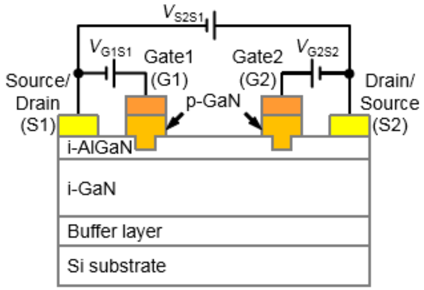
Assumption $u_{ab} < 0$

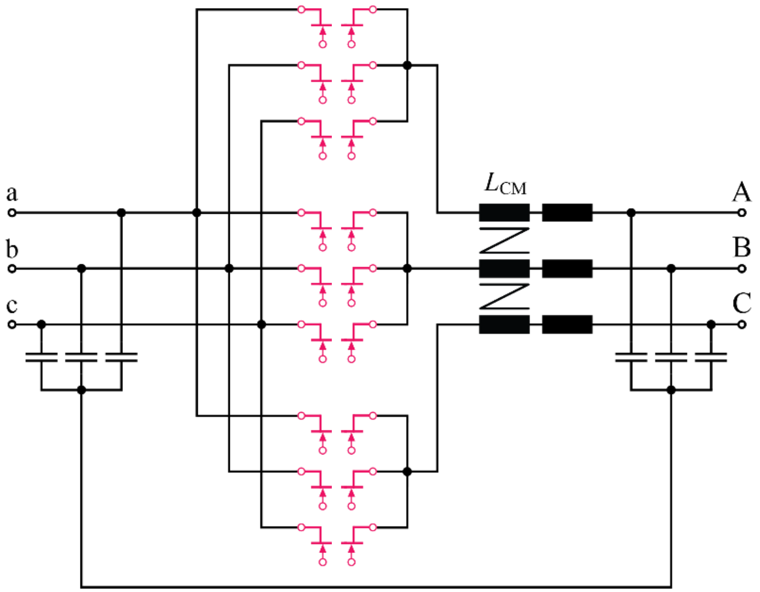
DMC Employing Monolithic GaN AC-Switches

- *Factor of 4 Saving in Chip Area vs. Discrete Realization*
- *2 Gates → 4-Step Commutation*









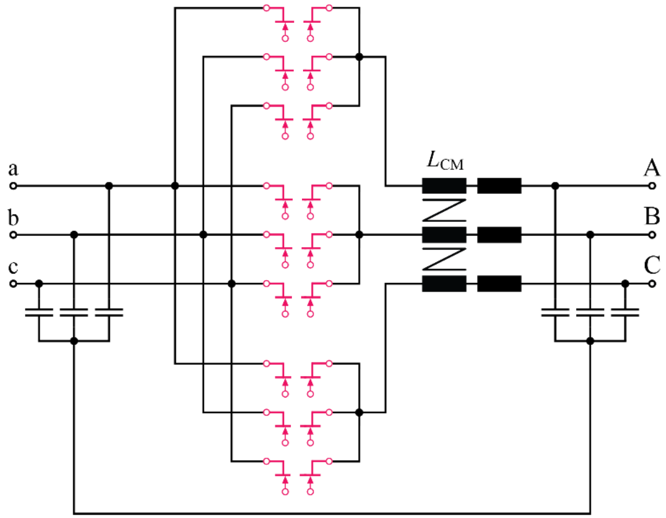
- *Full Sinusoidal Output Filter for Preventing Motor Insulation Stress | CM-EMI | Bearing Current*

Current Source AC/AC Converter

Comparative Evaluation vs. CMC
GaN M-BDS Realization

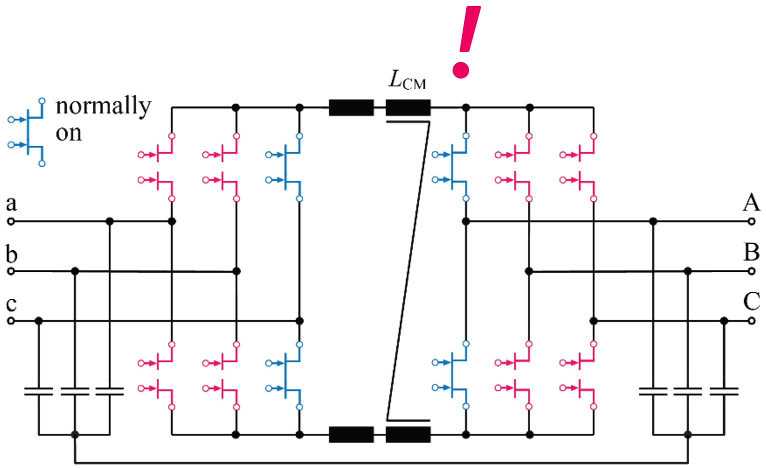
3-Φ AC/AC Converter Topologies

- **Direct Matrix Converter**
  - Application of M-BDSs | 9 Switches
  - 4-Step Commutation
  - Complex Space Vector Modulation
  - Limited to Buck-Operation (!)



- Challenging Overvoltage Protection

- **Current DC-Link Topology**
  - Application of M-BDSs | 12 Switches
  - 4-Step Commutation
  - Buck-Boost Functionality (!)
  - Low Filter Volume



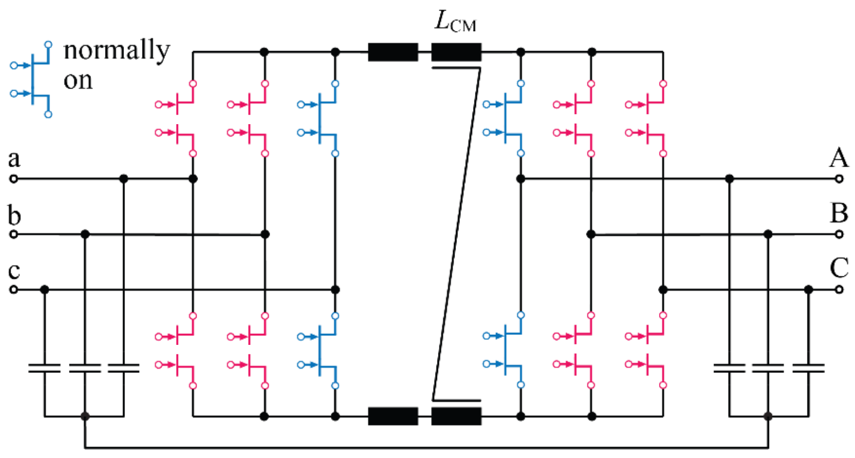
- Challenging Overvoltage Protection

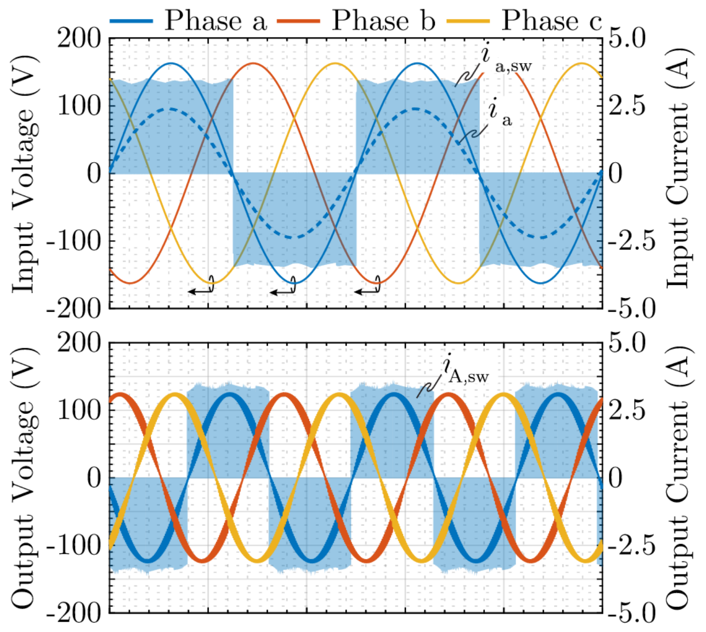
Current DC-Link AC/AC Converter

- Realization w/ GaN M-BDSs — 600V / 140mΩ
- CM/DM DC-Link Inductor Full-Sinusoidal Filtering
- Protection w/ Normally-On Switches

— Compressor Drive for More Electric Aircraft

ρ = 10kW/dm³
η = 98%
f_S = 72kHz



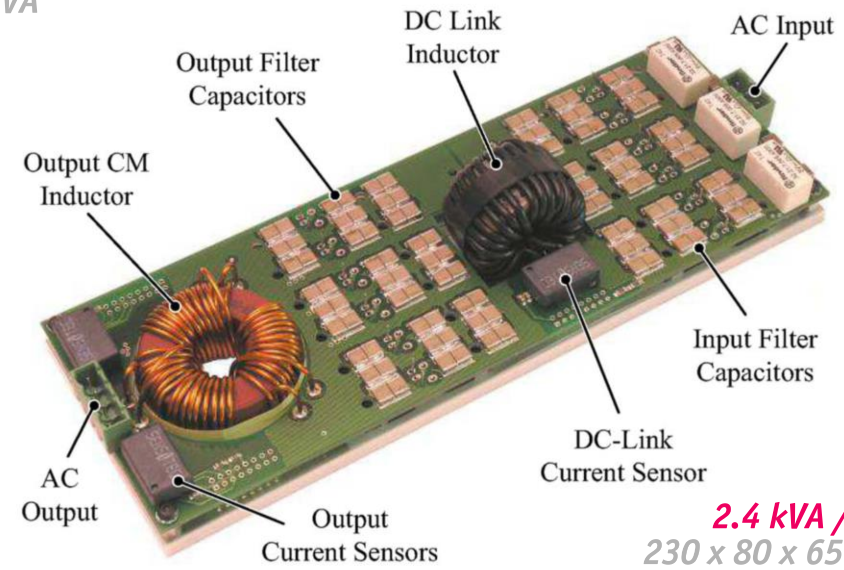


- Advanced Modulation Schemes → Significant Performance Improvement

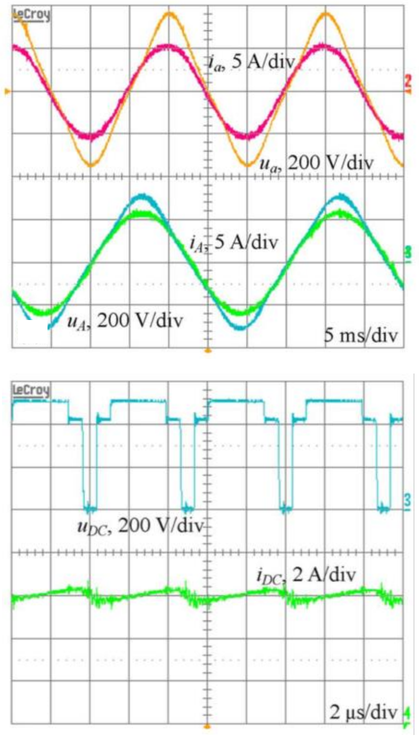
200kHz SiC Current DC-Link AC/AC Converter

- *SiC J-FETs — Normally-On TO-220 1200V/6A — Built in 2008 (!)*
- *1200V/10A SiC Schottky Series Diodes*
- *X7R Ceramic Filter Capacitors*

Input *$400V_{rms}$ Line-to-Line*
Output *0...300Hz*
Rated Power *2.5 kVA*



2.4 kVA / dm^3
230 x 80 x 65 mm^3



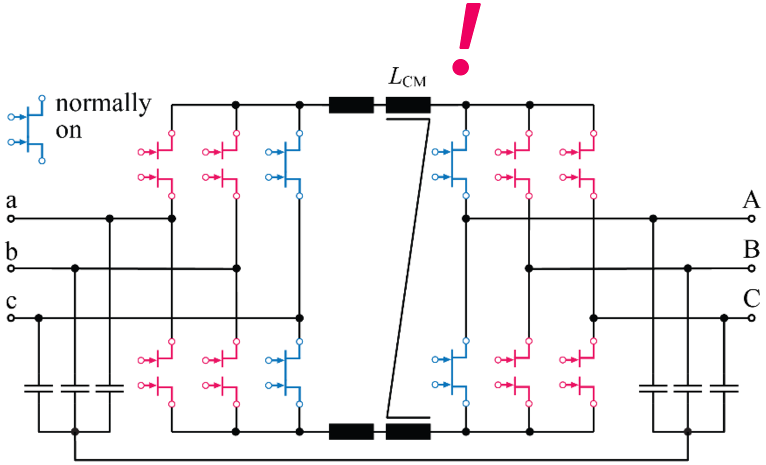
- *Low Volume DC-Link Inductor (320uH)*

Conclusion

3-Φ AC/AC Converter Topologies

■ *Current DC-Link Topology*

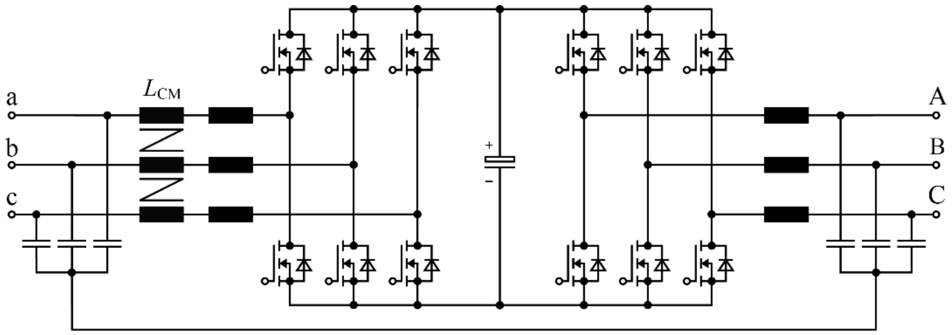
- *Application of M-BDSs*
- *Complex 4-Step Commutation*
- *Low Filter Volume*



- *Challenging Overvoltage Protection*
- *Limited Control Dynamics*

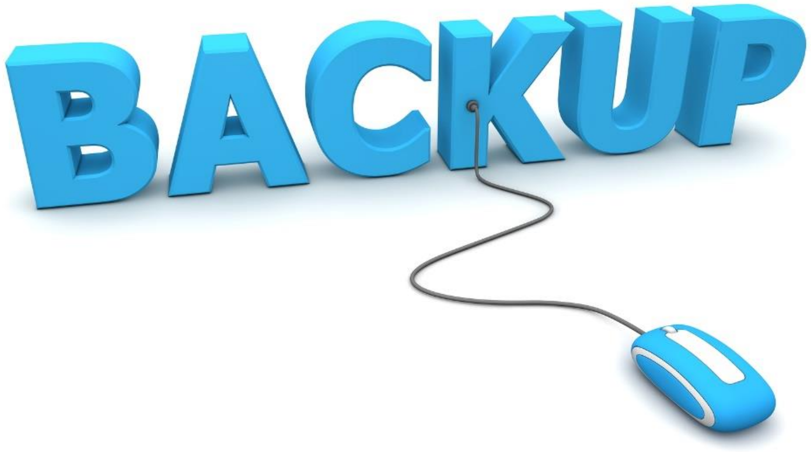
■ *Voltage DC-Link Topology*

- *Standard Bridge-Legs*
- *Low-Complexity Commutation*
- *Defined Semiconductor Voltage Stress*
- *Facilitates DC-Link Power Buffer*



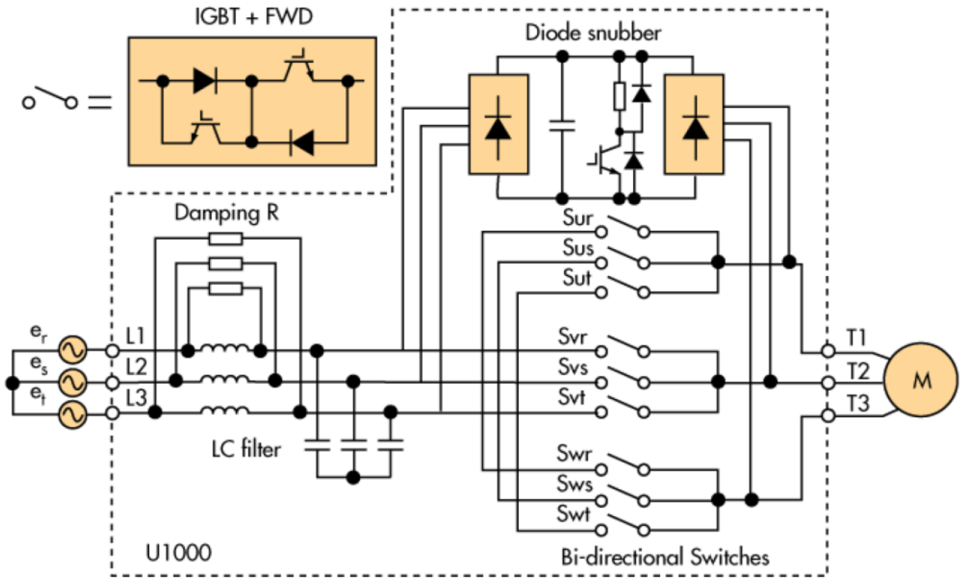
- *High Input / Output Filter Volume*

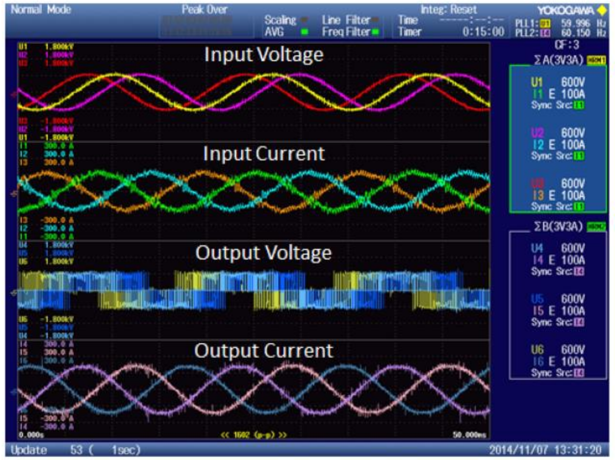
Thank you!


BACKUP

Industry Application of 3-Φ Matrix Converter

- *Direct Matrix Converter Topology*
- *Fully Regenerative → e.g. Downhill Conveyor etc.*
- *Higher Power Density Compared to Voltage DC Link System / No Front-End Boost Inductors*
- *Quasi Three-Level Output Characteristic*
- *No-Switching Eco Operation for f_2=f_{Mains}*
- *Close to Unity Power Factor*

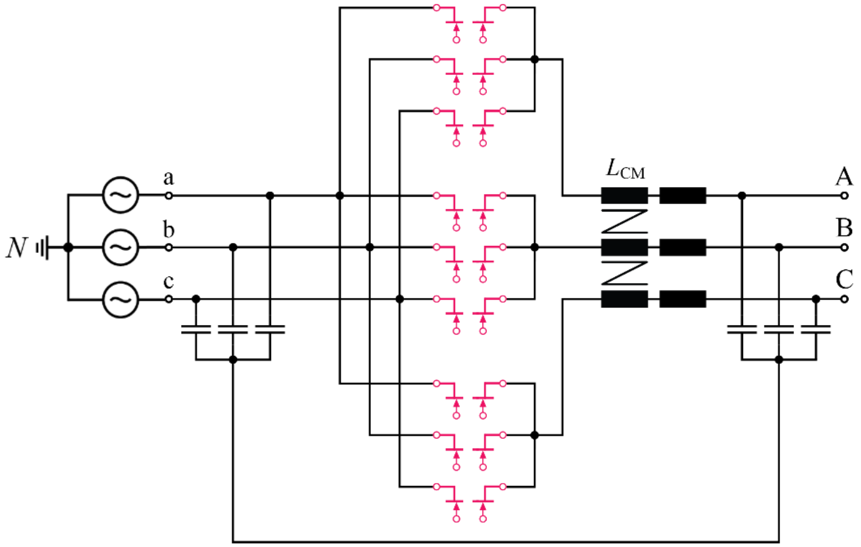




- *Challenging Overvoltage Protection*
- *Limited Output Voltage Range*

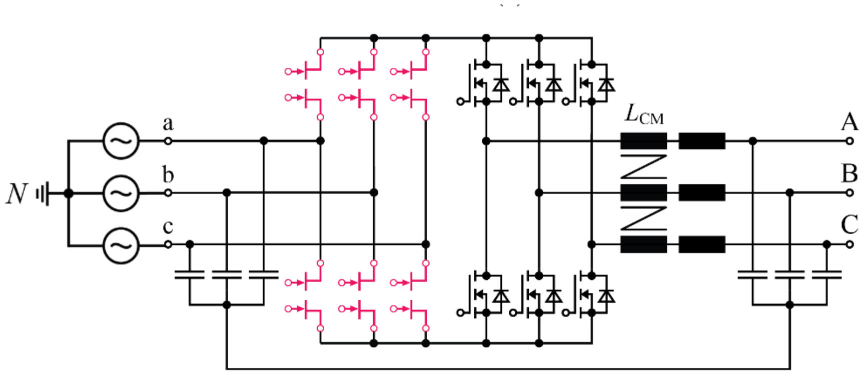
3-Φ AC/AC Matrix Converter

- *Direct Matrix Converter (CMC)*
  - 4-Step Commutation
  - Exclusive Use of GaN M-BDSs



— Thermally Critical @ $f_{out} \approx f_{in}$

- *Indirect Matrix Converter (IMC)*
  - CSI GaN M-BDS AC/DC Front-End
  - ZCS Commutation of CSI Stage @ i_{DC}=0
  - No 4-Step Commutation



— Higher # of Switches Compared to CMC
— Lower Cond. Losses @ Low Output Voltage
— Thermally Critical @ $f_{out} \rightarrow 0$