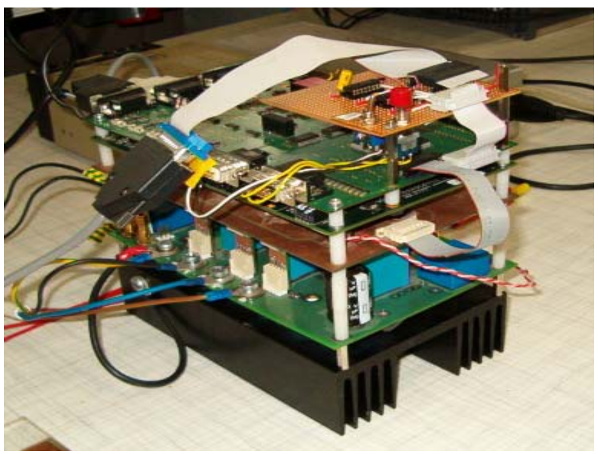
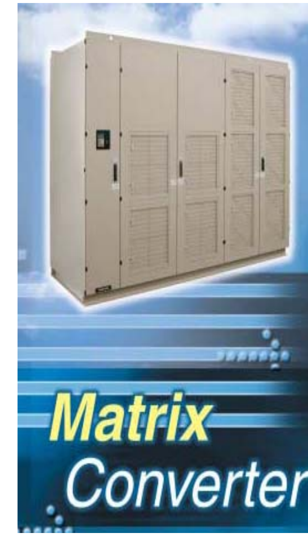
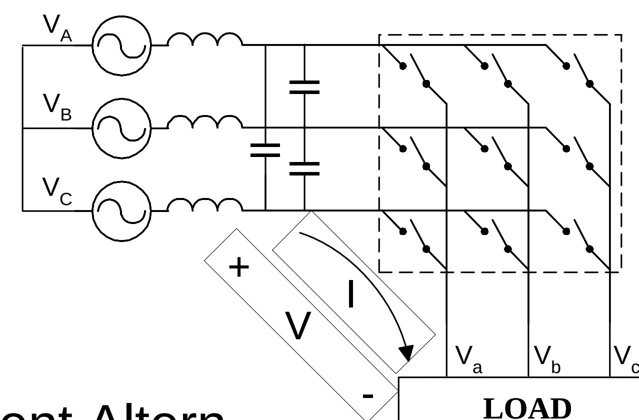
Notes on

Matrix Converters



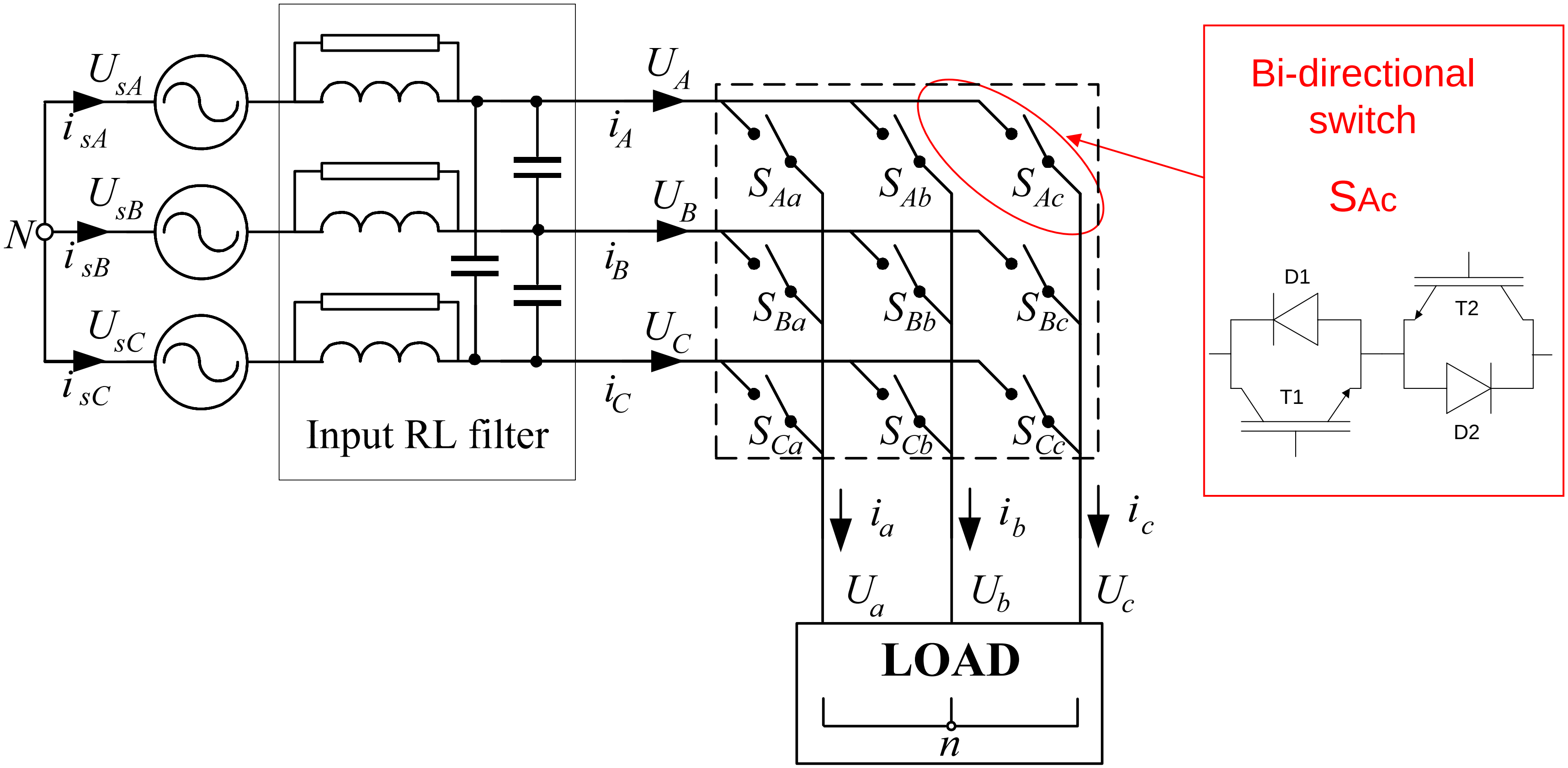




CECA – Convertidors Estàtics de Corrent Altern

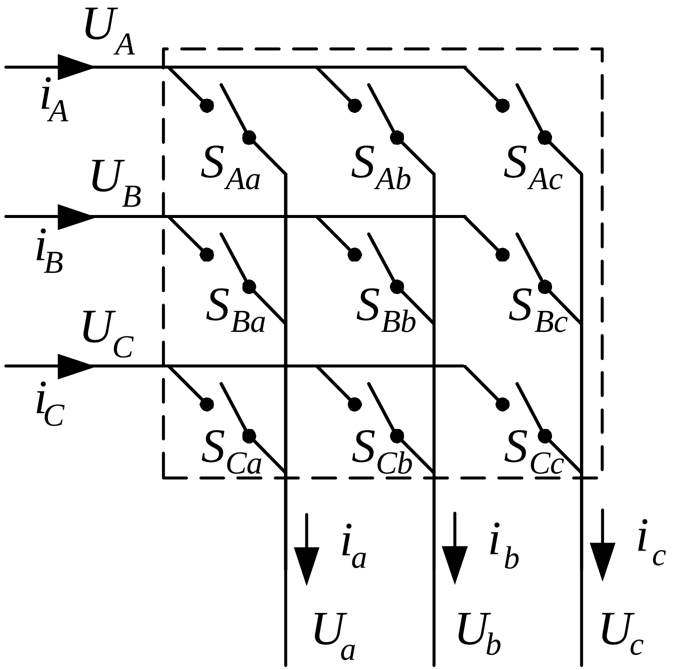
Dr. Antoni Arias

Matrix Concept



- AC / AC direct electrical power conversion
- *M X N* , inputs & outputs. Figure corresponds to the *3 X 3*
- Variable frequency and variable voltage

Fundamentals



- Switching function: $S_{io}(t) = \begin{cases} 1, & open \\ 0, & closed \end{cases}$

$$i = \{A, \quad B, \quad C\}$$
$$o = \{a, \quad b, \quad c\}$$

- Transfer Matrix:

$$[T] = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix}$$

- There are 2^9 (512) possible combinations
- Each output phase can be connected to any input phase
- There are several constraints:
  - Avoid line to line input short circuit
  - Avoid open circuits with inductive currents

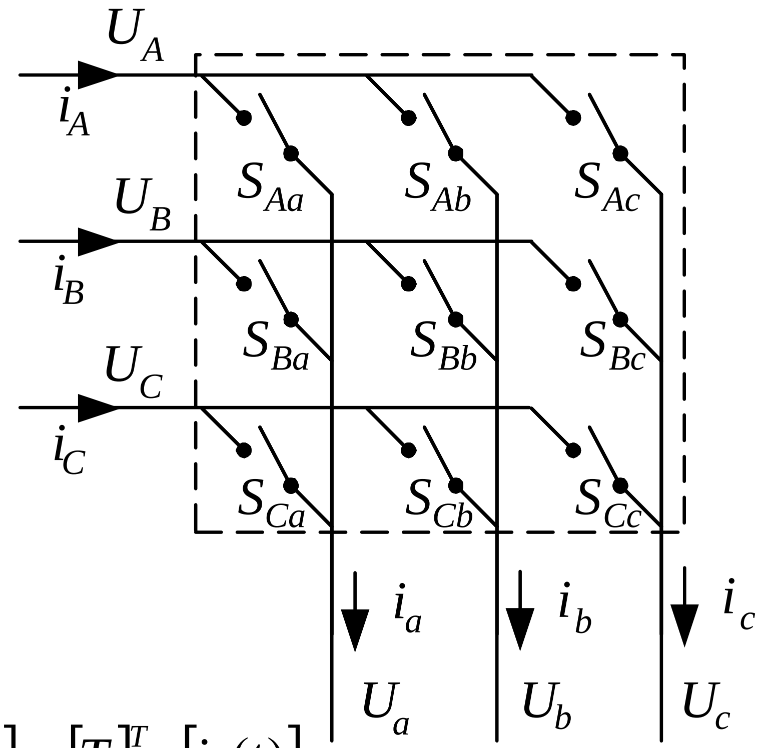
$$S_{Ao}(t) + S_{Bo}(t) + S_{Co}(t) = 1$$

Model

$$[U_{oN}(t)] = \begin{bmatrix} U_{aN}(t) \\ U_{bN}(t) \\ U_{cN}(t) \end{bmatrix} \qquad [U_{iN}(t)] = \begin{bmatrix} U_{AN}(t) \\ U_{BN}(t) \\ U_{CN}(t) \end{bmatrix}$$

$$[i_o(t)] = \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \qquad [i_i(t)] = \begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix}$$

$$i = \{A, \quad B, \quad C\} \qquad o = \{a, \quad b, \quad c\}$$



$$[U_{oN}(t)] = [T] \cdot [U_{iN}(t)] \qquad [i_i(t)] = [T]^T \cdot [i_o(t)]$$

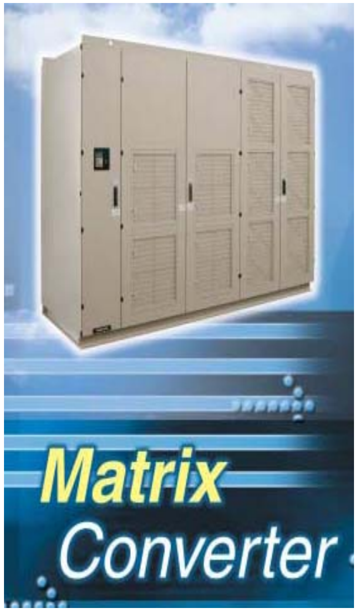
$$\begin{bmatrix} U_{aN}(t) \\ U_{bN}(t) \\ U_{cN}(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix} \cdot \begin{bmatrix} U_{AN}(t) \\ U_{BN}(t) \\ U_{CN}(t) \end{bmatrix}$$

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ab}(t) & S_{Ac}(t) \\ S_{Ba}(t) & S_{Bb}(t) & S_{Bc}(t) \\ S_{Ca}(t) & S_{Cb}(t) & S_{Cc}(t) \end{bmatrix} \cdot \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix}$$

Features

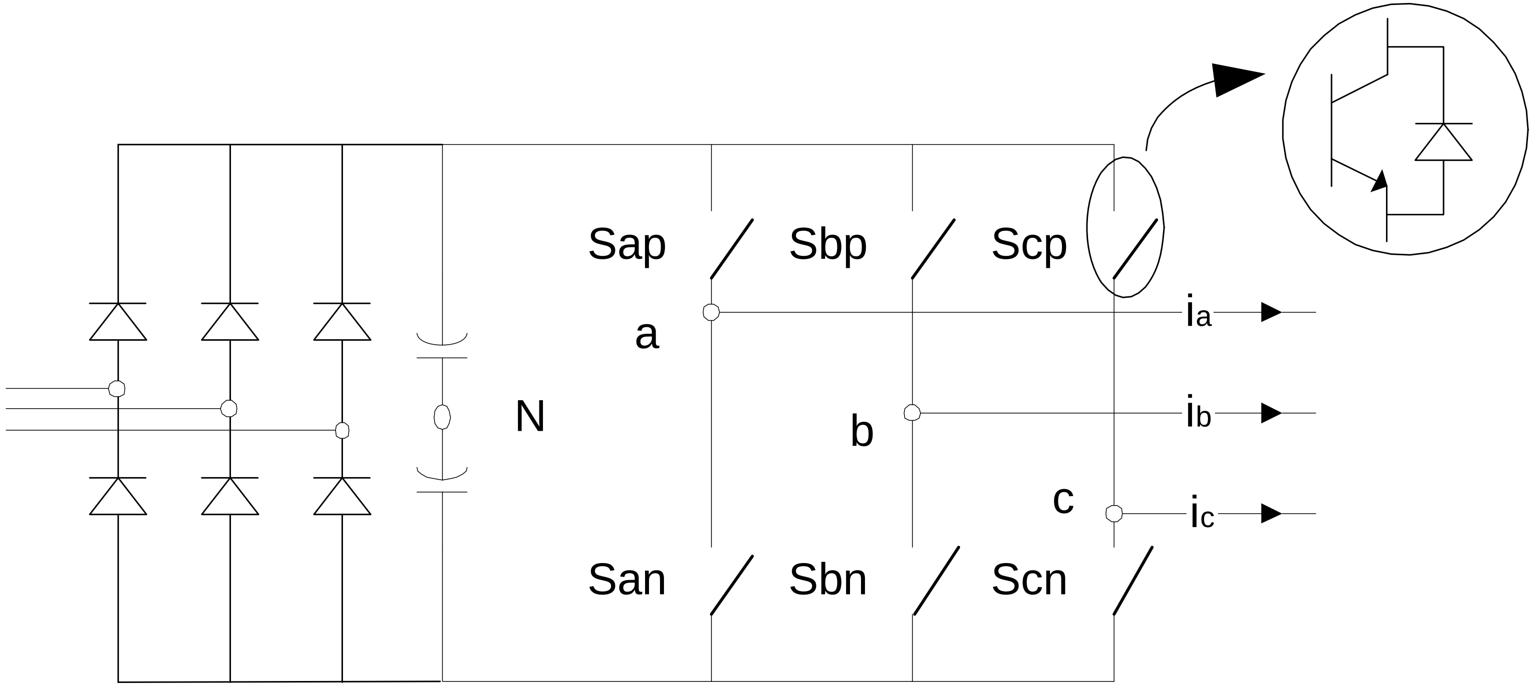
- Direct AC / AC Conversion. No DC Link: all silicon solution
  - Less bulky (compact motor drives)
  - Safer (hostile environments: aircraft, submarine…)
- Bidirectional power flow
- 4 quadrant converter
- Sinusoidal input and output currents waveforms
- No restriction on input and output frequency within limits imposed by switching frequency
- Output voltage limited to 86.6% (*cos30º*) of input voltage
- 9 bidirectional switches. (18 IGBT + 18 Diodes)

Applications



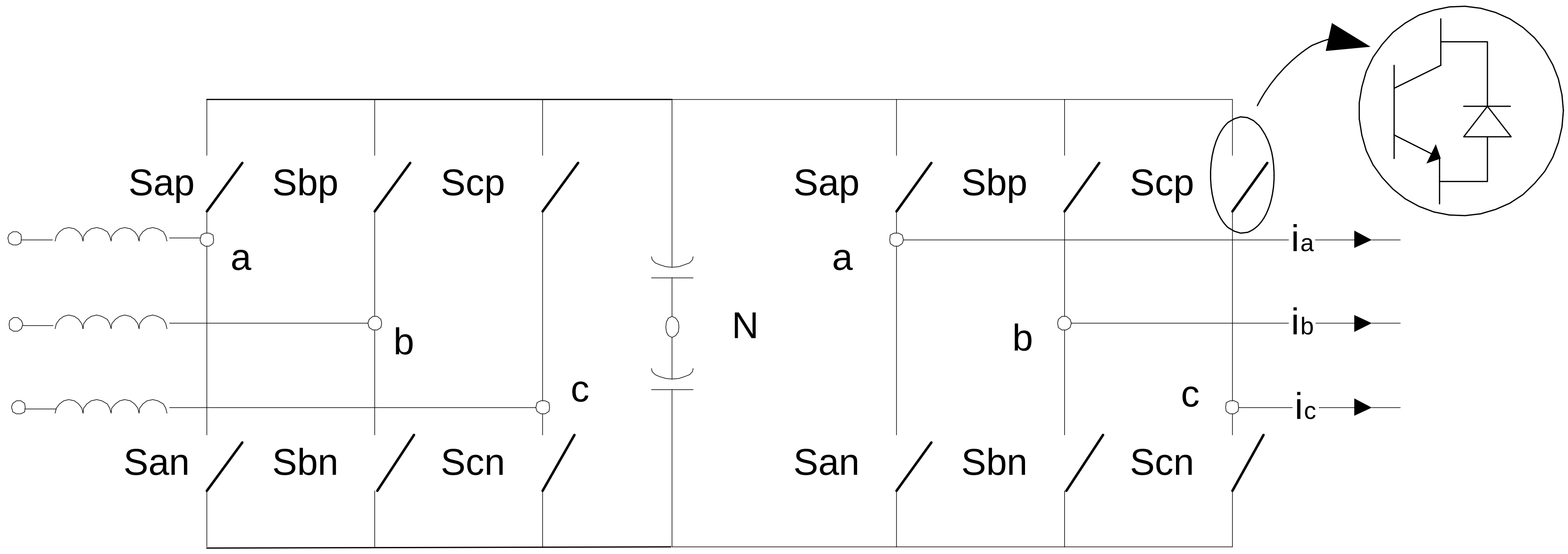
- Industrial Products:
  - Yaskawa FSDrive-MX1S.
    - Launched in 2004
    - World's first matrix converter Drive
    - Super energy –saving medium-voltage Matrix Converter with Power regeneration
    - 3kV 200 to 3000kVA
    - 6kV 400 to 6000kVA
    - Applications:
      - Wind/Water Force Machines (blowers, boilers, incinerators), pumps, and general Industrial Machines.
- Applications:
  - Compact or Integrated Motor Drives
  - Motor Drives for hostile environments (aircrafts, submarines)
  - AC/AC Power Conversions: wind energy, variable speed drives...

Alternatives



- Industry "workhorse" from less than kW to MW
- Unidirectional power flow
- 2 quadrant
  - When the current changes its sign, the power must be burn in the DC link
- DC link capacitor (30% -50% of the power circuit volume)
- Input currents very poor. (awful THD)

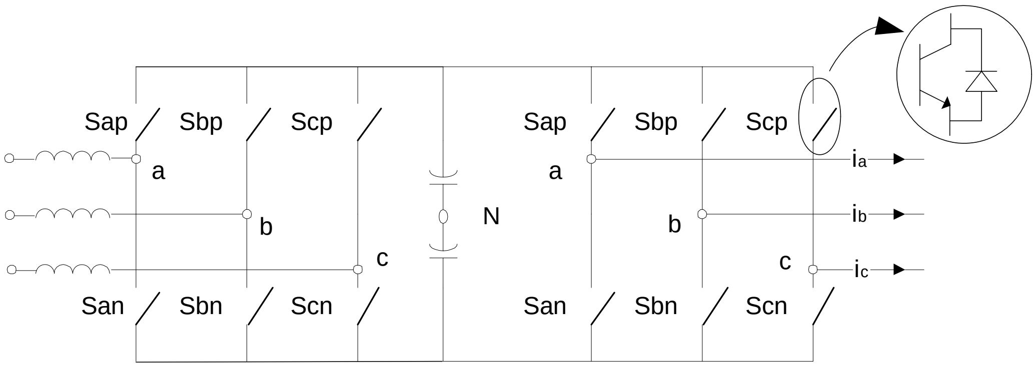
Alternatives

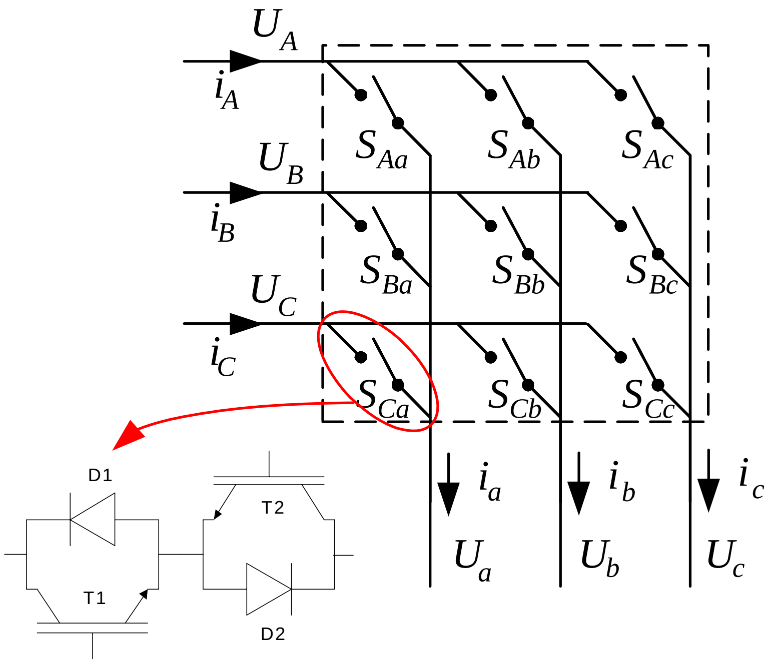


- Bi directional power flow
- 4 quadrant
- DC link capacitor and input inductors
- Sinusoidal input currents. Input Power Factor 1
- *Matrix Converter real alternative*

UPC

MC versus back to back





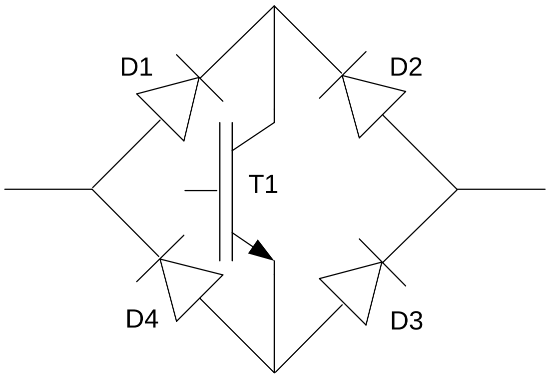
- 12 IGBTs + 12 Diodes
- 1 large electrolytic capacitor (DC link)
- Input filter (1st order)
  - 3 large inductors

- 18 IGBTs + 18 Diodes
- Input filter (2nd order)
  - 3 inductors
  - 3 capacitors
- *Clamp circuit*

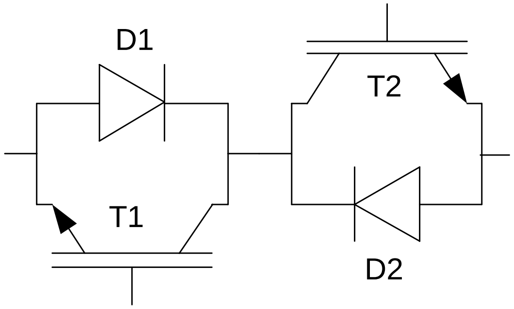
Bi Directional Switch

- Must be able to conduct positive and negative current and block positive and negative voltage

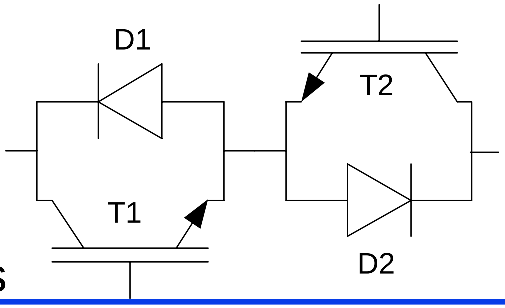
- Diode embedded switch
  - Switch: 1 IGBT + 4 diodes
  - Conducting losses: 2 diodes +1 IGBT



- Back to back switch with common collector
  - Switch: 2 IGBT + 2 diodes
  - Diode required for reverse blocking capability
  - Conducting losses: 1 diode +1 IGBT

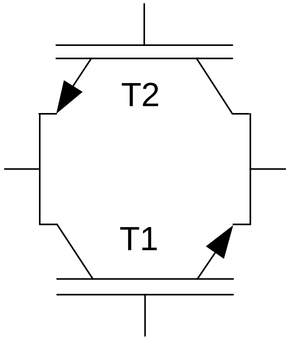


- Back to back switch with common emitter
  - Switch: 2 IGBT + 2 diodes
  - Diode required for reverse blocking capability
  - Conducting losses: 1 diode +1 IGBT
  - No need of isolation between both gate power supplies



Bi Directional Switch

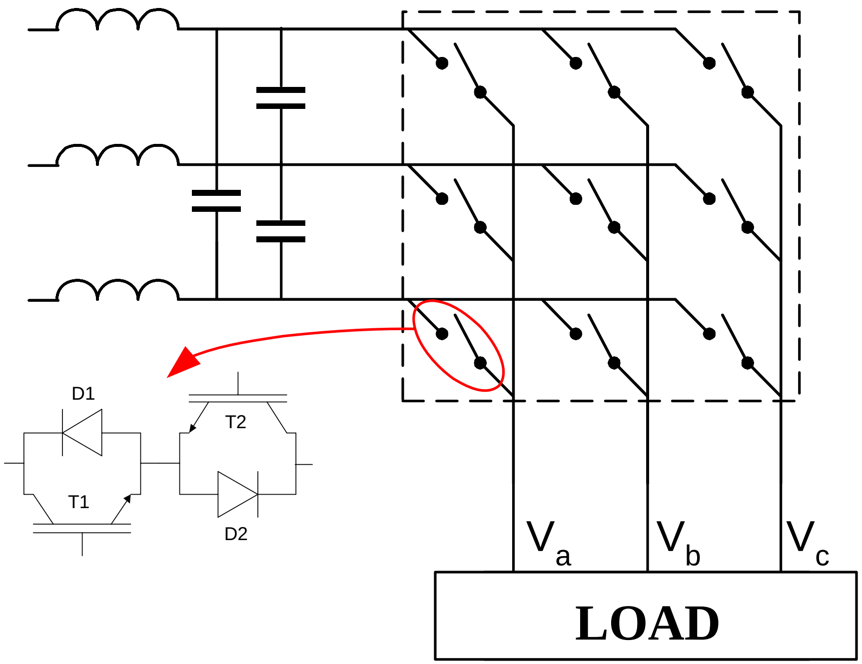
- Reverse Blocking IGBT, RBIGBT
  - Two reverse blocking IGBTs
  - Lower conducting losses: one switching device
  - *Still under research*
  - *Switch control will remain the same*



SUMMARY	*IGBTs*	Diodes	Isolated Power Supplies	Conducting Devices
Diode bridge	*9*	36	9	3
Common Emitter	*18*	18	9	2
Common Collector	*18*	18	6	2

Bi Directional Switch Device Packaging

- Dynex 200 (A) Bi directional Module
  - From standard one leg conventional VSI
  - 9 for a 3x3MC
  - Large Converters > 200 (A)
  - Common collector



Bi Directional Switch Device Packaging

….announced the release of two bi-directional IGBT modules for use in matrix converter power stages…

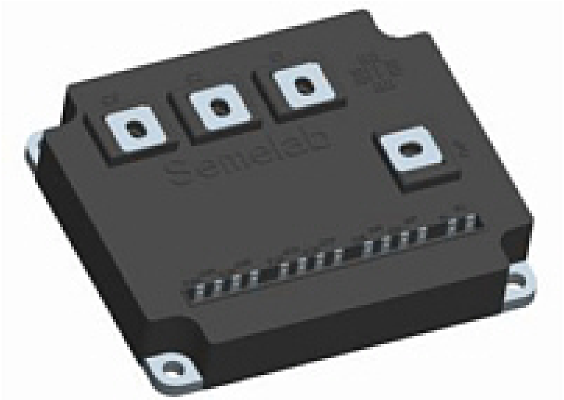
…Dynex Semiconductor is working closely with researchers at Nottingham University. Through this collaboration and in response to commercial requirements, Dynex has created the DIM400PBM17-A000 for use in a 60Hz to 400Hz fixed frequency converter and the GP200MBS12 for use in a high efficiency brushless dc motor drive.
The DIM400PBM17-A000 module is a 400A 1700V bi-directional switch mounted on a 140mm x 73mm metal matrix baseplate. Long-term reliability and enhanced thermal performance are achieved through the use of aluminium nitride substrates mounted on a metal matrix compound baseplate. The package has a 6 kV isolation rating…

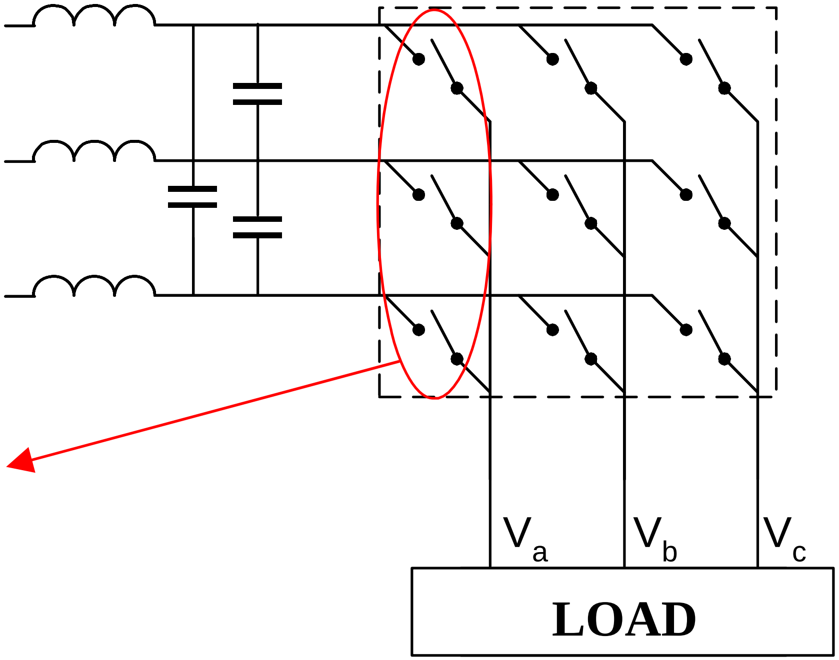
…The DIM200MBS12-A000 module is a 200A 1200V bi-directional switch mounted on a 106mm x 62mm copper baseplate. The package has a 4 kV isolation rating…

http://www.dynexsemi.com/corporate/news/items/20020514-prod-b.htm

Bi Directional Switch Device Packaging

- SEMELAB 200 (A) Bi directional Module
  - 3 for a 3x3MC
  - Large Converters



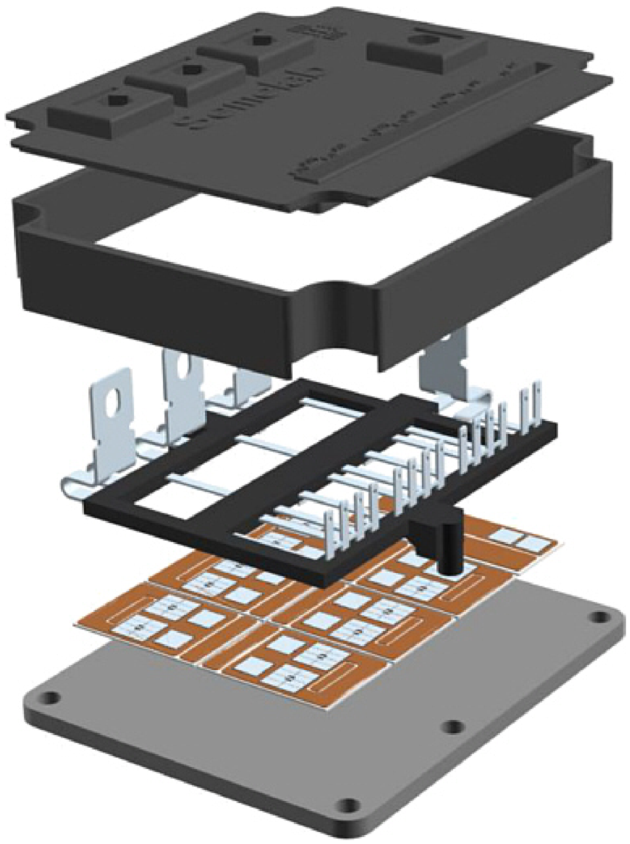


Bi Directional Switch Device Packaging

A Matrix Converter IGBT Bi-Directional switching module

A 360kVA (600V max line-line at up to 300A) matrix converter module designed by Semelab.

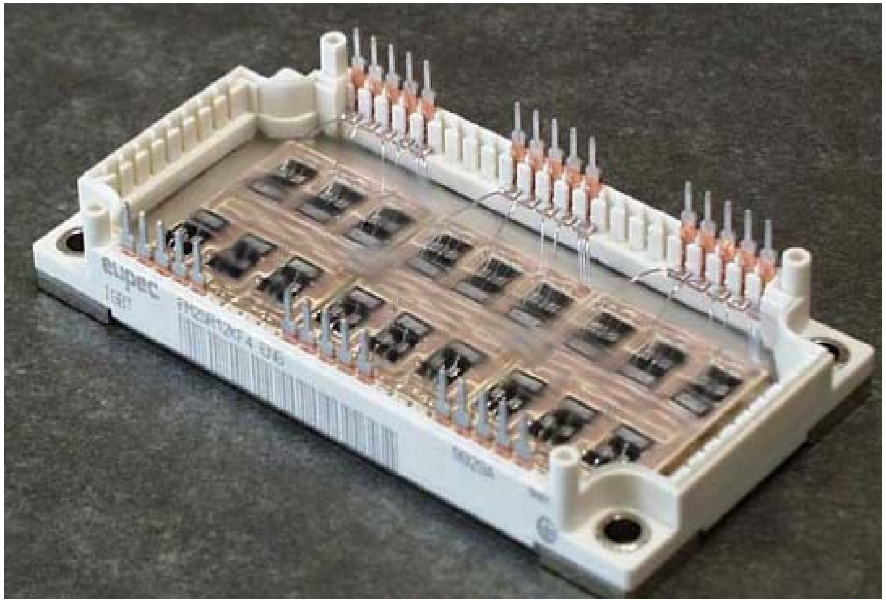
- IGBT Packaging Available in 300V to 1800V
- Aerospace
- Customised to fit your needs.
- Good CTE match, from Silicon to the metal matrix base plate.
- Excellent reliability module, temp cycling, humidity tested, elevated pressure.
- Low power losses.
- Plastic package / Hermitic packaging
- Power connection,
- Mounting holes
- Void free die attach, X-ray capability.

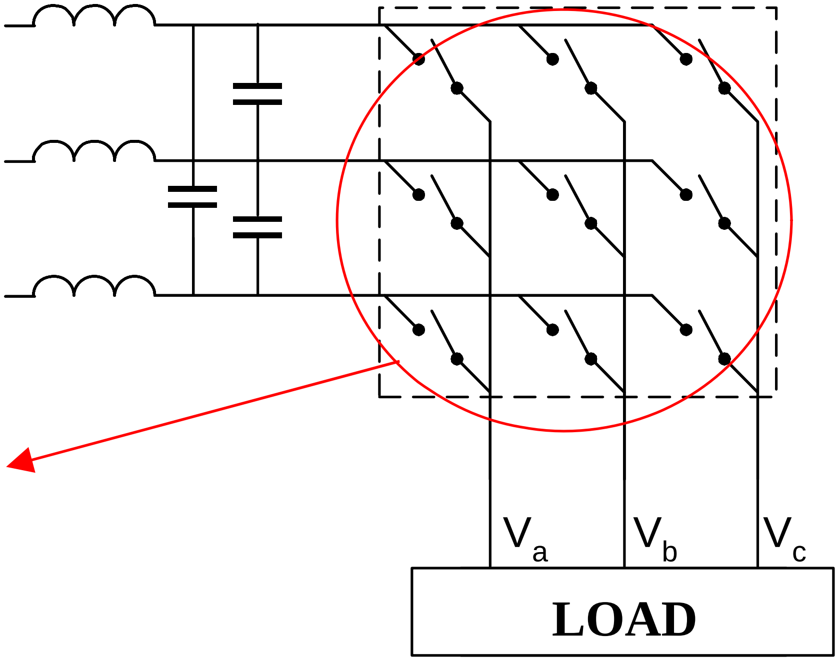


http://www.semelab.co.uk/power/

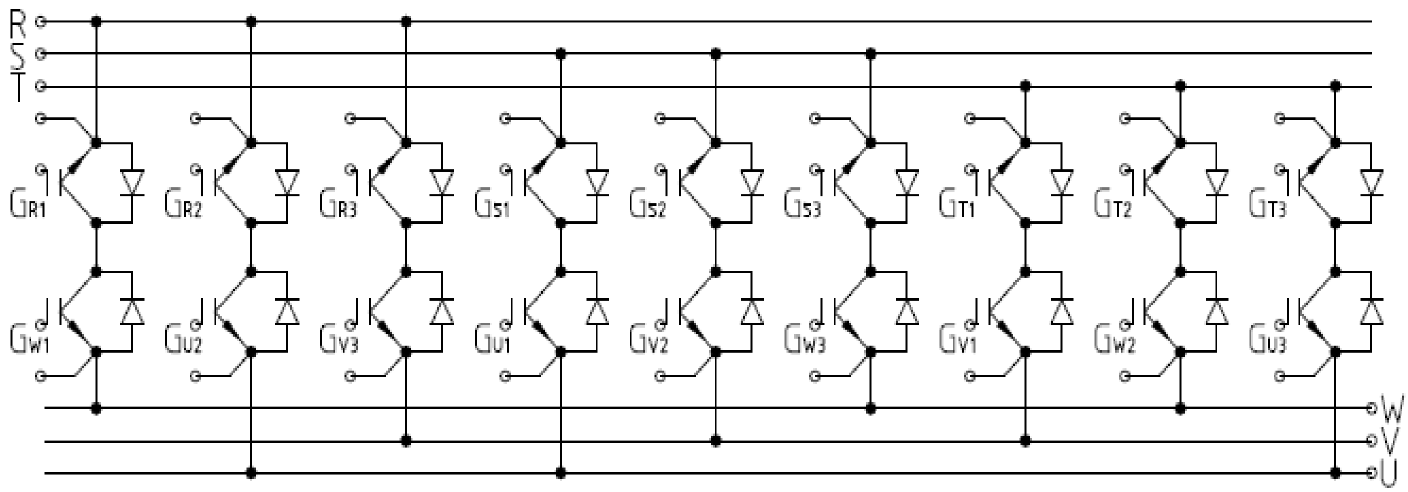
Bi Directional Switch Device Packaging

- EUPEC 35A Matrix Converter Module
  - 1 for a 3x3MC
  - Small Powers Converters. 7.5 kW



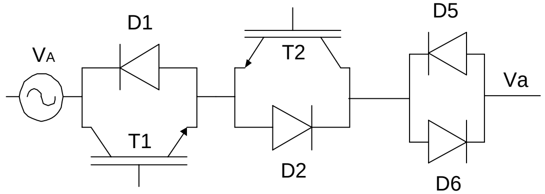


Bi Directional Switch Device Packaging

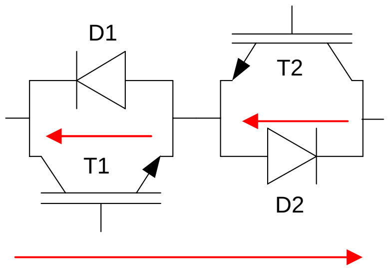


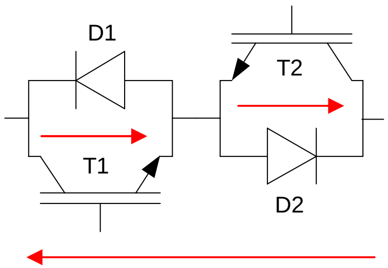
Commutation

- Current commutation
  - Needs the sign of the output current per phase
    - Add two anti parallel diodes and measure its voltage drops



    - Measure the device voltage drops





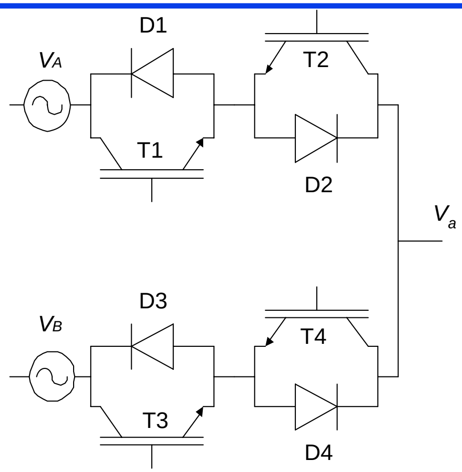
  - Most widely used

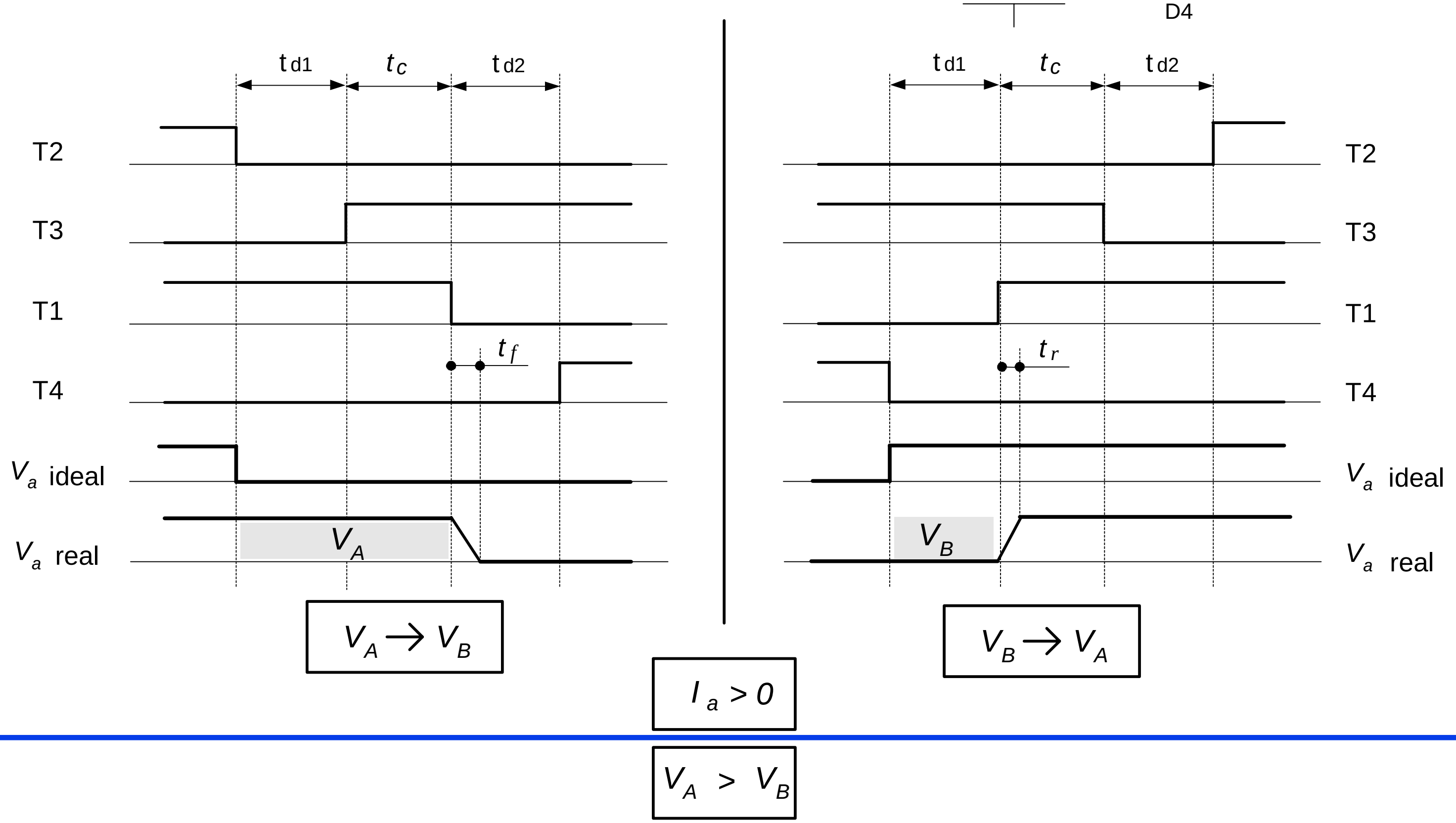
- Voltage commutation
  - Needs the input voltage values per phase

4 Step Current Commutation

UPC

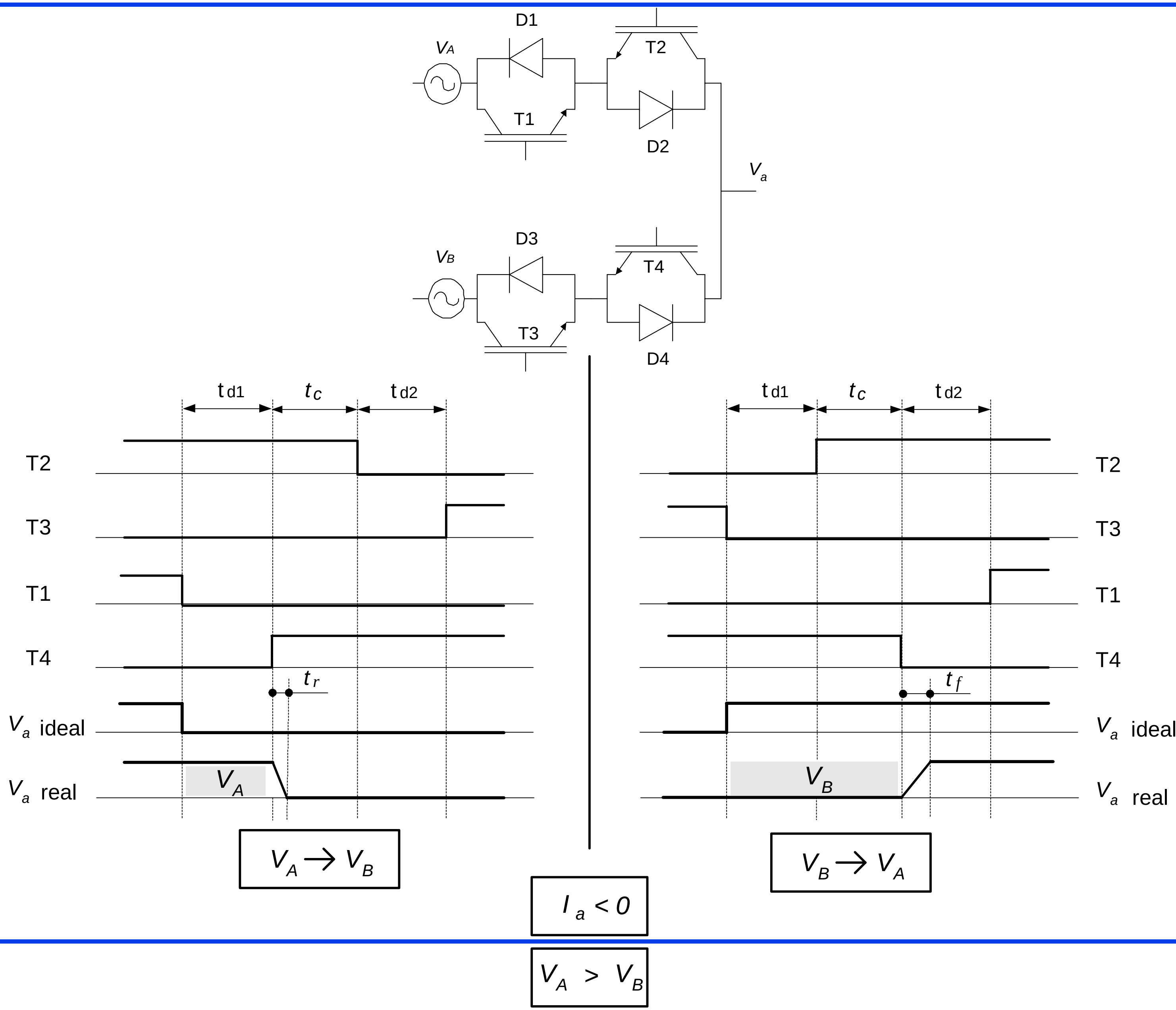
- No short circuits at the input
- No open circuit at the output (inductive loads)





4 Step Current Commutation

UPC



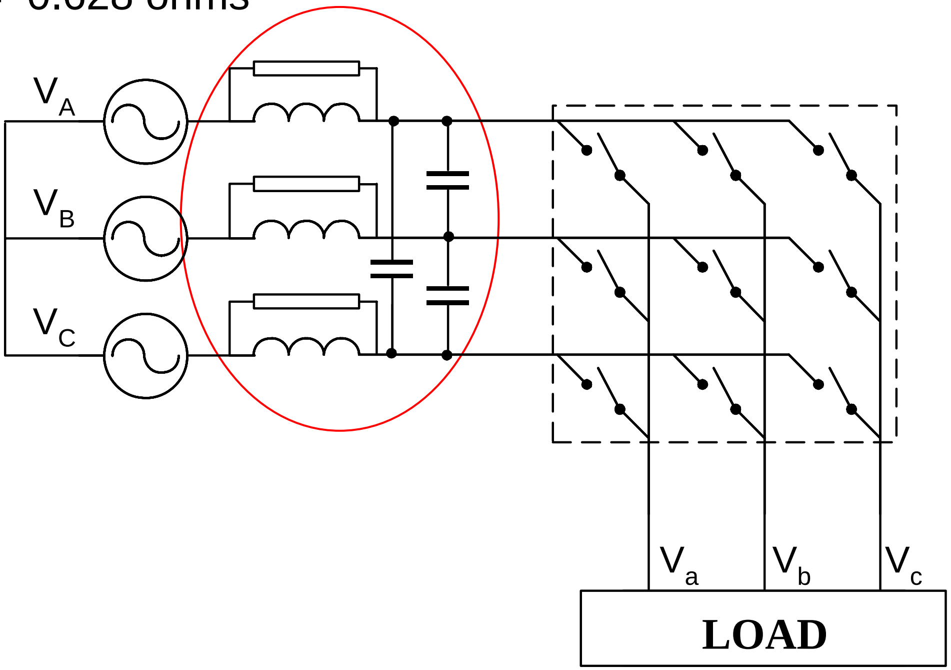
4 Step Current Commutation

Matrix Converter	
EUPEC FM35R12KE3ENG module	
Switching device	1200V, 35 A, IGBT
t_{d1} / t_c / t_{d2}	1 / 0.2 / 0.5 μs
t_f / t_r	65-90 ns / 30-45 ns
Power	7.5 kW
AC Input voltage	*3 x 415V*
Input filter (L/C) values	*1mH / 1.5μF*

Input Filter

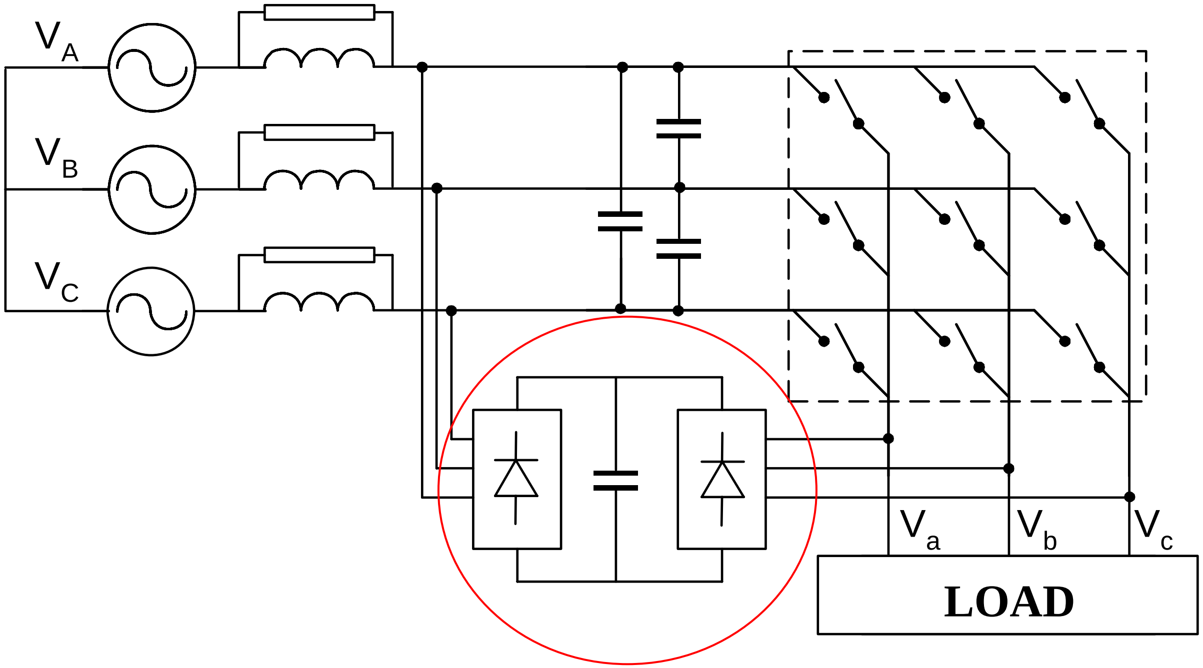
- 2nd Order Input L-C filter
  - Typical cut off frequency 1-3 kHz
    - between the fundamental 0-100Hz
    - and the PWM frequency 10-20 kHz
  - R in parallel with L in order to have an adequate damping
  - L impedance at 100Hz should be negligible
    - 2*pi*f*L = 2*3.14*100*10^-3 = 0.628 ohms

Matrix Converter	
EUPEC FM35R12KE3ENG module	
Switching device	1200V, 35 A, IGBT
Power	7.5 kW
AC Input voltage	*3 x 415V*
Input filter (L/C) values	*1mH / 1.5μF*



Clamp circuit

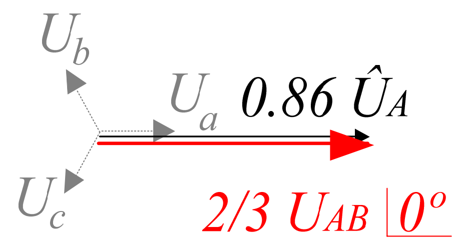
- Diode bridge like a standard rectifier
- Protection against
  - open circuits with inductive currents
  - over voltage caused by transients in power up and voltage sags



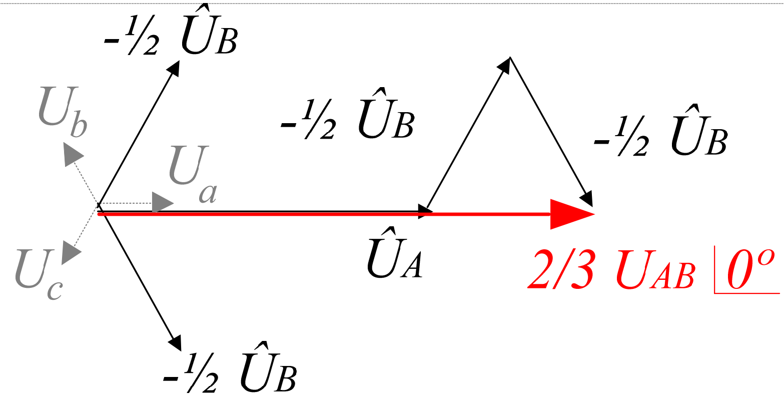
MC Output Voltage vectors

- Space Vector Concept: $\overrightarrow{U_o}(t) = \frac{2}{3}\left(U_a(t) + U_b(t)\cdot e^{j2\pi/3} + U_c(t)\cdot e^{j4\pi/3}\right)$

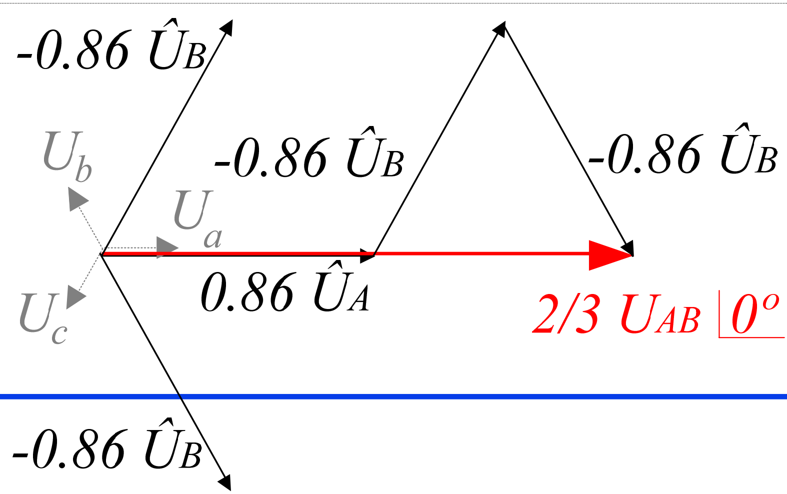
$U_a = \hat{U}_A \cos(30^o)$
$U_b = \hat{U}_B \cos(-90^o)$
$U_c = \hat{U}_B \cos(-90^o)$



$U_a = \hat{U}_A \cos(0^o)$
$U_b = \hat{U}_B \cos(-120^o)$
$U_c = \hat{U}_B \sin(-120^o)$

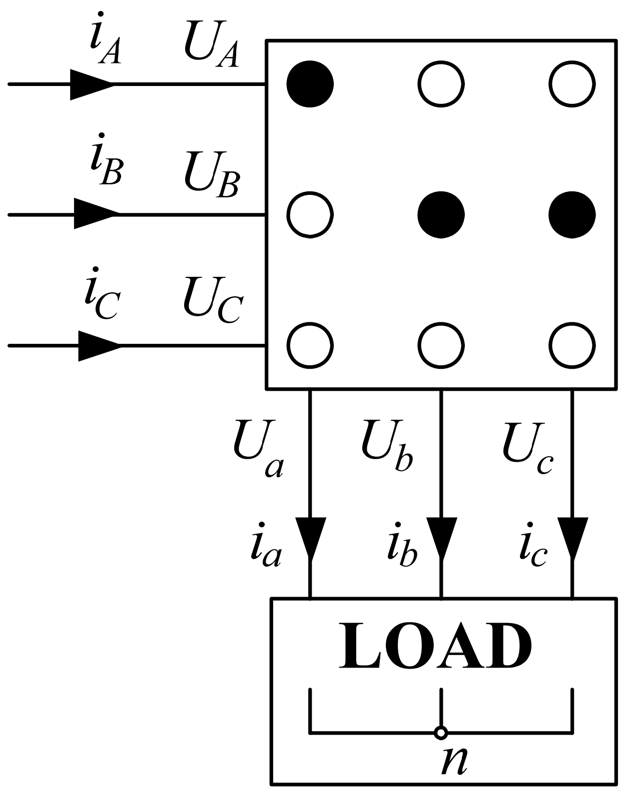


$U_a = \hat{U}_A \cos(-30^o)$
$U_b = \hat{U}_B \cos(-150^o)$
$U_c = \hat{U}_B \cos(-150^o)$

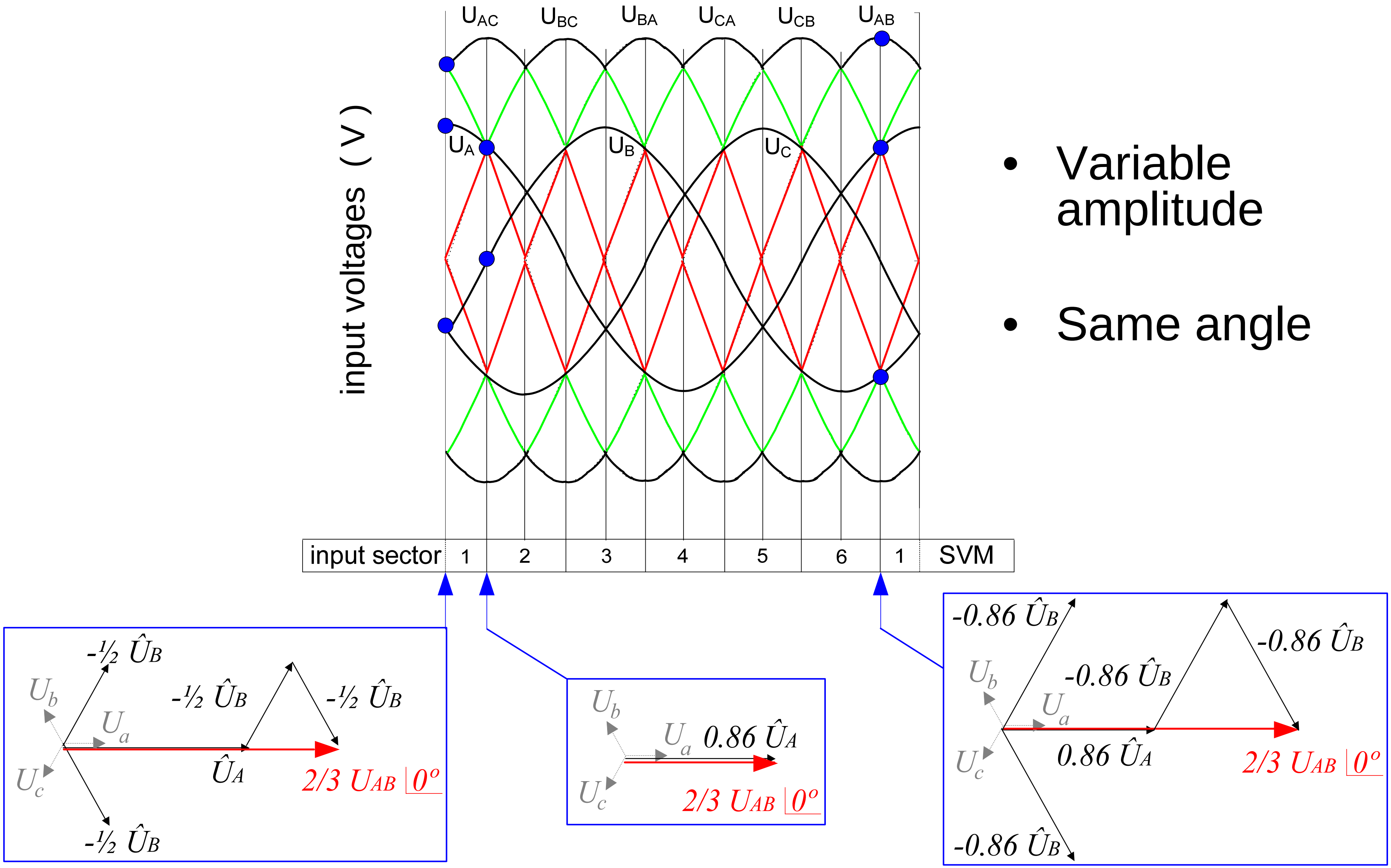


State +1

$U_a = U_A \quad U_b = U_B \quad U_c = U_B$



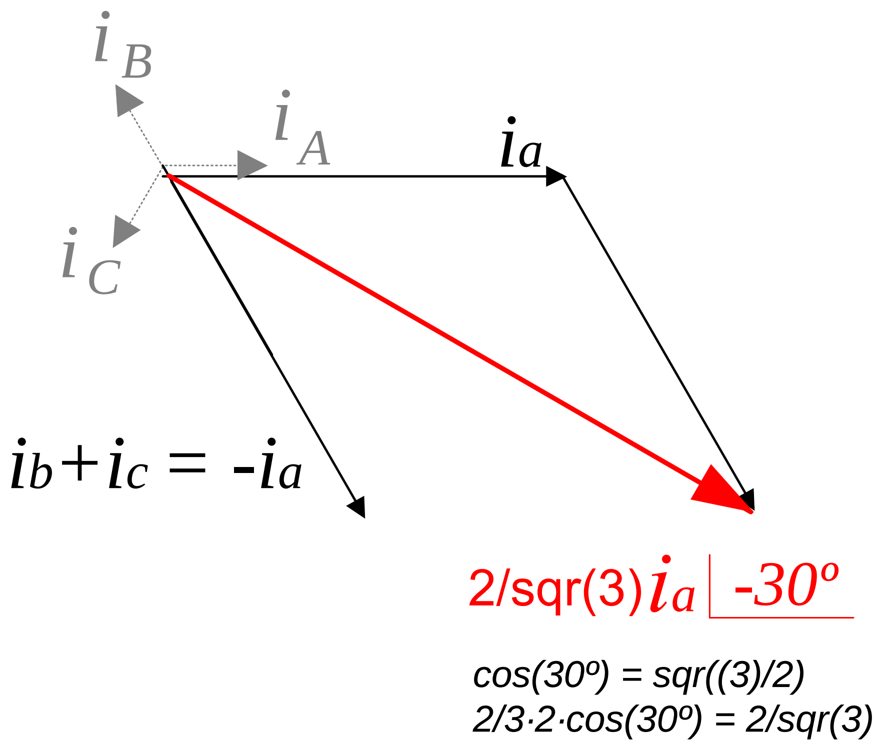
MC Output Voltage vectors

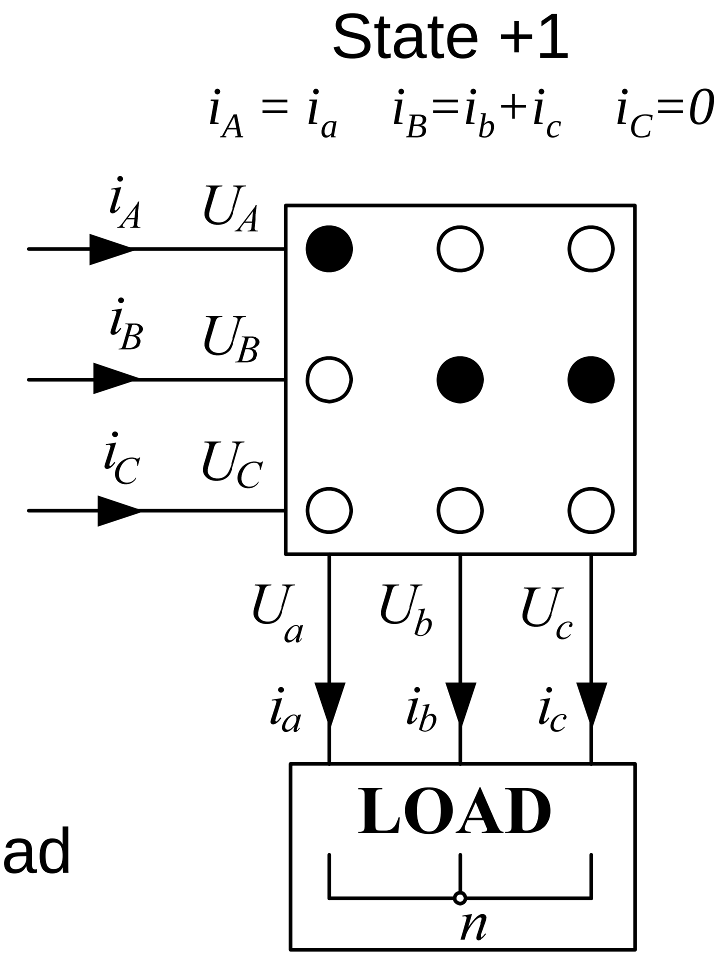


- Variable amplitude
- Same angle

MC Input Current vectors

- Space Vector Concept: $\vec{i}_i(t) = \frac{2}{3}\left(i_A(t) + i_B(t)\cdot e^{j2\pi/3} + i_C(t)\cdot e^{j4\pi/3}\right)$





- Amplitude dependant on the load
- Same angle

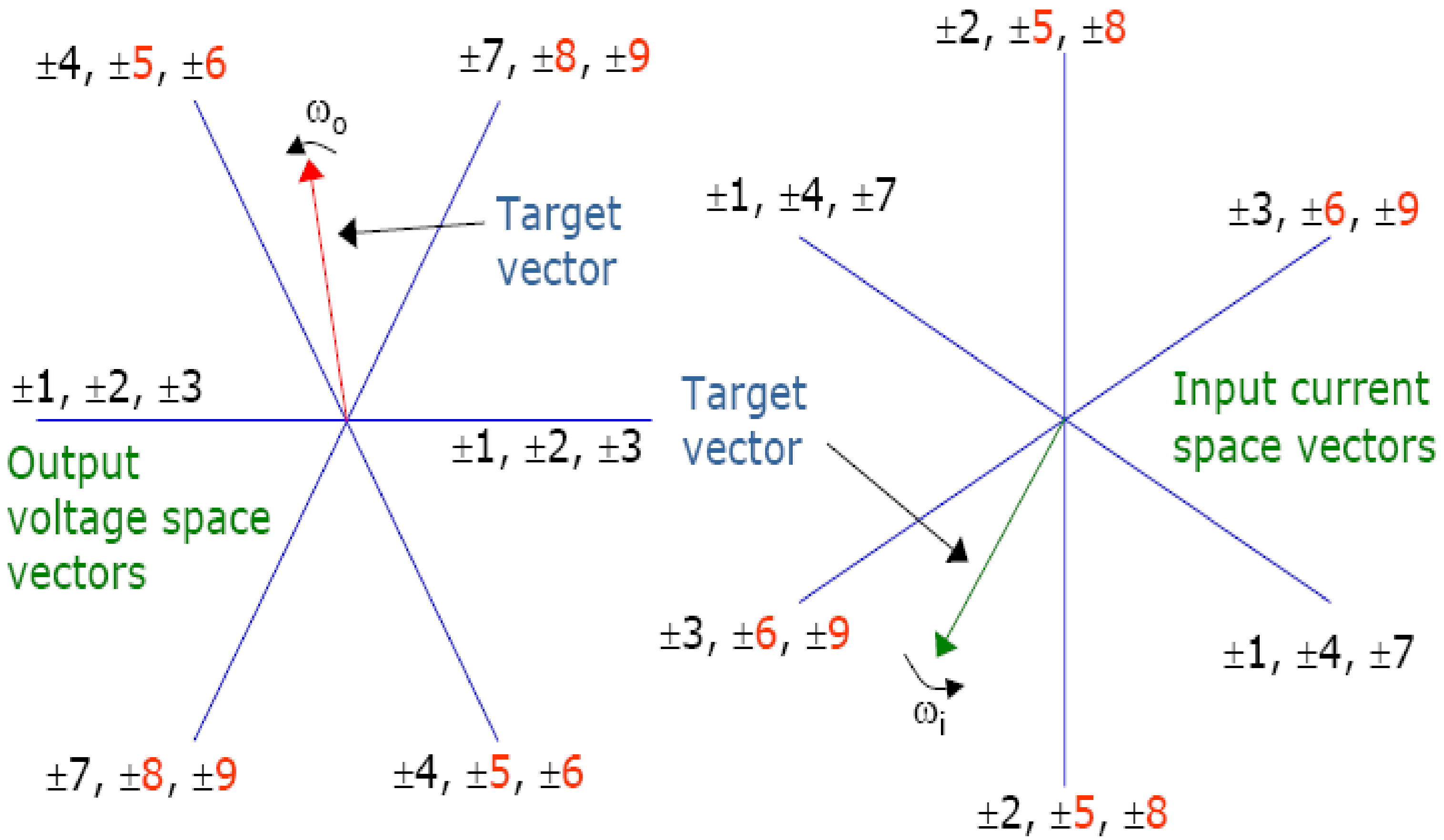
MC Output Voltage & Input Current vectors

	a b c	$\lvert\vec{Vo}\rvert$	α_o	$\lvert\vec{i_i}\rvert$	β_i
+1	A B B	$2/3U_{AB}$	0	2/sqr(3) i_a	11π/6
+2	B C C	$2/3U_{BC}$	0	2/sqr(3) i_a	π/2
+3	C A A	$2/3U_{CA}$	0	2/sqr(3) i_a	7π/6
+4	B A B	$2/3U_{AB}$	2π/3	2/sqr(3) i_b	11π/6
+5	C B C	$2/3U_{BC}$	2π/3	2/sqr(3) i_b	π/2
+6	A C A	$2/3U_{CA}$	2π/3	2/sqr(3) i_b	7π/6
+7	B B A	$2/3U_{AB}$	4π/3	2/sqr(3) i_c	11π/6
+8	C C B	$2/3U_{BC}$	4π/3	2/sqr(3) i_c	π/2
+9	A A C	$2/3U_{CA}$	4π/3	2/sqr(3) i_c	7π/6
+R1	A B C	Ûi	[Ûi]	$i_{o\ MAX}$	[$i_{o\ MAX}$]
+R2	C A B	Ûi	[Ûi+2π/3]	$i_{o\ MAX}$	[$i_{o\ MAX}$+2π/3]
+R3	B C A	Ûi	[Ûi+4π/3]	$i_{o\ MAX}$	[$i_{o\ MAX}$+4π/3]
0_A	A A A	0	….	0	….
0_B	B B B	0	….	0	….
0_C	C C C	0	….	0	….

	a b c	$\lvert\vec{Vo}\rvert$	α_o	$\lvert\vec{i_i}\rvert$	β_i
-1	B A A	$-2/3U_{AB}$	0	-2/sqr(3) i_a	11π/6
-2	C B B	$-2/3U_{BC}$	0	-2/sqr(3) i_a	π/2
-3	A C C	$-2/3U_{CA}$	0	-2/sqr(3) i_a	7π/6
-4	A B A	$-2/3U_{AB}$	2π/3	-2/sqr(3) i_b	11π/6
-5	B C B	$-2/3U_{BC}$	2π/3	-2/sqr(3) i_b	π/2
-6	C A C	$-2/3U_{CA}$	2π/3	-2/sqr(3) i_b	7π/6
-7	A A B	$-2/3U_{AB}$	4π/3	-2/sqr(3) i_c	11π/6
-8	B B C	$-2/3U_{BC}$	4π/3	-2/sqr(3) i_c	π/2
-9	C C A	$-2/3U_{CA}$	4π/3	-2/sqr(3) i_c	7π/6
-R1	A C B	Ûi	[-Ûi]	$i_{o\ MAX}$	[-$i_{o\ MAX}$]
-R2	B A C	Ûi	[-Ûi+2π/3]	$i_{o\ MAX}$	[-$i_{o\ MAX}$+2π/3]
-R3	C B A	Ûi	[-Ûi+4π/3]	$i_{o\ MAX}$	[-$i_{o\ MAX}$+4π/3]

27 vectors: 18 constant in direction + 3 nulls + 6 rotating

MC Output Voltage & Input Current vectors

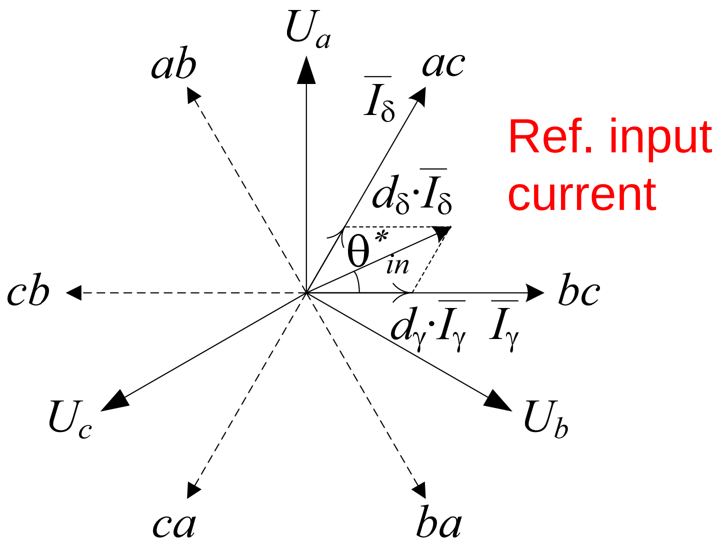


Modulation

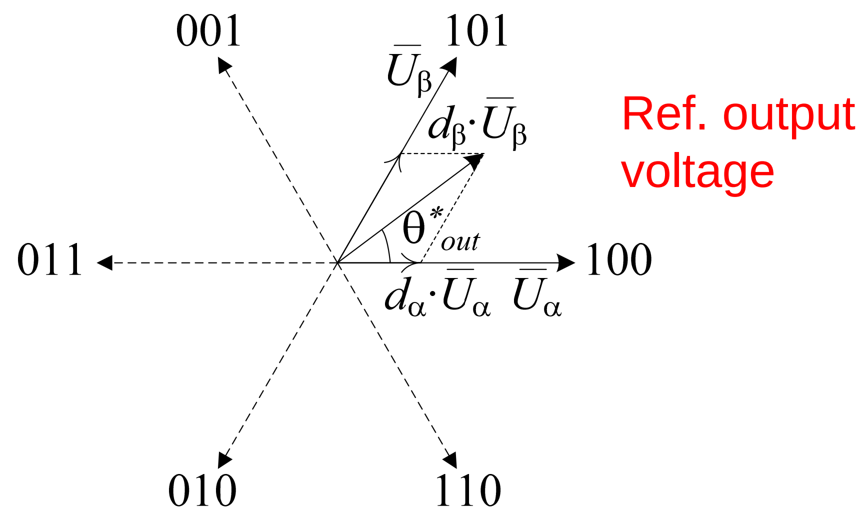
- PWM Modulation technique is applied in order to:
  - follow a reference at the output, which on average will be a sinusoidal
  - get sinusoidal input currents on phase with the input voltage (power factor 1)
- Several modulation techniques:
  - Venturini, Scalar…
- Direct Space Vector Modulation
- Indirect Space Vector Modulation
  - Based on the Space Vector Modulation for Standard PWM Inverters
  - There are two reference vectors:
    - Input current
    - Output voltage

Modulation

Rectification stage



Inversion stage



$$d_\gamma = m_I \cdot \sin\left(\frac{\pi}{3} - \theta^*{}_{in}\right) \qquad d_\delta = m_I \cdot \sin\left(\theta^*{}_{in}\right)$$

$$d_\alpha = m_U \cdot \sin\left(\frac{\pi}{3} - \theta^*{}_{out}\right) \qquad d_\beta = m_U \cdot \sin\left(\theta^*{}_{out}\right)$$

- To obtain a correct balance of the input currents and the output voltages, the modulation pattern should be a combination of all 4 duty-cycles

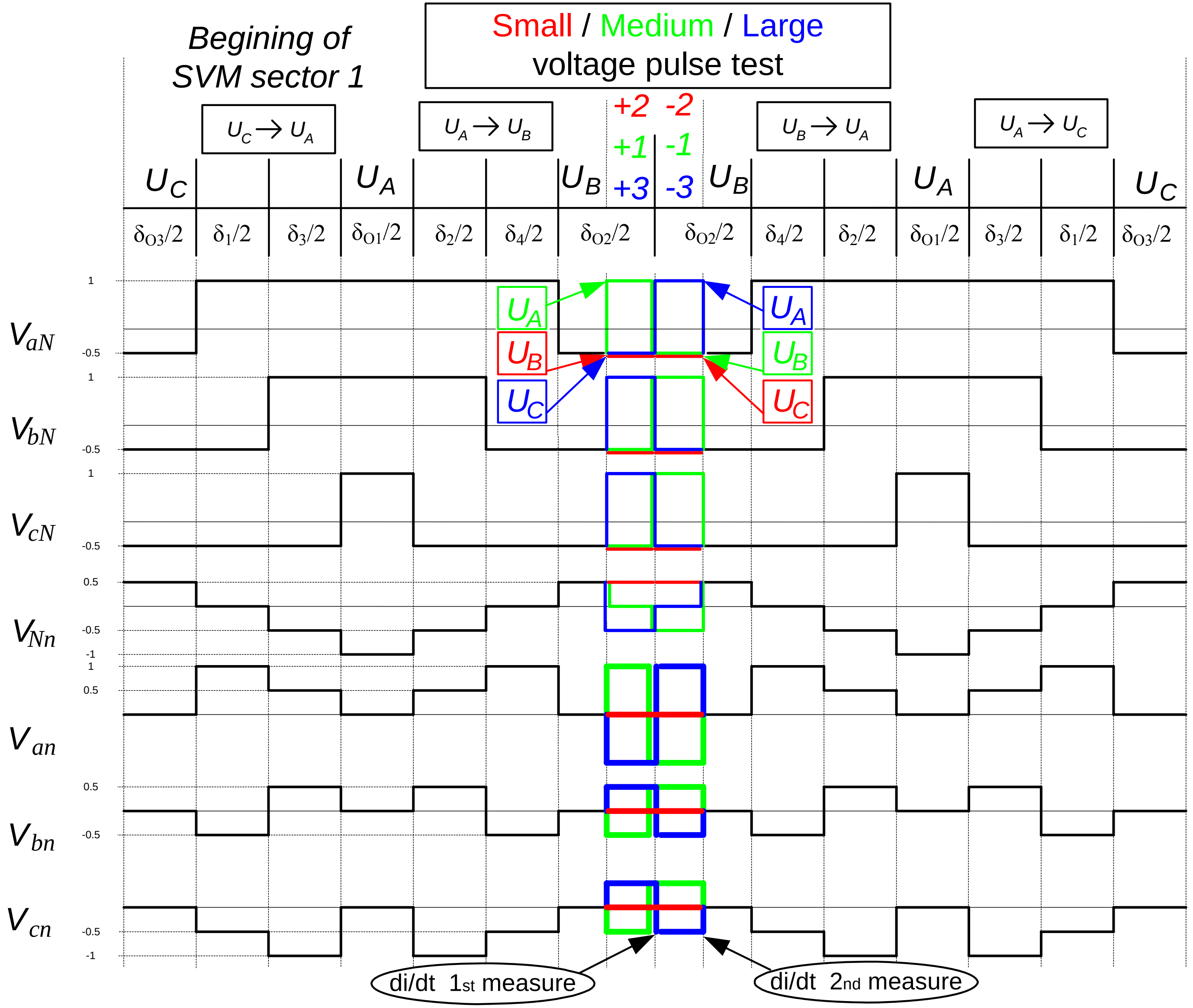
$$d_{\alpha\gamma} = d_\alpha \cdot d_\gamma \qquad d_{\alpha\delta} = d_\alpha \cdot d_\delta \qquad d_{\beta\delta} = d_\beta \cdot d_\delta \qquad d_{\beta\gamma} = d_\beta \cdot d_\gamma$$

- And the zero vector is calculated as follows

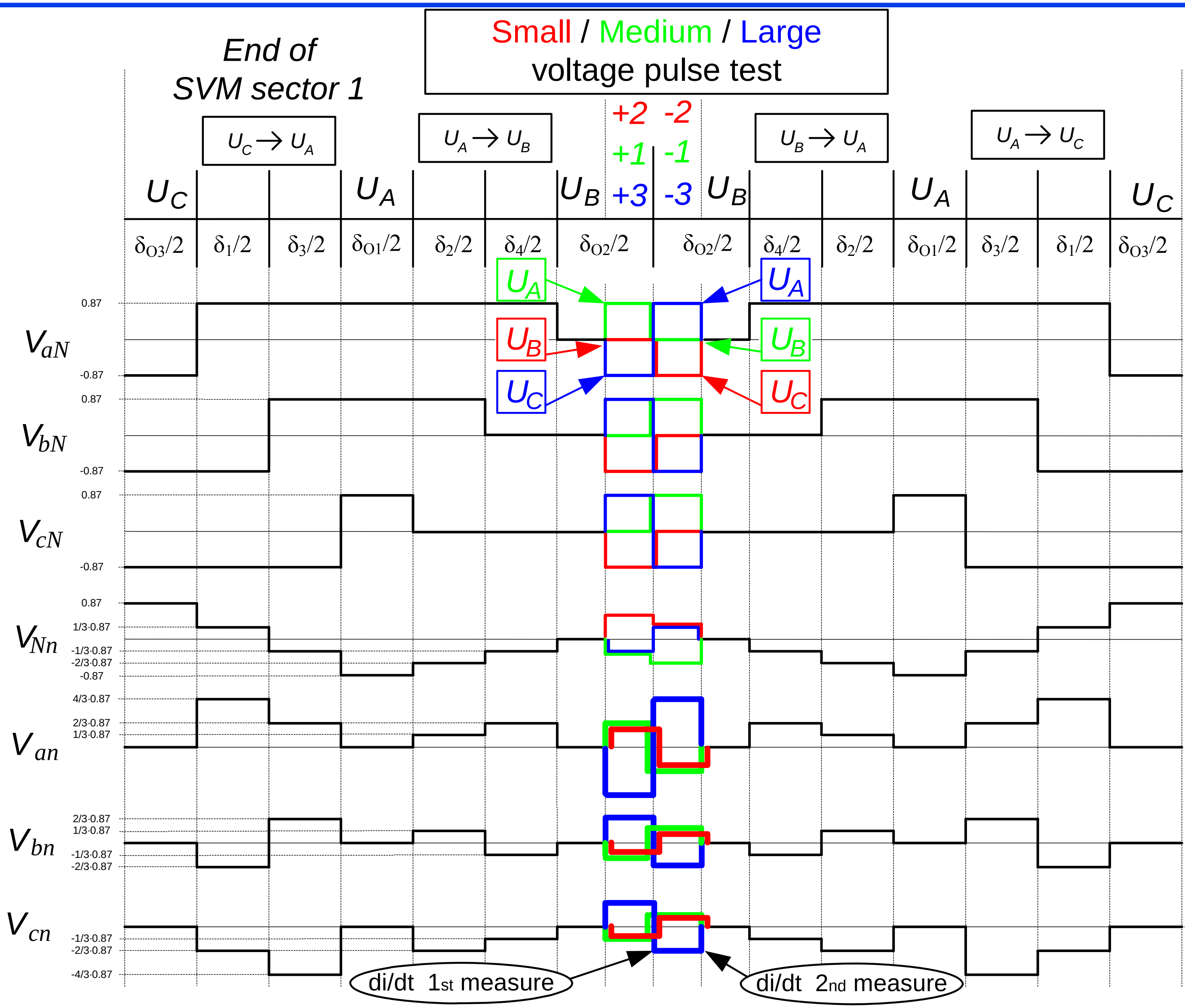
$$d_0 = 1 - \left(d_{\alpha\gamma} + d_{\alpha\delta} + d_{\beta\delta} + d_{\beta\gamma}\right)$$

- *The typical modulation pattern is as shown in next slide*

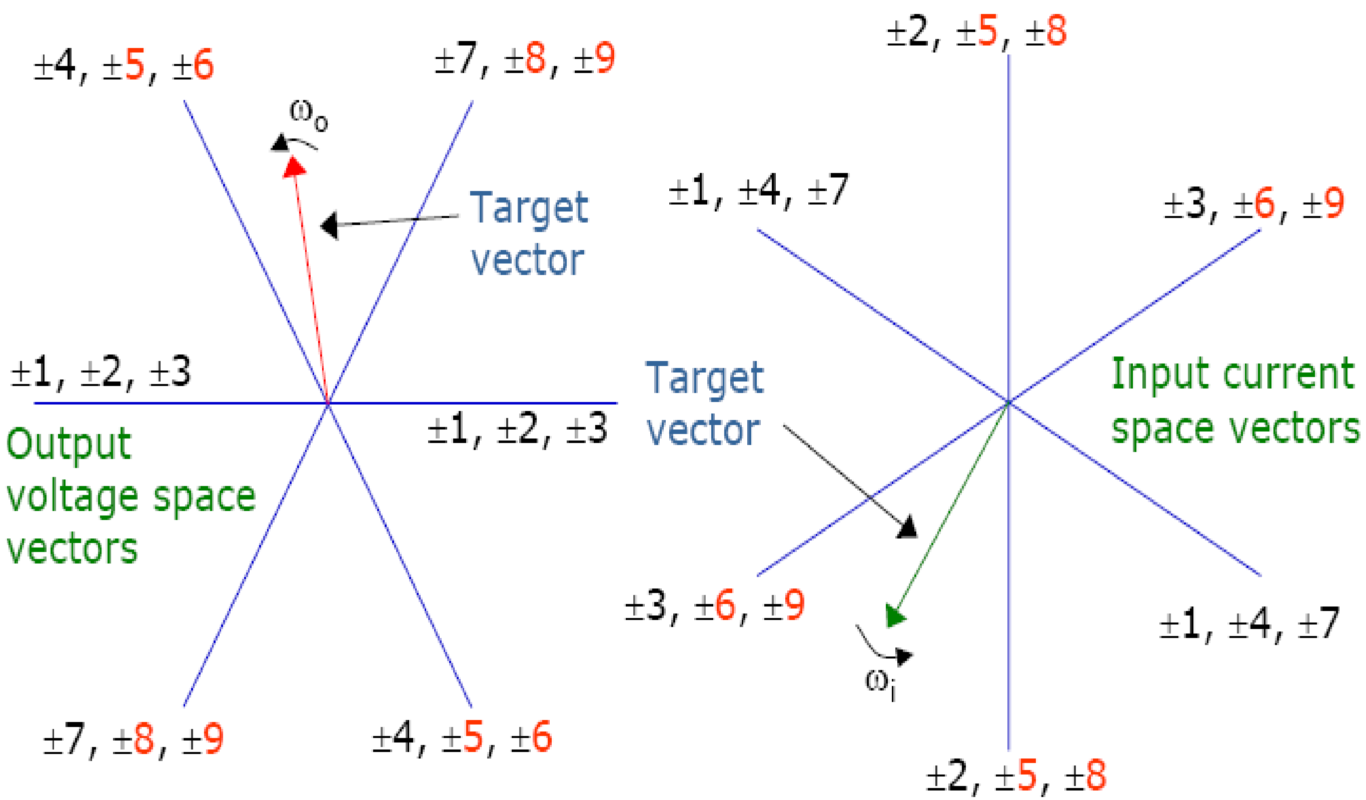
Modulation switching pattern



Modulation switching pattern



Modulation

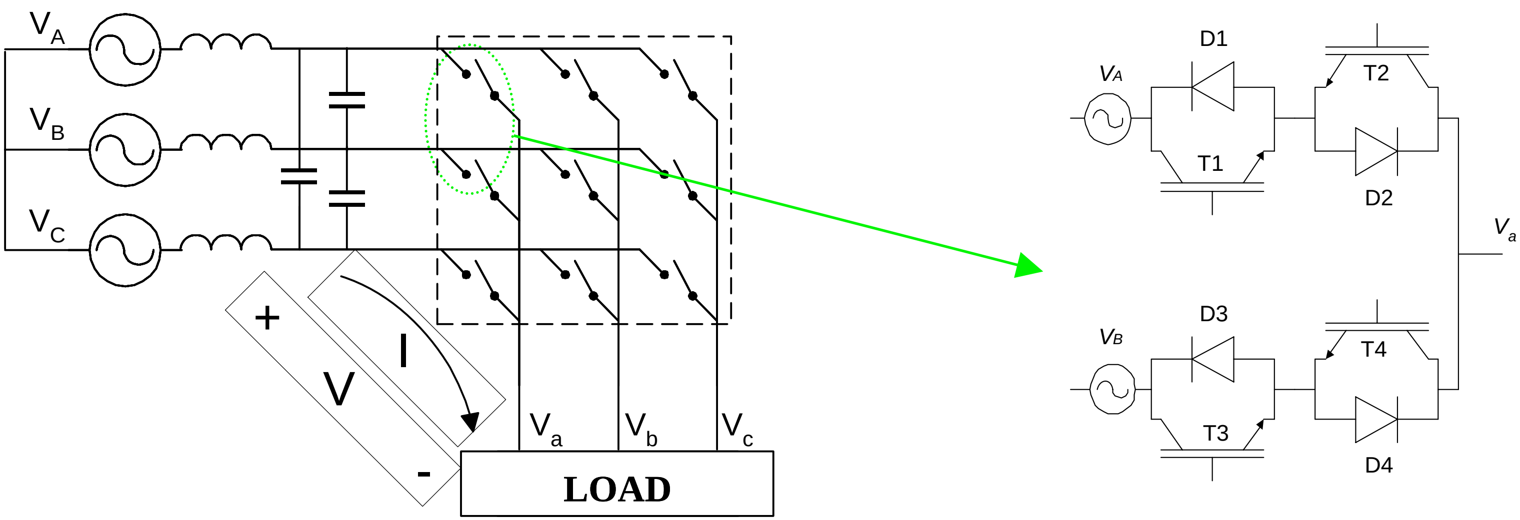


- In such case the four active states used would be:
  - 5,6,8 and 9
  - There will always be four vectors: 2 for the inversion stage and 2 for the rectifier stage.

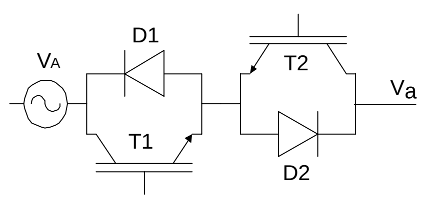
Matrix Converter linearization

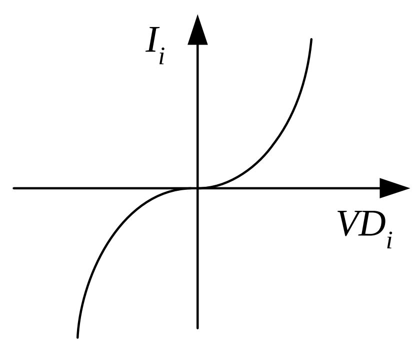
Matrix Converter linearization

- General scheme

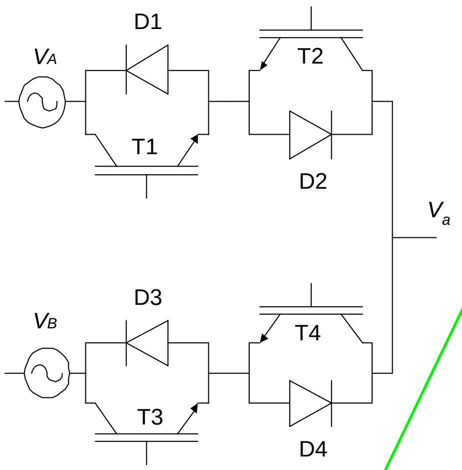


- Voltage Drop effect

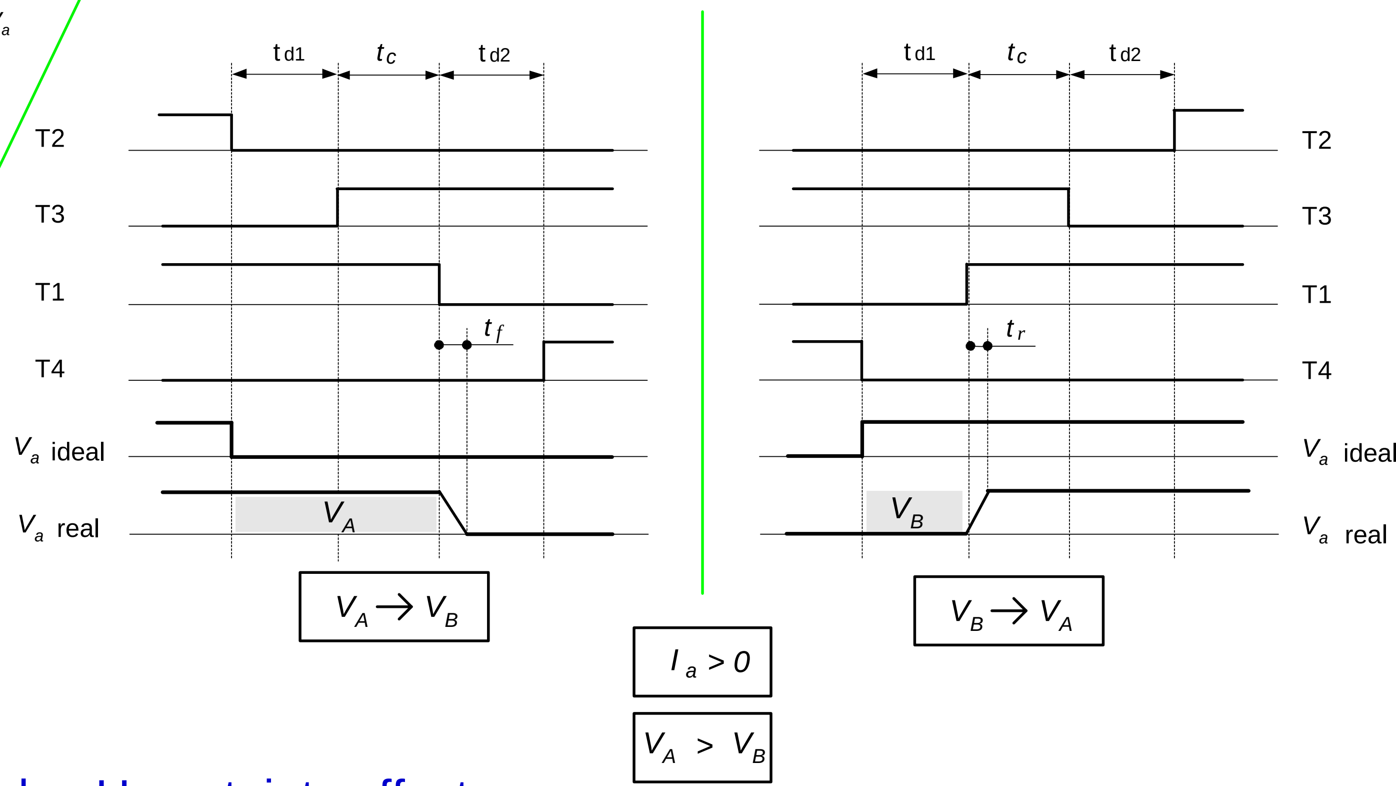




Matrix Converter linearization



- Four step commutation
- $(t_{d1} + t_c + t_{d2} = 1\mu s + 0.2\mu s + 0.5\mu s)$

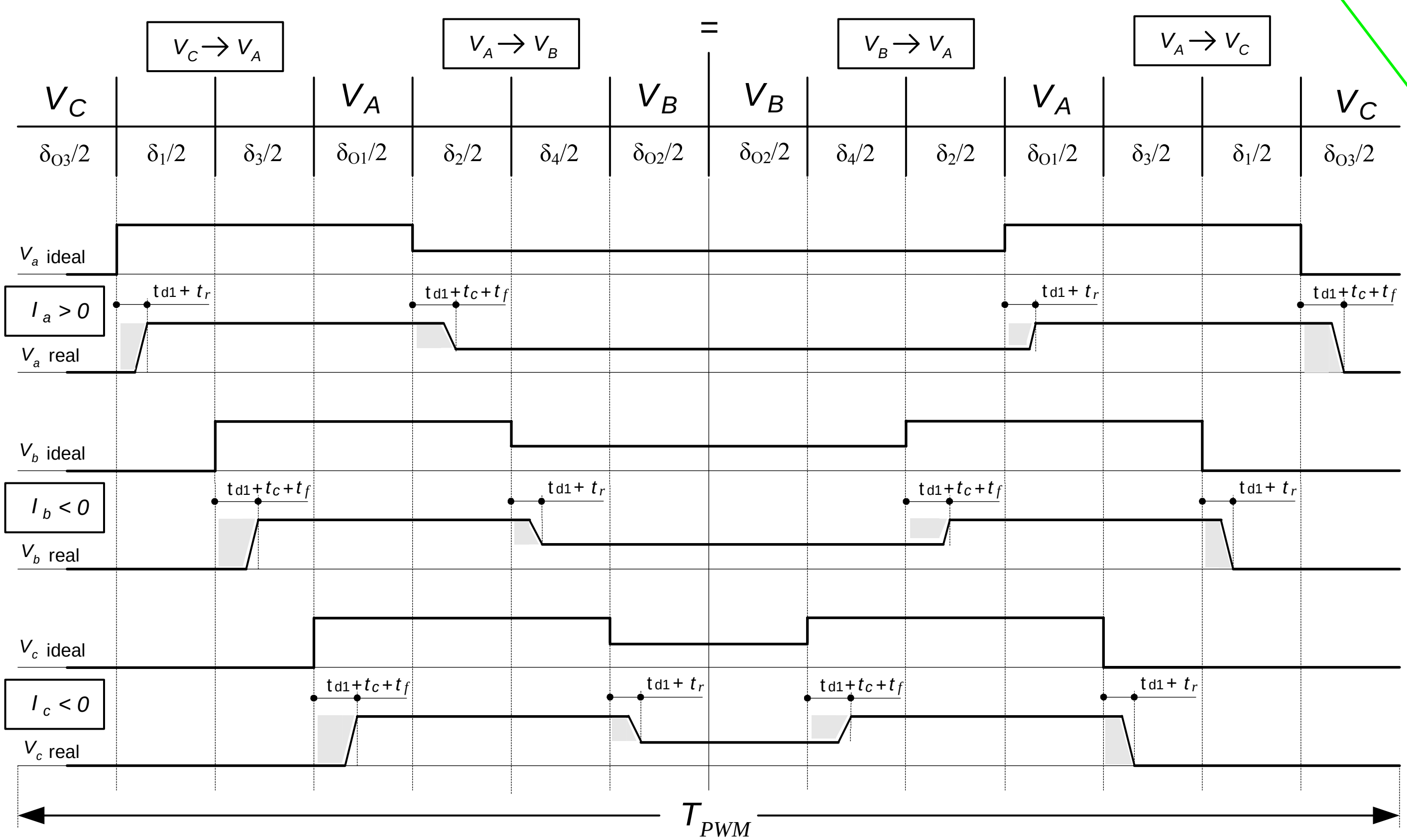


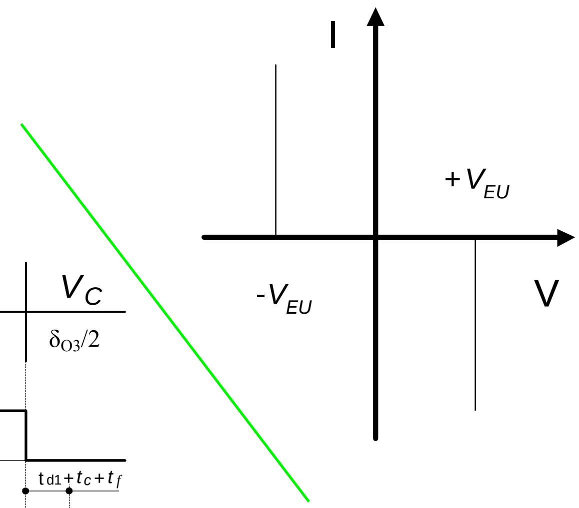
- Voltage Edge Uncertainty effect

Matrix Converter linearization

- Model for Voltage Edge Uncertainty effect
- SVM

SECTOR 1

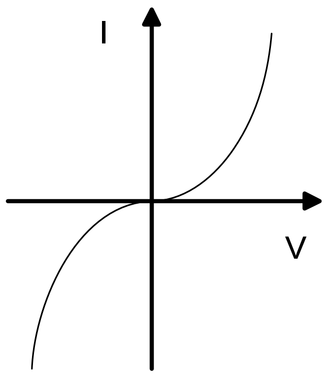




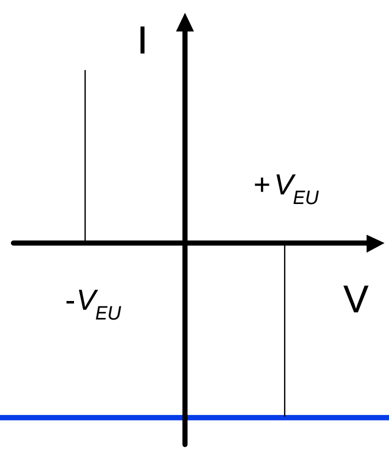
Matrix Converter linearization

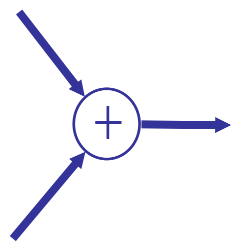
DUAL COMPENSATION

- Voltage Drop effect

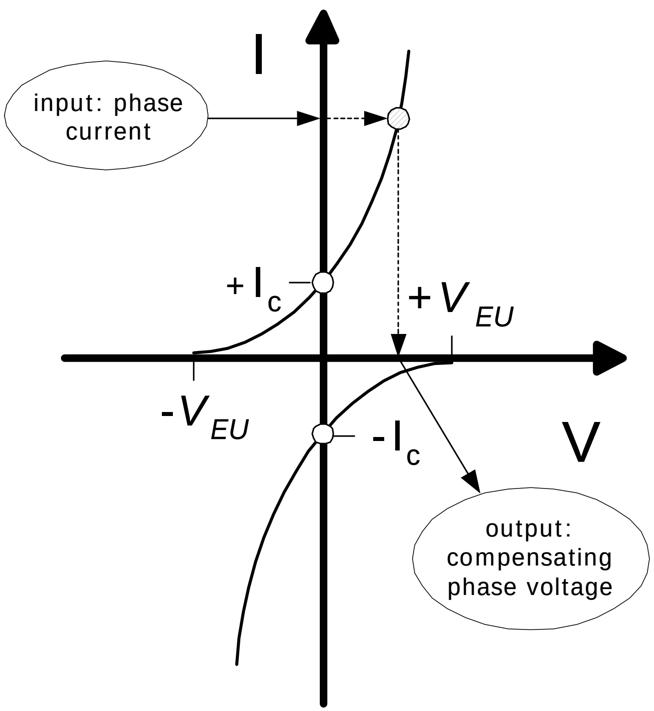


- Voltage Edge Uncertainty effect



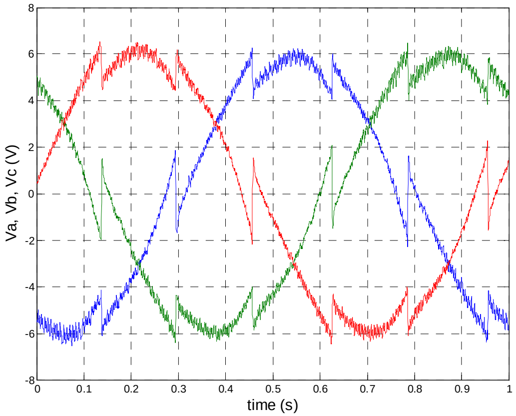


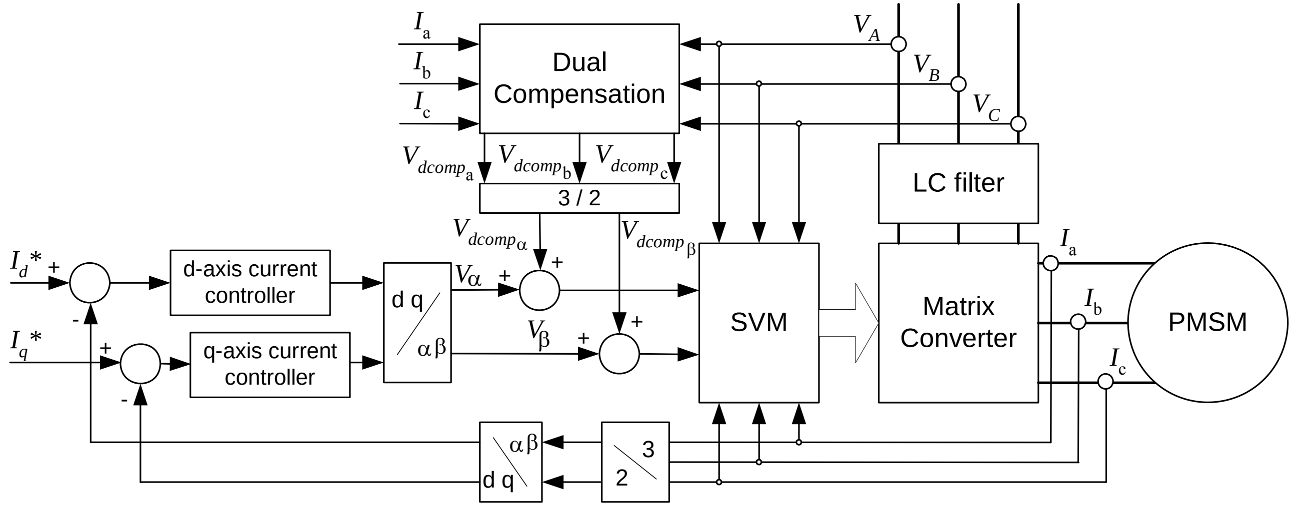
- Dual Compensation

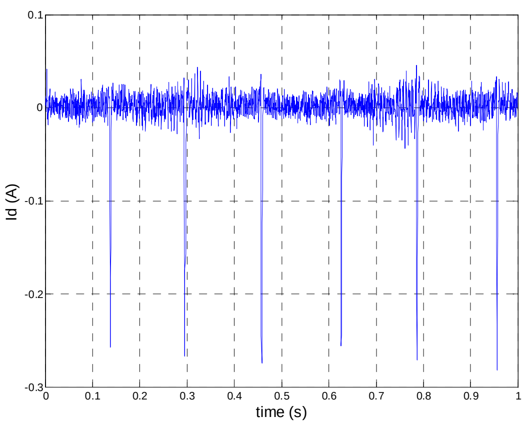


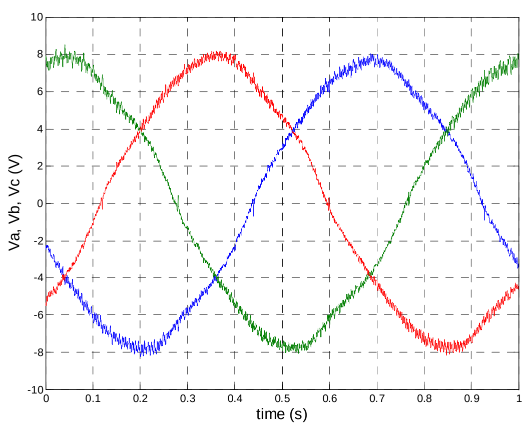
Matrix Converter linearization

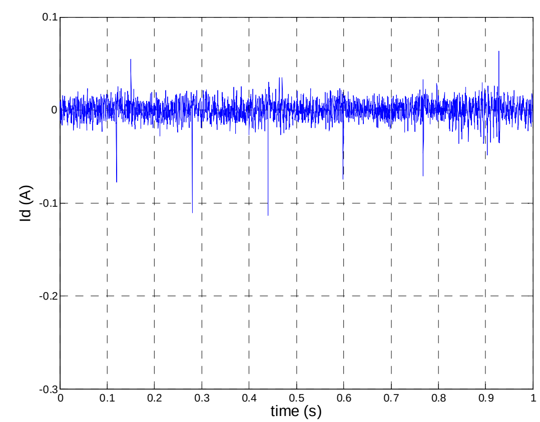
Dual Compensation in Matrix Converters FOC Scheme$_{Grid}$











Conclusions

- Matrix Converter topology
  - 9 Bidirectional switch
- 4 step commutation
- Space Vector Modulation
- Input Filter
- Clamp Circuit
- Matrix Converter linearization
- Advantages of Matrix Converters:
  - Size
  - Sinusoidal input/output
  - Hostile environments
  - 4 quadrant
- *Applications*