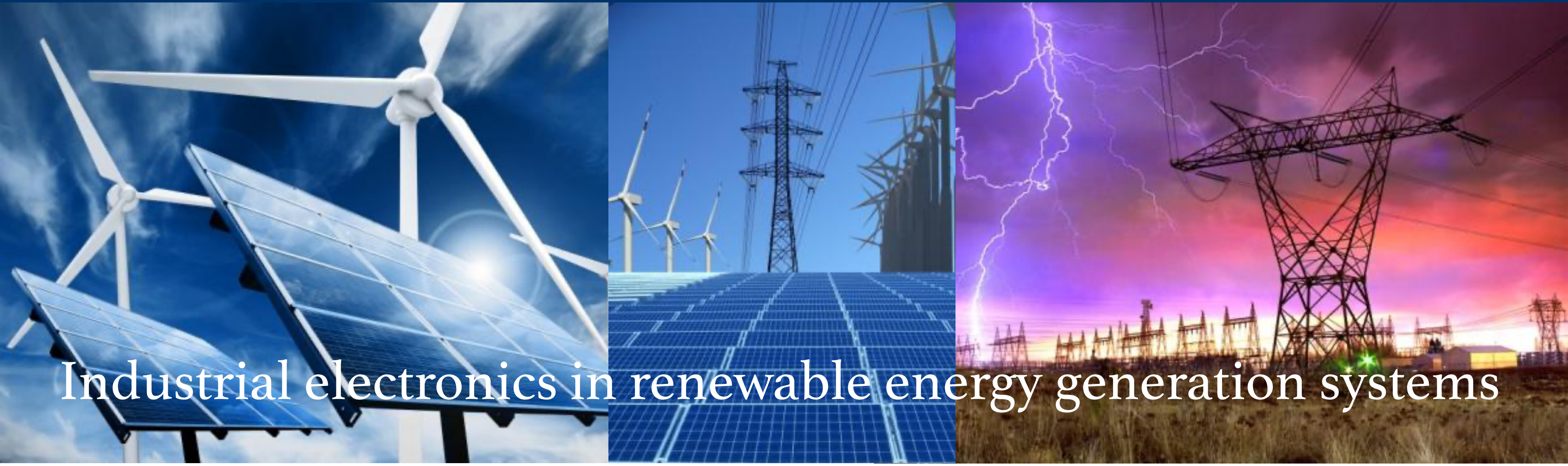
M.Sc. In Electrical Energy Conversion and Power Systems



Industrial electronics in renewable energy generation systems

Unit 4.- Three-Phase converters

4.2 DC-AC conversion. The three-phase inverter

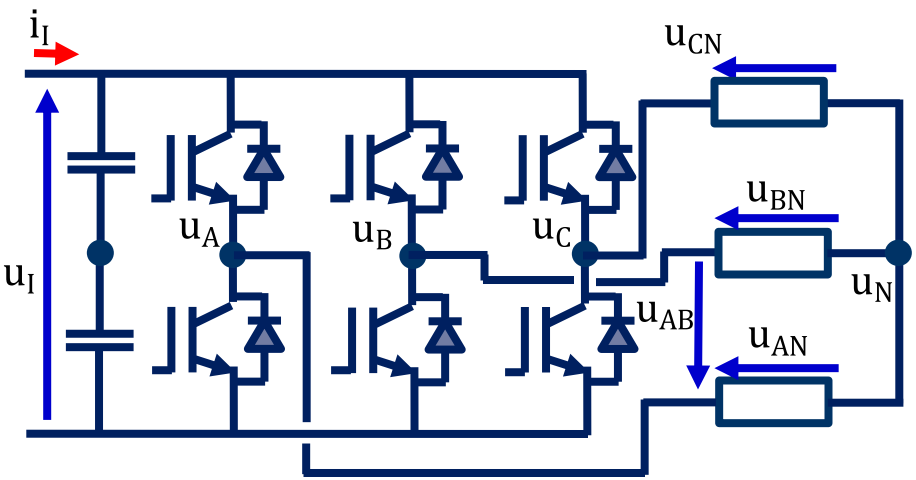
Semester 2 – Industrial electronics in renewable energy generation systems

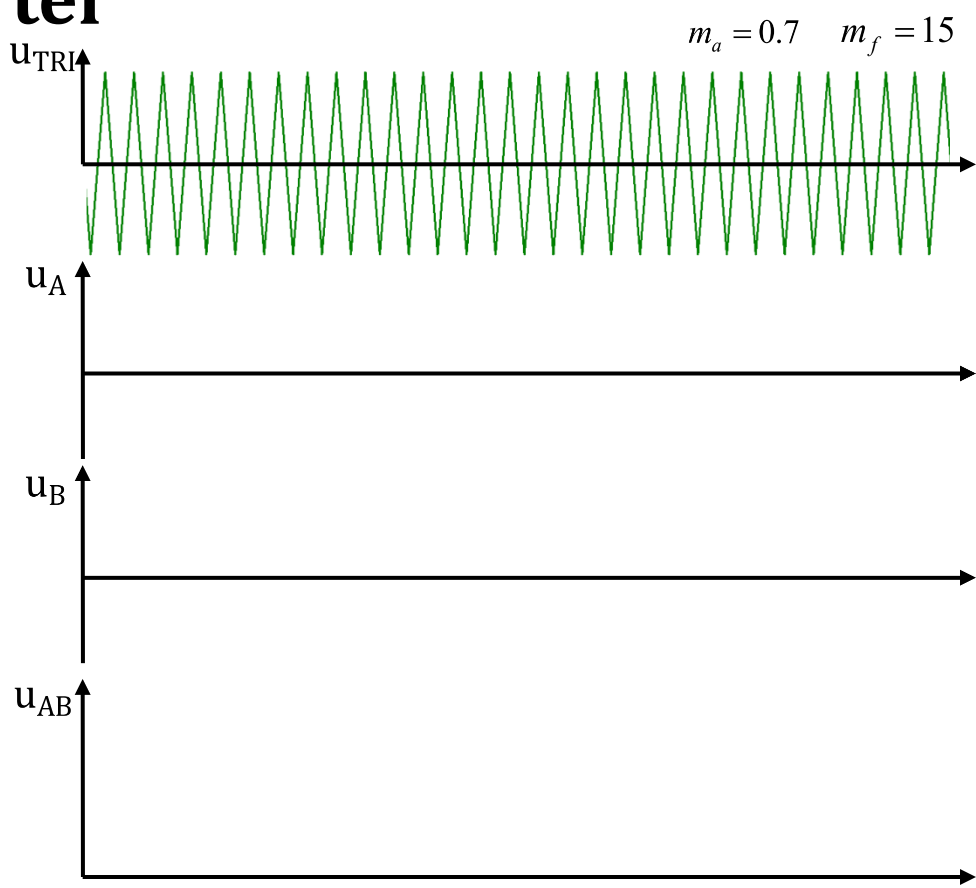
Lecturer: Jorge García, garciajorge@uniovi.es

Unit 4.- Three-phase converters	
4.1	DC-AC conversion. The single-phase inverter
	General concepts in inverters. Characteristics and types Half-bridge square wave single-phase inverter Full-bridge square wave single-phase inverter Sine-waveform PWM modulation Output LC filter and harmonics analysis Input filter and DC-link current
4.2	DC-AC conversion. The three-phase inverter
	General concepts in inverters. 6-pulses inverter. Sine-waveform PWM modulation Output LC filter and harmonics analysis Input filter and DC-link current Effect of the dead-times. Limitations. Alternative modulations, 3rd harmonic injection, SVPWM.
4.3	AC-DC conversion. The three-phase controlled rectifier
	Reverse operation of the three-phase inverter Equivalent single-phase circuit Control of the filter current Main electrical magnitudes relations Evolution of waveforms

Three-Phase, Full-Bridge PWM Inverter

Three-Phase PWM Inverter

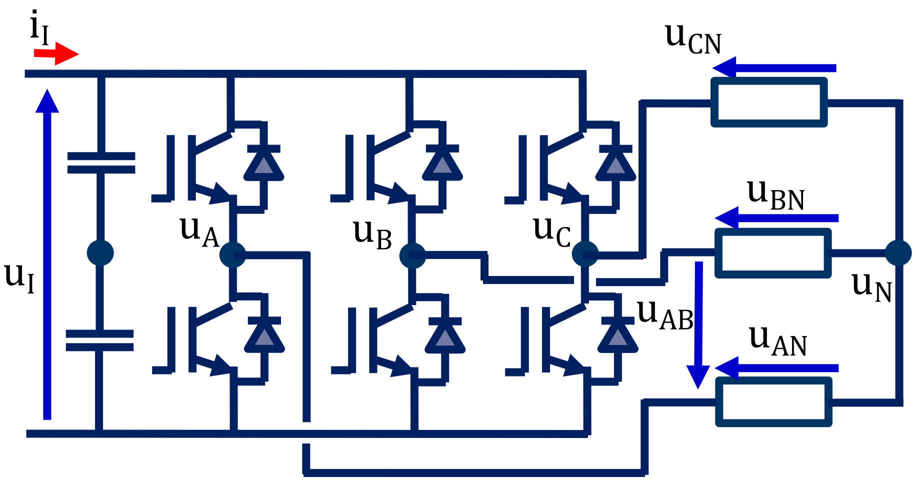


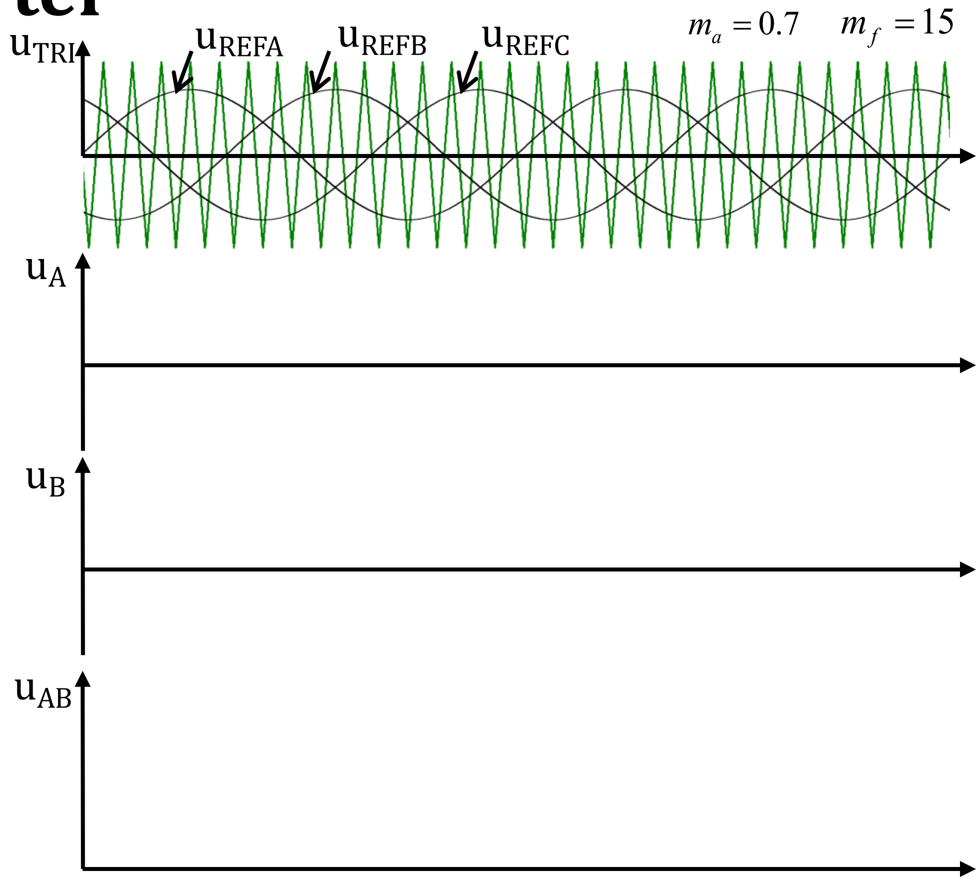


The Square Waveform Control (Six Step Operation) can be applied, but again PWM provides smaller harmonics

For PWM, the modulation ratios $\mathbf{m_a}$ and $\mathbf{m_f}$ can be defined

Three-Phase PWM Inverter





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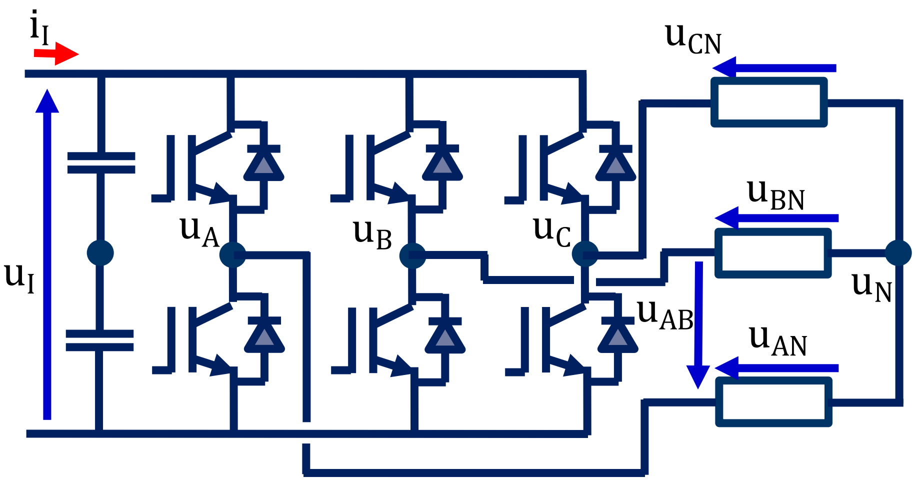
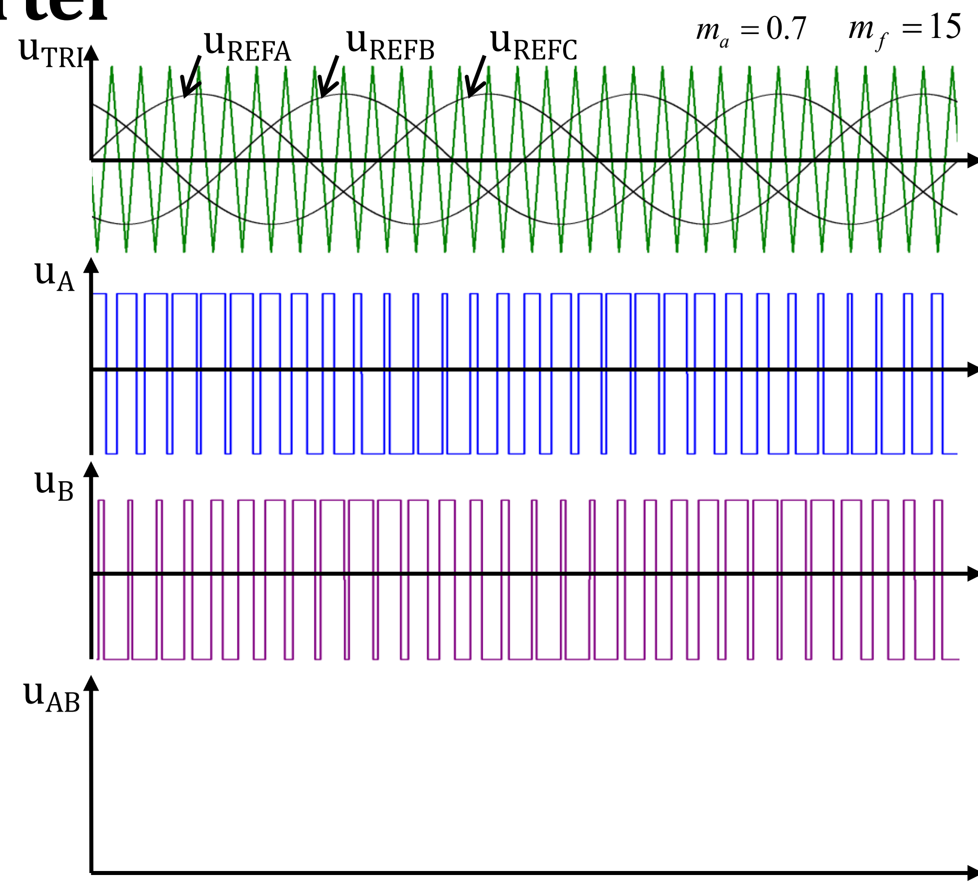
For PWM, the modulation ratios $\mathbf{m_a}$ and $\mathbf{m_f}$ can be defined

To minimize harmonics, $\mathbf{m_f}$ should be large, odd, and $\mathbf{u_{REF}}$ with opposite slope with respect to $\mathbf{u_{TRI}}$, $\mathbf{m_a}$ should be <1 (overmodulation is used in some applications, particularly in industrial drives).

Three-Phase PWM Inverter





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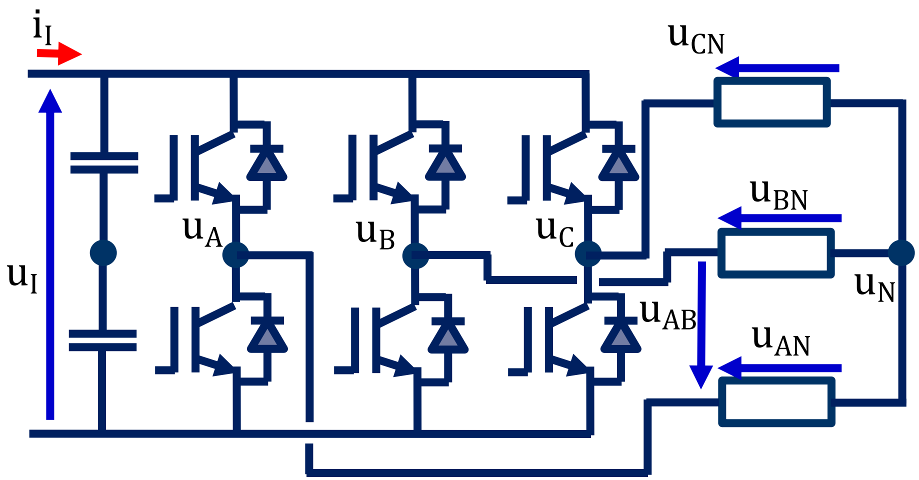
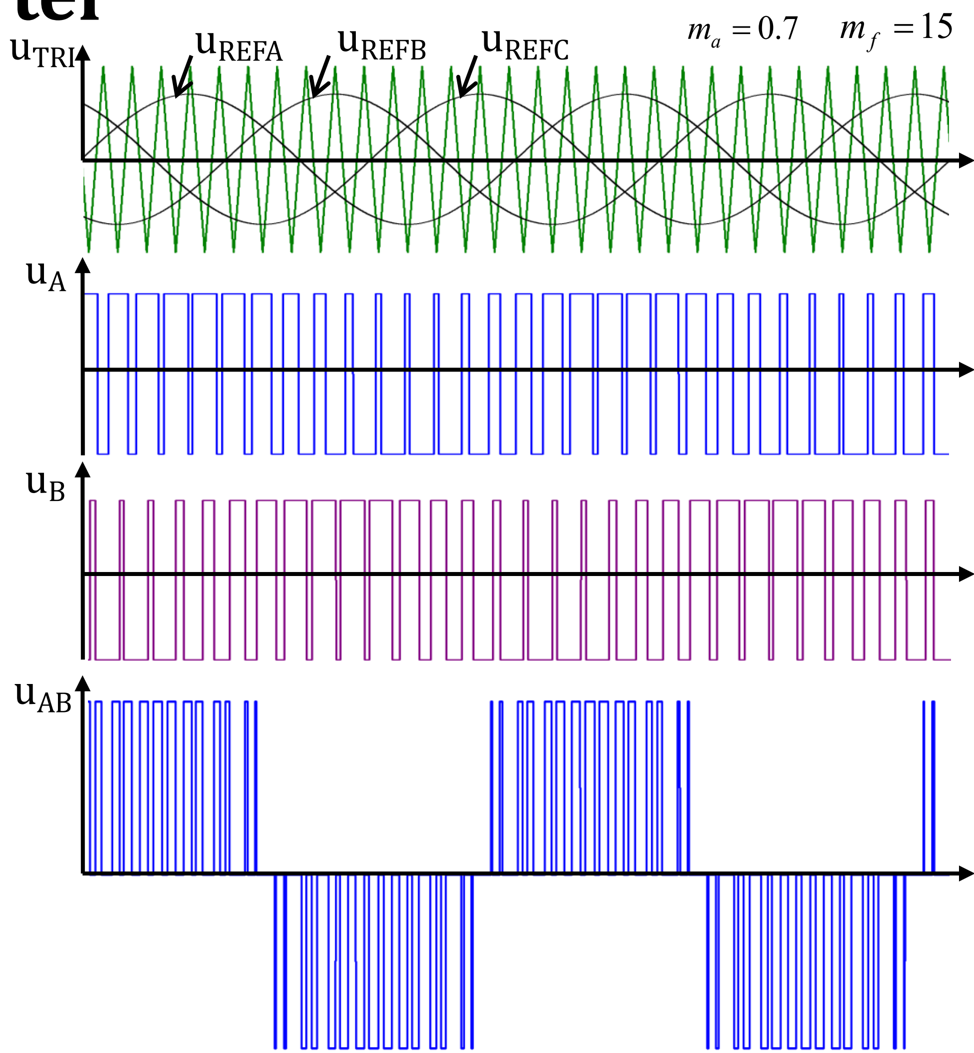
Three-Phase PWM Inverter





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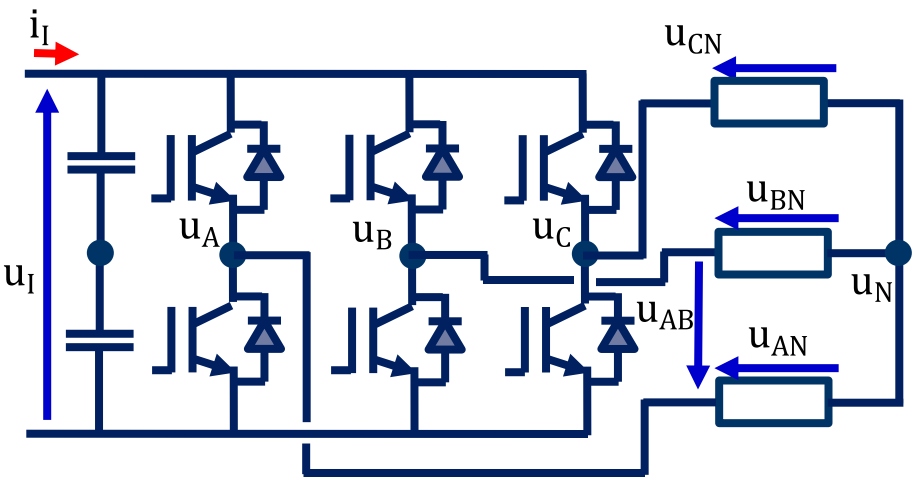
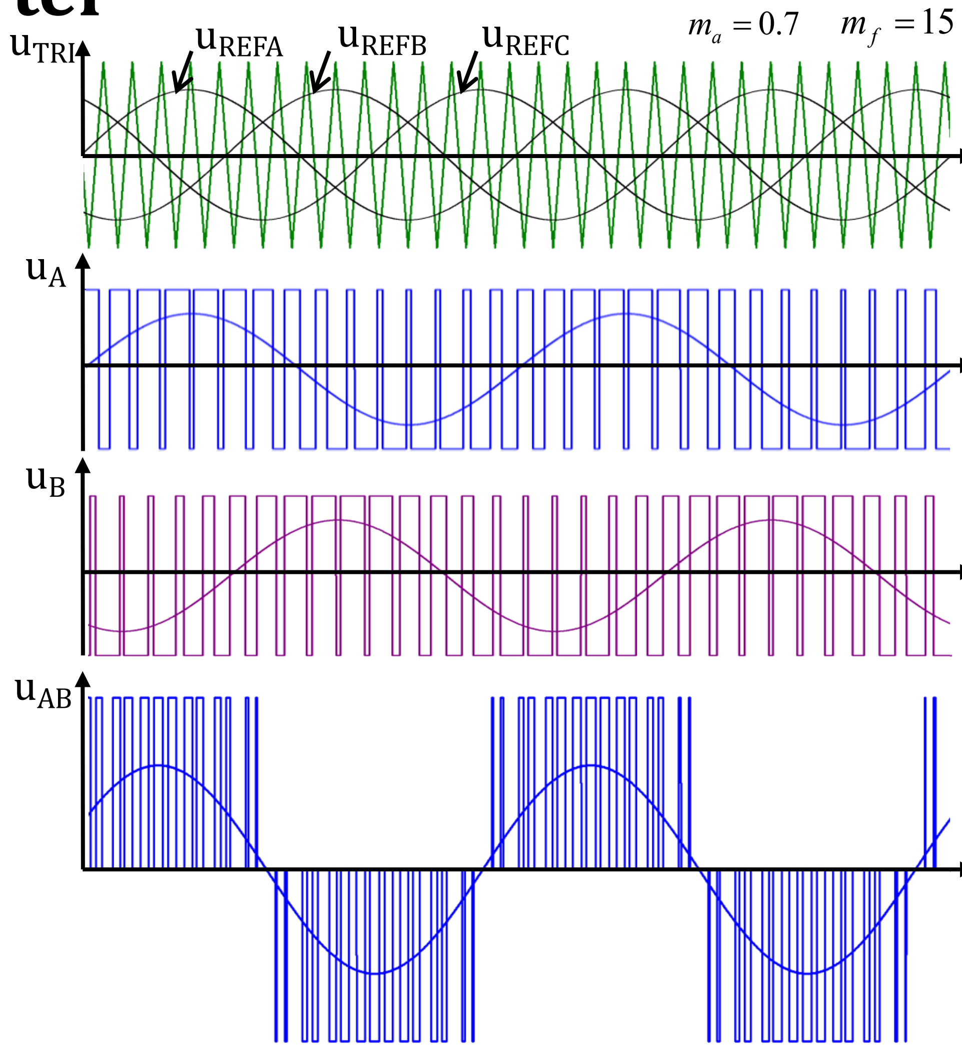
$\mathbf{u_A}$ and $\mathbf{u_B}$ have a 120º lag, what yields to a UNIPOLAR scheme of the output line voltages

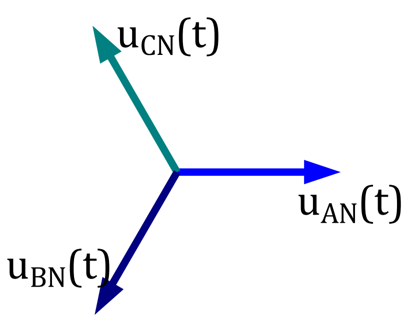
Three-Phase PWM Inverter



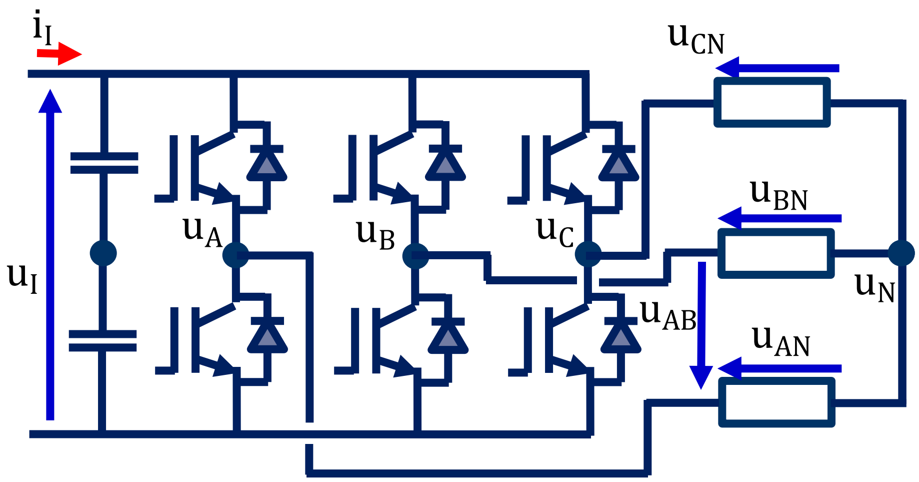


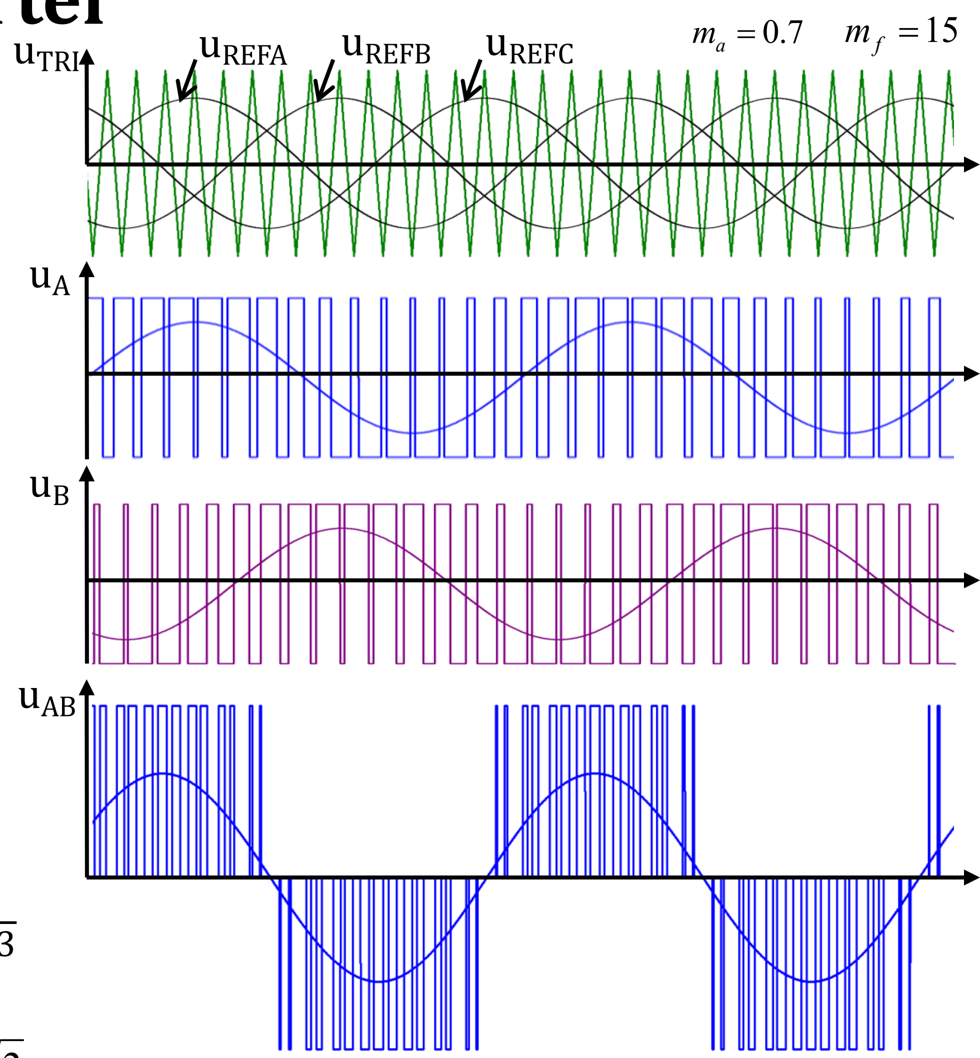
$$|u_{AN}(t)| = m_a \frac{U_I}{2}$$

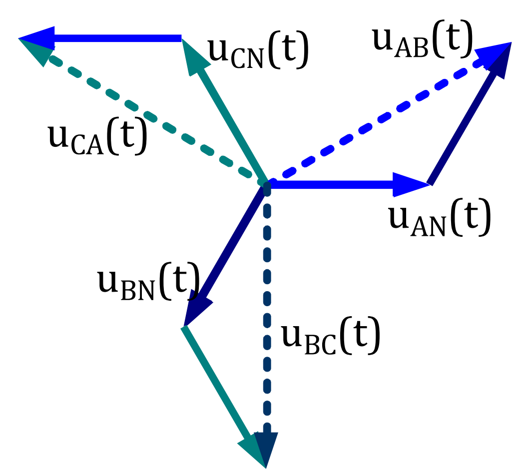
$$u_{AN\langle RMS\rangle} = m_a \frac{U_I}{2\sqrt{2}}$$



Three-Phase PWM Inverter







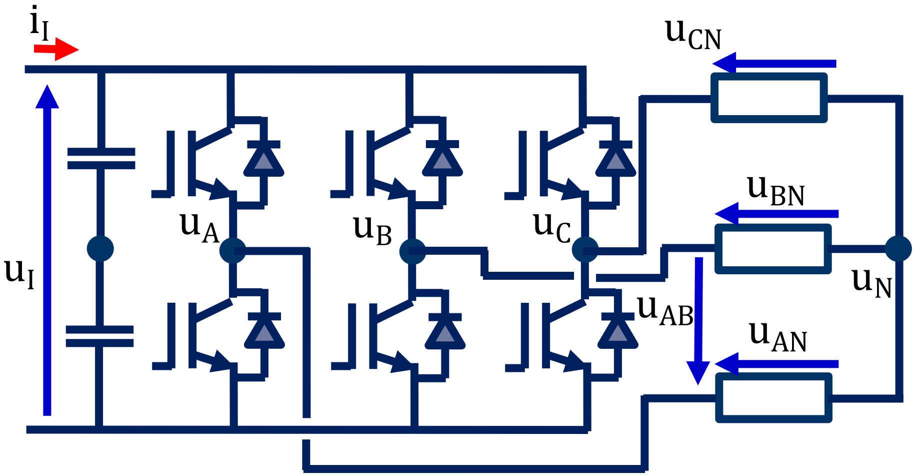
$$|u_{AN}(t)| = m_a \frac{U_I}{2}$$

$$u_{AN\langle RMS\rangle} = m_a \frac{U_I}{2\sqrt{2}}$$

$$|u_{AB}(t)| = \frac{m_a \cdot U_I}{2} \cdot \sqrt{3}$$

$$u_{AB\langle RMS\rangle} = m_a \frac{U_I\sqrt{3}}{2\sqrt{2}}$$

Three-Phase PWM Inverter



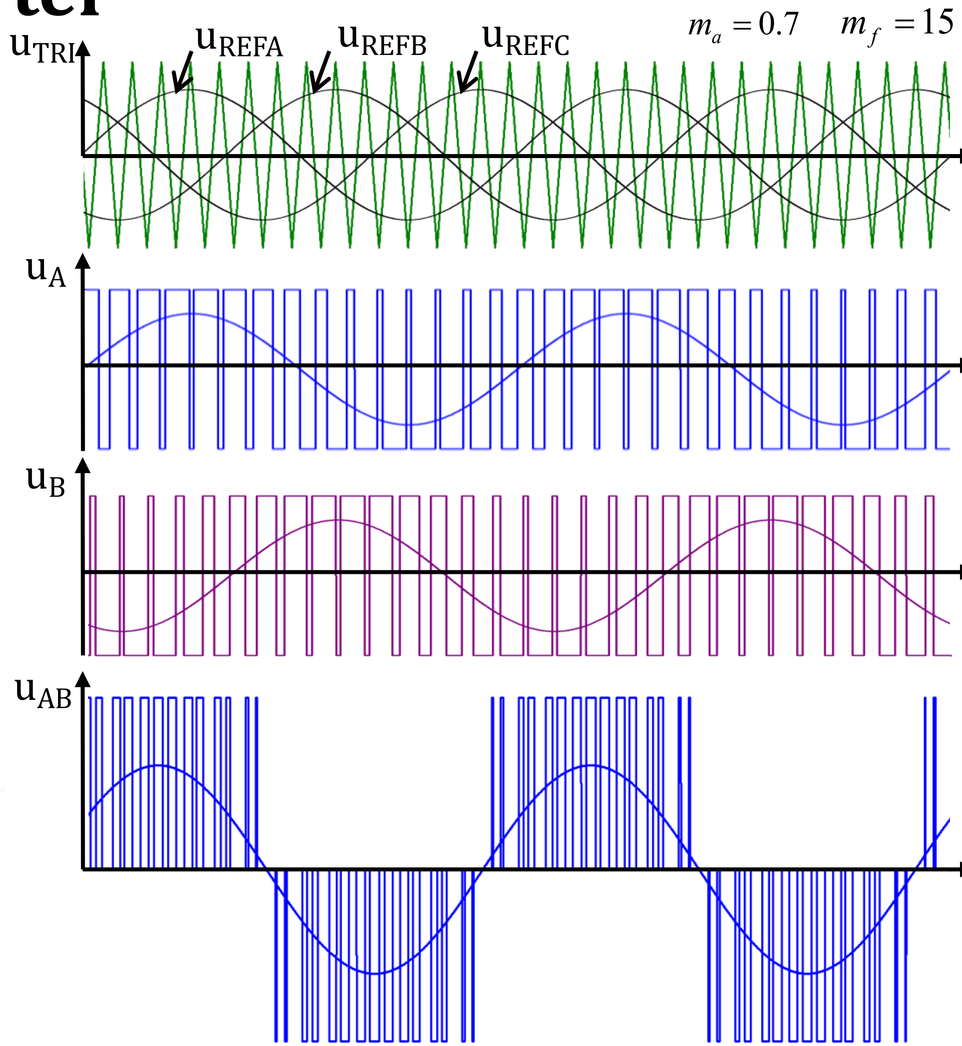


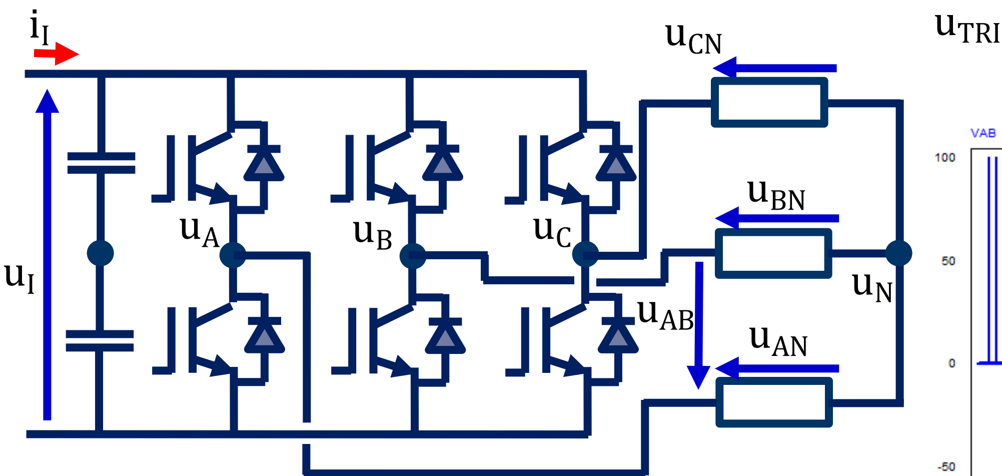
Table 8-2 Generalized Harmonics of v_{LL} for a Large and Odd m_f That Is a Multiple of 3.

h \ m_a	*0.2*	*0.4*	*0.6*	*0.8*	*1.0*
1	*0.122*	*0.245*	*0.367*	*0.490*	*0.612*
$m_f \pm 2$	0.010	0.037	0.080	0.135	0.195
$m_f \pm 4$				0.005	0.011
$2m_f \pm 1$	0.116	0.200	0.227	0.192	0.111
$2m_f \pm 5$				0.008	0.020
$3m_f \pm 2$	0.027	0.085	0.124	0.108	0.038
$3m_f \pm 4$		0.007	0.029	0.064	0.096
$4m_f \pm 1$	0.100	0.096	0.005	0.064	0.042
$4m_f \pm 5$			0.021	0.051	0.073
$4m_f \pm 7$				0.010	0.030

Note: $(V_{LL})_h/V_d$ are tabulated as a function of m_a where $(V_{LL})_h$ are the rms values of the harmonic voltages.

"Power Electronics Handbook, Second Edition: Devices, Circuits and Applications" *Editor: Muhammad H. Rashid, Ed. Elsevier Inc., 2007.*

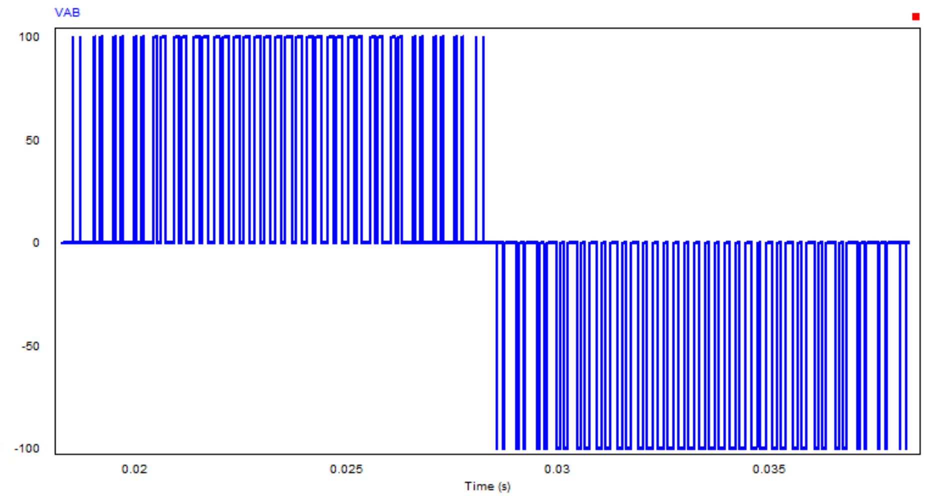
Three-Phase PWM Inverter



THREE-PHASE PWM

$m_a = 0.7$

$m_f = 41$



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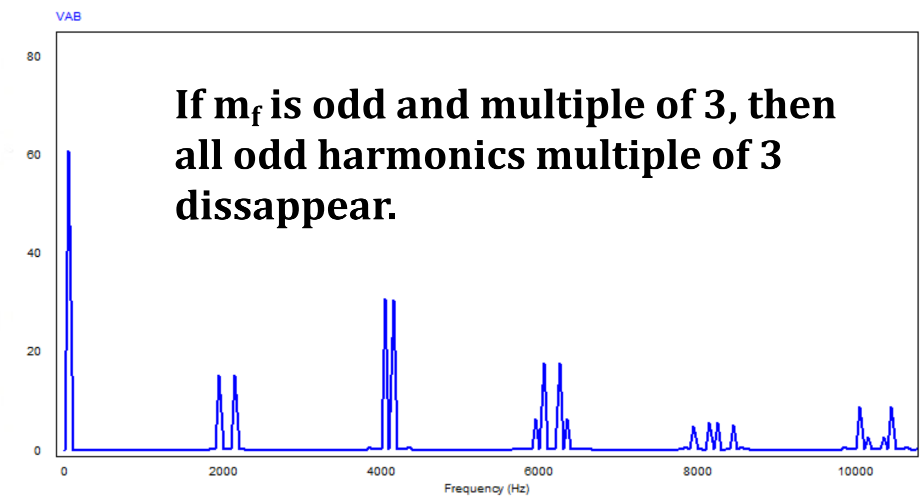

If m_f is odd and multiple of 3, then all odd harmonics multiple of 3 dissappear.

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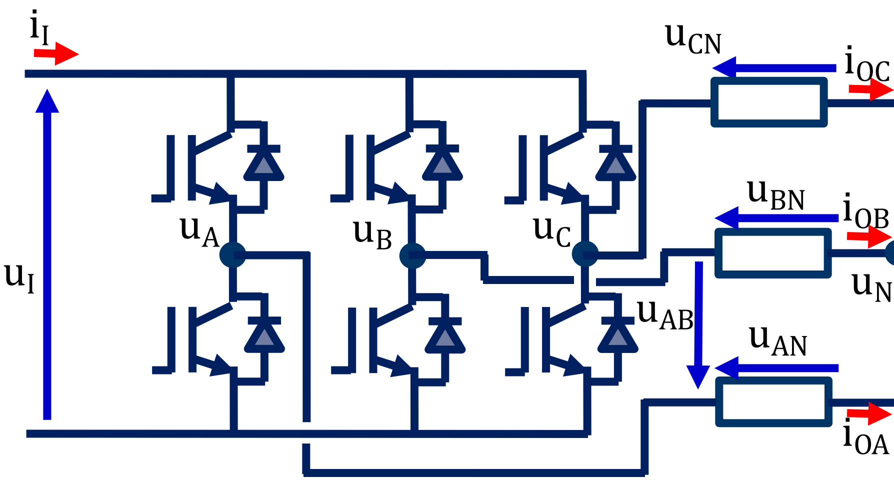
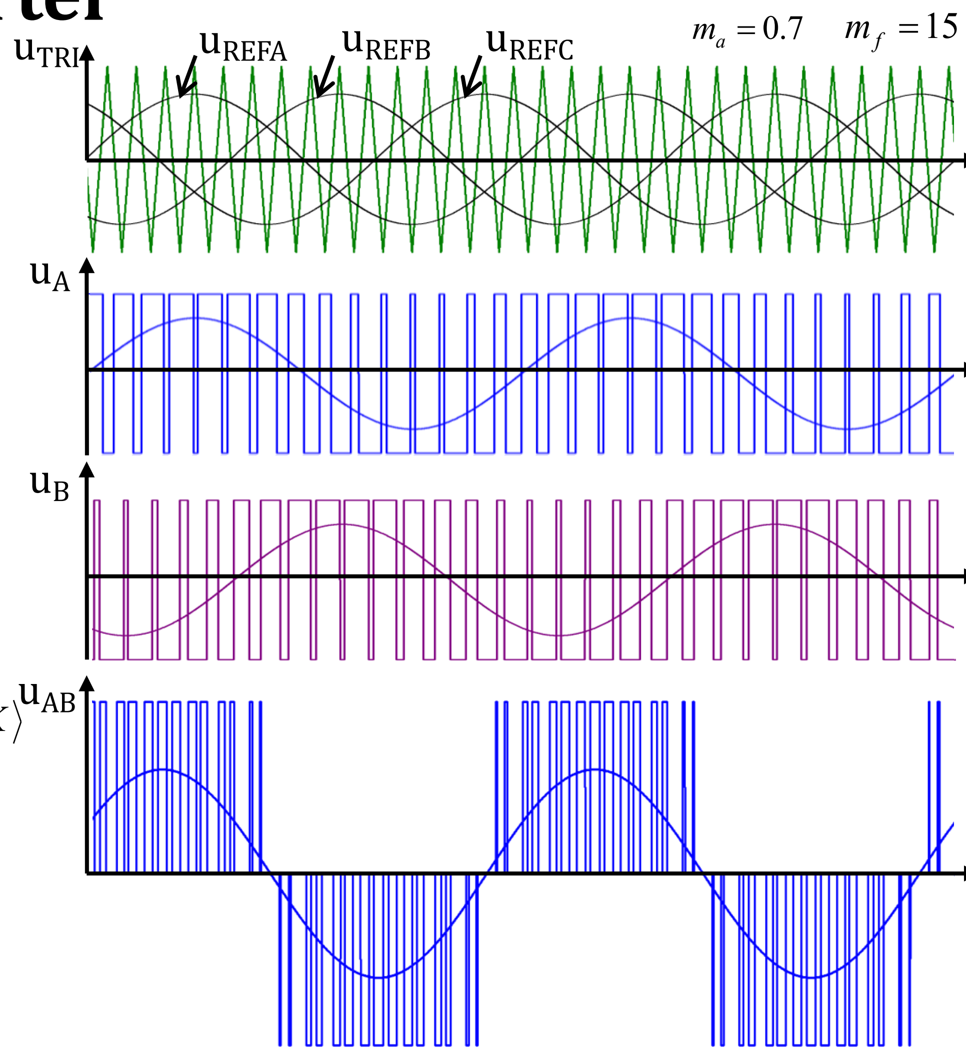
Three-Phase PWM Inverter



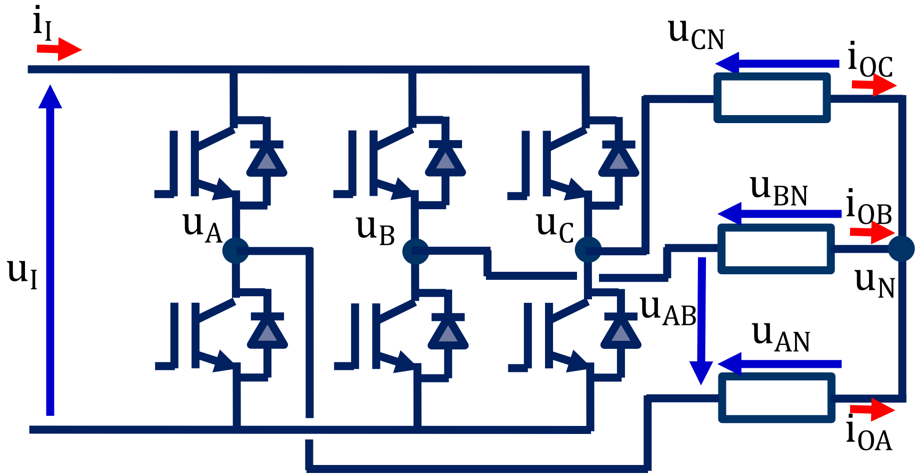


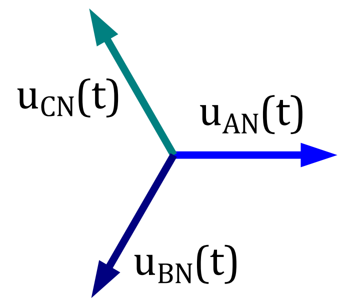
Size of components:

Voltage stress in Switches: $u_{CE\langle PEAK\rangle} = u_I$

Current stress in Switches: $i_{C\langle PEAK\rangle} = i_{O\langle PEAK\rangle}$

Three-Phase PWM Inverter





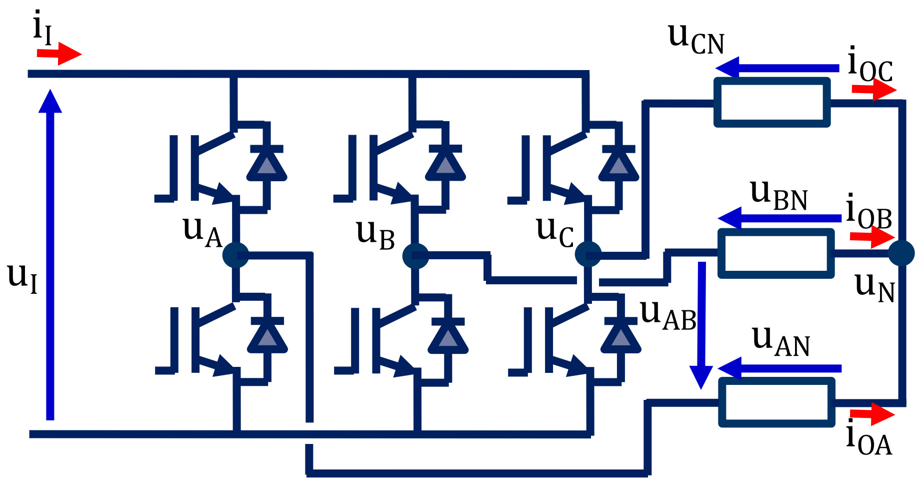
Input current:

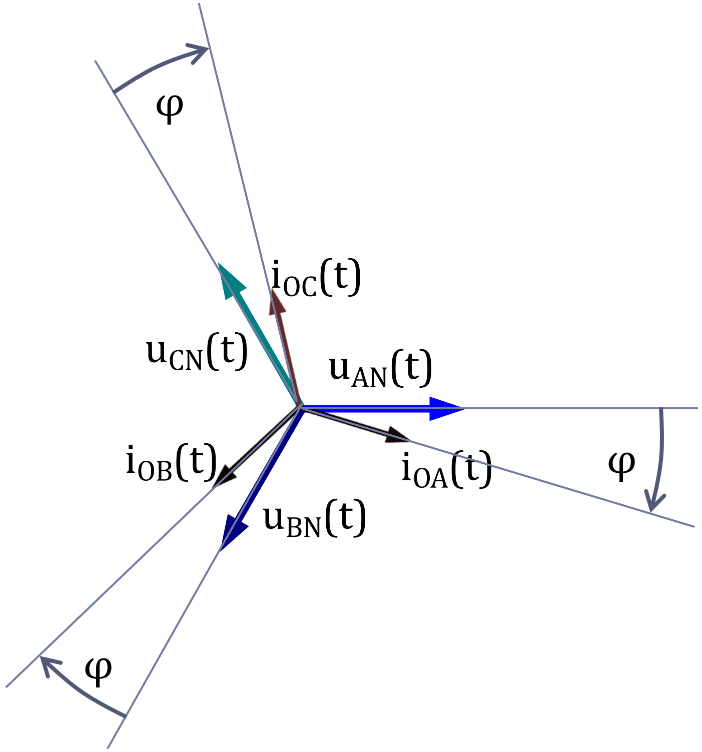
$$u_{AN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t)$$

$$u_{BN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t - 120^{\circ})$$

$$u_{CN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + 120^{\circ})$$

Three-Phase PWM Inverter





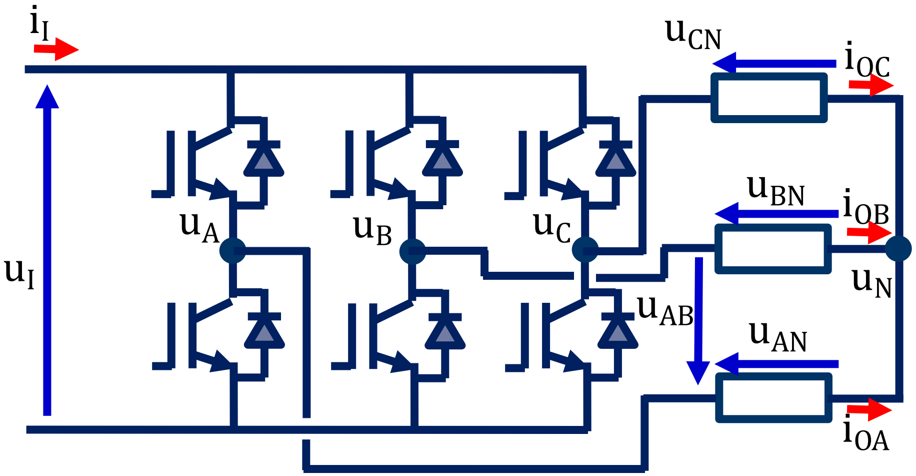
Input current:

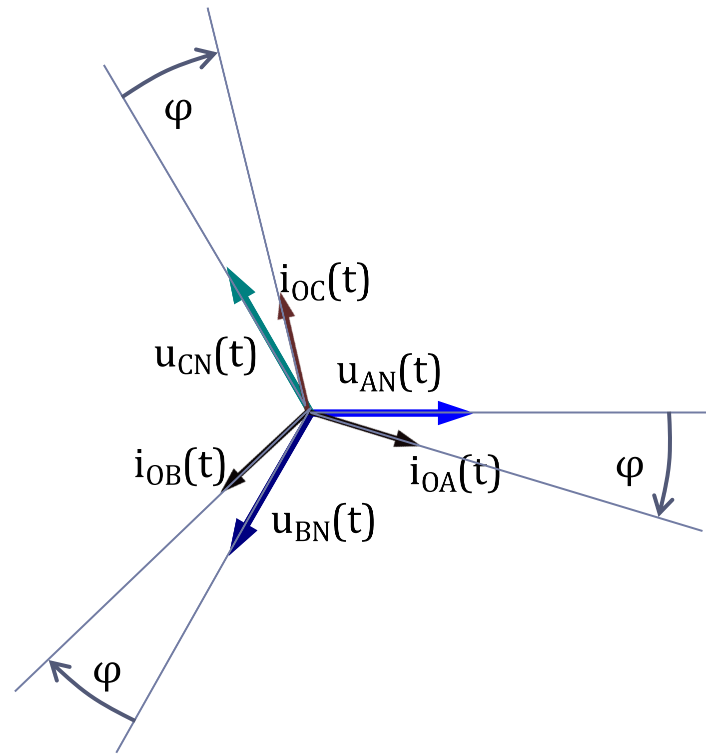
$$u_{AN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t) \qquad i_{OA}(t) = I_{OA} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi)$$

$$u_{BN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t - 120^o) \qquad i_{OB}(t) = I_{OB} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi - 120^o)$$

$$u_{CN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + 120^o) \qquad i_{OC}(t) = I_{OC} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi + 120^o)$$

Three-Phase PWM Inverter





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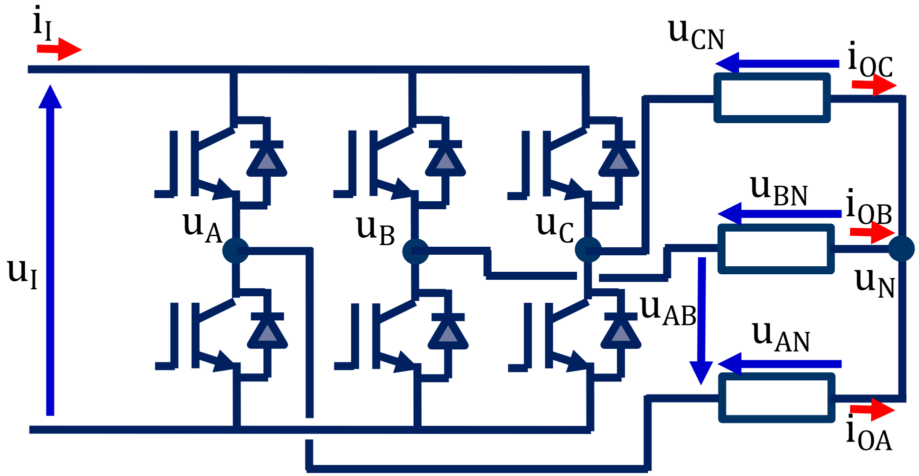
$$u_{BN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t - 120^{\circ}) \qquad i_{OB}(t) = I_{OB} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi - 120^{\circ})$$

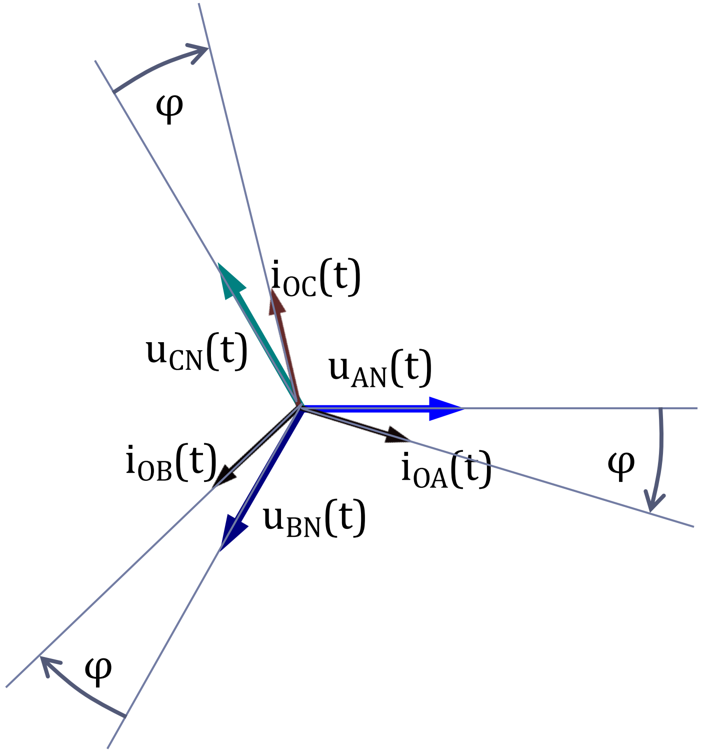
$$u_{CN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + 120^{\circ}) \qquad i_{OC}(t) = I_{OC} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi + 120^{\circ})$$

$$p_O(t) = u_{AN}(t) \cdot i_{OA}(t) + u_{BN}(t) \cdot i_{OB}(t) + u_{CN}(t) \cdot i_{OC}(t)$$

$$\begin{aligned} p_O(t) = U_{PN} I_{OP} \cdot \big[&\sin(2\pi f_R t)\sin(2\pi f_R t + \varphi) + \\ &+ \sin(2\pi f_R t - 120^{\circ})\sin(2\pi f_R t + \varphi - 120^{\circ}) + \\ &+ \sin(2\pi f_R t + 120^{\circ})\sin(2\pi f_R t + \varphi - 120^{\circ}) \big] = \ldots = 3 U_{PN} I_{OP} \cos\varphi \end{aligned}$$

Three-Phase PWM Inverter





Input current:

$$u_{AN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t) \qquad i_{OA}(t) = I_{OA} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi)$$

$$u_{BN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t - 120^{\circ}) \qquad i_{OB}(t) = I_{OB} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi - 120^{\circ})$$

$$u_{CN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + 120^{\circ}) \qquad i_{OC}(t) = I_{OC} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi + 120^{\circ})$$

$$p_O(t) = u_{AN}(t) \cdot i_{OA}(t) + u_{BN}(t) \cdot i_{OB}(t) + u_{CN}(t) \cdot i_{OC}(t)$$

$$\begin{aligned} p_O(t) = U_{PN} I_{OP} \cdot [&\sin(2\pi f_R t)\sin(2\pi f_R t + \varphi) + \\ &+ \sin(2\pi f_R t - 120^{\circ})\sin(2\pi f_R t + \varphi - 120^{\circ}) + \\ &+ \sin(2\pi f_R t + 120^{\circ})\sin(2\pi f_R t + \varphi - 120^{\circ})] = \ldots = 3U_{PN} I_{OP} \cos\varphi \end{aligned}$$

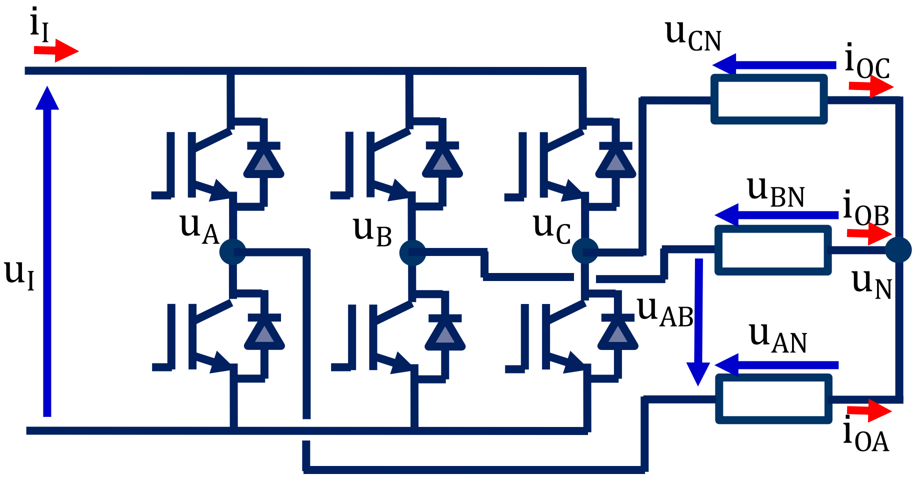
$$u_I(t) = U_I \qquad p_I(t) = u_I(t) \cdot i_I(t)$$

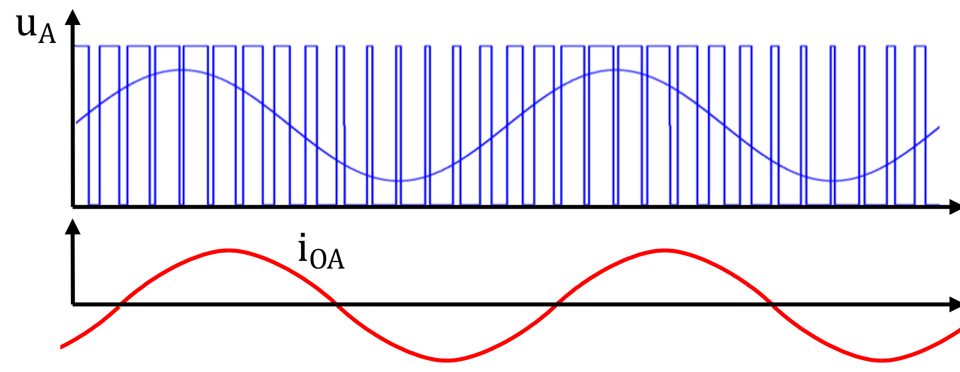
The filter has no effect at line frequencies!!!

$$p_I(t) = p_O(t)$$

$$\boxed{i_I(t) = \frac{3U_{PN} I_{OP} \cos\varphi}{U_I}}$$

Three-Phase PWM Inverter





Input current:

$$u_{AN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t) \qquad i_{OA}(t) = I_{OA} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi)$$

$$u_{BN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t - 120^o) \qquad i_{OB}(t) = I_{OB} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi - 120^o)$$

$$u_{CN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + 120^o) \qquad i_{OC}(t) = I_{OC} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + \varphi + 120^o)$$

$$p_O(t) = u_{AN}(t) \cdot i_{OA}(t) + u_{BN}(t) \cdot i_{OB}(t) + u_{CN}(t) \cdot i_{OC}(t)$$

$$p_O(t) = U_{PN} I_{OP} \cdot [\sin(2\pi f_R t)\sin(2\pi f_R t + \varphi) + \\ + \sin(2\pi f_R t - 120^o)\sin(2\pi f_R t + \varphi - 120^o) + \\ + \sin(2\pi f_R t + 120^o)\sin(2\pi f_R t + \varphi - 120^o)] = \ldots = 3 U_{PN} I_{OP} \cos\varphi$$

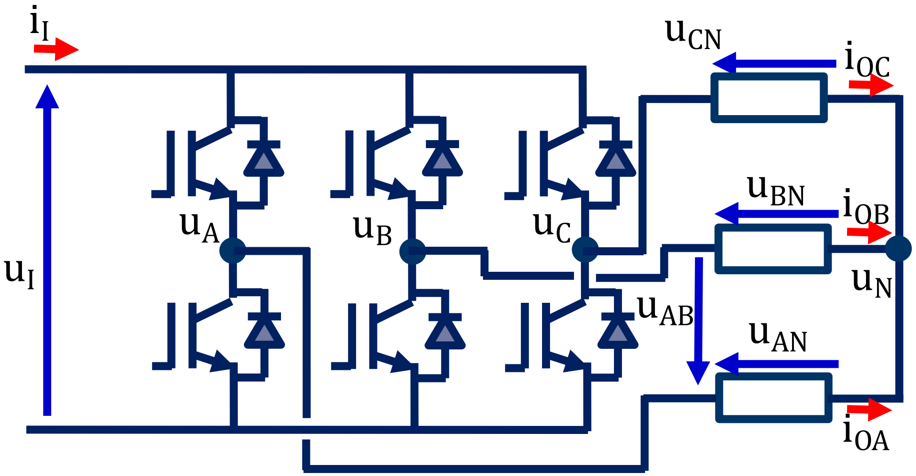
$$u_I(t) = U_I \qquad p_I(t) = u_I(t) \cdot i_I(t)$$

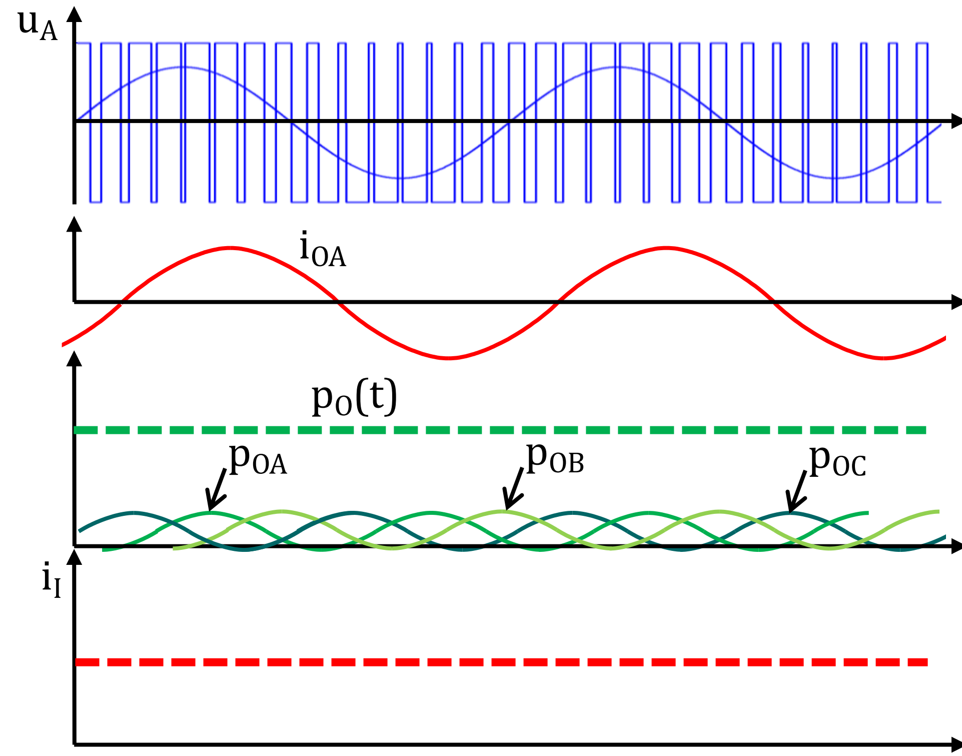
The filter has no effect at line frequencies!!!

$$p_I(t) = p_O(t)$$

$$i_I(t) = \frac{3 U_{PN} I_{OP} \cos\varphi}{U_I}$$

Three-Phase PWM Inverter





Input current:

$$u_{AN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t) \qquad i_{OA}(t) = I_{OA} \cdot \sin(2 \cdot \pi \cdot$$

$$u_{BN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t - 120^{o}) \qquad i_{OB}(t) = I_{OB} \cdot \sin(2 \cdot \pi \cdot$$

$$u_{CN}(t) = U_{PN} \cdot \sin(2 \cdot \pi \cdot f_R \cdot t + 120^{o}) \qquad i_{OC}(t) = I_{OC} \cdot \sin(2 \cdot \pi \cdot$$

$$p_O(t) = u_{AN}(t) \cdot i_{OA}(t) + u_{BN}(t) \cdot i_{OB}(t) + u_{CN}(t) \cdot i_{OC}(t)$$

$$p_O(t) = U_{PN} I_{OP} \cdot [\sin(2\pi f_R t)\sin(2\pi f_R t + \varphi) +$$
$$+ \sin(2\pi f_R t - 120^{o})\sin(2\pi f_R t + \varphi - 120^{o}) +$$
$$+ \sin(2\pi f_R t + 120^{o})\sin(2\pi f_R t + \varphi - 120^{o})] = \ldots = 3 U_{PN} I_{OP} \cos\varphi$$

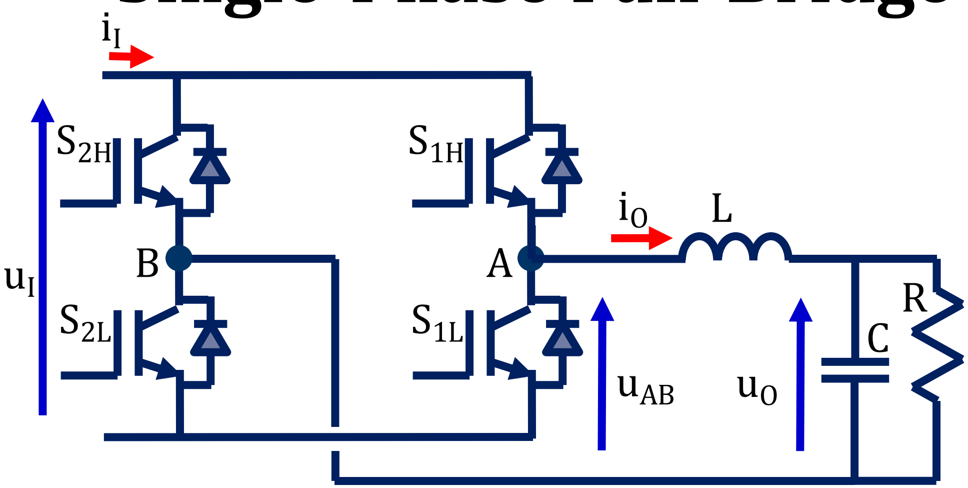
$$u_I(t) = U_I \qquad p_I(t) = u_I(t) \cdot i_I(t)$$

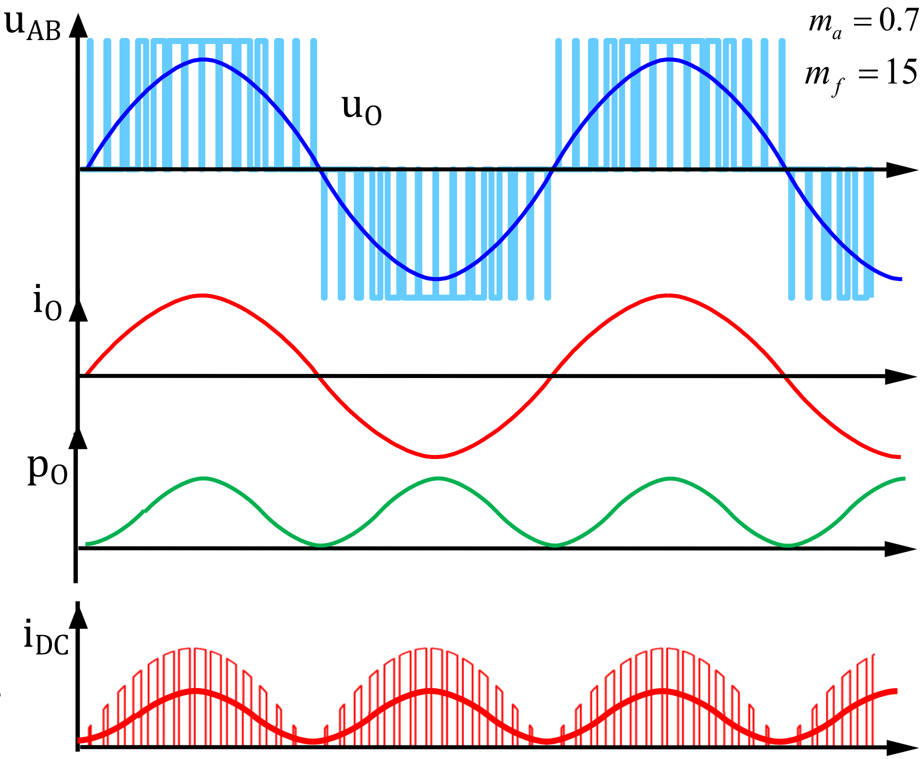
The filter has no effect at line frequencies!!!

$$p_I(t) = p_O(t)$$

$$i_I(t) = \frac{3 U_{PN} I_{OP} \cos\varphi}{U_I}$$

Single-Phase Full-Bridge PWM Inverter





Size of components:

Voltage stress in Switches: $u_{CE\langle PEAK\rangle} = u_I$

Current stress in Switches: $i_{C\langle PEAK\rangle} = i_{O\langle PEAK\rangle}$

Input current:

$$u_O(t) = \langle u_{AB}(t)\rangle_{T_S} = U_I \cdot m_a \cdot \sin(2\cdot\pi\cdot f_R \cdot t) \qquad i_O(t) = \frac{U_I}{R}\cdot m_a \cdot \sin(2\cdot\pi\cdot f_R\cdot t)$$

$$p_O(t) = \frac{U_I^{\,2}}{R}\cdot m_a^{\,2}\cdot \sin^2(2\cdot\pi\cdot f_R\cdot t) \qquad p_O(t) = \frac{U_I^{\,2}}{R}\cdot m_a^{\,2}\,\frac{1-\cos(2\cdot\pi\cdot 2\cdot f_R\cdot t)}{2}$$

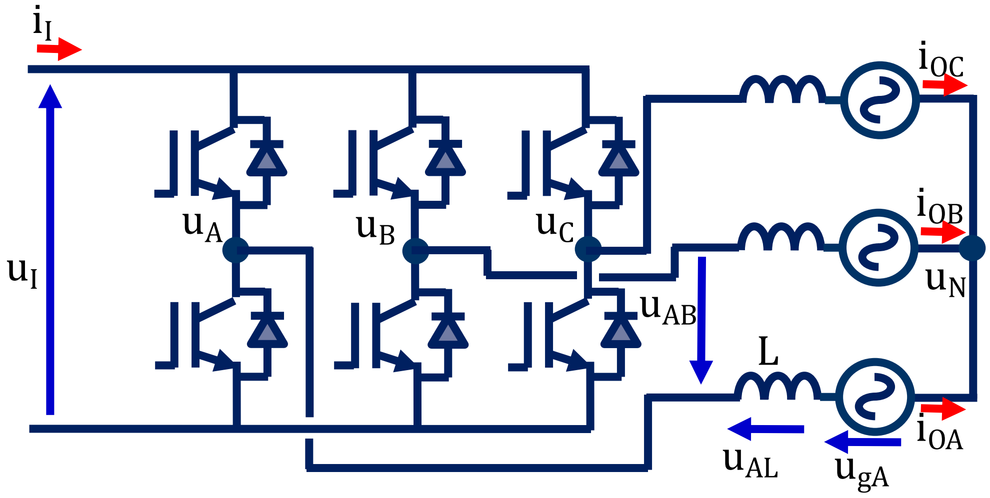
$$u_I(t) = U_I \qquad p_I(t) = u_I(t)\cdot i_I(t)$$

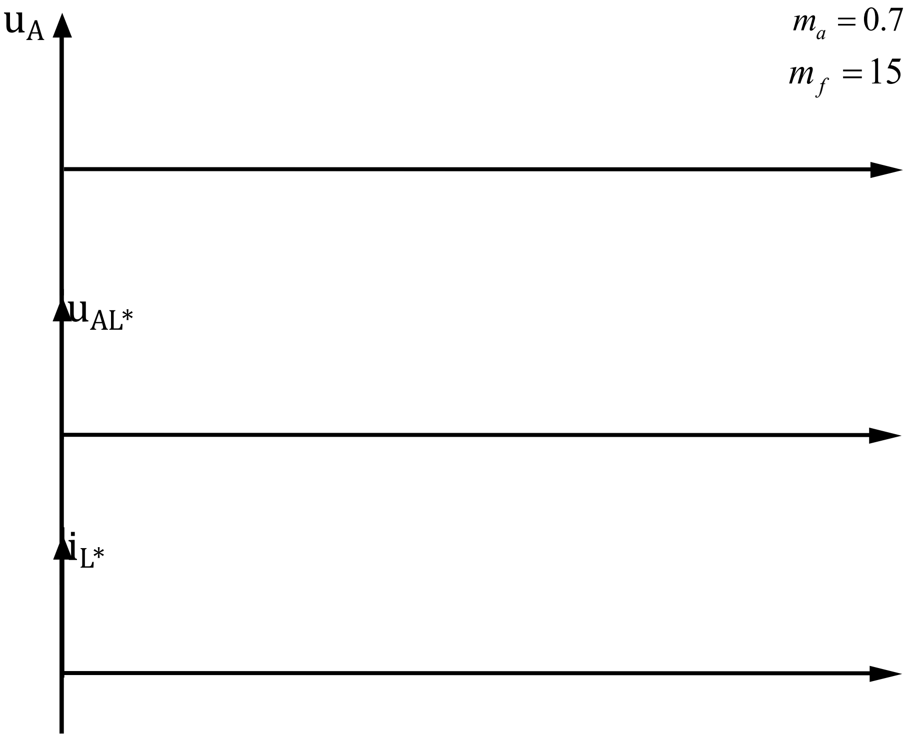
The filter has no effect at line frequencies!!!

$$p_I(t) = p_O(t)$$

$$i_I(t) = \frac{U_I}{R}\cdot m_a^{\,2}\,\frac{1-\cos(2\cdot\pi\cdot 2\cdot f_R\cdot t)}{2}$$

Three-Phase PWM Inverter

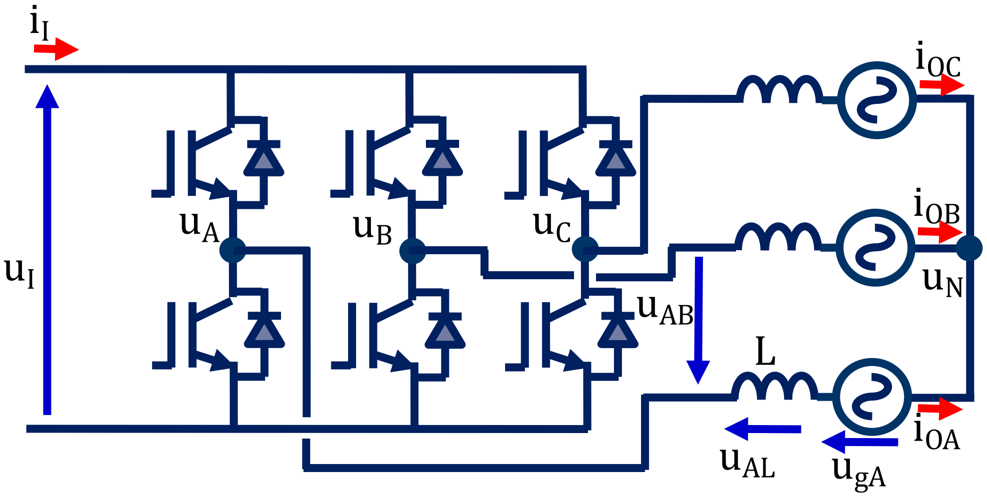


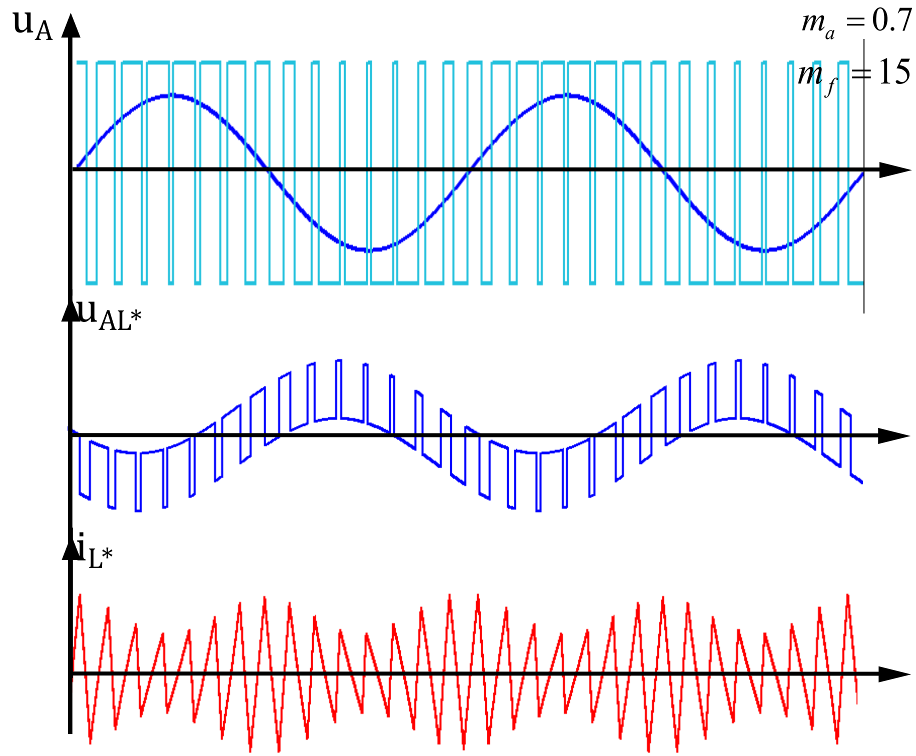


Output current ripple and switching frequency

Consider as a load an AC motor (or the grid line).

Three-Phase PWM Inverter



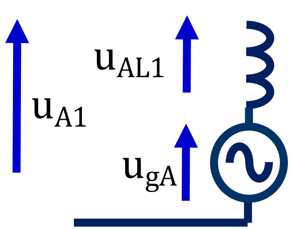


Output current ripple and switching frequency

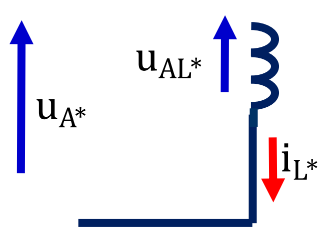
Consider as a load an AC motor (or the grid line).

Superposition:

1st harmonic:



Rest of harmonics:

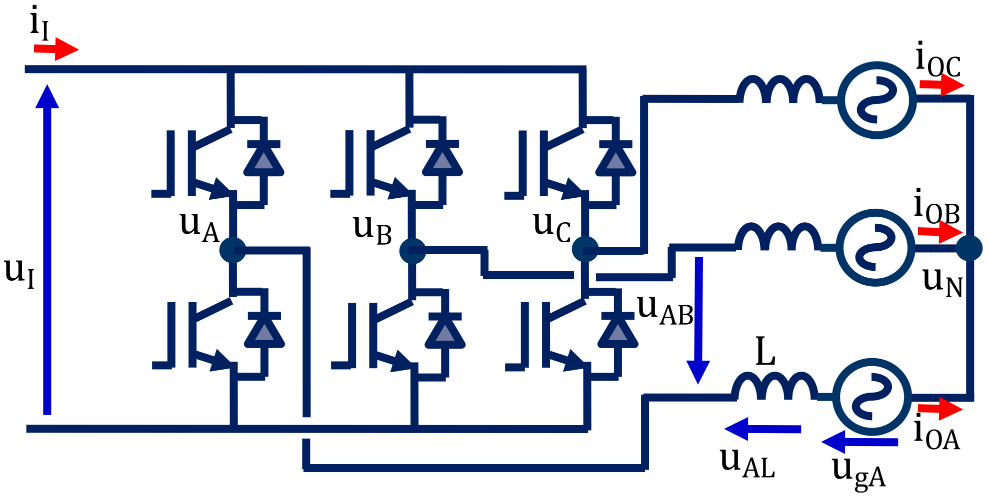


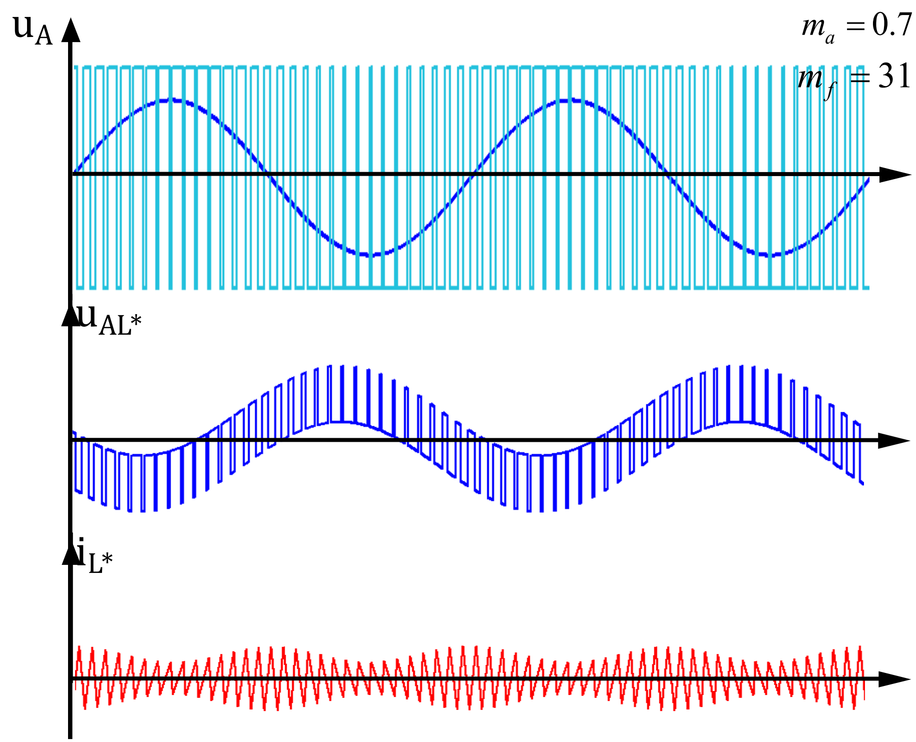
$$u_{A^*}(t) = u_A - u_{A1}$$

$$u_{AL^*}(t) = L \cdot \frac{di_{L^*}}{dt}$$

This current ripple implies losses (no active power delivered)

Three-Phase PWM Inverter



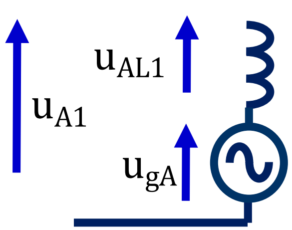


Output current ripple and switching frequency

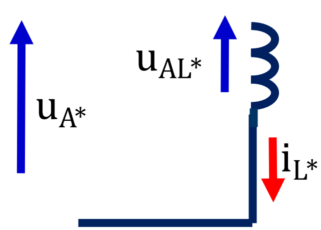
Consider as a load an AC motor (or the grid line).

Superposition:

1st harmonic:



Rest of harmonics:

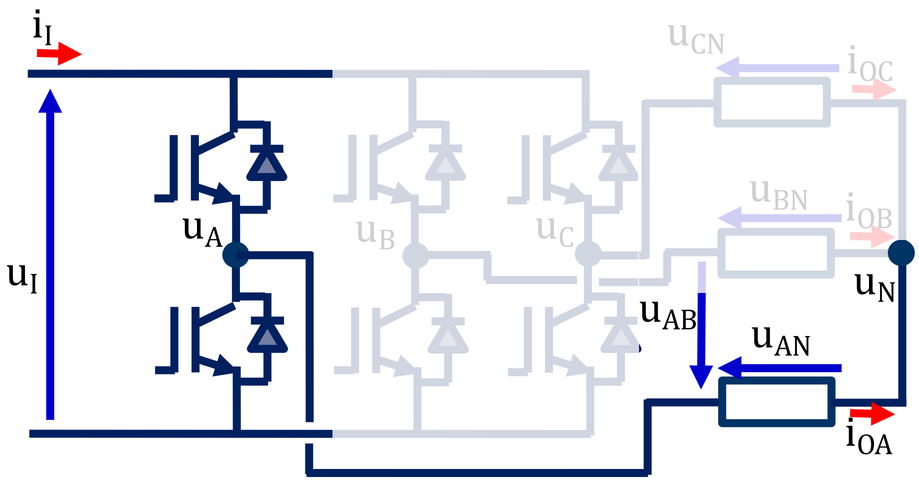


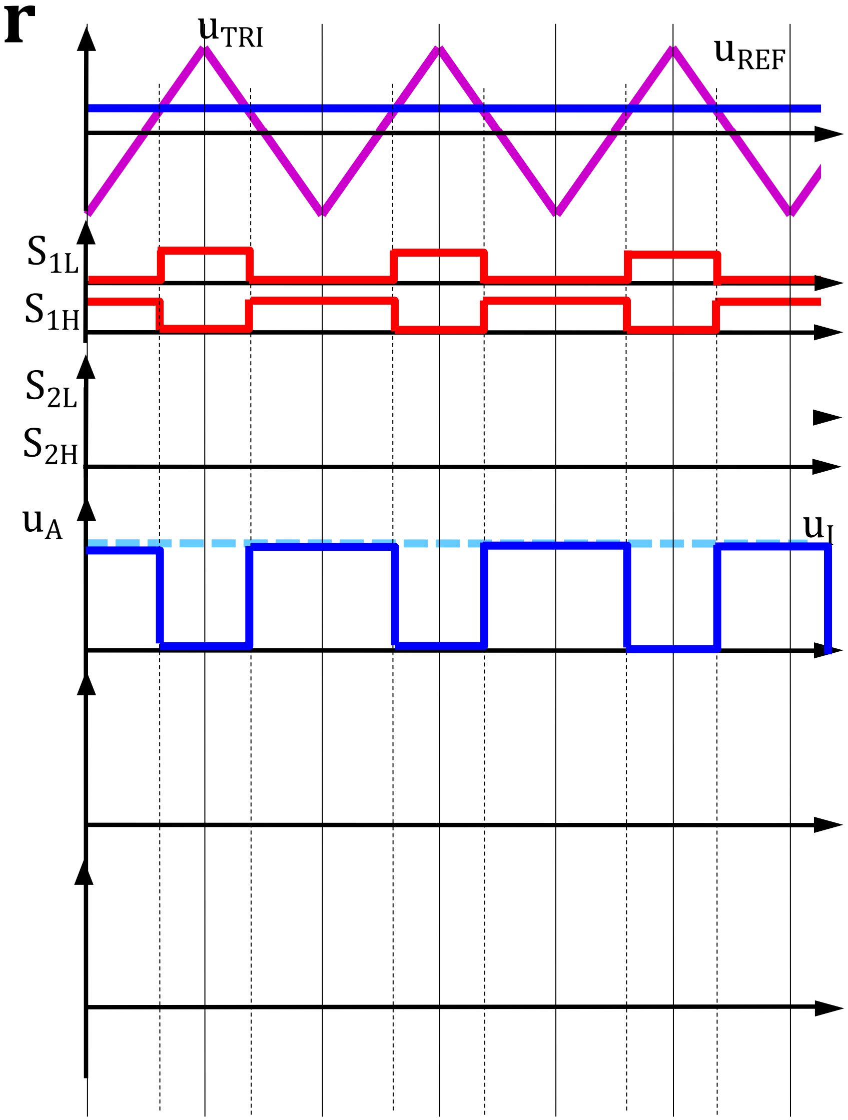
$$u_{A*}(t) = u_A - u_{A1}$$

$$u_{AL*}(t) = L \cdot \frac{di_{L*}}{dt}$$

This current ripple implies losses (no active power delivered)

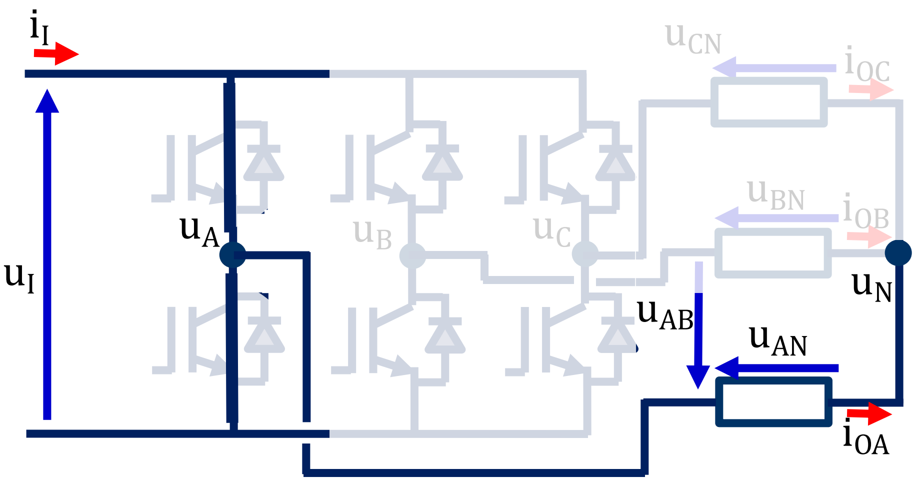
Three-Phase PWM Inverter

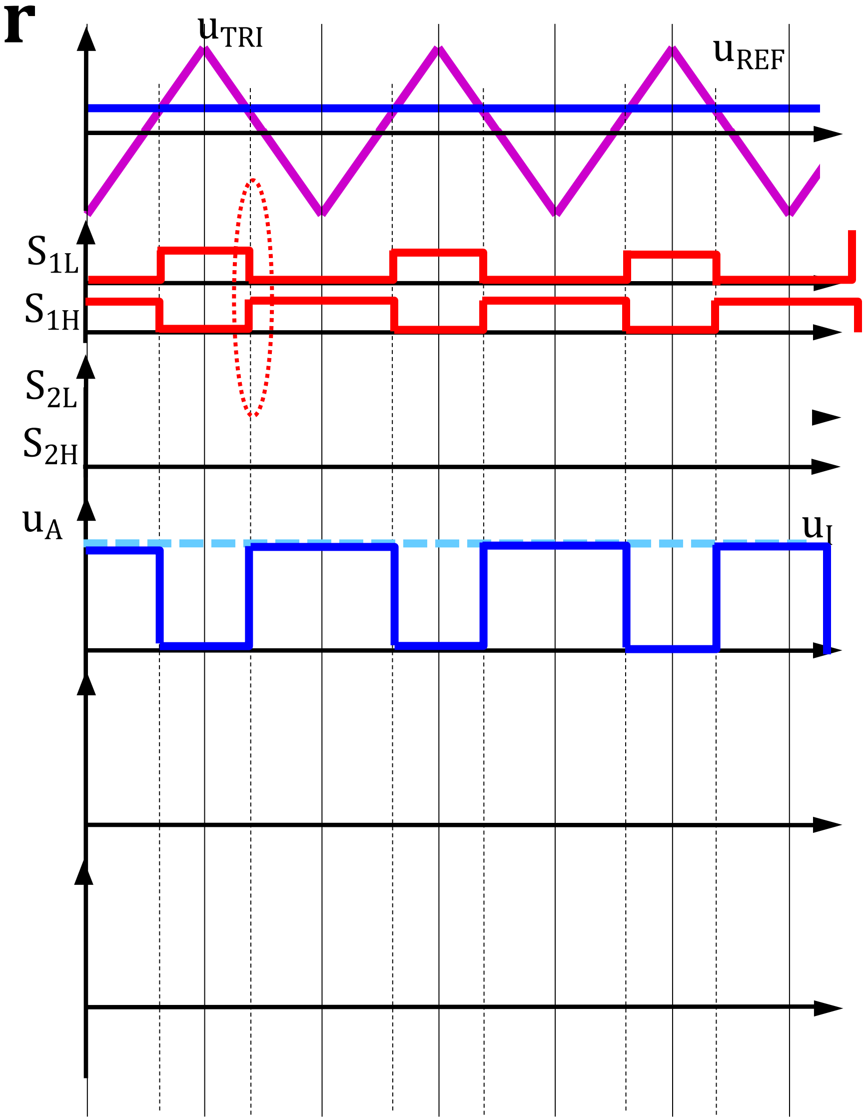




Need for Dead Times

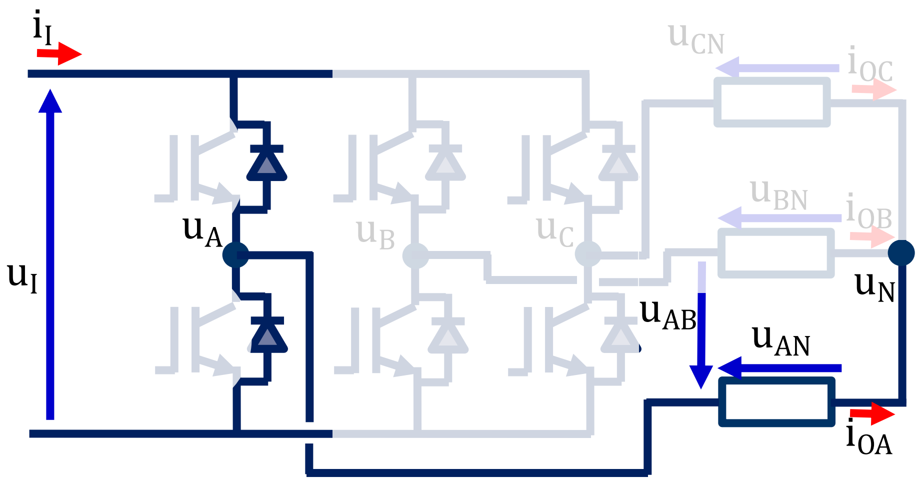
Three-Phase PWM Inverter

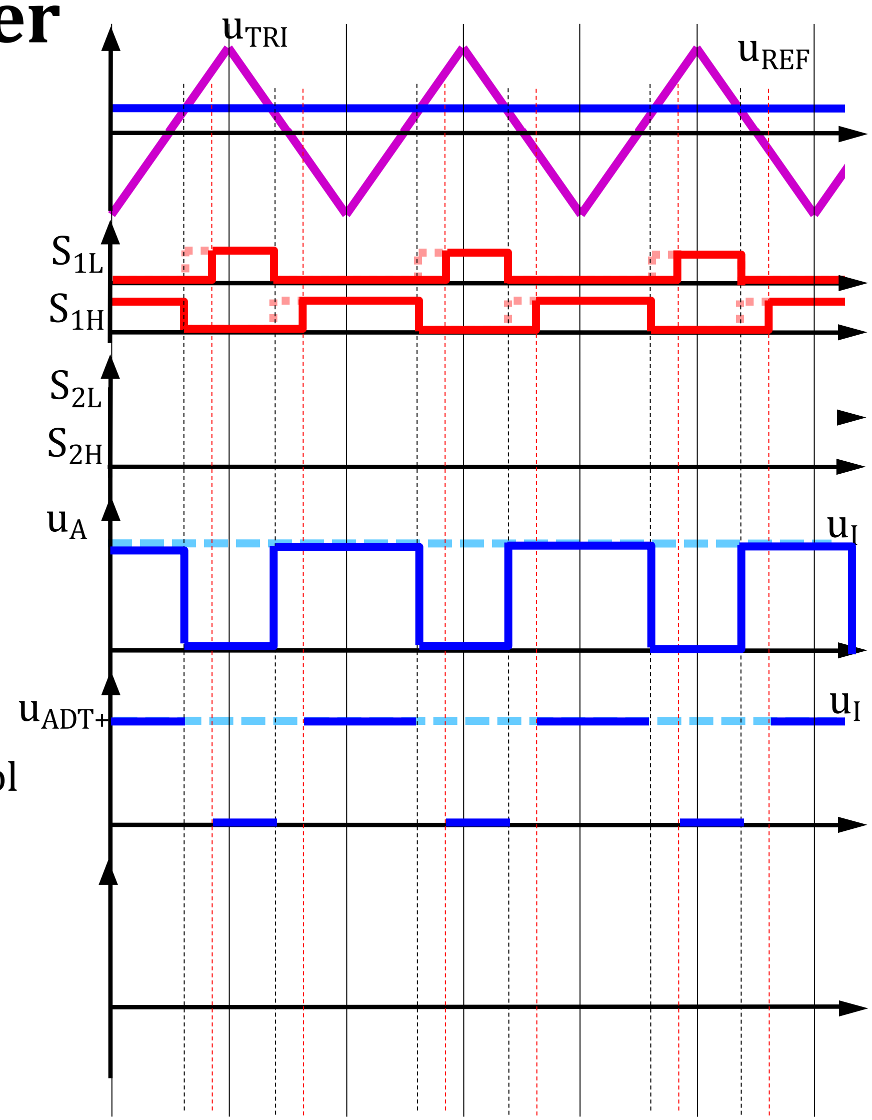




Need for Dead Times:
If both transistors in a leg are switched on simultaneously, a short circuit appears…

Three-Phase PWM Inverter





Need for Dead Times:

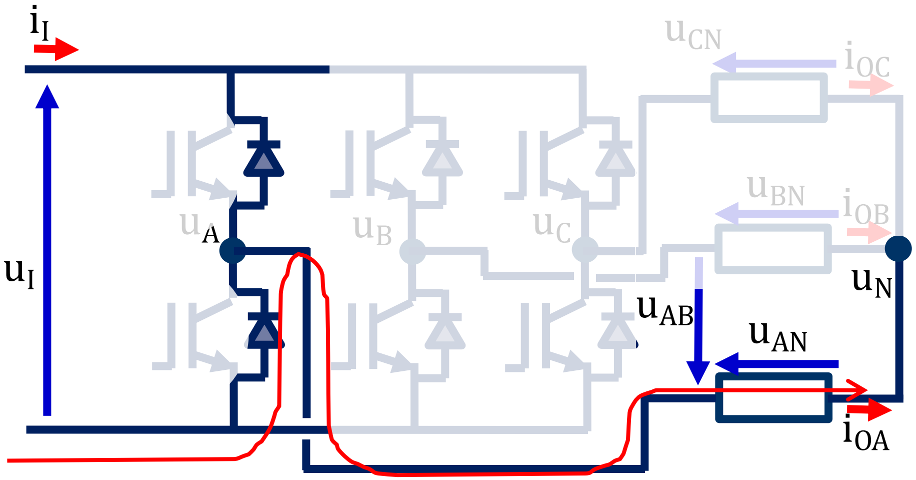
Dead times avoid these cross-conduction problems

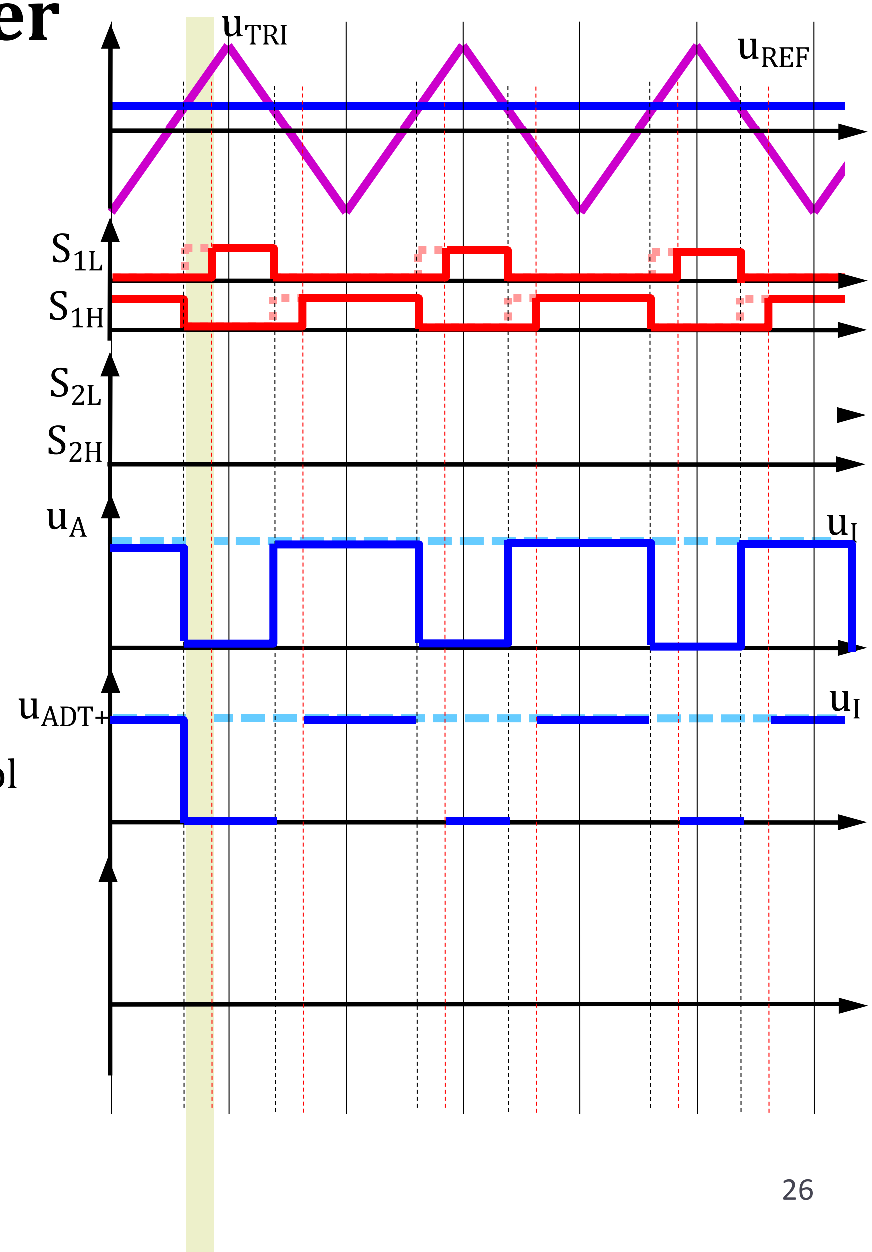
Effect of Dead Times:

Consider a dead time at the rising edge of the control waveforms.

The voltage during the blank times depends on the direction of the line current i_{OA} !!!

Three-Phase PWM Inverter





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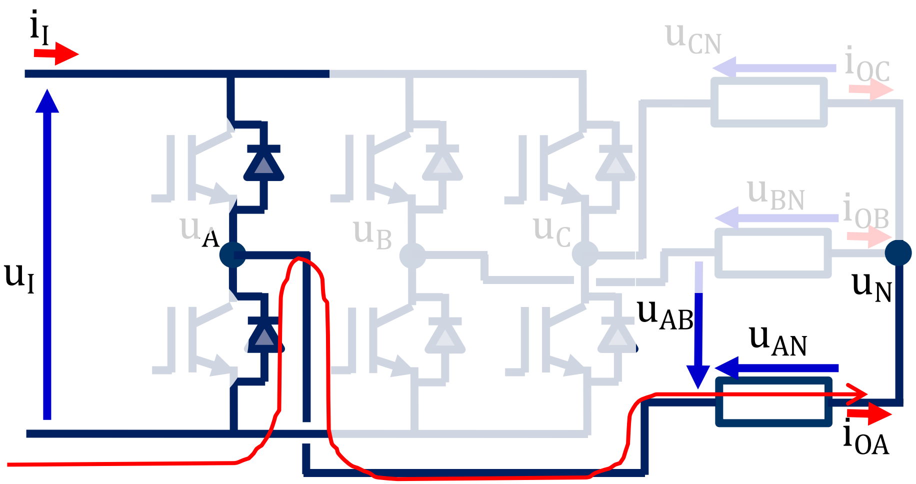
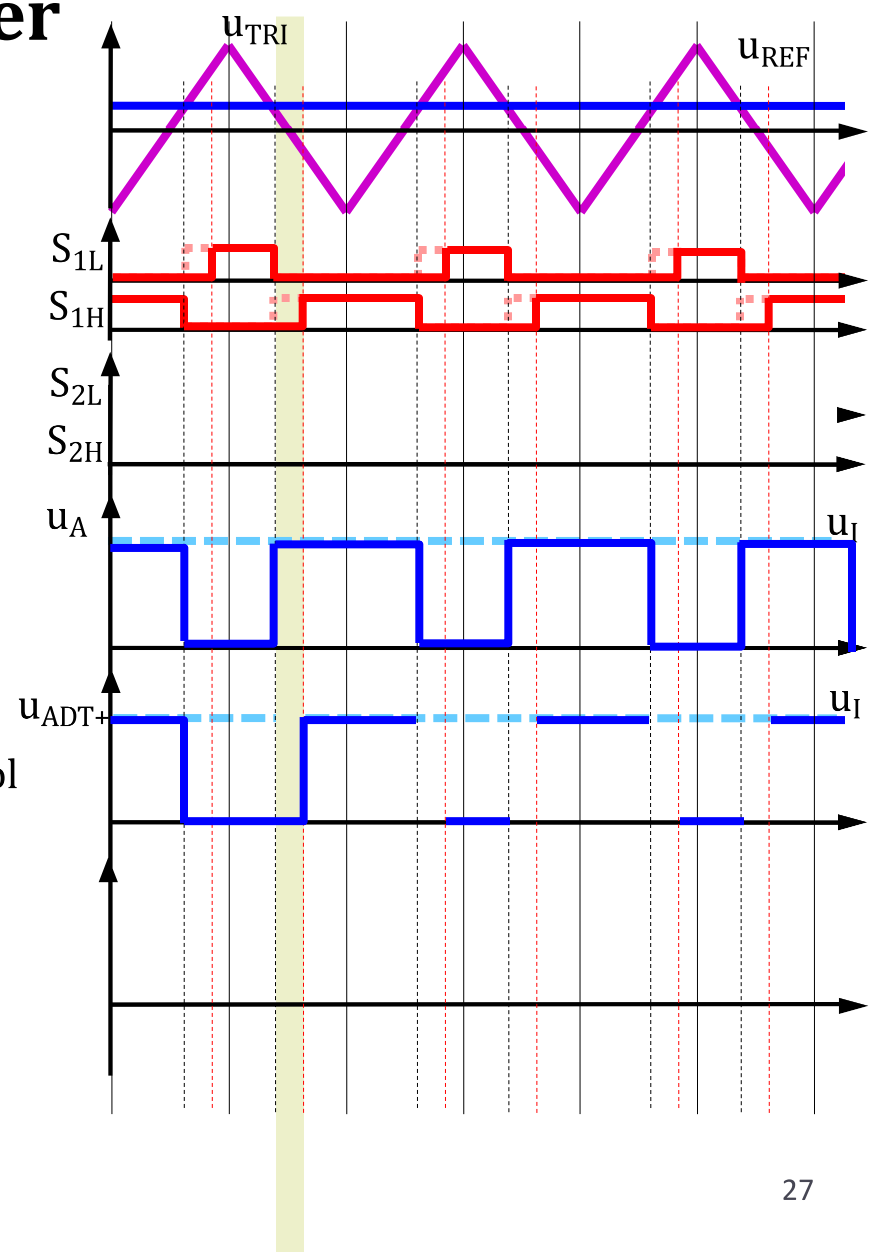
The voltage during the blank times depends on the direction of the line current i_{OA} !!!

Considering **POSITIVE** current:

Three-Phase PWM Inverter





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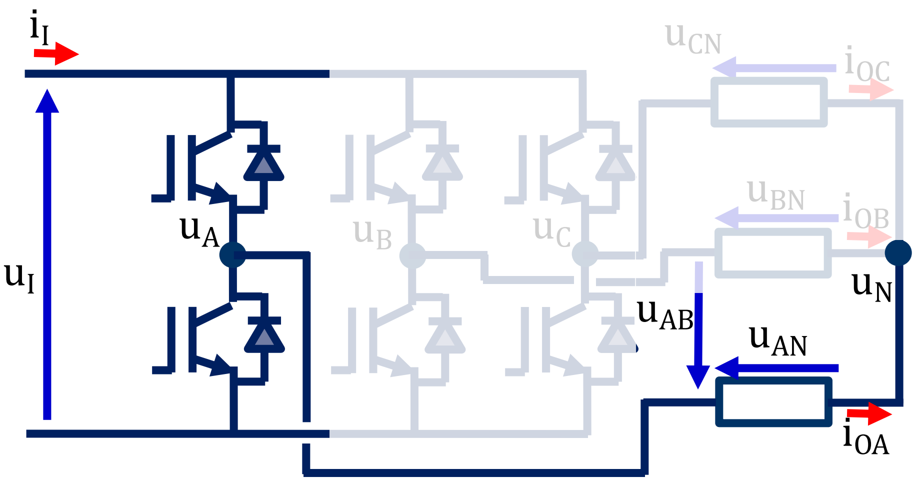
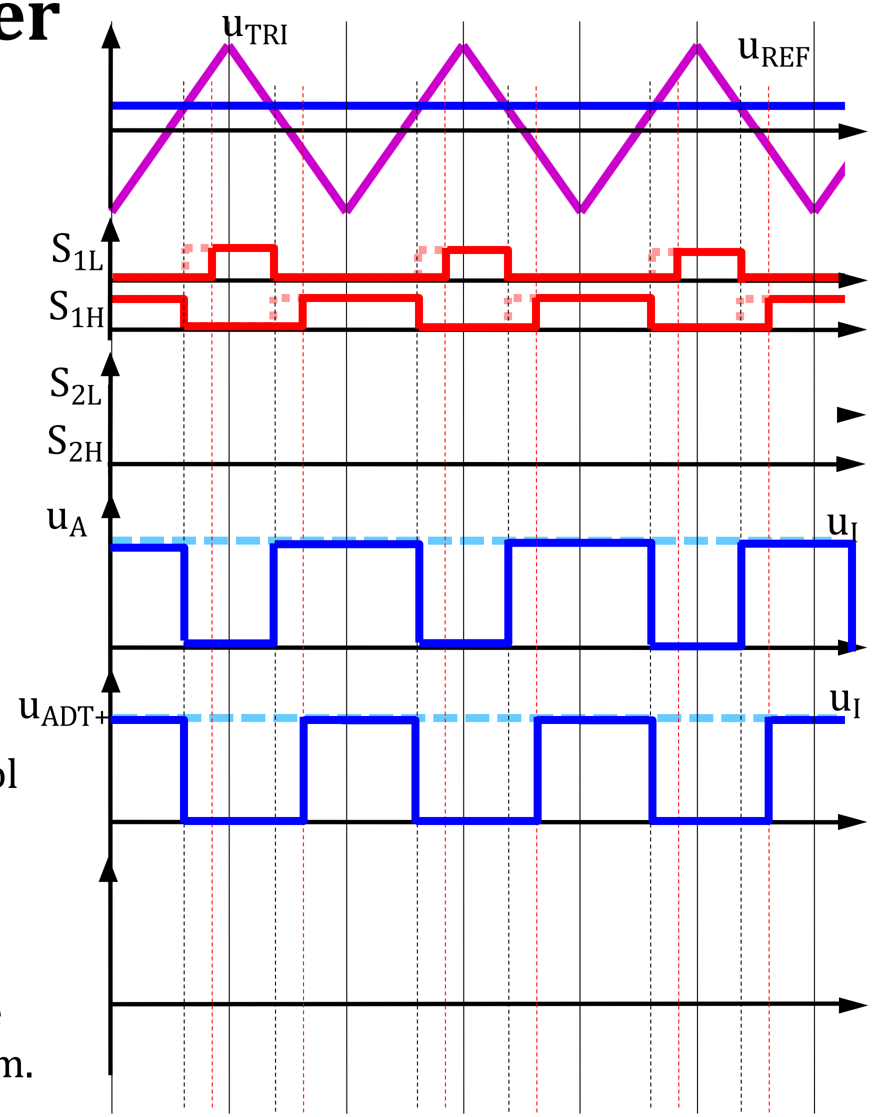
Three-Phase PWM Inverter



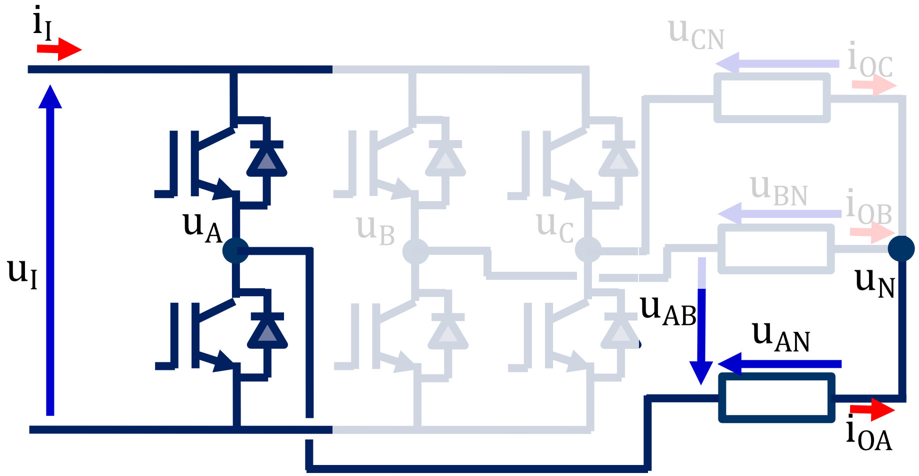


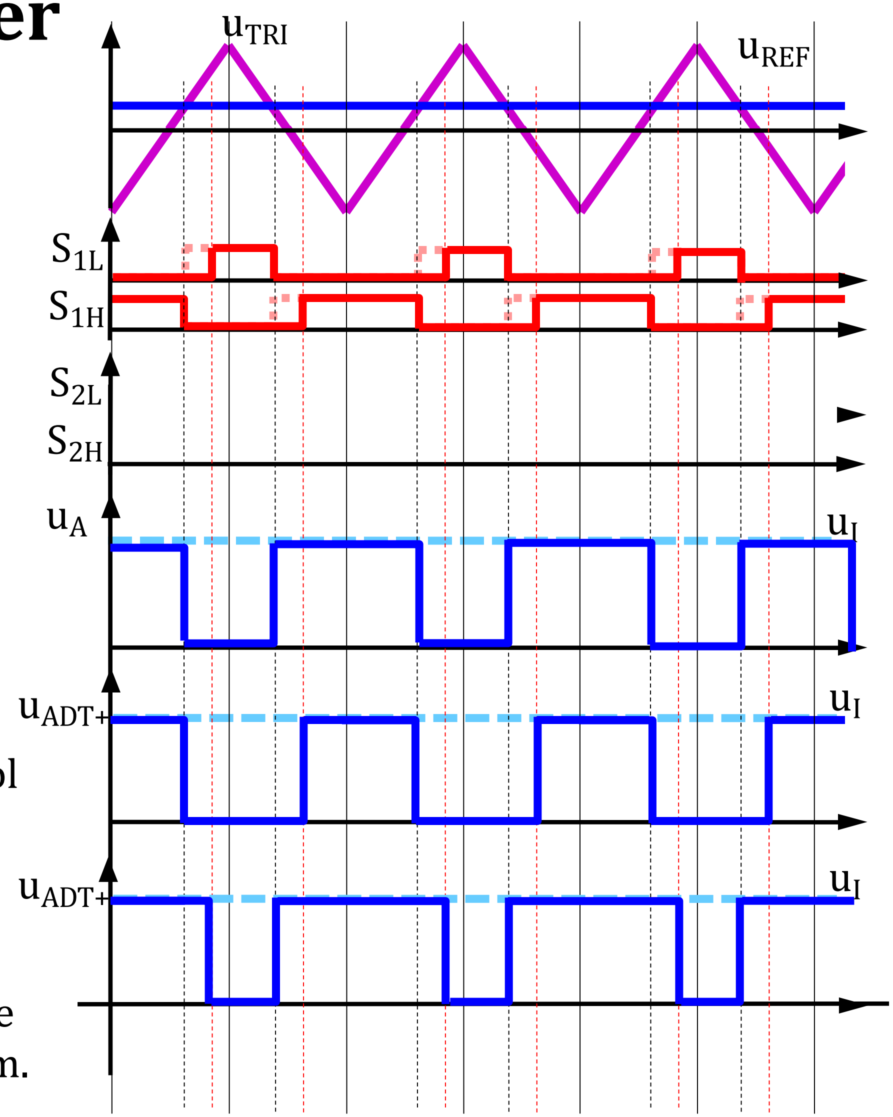
Need for Dead Times:
Dead times avoid these cross-conduction problems

Effect of Dead Times:
Consider a dead time at the rising edge of the control waveforms.
The voltage during the blank times depends on the direction of the line current i_{OA} !!!

Considering **POSITIVE** current: The output phase voltage is **smaller** than the ideal voltage waveform.

Three-Phase PWM Inverter



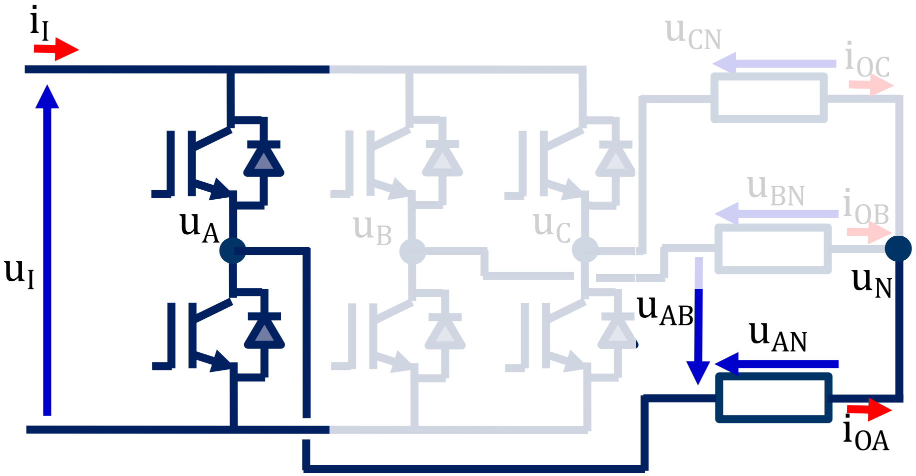


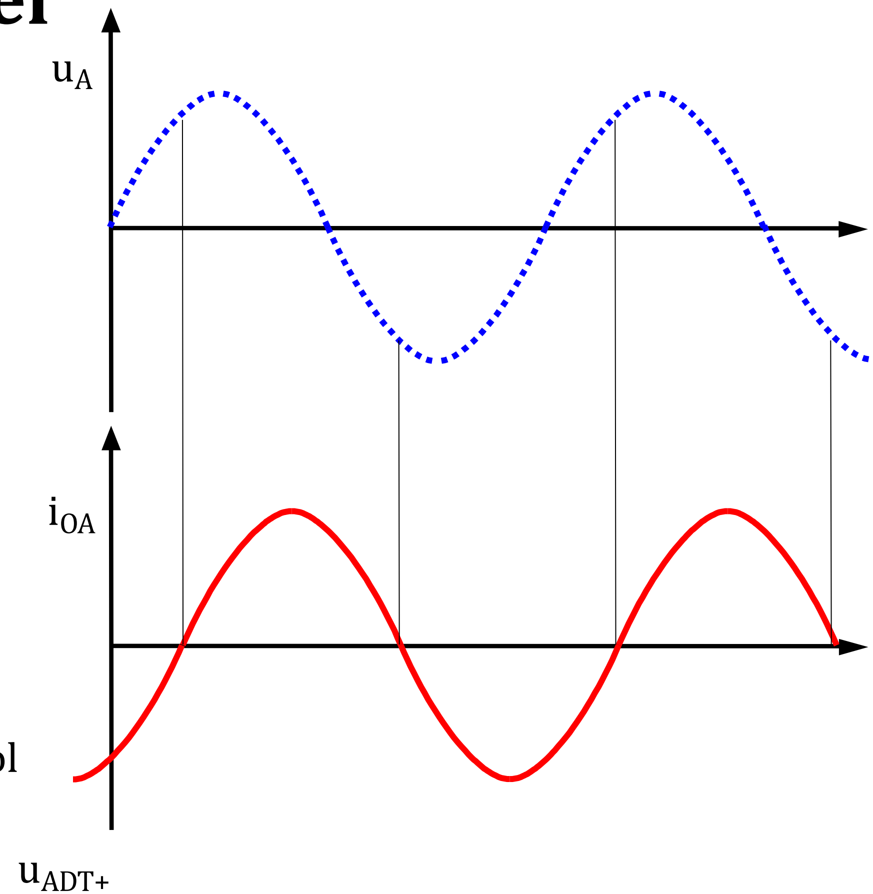
Need for Dead Times:
Dead times avoid these cross-conduction problems

Effect of Dead Times:
Consider a dead time at the rising edge of the control waveforms.
The voltage during the blank times depends on the direction of the line current i_{OA} !!!

Considering **NEGATIVE** current: The output phase voltage is **greater** than the ideal voltage waveform.

Three-Phase PWM Inverter



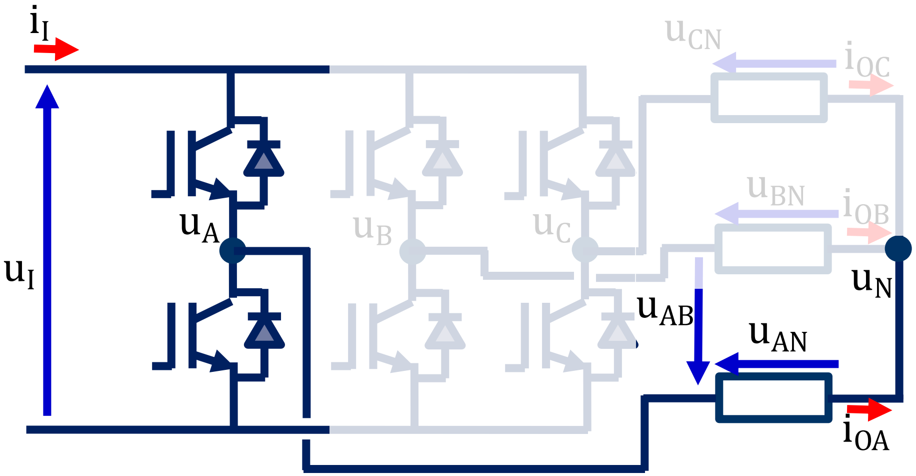


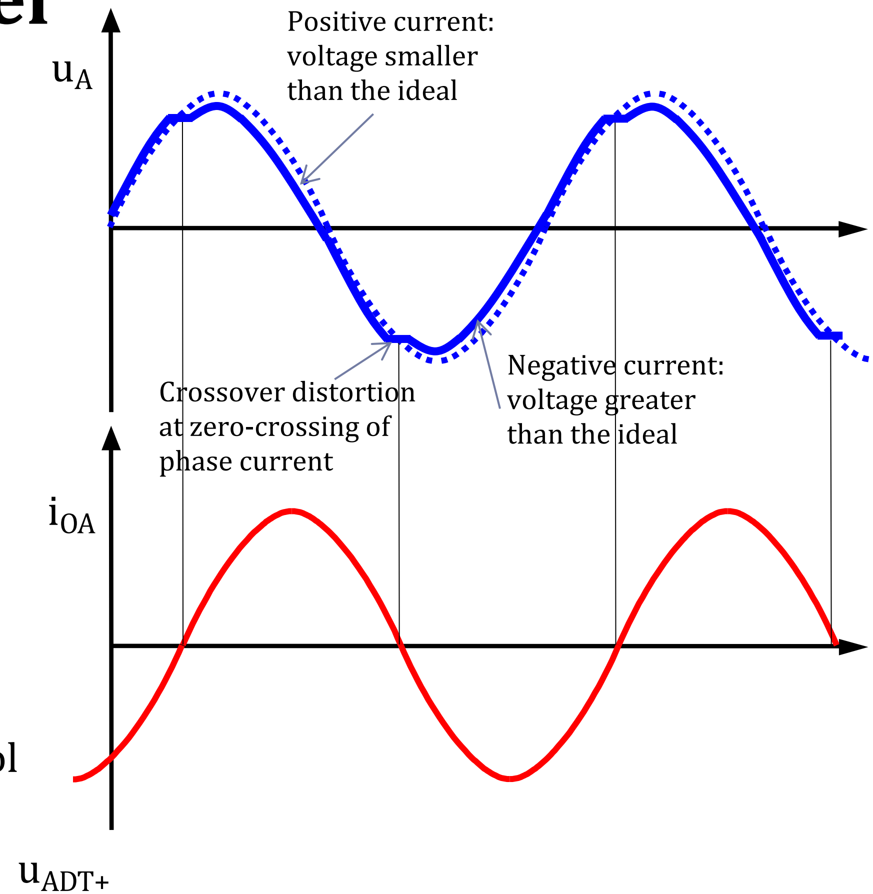
Need for Dead Times:
Dead times avoid these cross-conduction problems

Effect of Dead Times:
Consider a dead time at the rising edge of the control waveforms.
The voltage during the blank times depends on the direction of the line current i_{OA} !!!

The dead time implies a distortion in the output voltage waveform, that must be takeninto account by the control stage.

Three-Phase PWM Inverter





Need for Dead Times:
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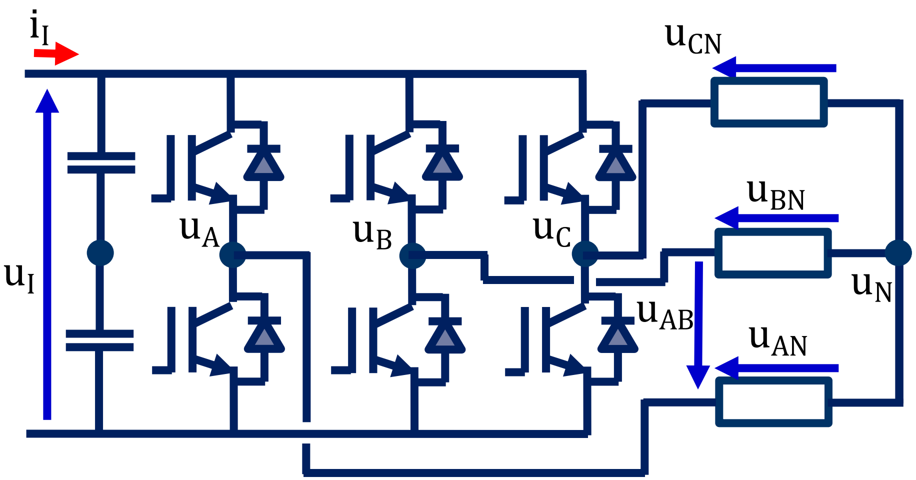
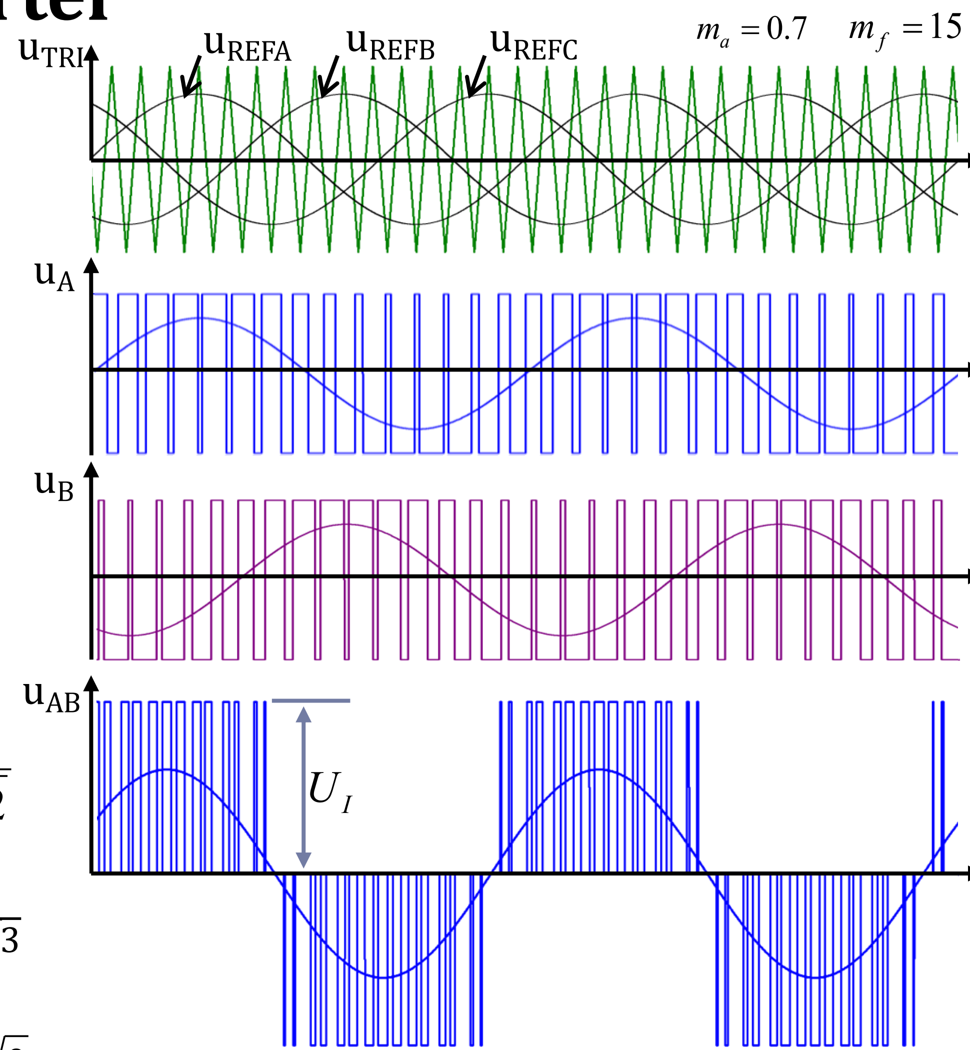
Limitations of the Sine-Triangle PWM Modulation

Three-Phase PWM Inverter





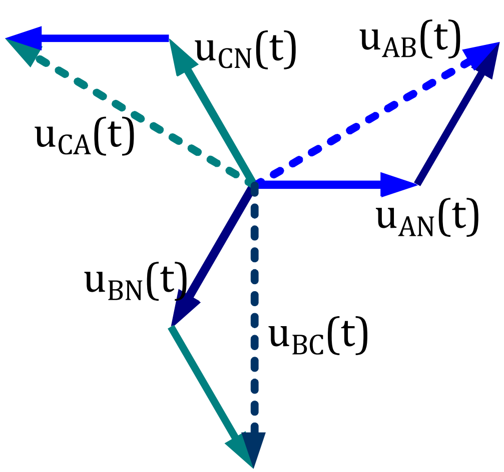
Which is the maximum output voltage reachable?

$$|u_{AN}(t)| = m_a \frac{U_I}{2}$$

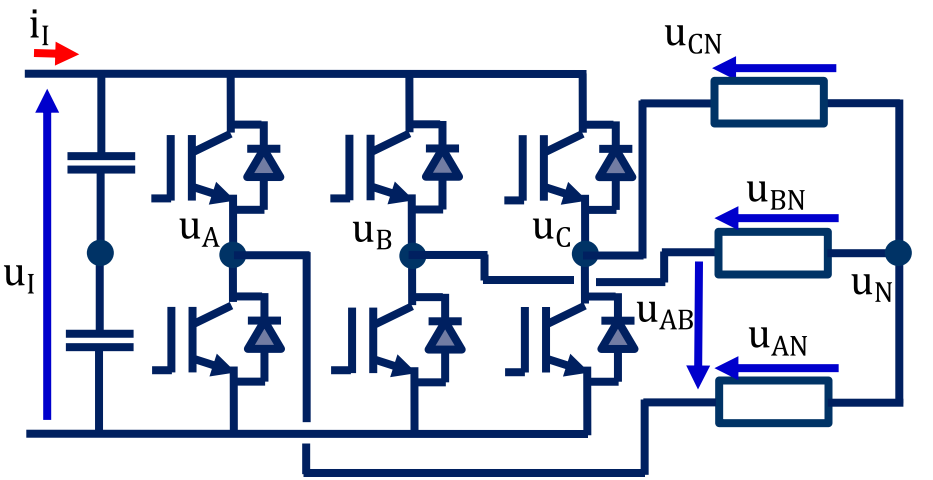
$$u_{AN\langle RMS\rangle} = m_a \frac{U_I}{2\sqrt{2}}$$

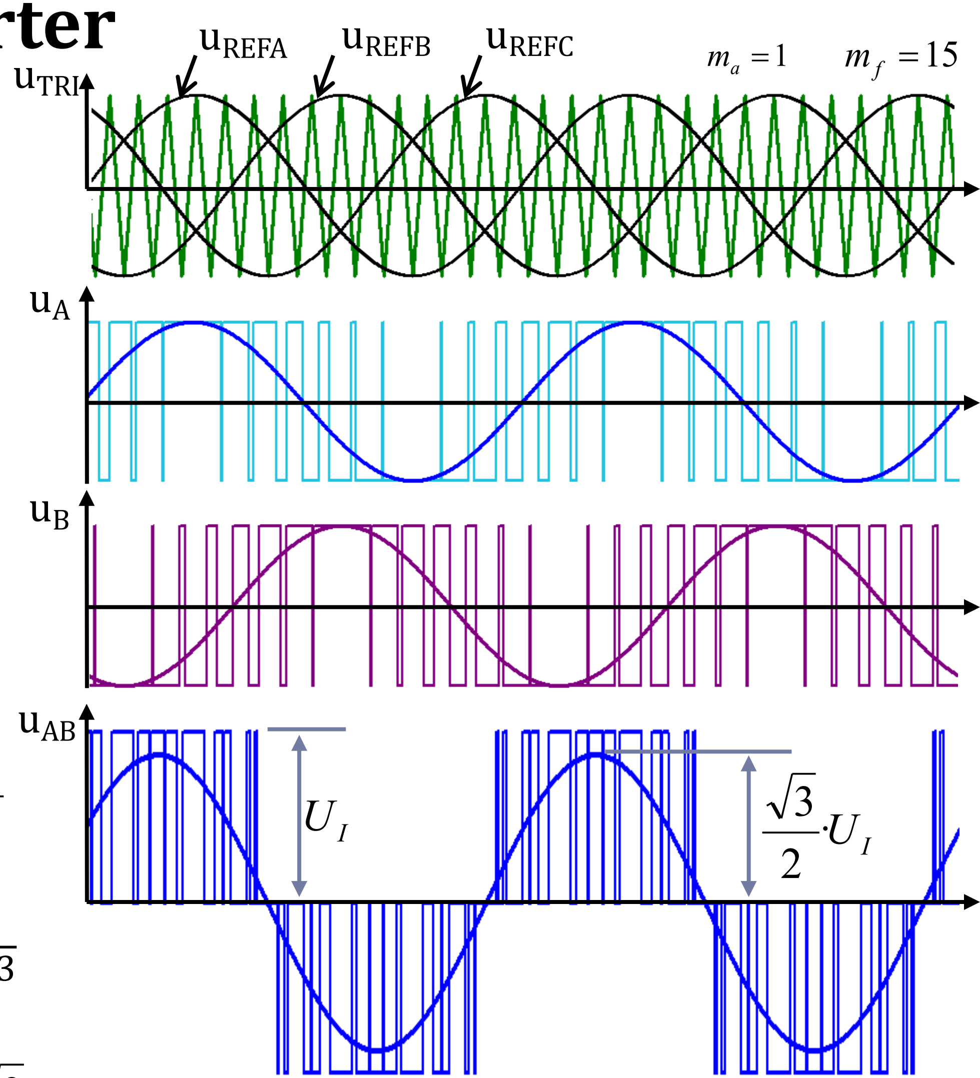
$$|u_{AB}(t)| = \frac{m_a \cdot U_I}{2} \cdot \sqrt{3}$$

$$u_{AB\langle RMS\rangle} = m_a \frac{U_I\sqrt{3}}{2\sqrt{2}}$$



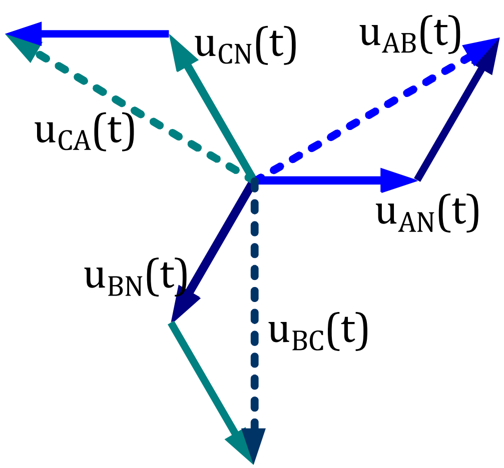
Three-Phase PWM Inverter





Which is the maximum output voltage reachable?

m_a=1



$$|u_{AN}(t)| = m_a \frac{U_I}{2}$$

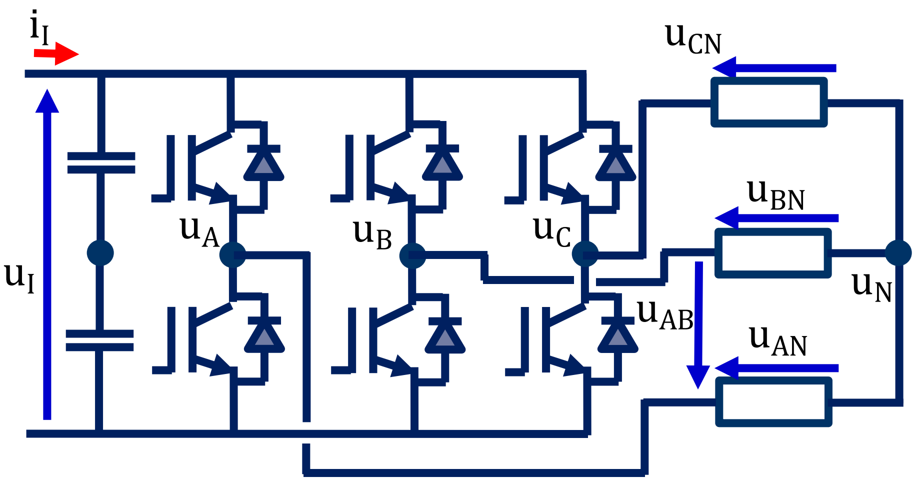
$$u_{AN\langle RMS\rangle} = m_a \frac{U_I}{2\sqrt{2}}$$

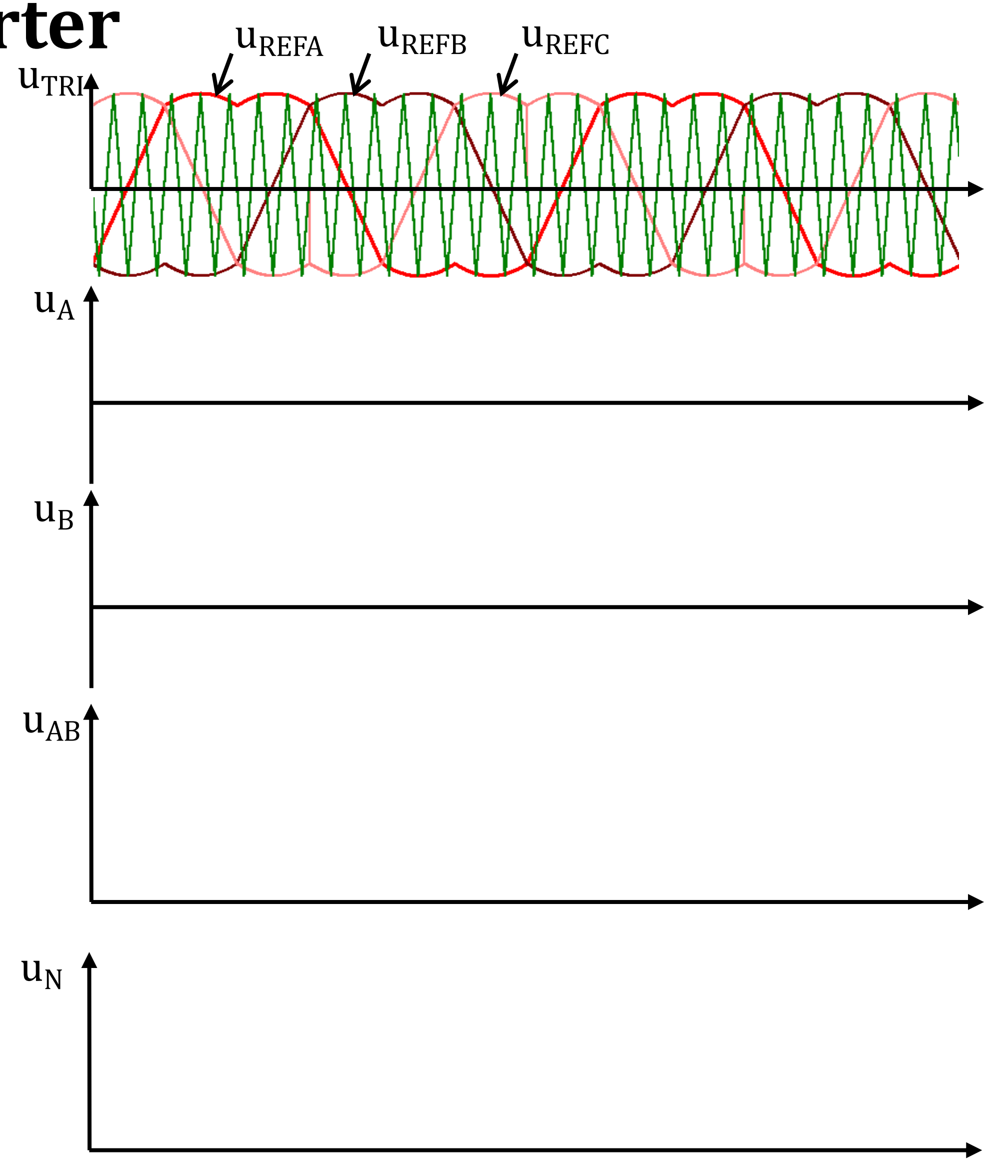
$$|u_{AB}(t)| = \frac{m_a \cdot U_I}{2} \cdot \sqrt{3}$$

$$u_{AB\langle RMS\rangle} = m_a \frac{U_I\sqrt{3}}{2\sqrt{2}}$$

Is it possible to reach a higher line-to-line voltage?

Three-Phase PWM Inverter

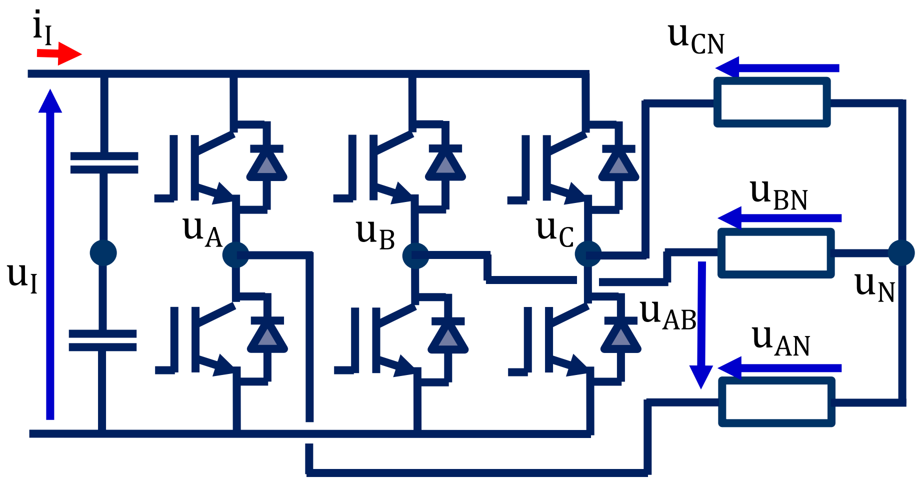


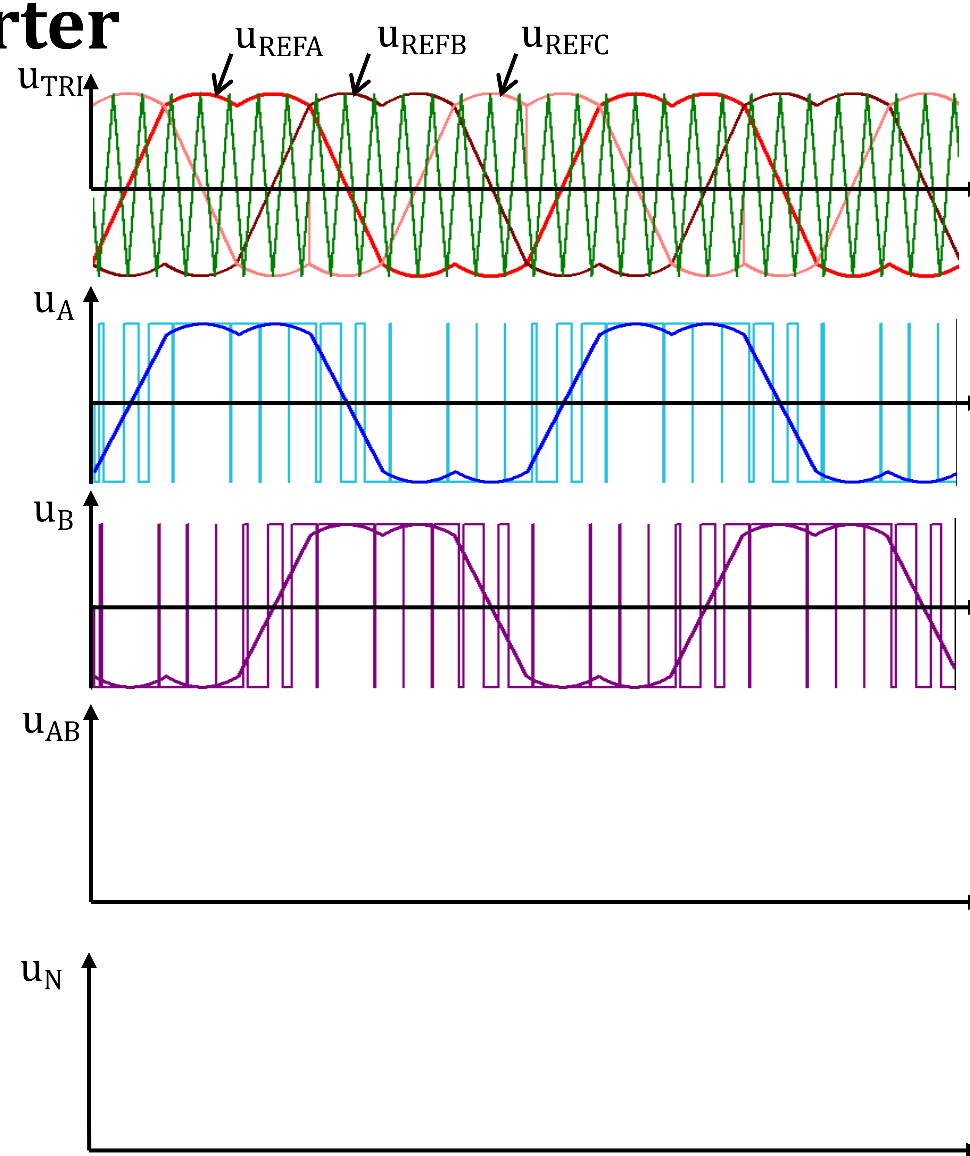


Which is the maximum output voltage?

Consider modulating waveforms different than pure sine waves.

Three-Phase PWM Inverter

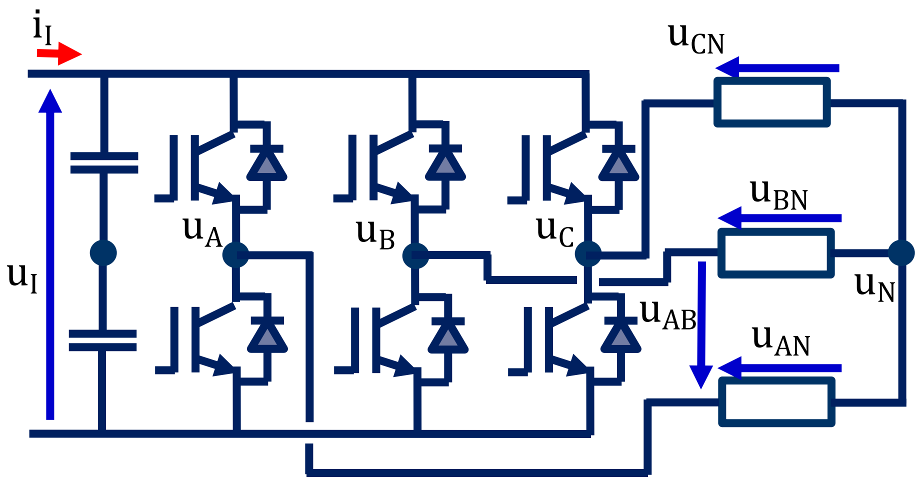


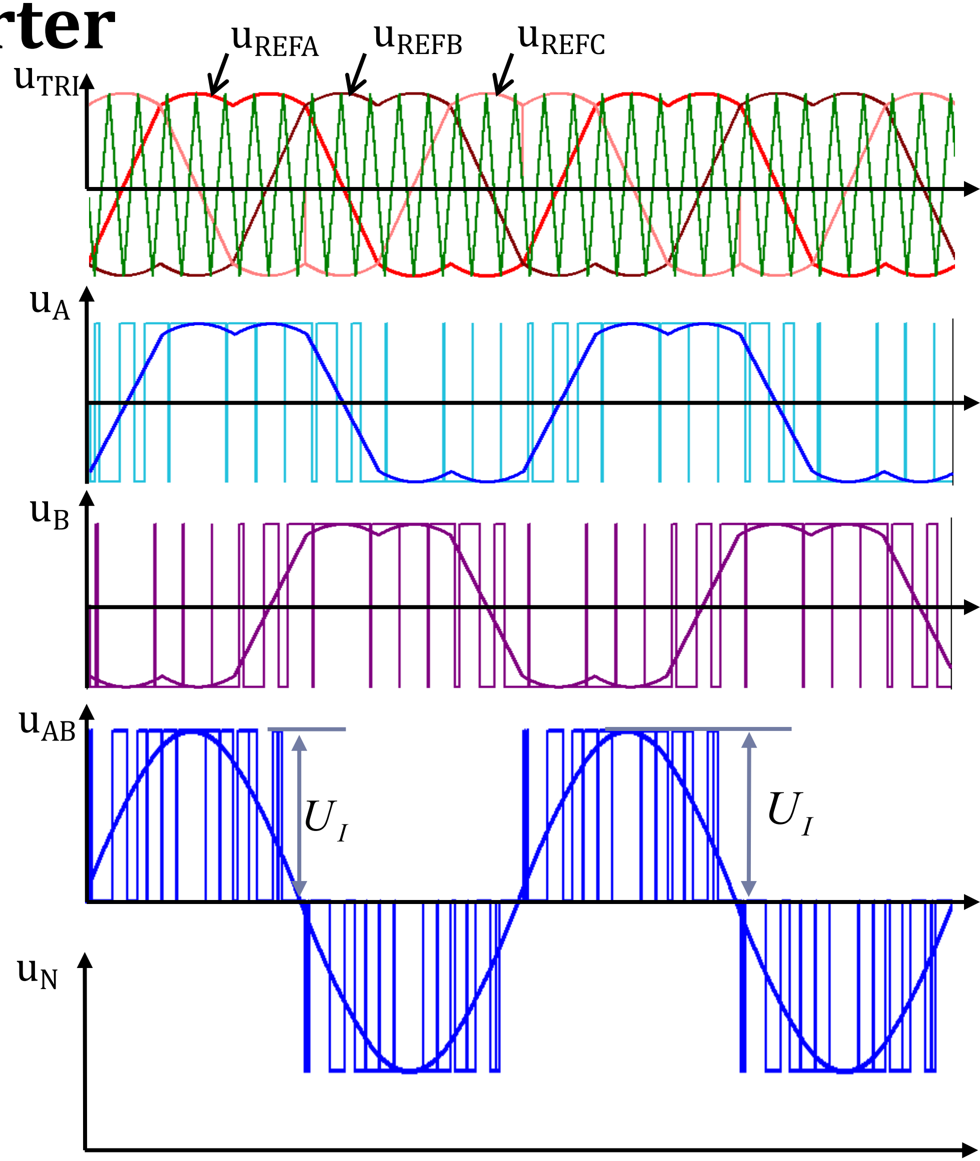


Which is the maximum output voltage?

Consider modulating waveforms different than pure sine waves.

Three-Phase PWM Inverter



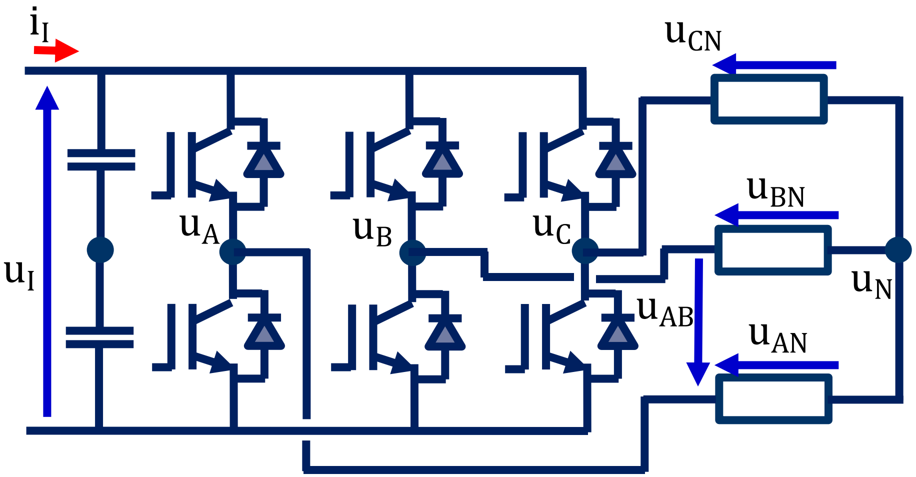


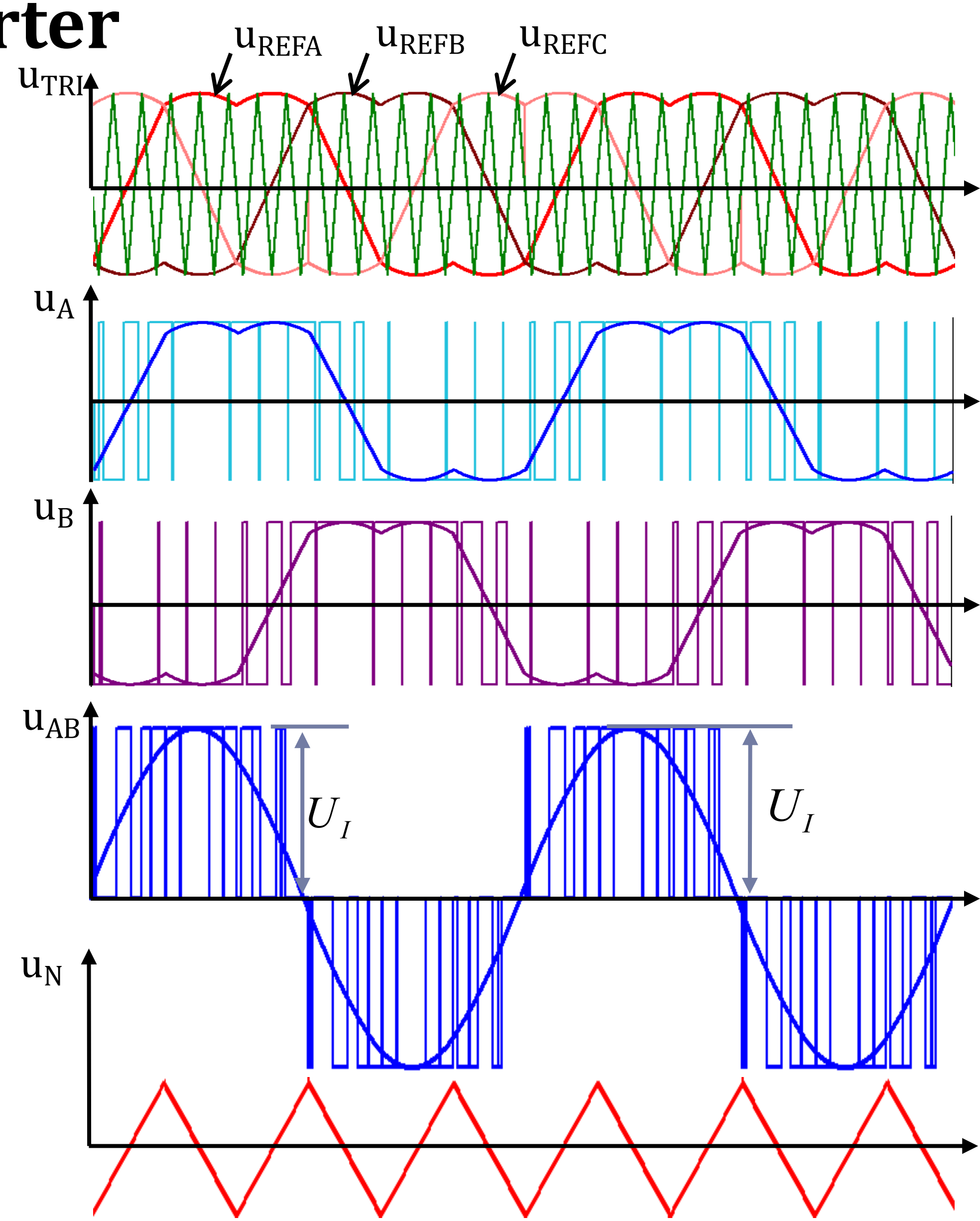
Which is the maximum output voltage?

Consider modulating waveforms different than pure sine waves.

The line-to-line voltage is a pure sine waveform, with higher amplitude than with the sine-triangle modulation

Three-Phase PWM Inverter





Which is the maximum output voltage?

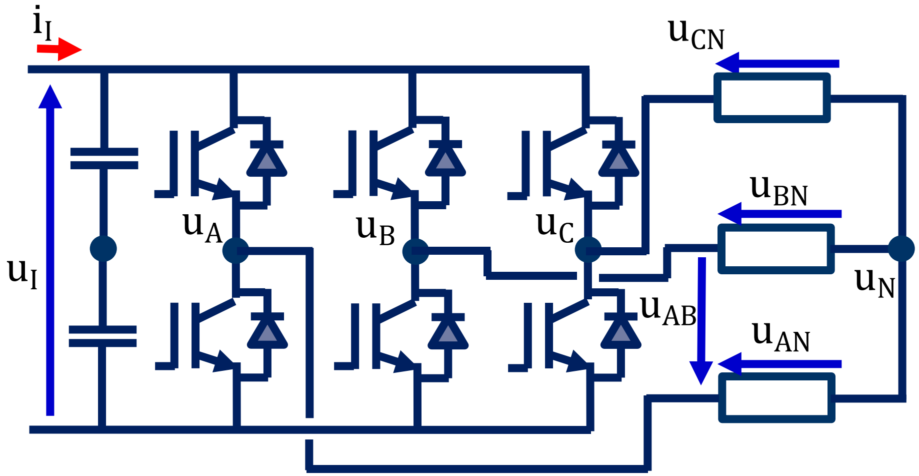
Consider modulating waveforms different than pure sine waves.

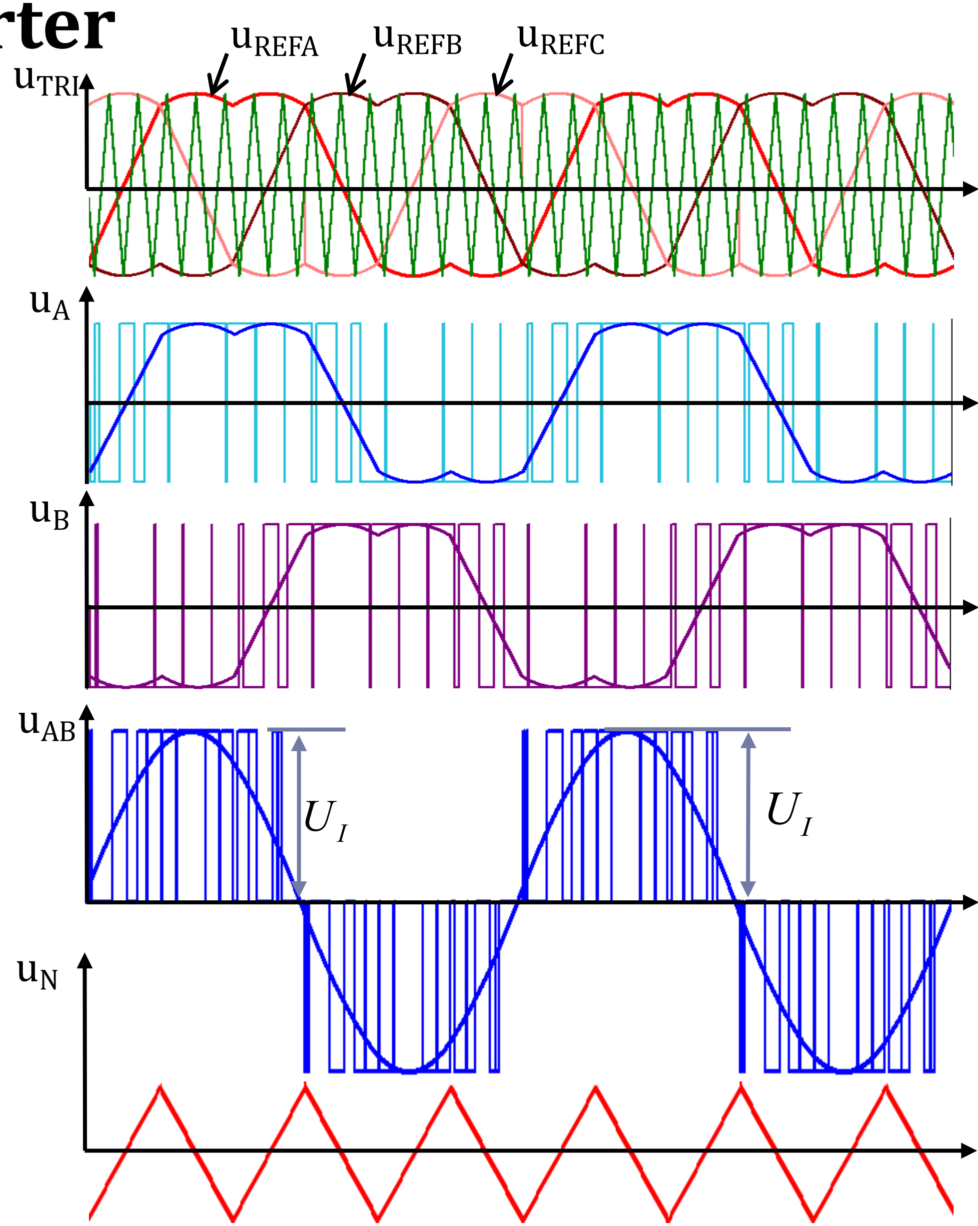
The line-to-line voltage is a pure sine waveform, with higher amplitude than with the sine-triangle modulation

A voltage appears at the neutral point.

...but the phase-to neutral voltage is again a sinusoidal waveform!!!

Three-Phase PWM Inverter

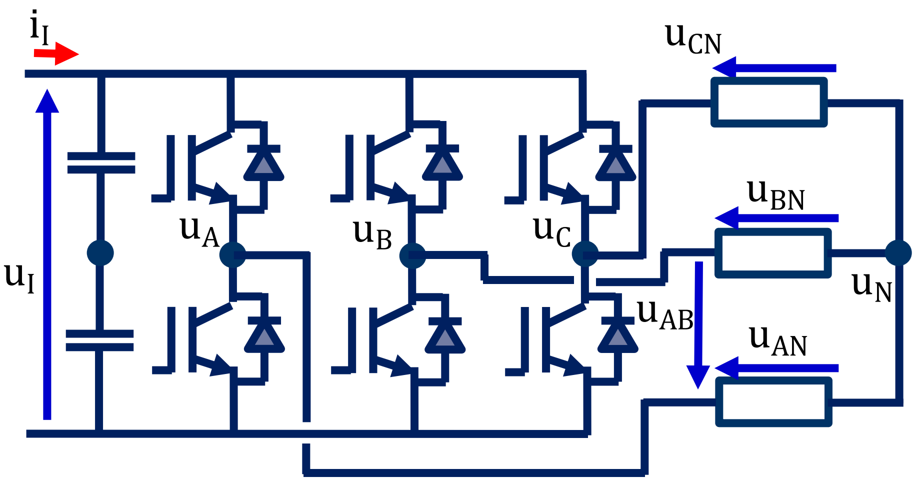


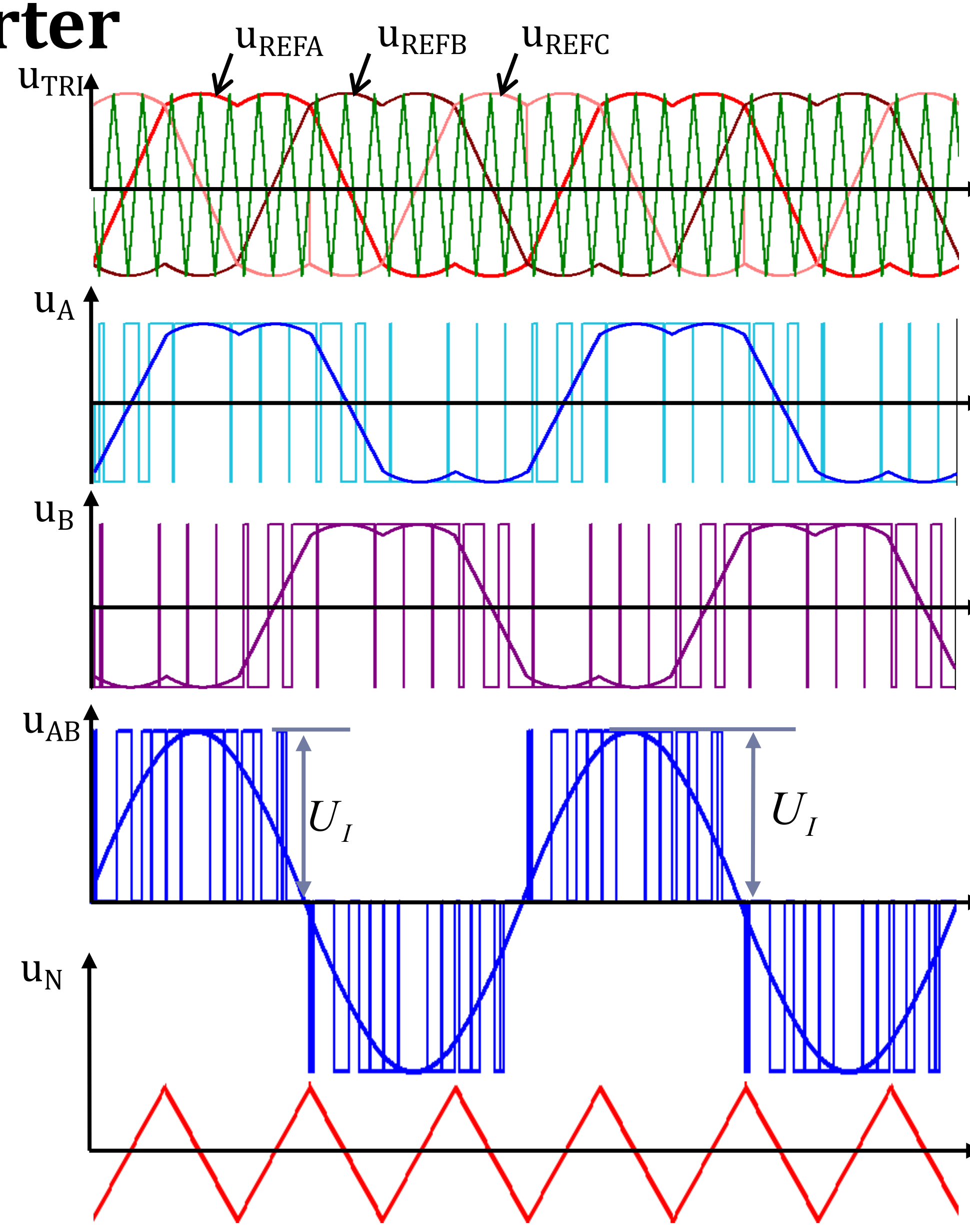


More complex modulaton schemes can be implemented in the control of PWM inverters.

The Space Vector Modulation (SVM) is an algorithm for the control of PWM inverters (mainly three-phase). The development of this technique provides inherently the adequate control waveforms for obtaining the desired output voltage waveforms.

Three-Phase PWM Inverter





Task:

a.- Simulate a 3 phase inverter, with usual sine-triangle modulation.
b.- Try to increase the line-to-line voltage obtained beyond the máximum value posible with sine-triangle modulation only. Try to use different waveforms for modulation, try to add a voltage to the neutral, explore what happens with the 3rd harmonic...)

Input voltage: 3-phase system, 125 VRMS line to neutral, 60 Hz. Switching frequency=12kHz.
Load: Resistive balanced load, 5 ohms per phase.

Space Vector PWM

https://www.switchcraft.org/

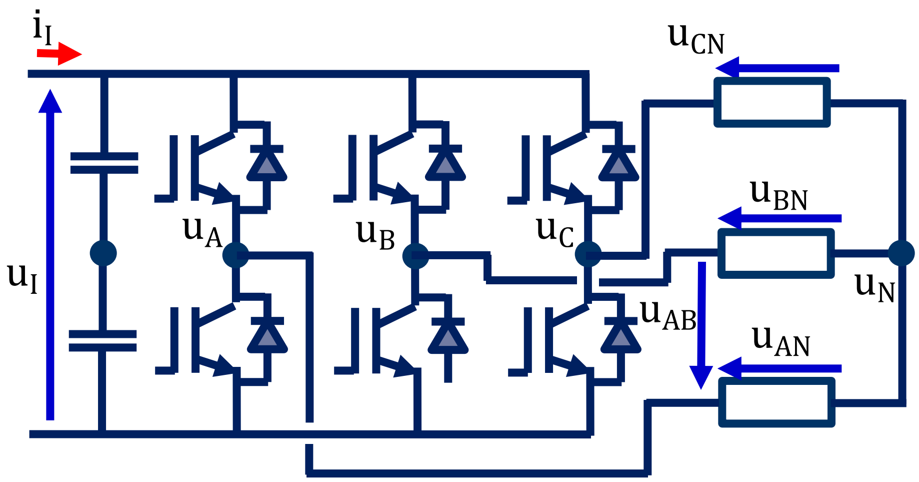
SPACE VECTOR PWM INTRO
MAY 1, 2017
BY YNGVE SOLBAKKEN

https://www.switchcraft.org/learning/2017/3/15/space-vector-pwm-intro

VECTOR CONTROL FOR DUMMIES
MAY 14, 2017
BY YNGVE SOLBAKKEN

https://www.switchcraft.org/learning/2016/12/16/vector-control-for-dummies

SV PWM

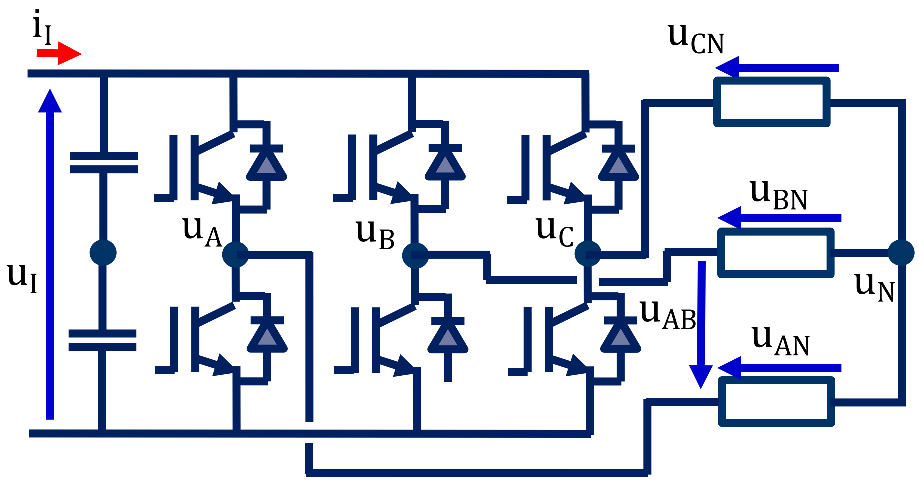


The three phased system is illustrated using two different, but equal forms:

•A vector diagram showing all three phases and their vector sum (*space vector).*

•An ordinary instantaneous sine wave representation, also showing the resultant space vector.

SV PWM



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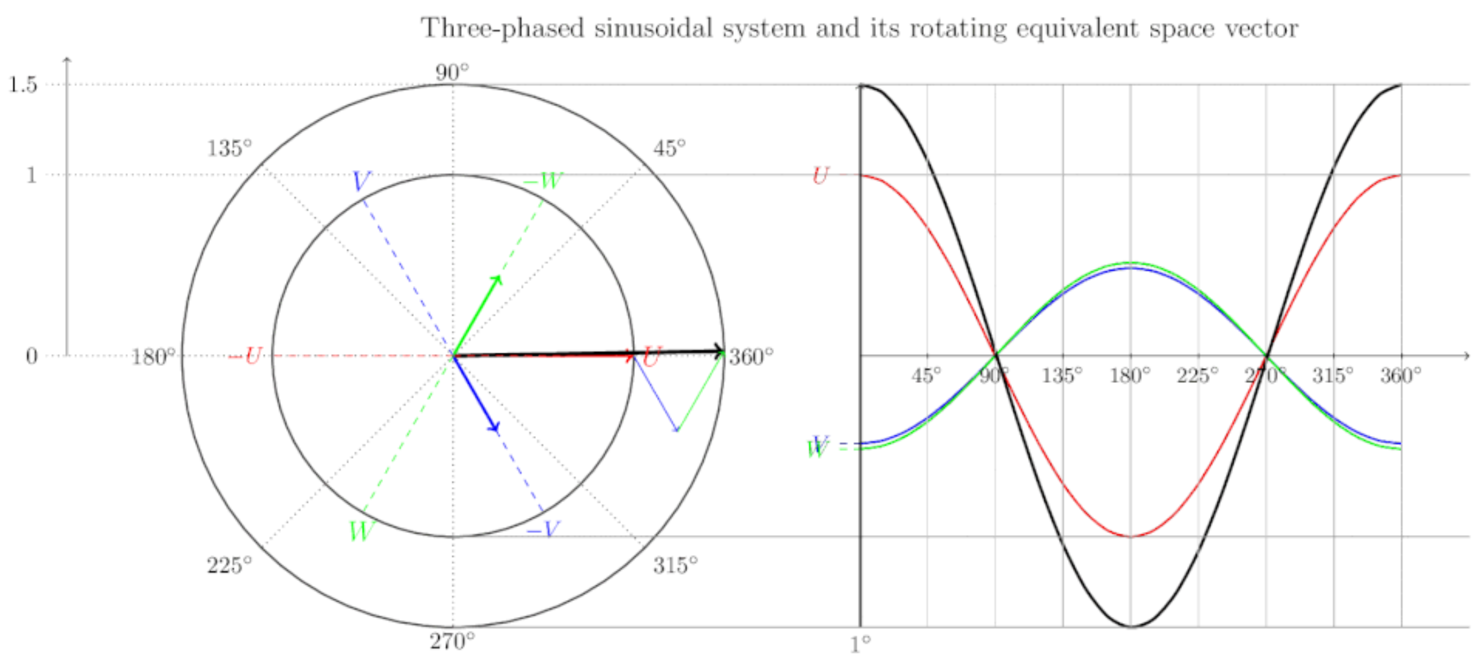
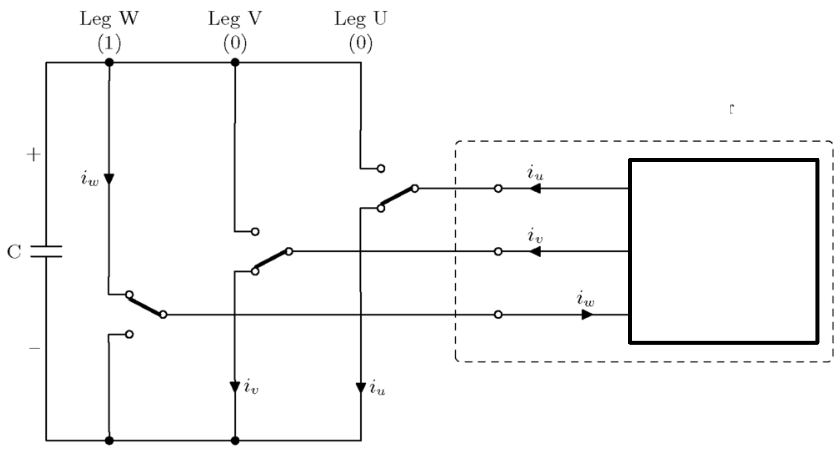
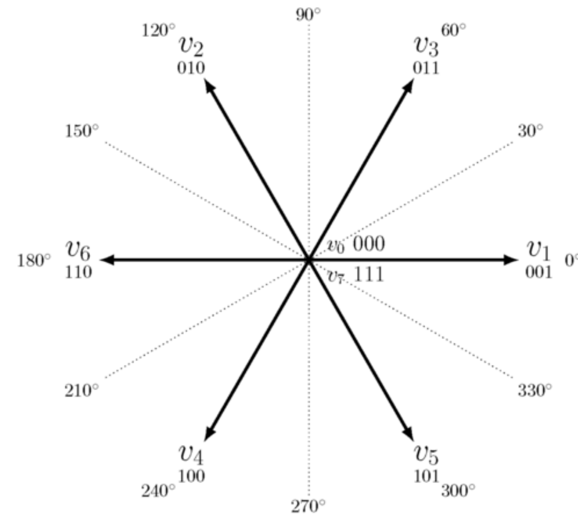


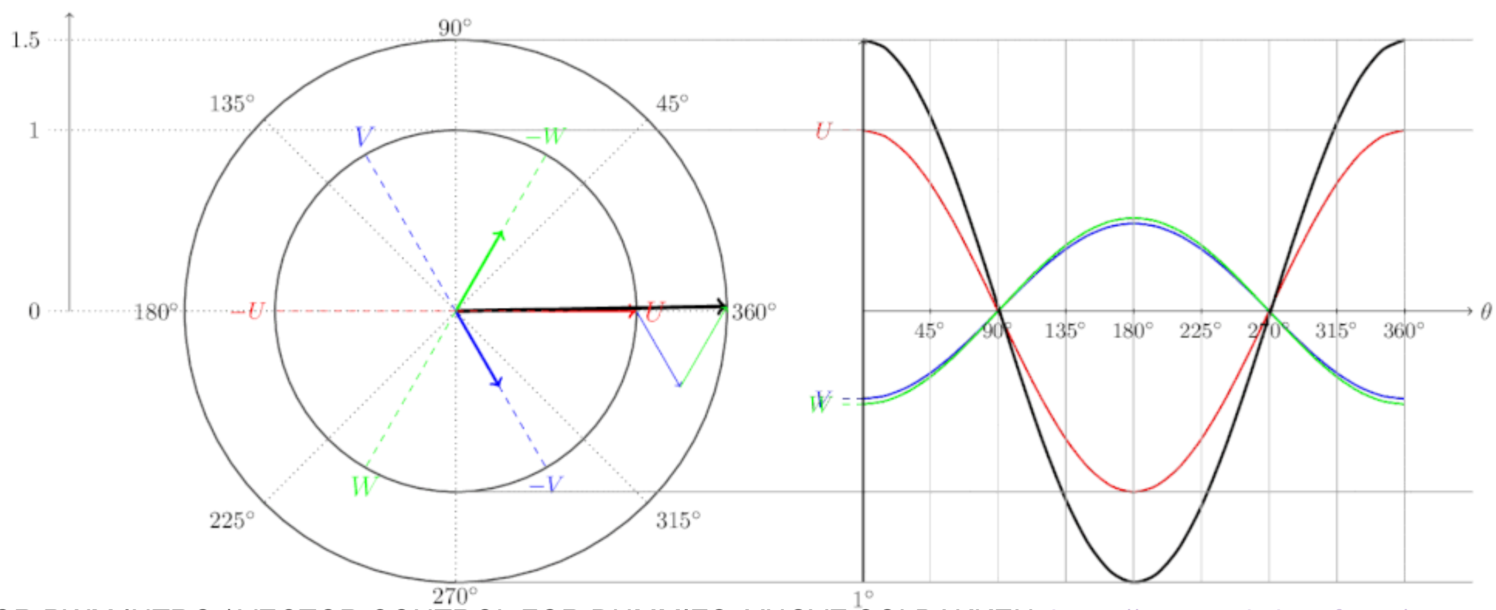
SPACE VECTOR PWM INTRO / VECTOR CONTROL FOR DUMMIES, YNGVE SOLBAKKEN, https://www.switchcraft.org/

SV PWM





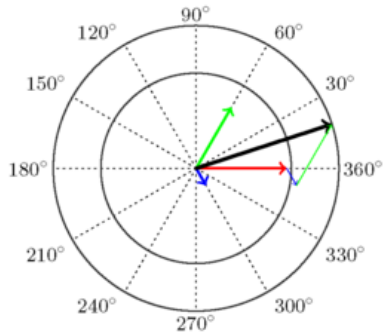
Three-phased sinusoidal system and its rotating equivalent space vector



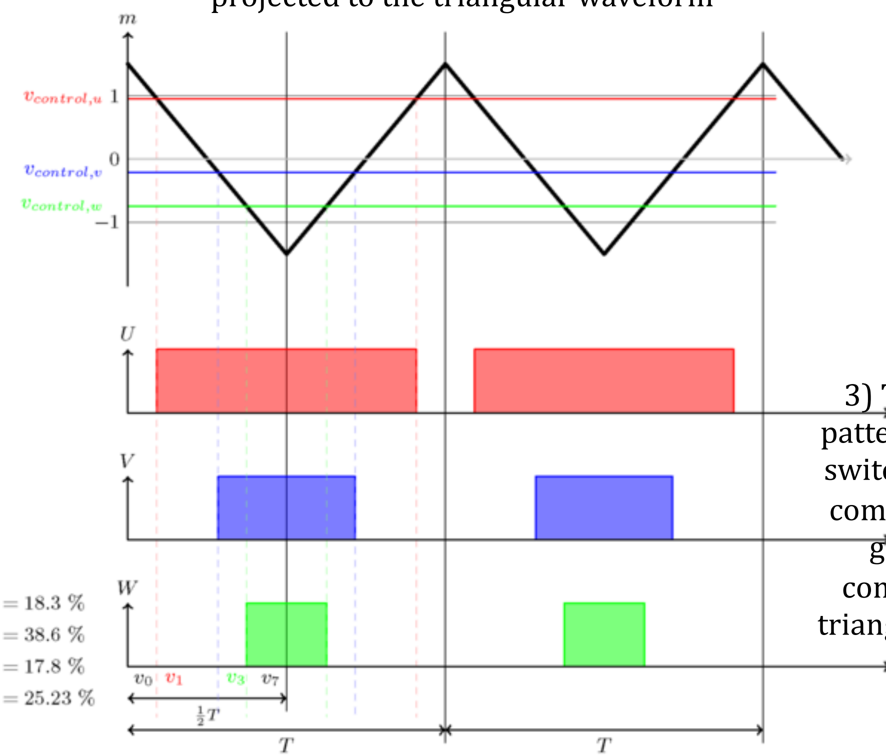
SPACE VECTOR PWM INTRO / VECTOR CONTROL FOR DUMMIES, YNGVE SOLBAKKEN, https://www.switchcraft.org/

SV PWM

1) The 3 phase system forming the reference vector. It is assumed that the desired voltage reference is already available, e.g calculated by the reverse Clarke/Park transformation

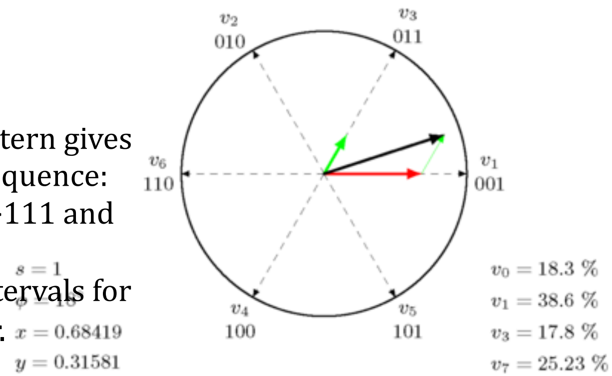


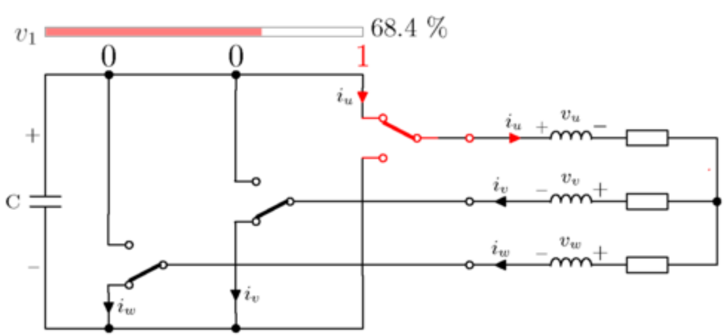
2) The amplitudes of the 3 phase system voltages are projected to the triangular waveform

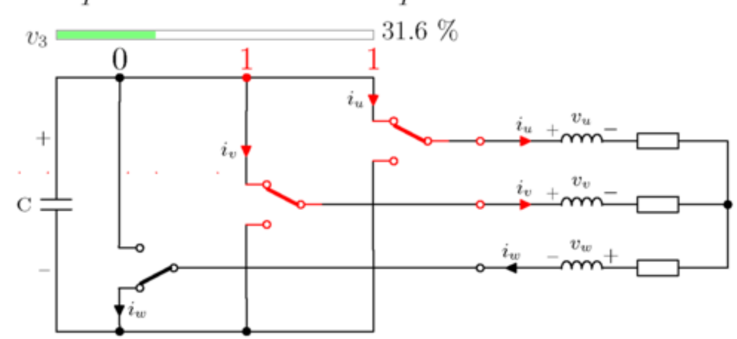


3) The switching pattern of the upper switches (lower are complementary) is generated by comparing to the triangular waveform

4) The switching pattern gives the space vector sequence: 000=>001=>011=>111 and viceversa,
And also the time intervals for each vector.

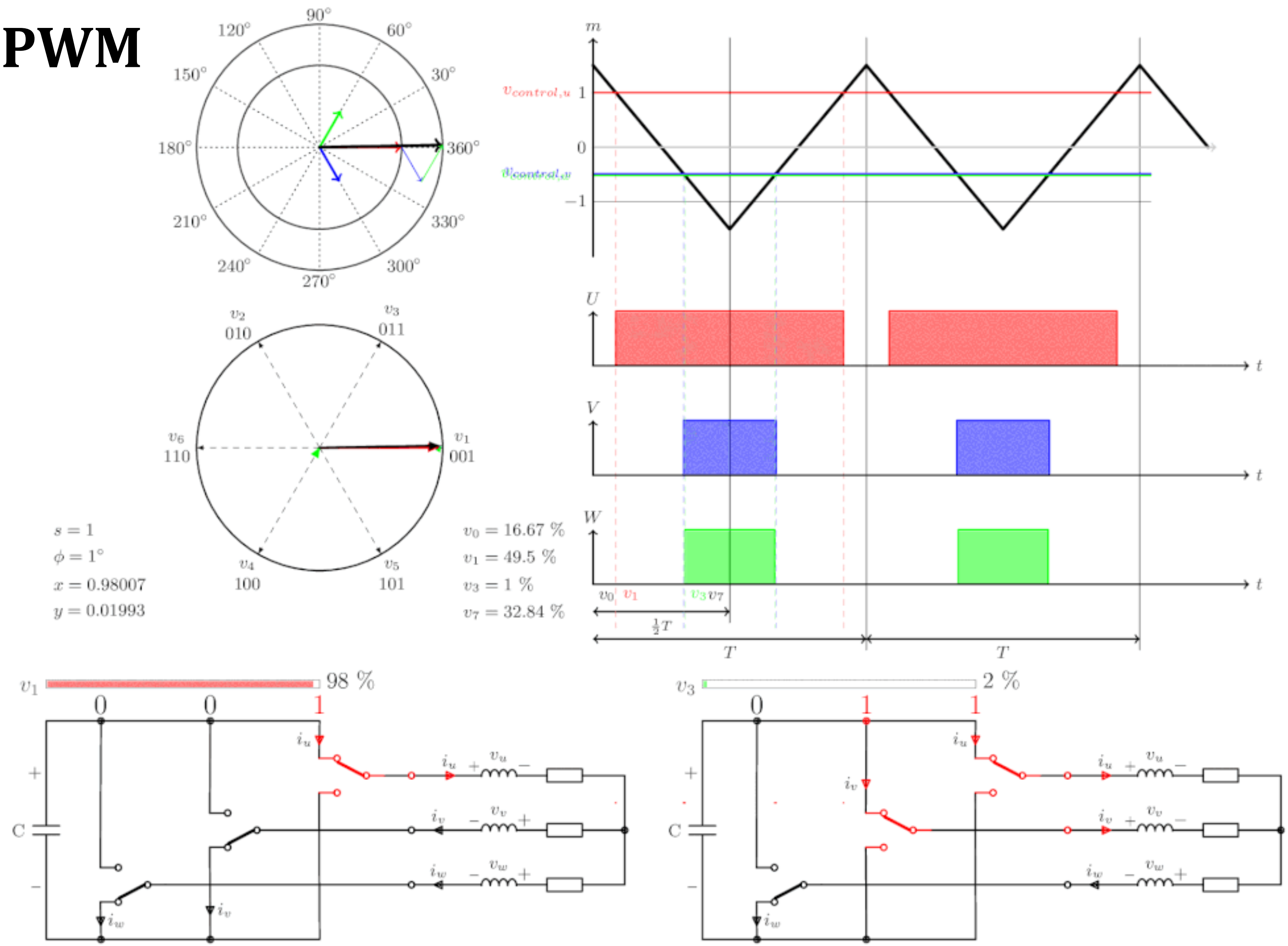






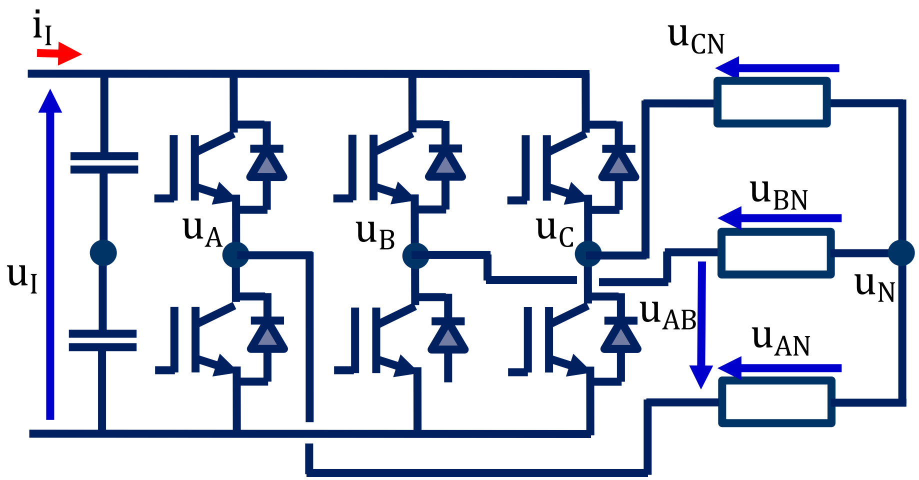
SPACE VECTOR PWM INTRO / VECTOR CONTROL FOR DUMMIES, YNGVE SOLBAKKEN, https://www.switchcraft.org/

SV PWM



SPACE VECTOR PWM INTRO / VECTOR CONTROL FOR DUMMIES, YNGVE SOLBAKKEN, https://www.switchcraft.org/

SV PWM



Conclusions:

•Every pattern starts and ends with a zero vector, and that between every transition, only one switch is being changed. This issue:

a) decreases switching losses (increases power density, simplifies cooling systems)

b) greatly reduces harmonics (THD)

•Easy to include 3rd harmonic injection, therefore:

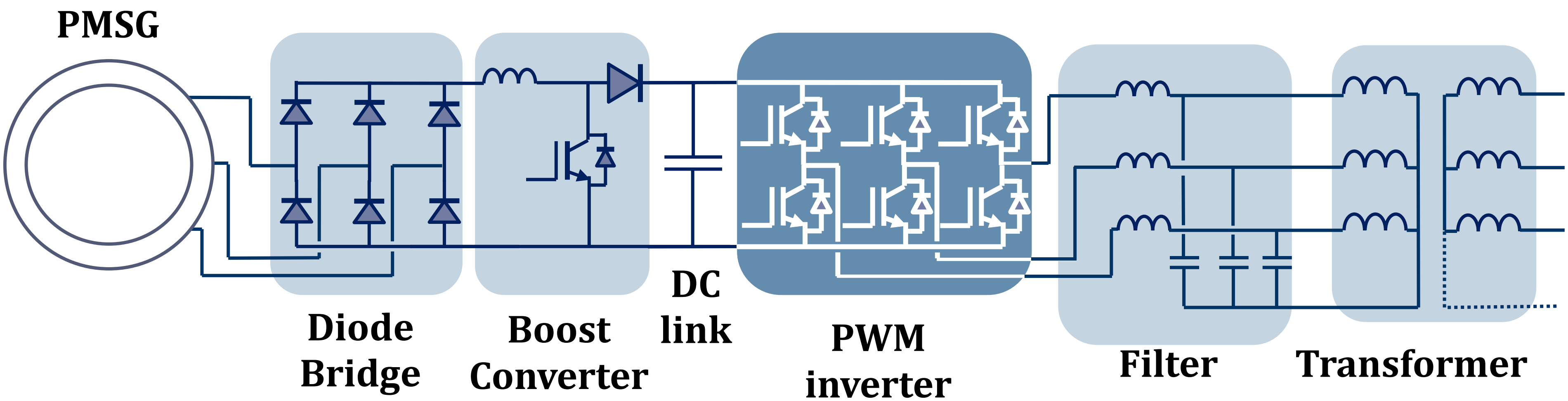
a) higher voltage to the load/grid.

b) Greater DC-bus voltage utilization

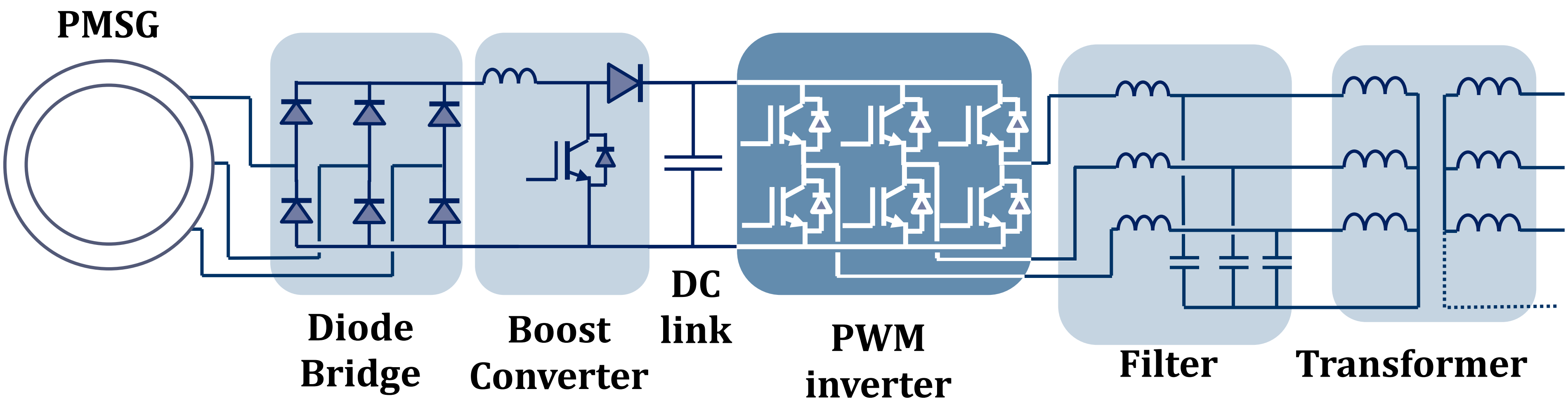
SVPWM is an advanced; computation intensive PWM method and possibly the best techniques for variable frequency drive application.

Consideration for dynamic analysis

Three-Phase PWM Inverter



Three-Phase PWM Inverter

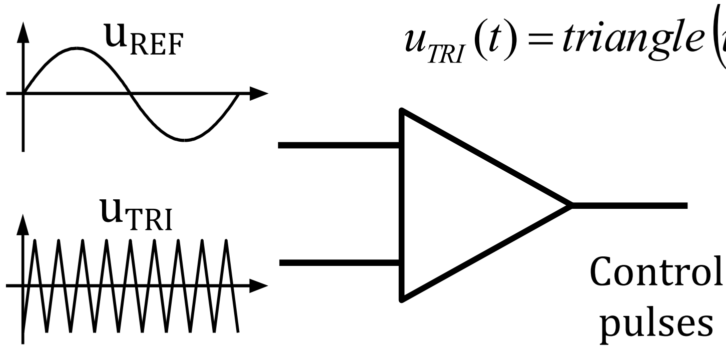


If we consider the filter/load as another block of the system, then **the Dynamic analysis of the PWM inverter is very simple**:

$$u_{REF}(t) = u_{REF\langle PEAK\rangle} \cdot \sin(2\cdot\pi\cdot f_R \cdot t)$$

$$u_{TRI}(t) = triangle\left(u_{TRI\langle PEAK\rangle}, T_S\right)$$

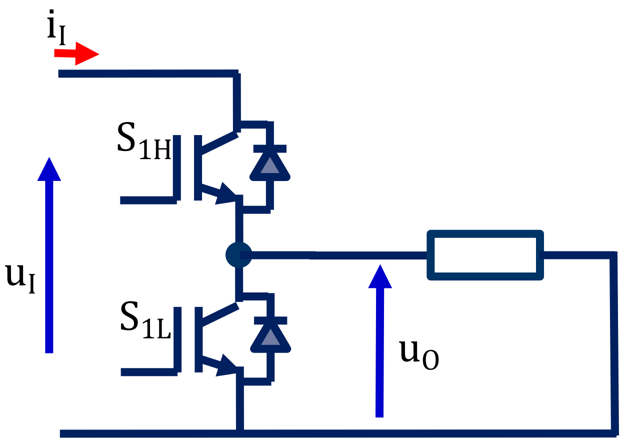
$$\left\langle u_{Phase}(t)\right\rangle_{T_S} = u_I \cdot m_a \cdot sen(2\cdot\pi\cdot f_R \cdot t)$$

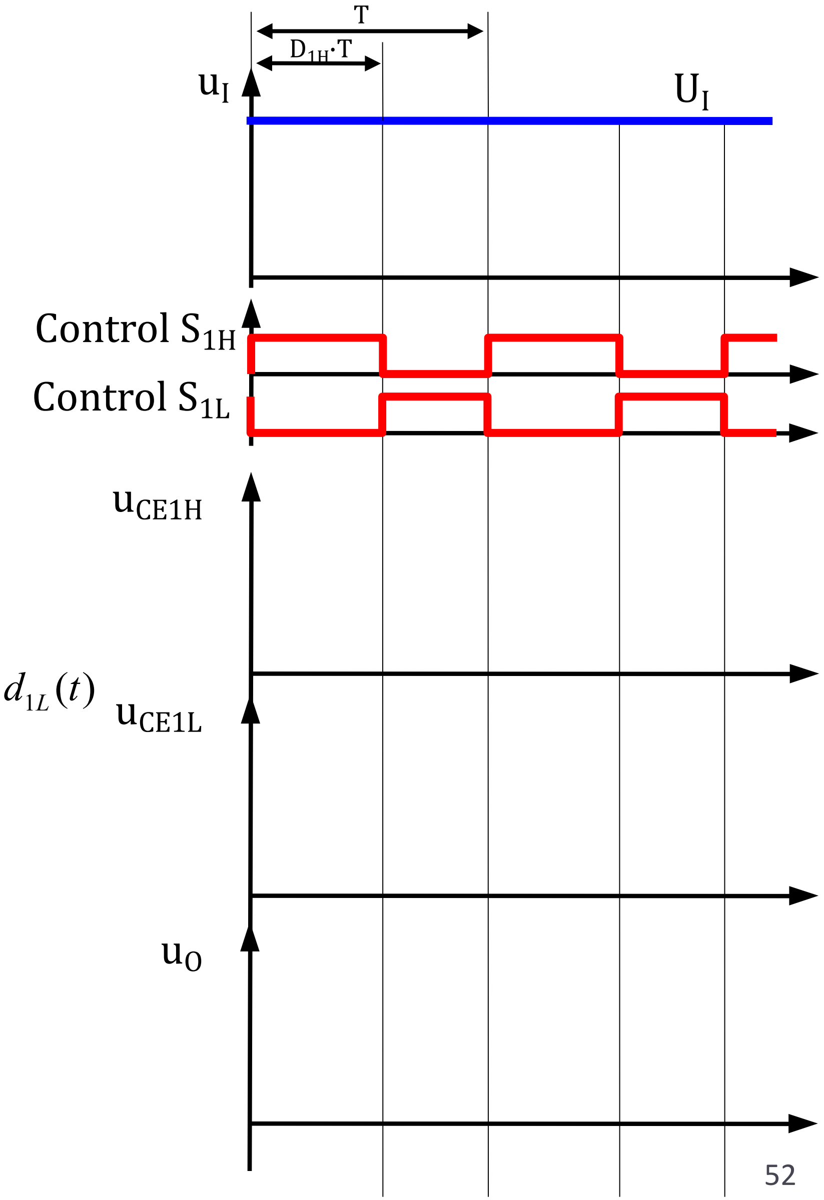


No elements that store energy: NO DYNAMICS
(Except for dead times, switching losses, etc…)

Derivation of the buck and boost converters

The PWM inverter: 1 leg

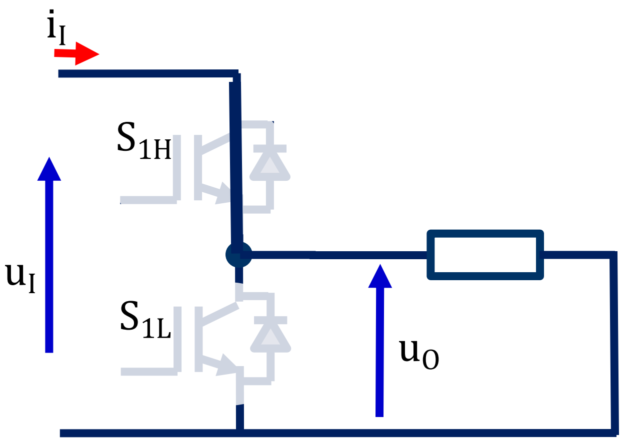


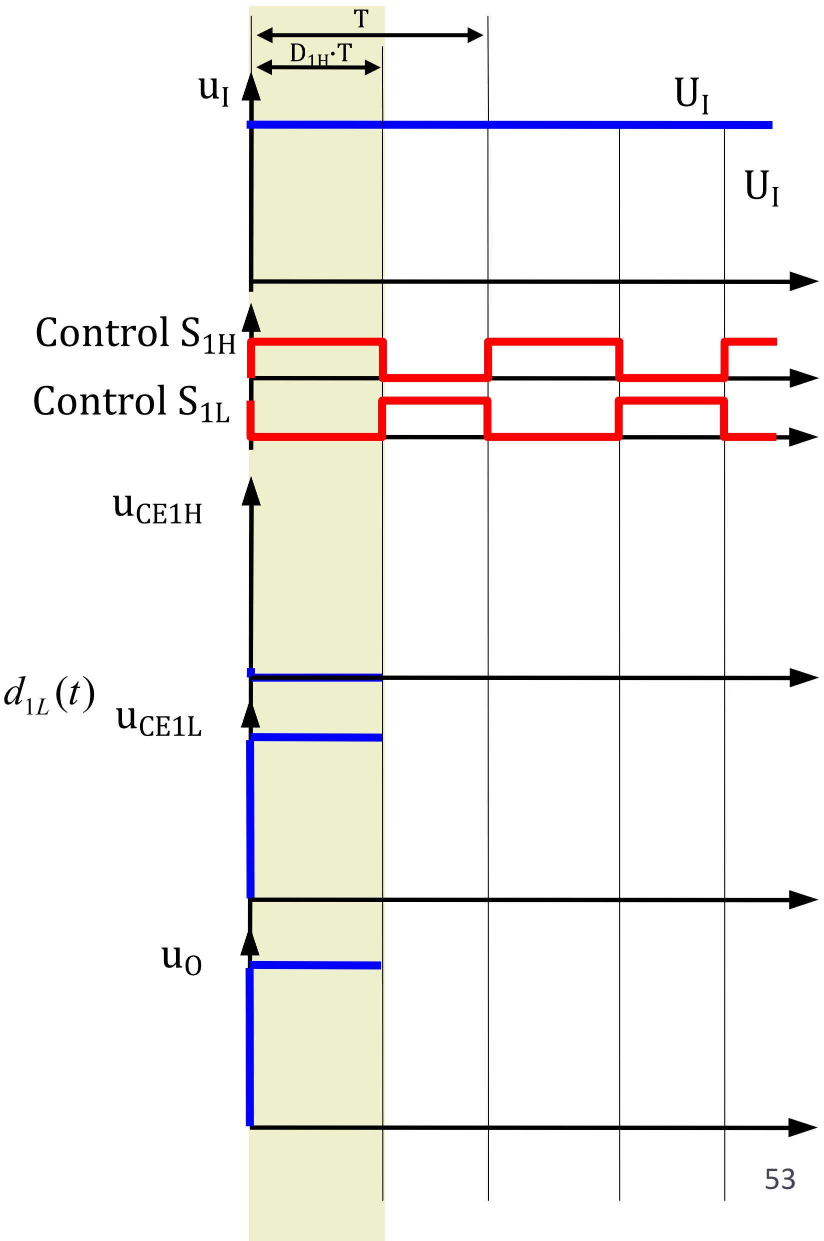


Consider only 1 leg. Also consider:

- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$

The PWM inverter: 1 leg





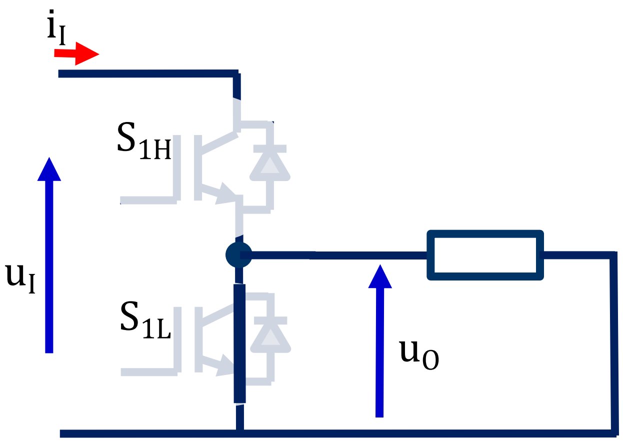
Consider only 1 leg. Also consider:

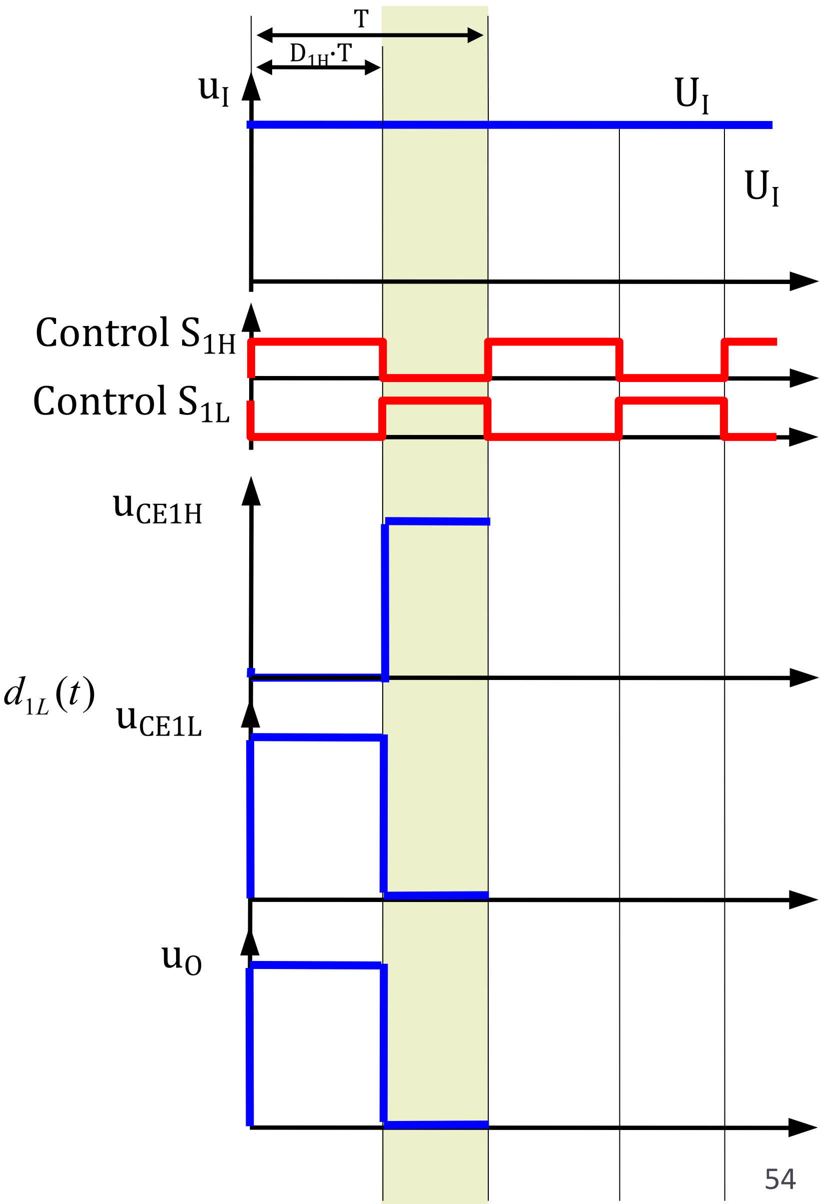
- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$

If Switch S_{1H} is ON $\quad 0 \le t < d_{1H}(t) \cdot T$

$$u_O(t) = U_I$$

The PWM inverter: 1 leg





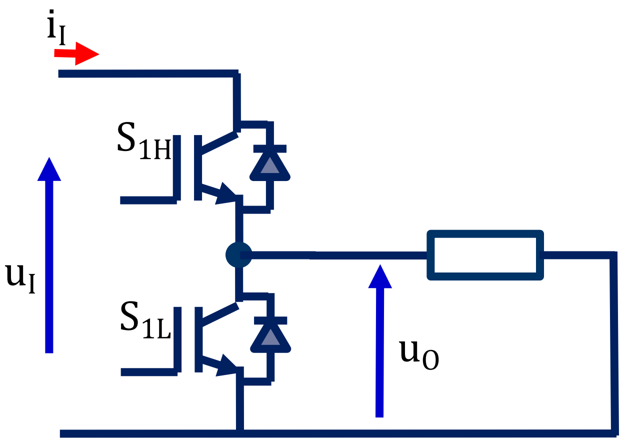
Consider only 1 leg. Also consider:

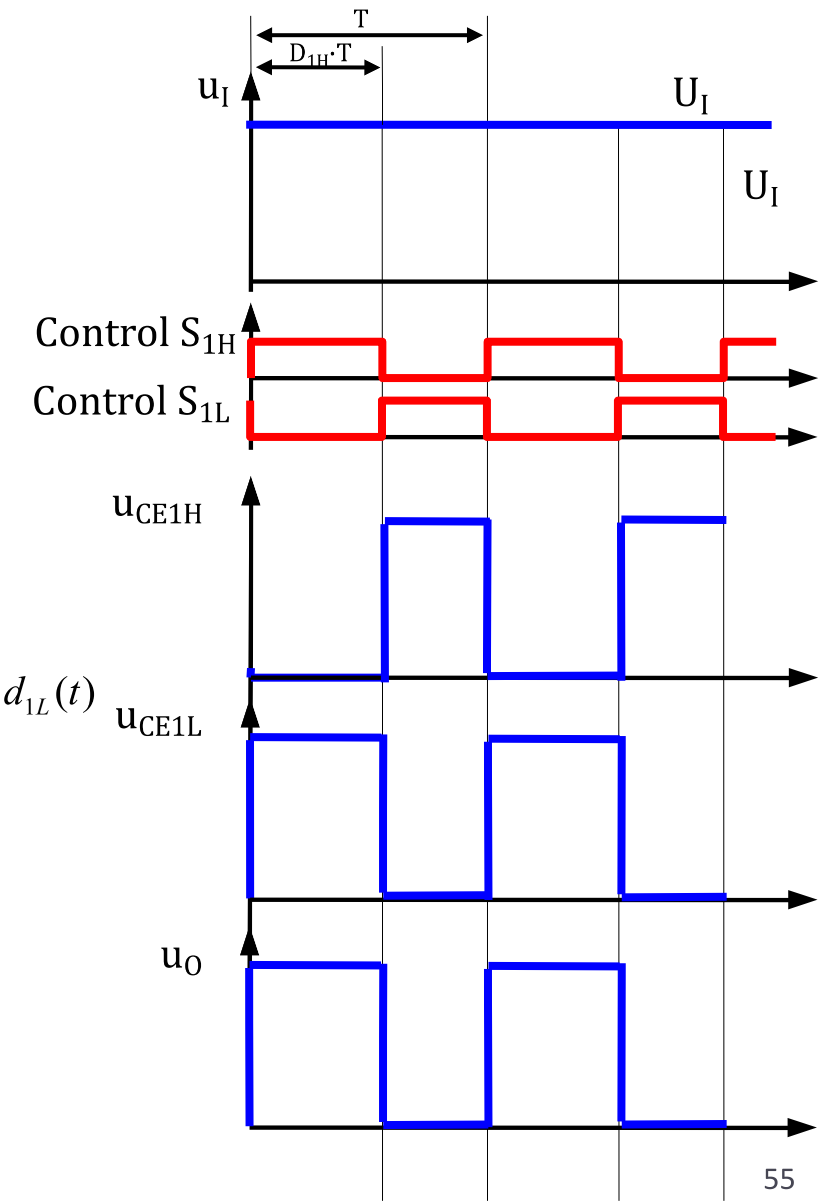
- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$

If Switch S_{1H} is OFF $\quad d_{1H}(t) \cdot T \leq t < T$

$$u_O(t) = 0$$

The PWM inverter: 1 leg





Consider only 1 leg. Also consider:

- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$

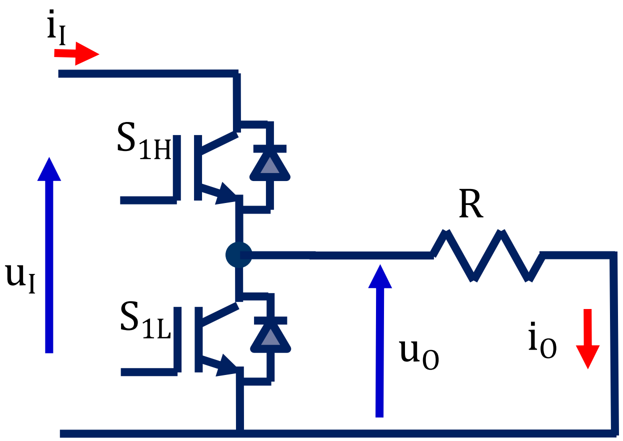
$$u_O(t) = \begin{cases} U_I & 0 \le t < D_{1H} \cdot T \\ 0 & D_{1H} \cdot T \le t < T \end{cases}$$

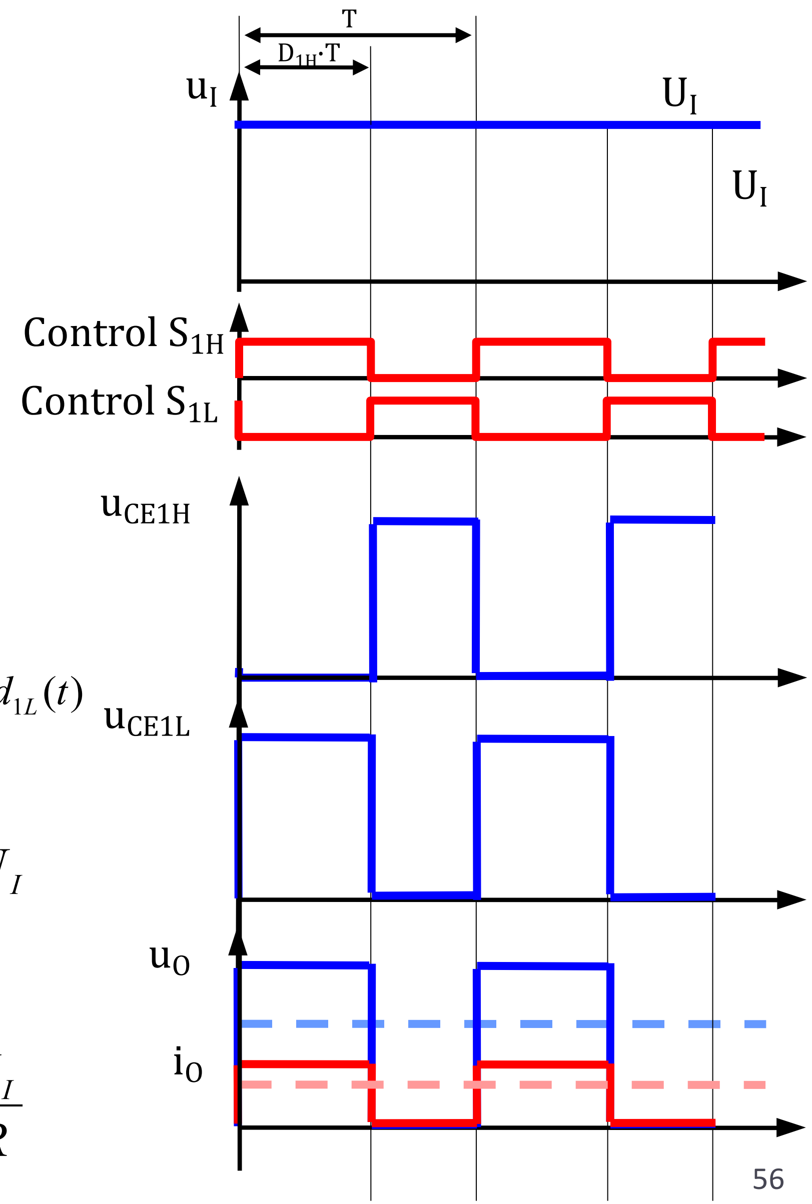
$$\langle x(t) \rangle_T = \frac{1}{T} \int_t^{t+T} x(\tau) d\tau$$

Averaged value of x(t) during a period T

$$u_{O\langle AVG \rangle} = \langle u_O(t) \rangle_T = \frac{1}{T} \int_t^{t+T} u_O(\tau) d\tau = \ldots = D_{1H} \cdot U_I$$

The PWM inverter: 1 leg





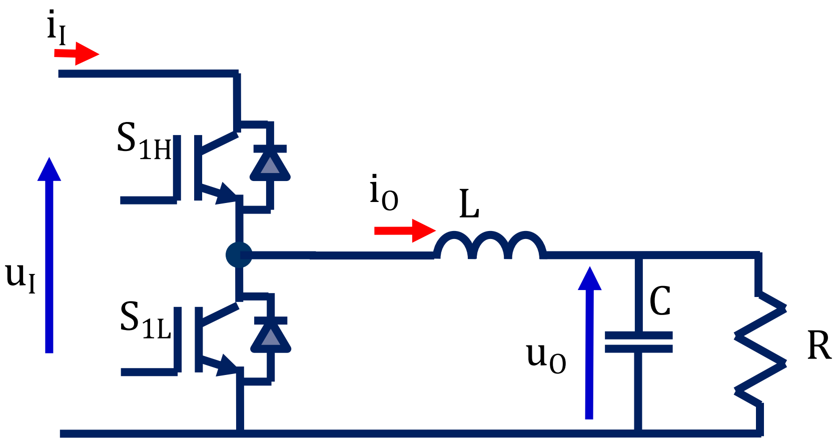
Consider only 1 leg. Also consider:

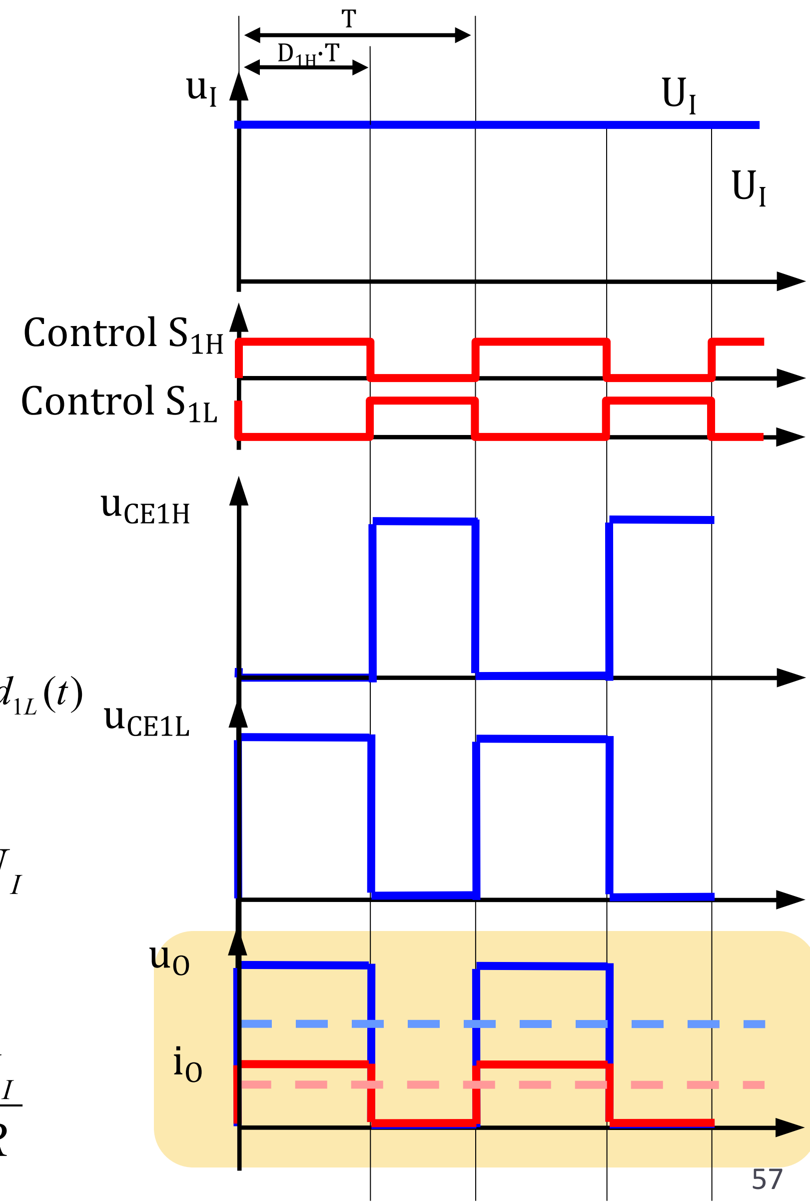
- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$
- Resistive load

$$u_O(t) = \begin{cases} U_I & 0 \le t < D_{1H} \cdot T \\ 0 & D_{1H} \cdot T \le t < T \end{cases} \qquad \langle u_O(t) \rangle_T = D_{1H} \cdot U_I$$

$$i_O(t) = \begin{cases} \dfrac{U_I}{R} & 0 \le t < D_{1H} \cdot T \\ 0 & D_{1H} \cdot T \le t < T \end{cases} \qquad \langle i_O(t) \rangle_T = D_{1H} \cdot \frac{U_I}{R}$$

The PWM inverter: 1 leg





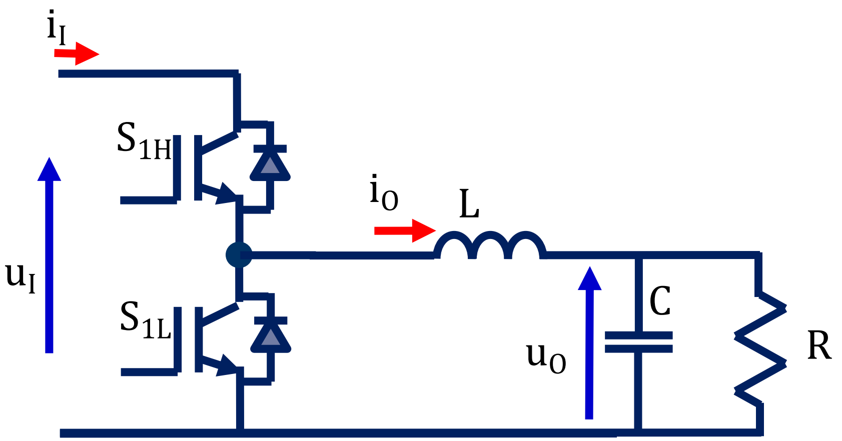
Consider only 1 leg. Also consider:

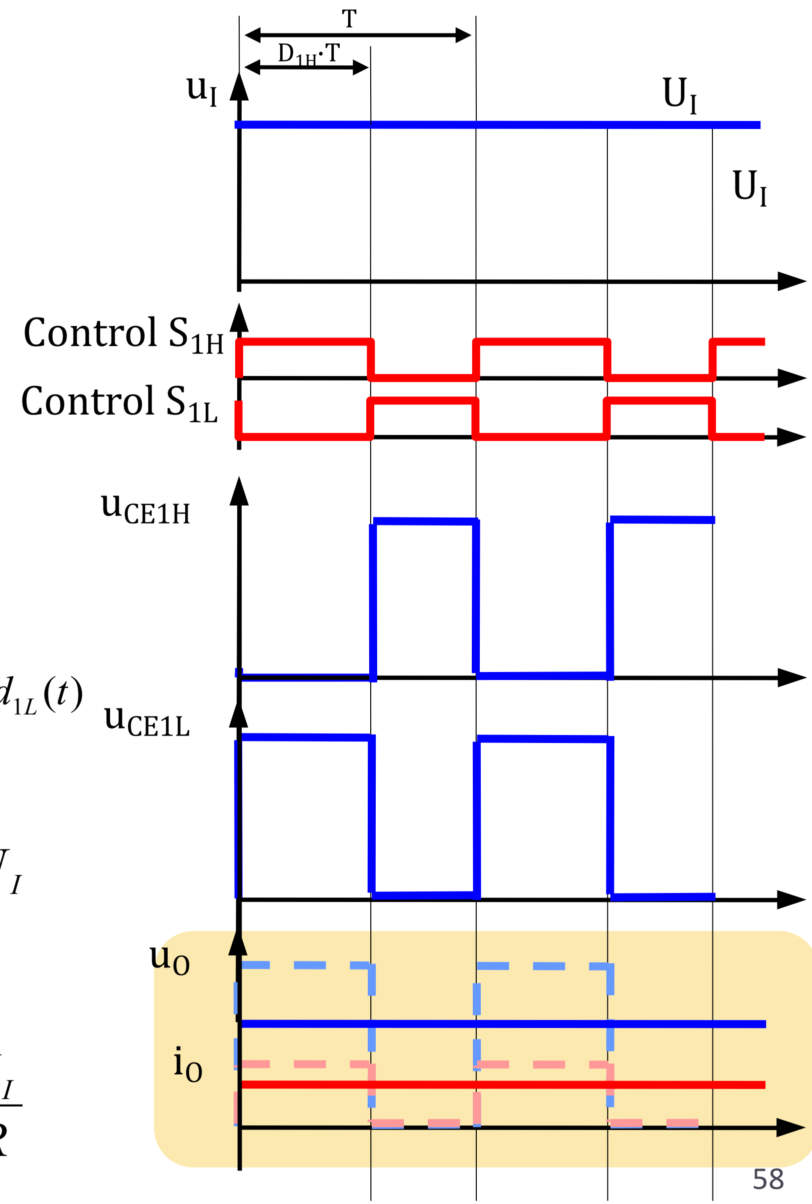
- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$
- LC filtered load (L↑↑, C ↑↑)

$$u_O(t) = \begin{cases} U_I & 0 \le t < D_{1H} \cdot T \\ 0 & D_{1H} \cdot T \le t < T \end{cases} \qquad \langle u_O(t) \rangle_T = D_{1H} \cdot U_I$$

$$i_O(t) = \begin{cases} \dfrac{U_I}{R} & 0 \le t < D_{1H} \cdot T \\ 0 & D_{1H} \cdot T \le t < T \end{cases} \qquad \langle i_O(t) \rangle_T = D_{1H} \cdot \frac{U_I}{R}$$

The PWM inverter: 1 leg





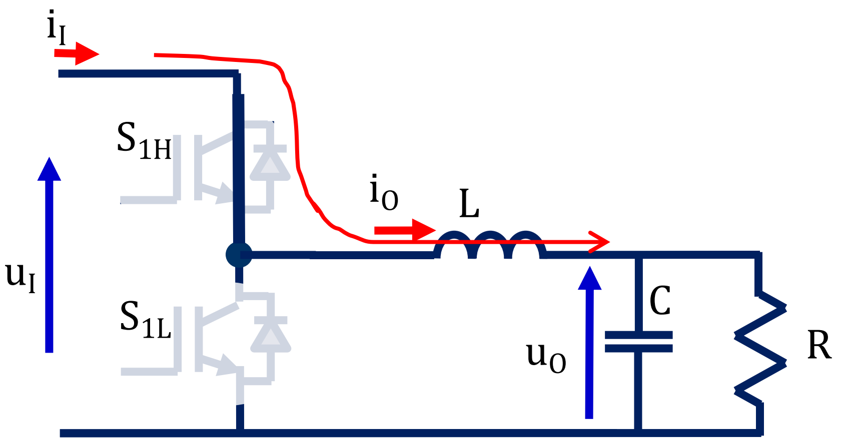
Consider only 1 leg. Also consider:

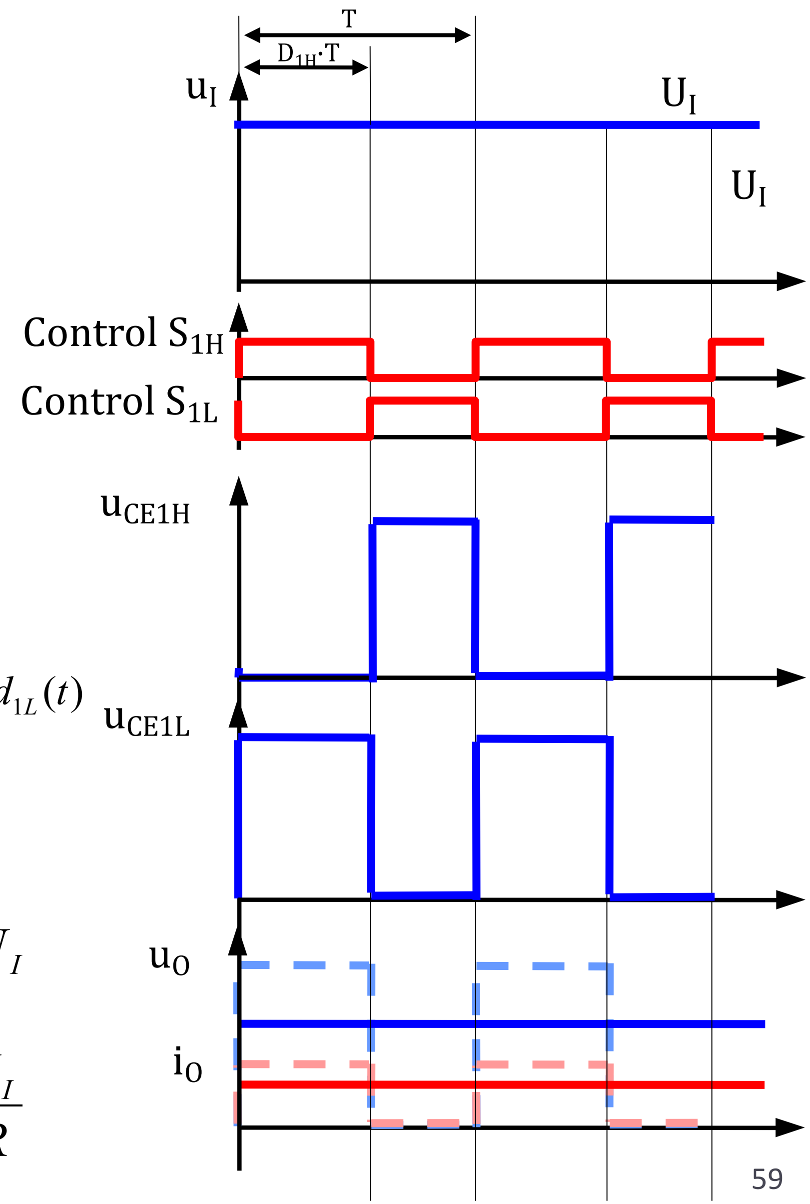
- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$
- LC filtered load (L↑↑, C ↑↑)

$u_O(t) = D_{1H} \cdot U_I$ (ripple neglected) $\qquad \langle u_O(t) \rangle_T = D_{1H} \cdot U_I$

$i_O(t) \cong D_{1H} \dfrac{U_I}{R}$ (ripple neglected) $\qquad \langle i_O(t) \rangle_T = D_{1H} \cdot \dfrac{U_I}{R}$

The PWM inverter: 1 leg





Consider only 1 leg. Also consider:

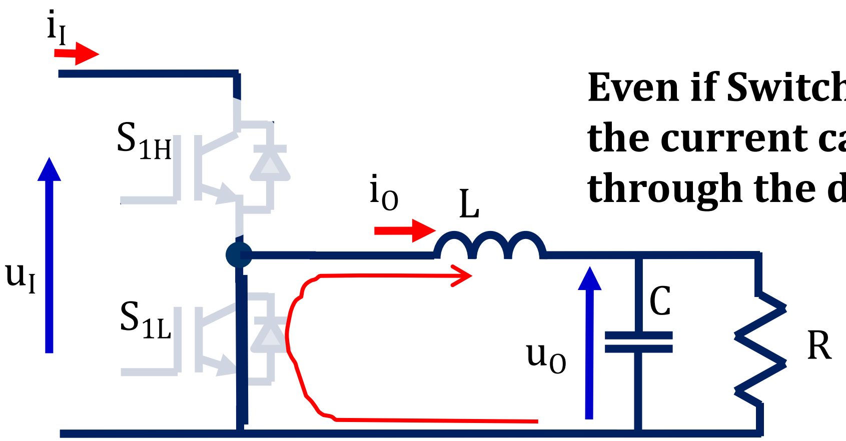
- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$
- LC filtered load (L↑↑, C ↑↑)

If Switch S_{1H} is ON $\quad 0 \le t < d_{1H}(t) \cdot T$

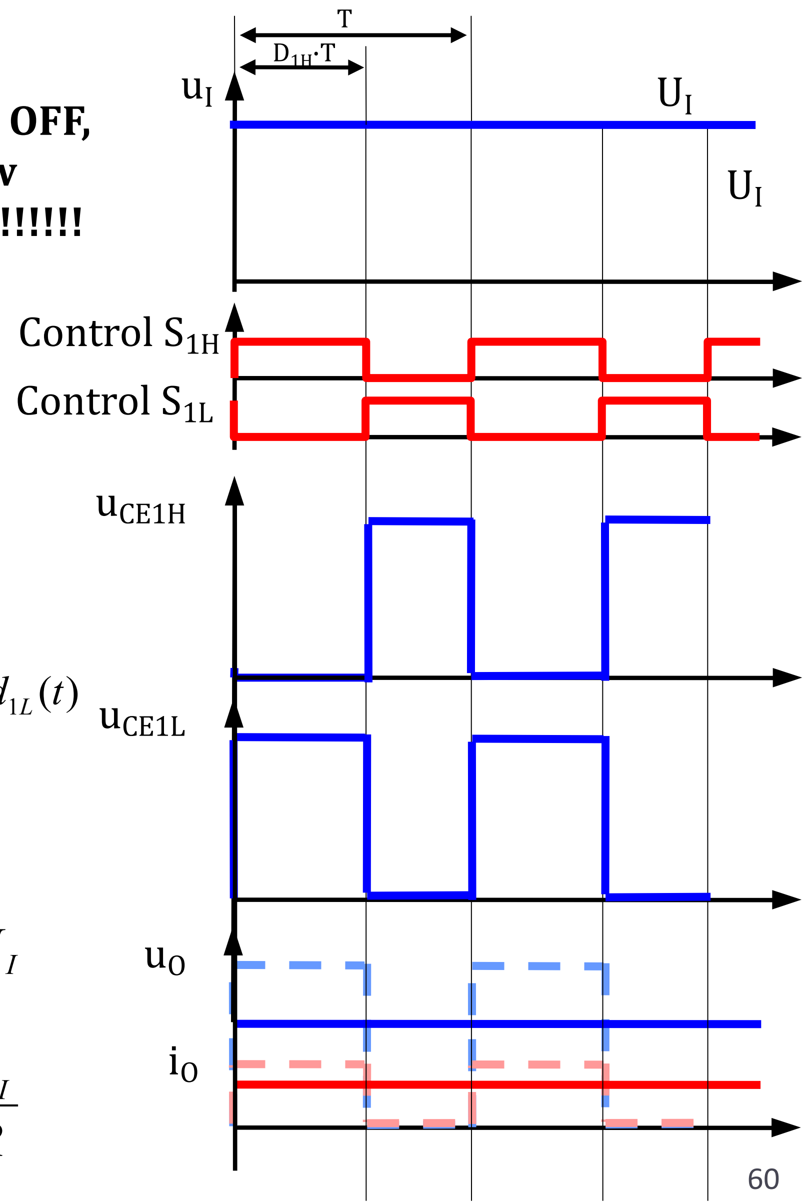
$$u_O(t) = D_{1H} \cdot U_I$$ (ripple neglected) $$\langle u_O(t) \rangle_T = D_{1H} \cdot U_I$$

$$i_O(t) \cong D_{1H} \frac{U_I}{R}$$ (ripple neglected) $$\langle i_O(t) \rangle_T = D_{1H} \cdot \frac{U_I}{R}$$

The PWM inverter: 1 leg



Even if Switch S_{1L} is OFF, the current can flow through the diode !!!!!!!



Consider only 1 leg. Also consider:

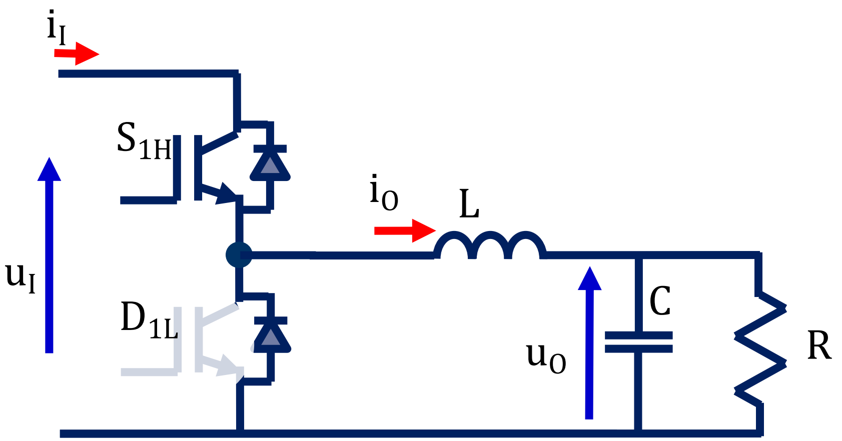
- Ideal switches (no losses)
- Complementary control of S_{1H} and S_{1L} $\quad d_{1H}(t) = 1 - d_{1L}(t)$
- LC filtered load (L↑↑, C ↑↑)

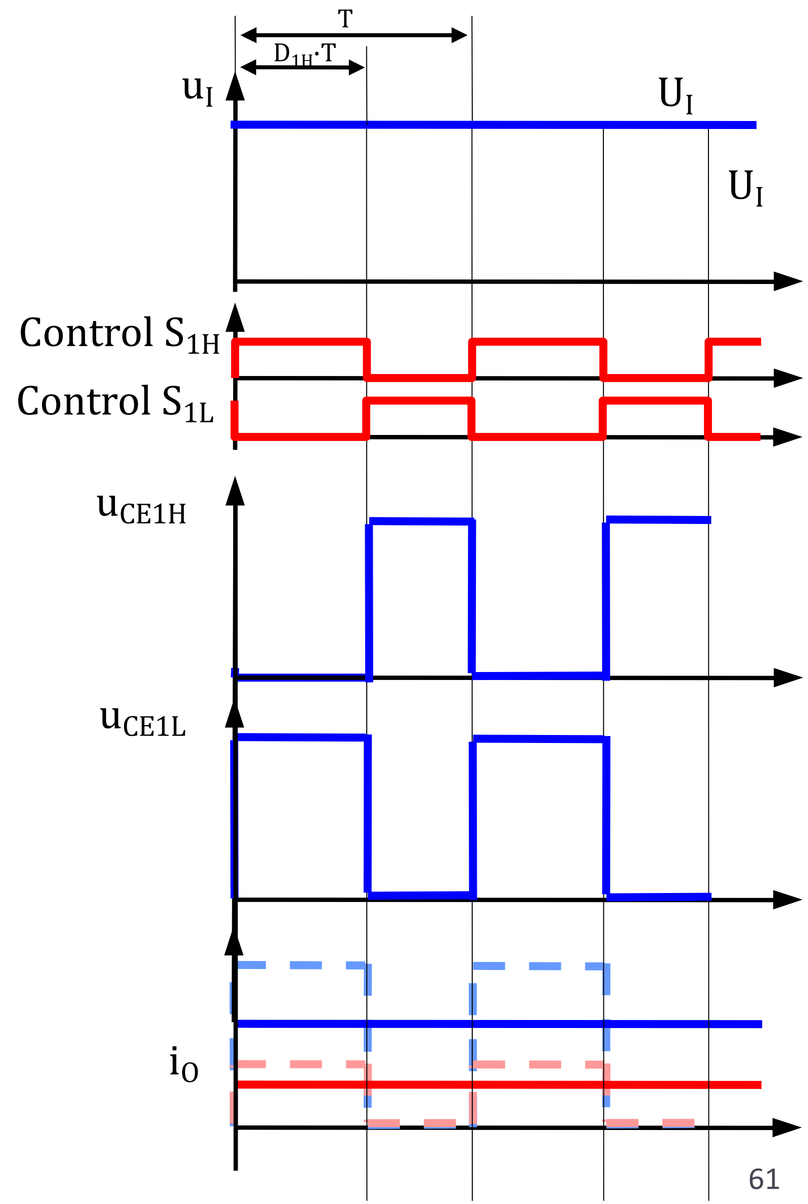
If Switch S_{1H} is OFF $\quad d_{1H}(t)\cdot T \le t < T$

$$u_O(t) = D_{1H}\cdot U_I$$ (ripple neglected) $$\langle u_O(t)\rangle_T = D_{1H}\cdot U_I$$

$$i_O(t) \cong D_{1H}\frac{U_I}{R}$$ (ripple neglected) $$\langle i_O(t)\rangle_T = D_{1H}\cdot\frac{U_I}{R}$$

The PWM inverter: 1 leg

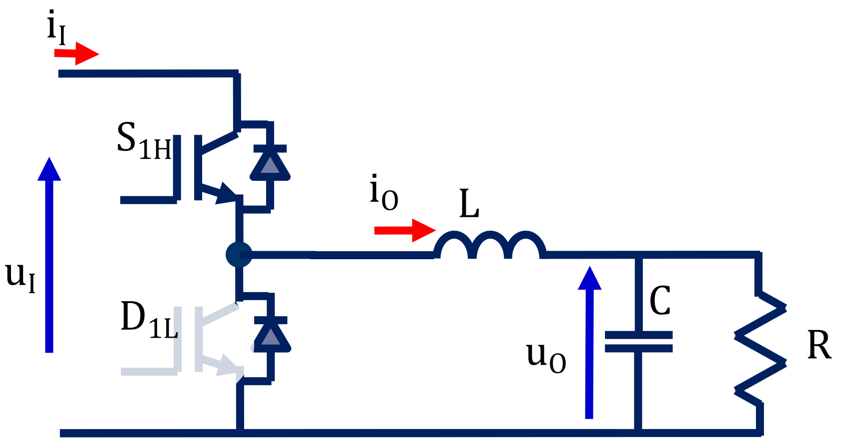


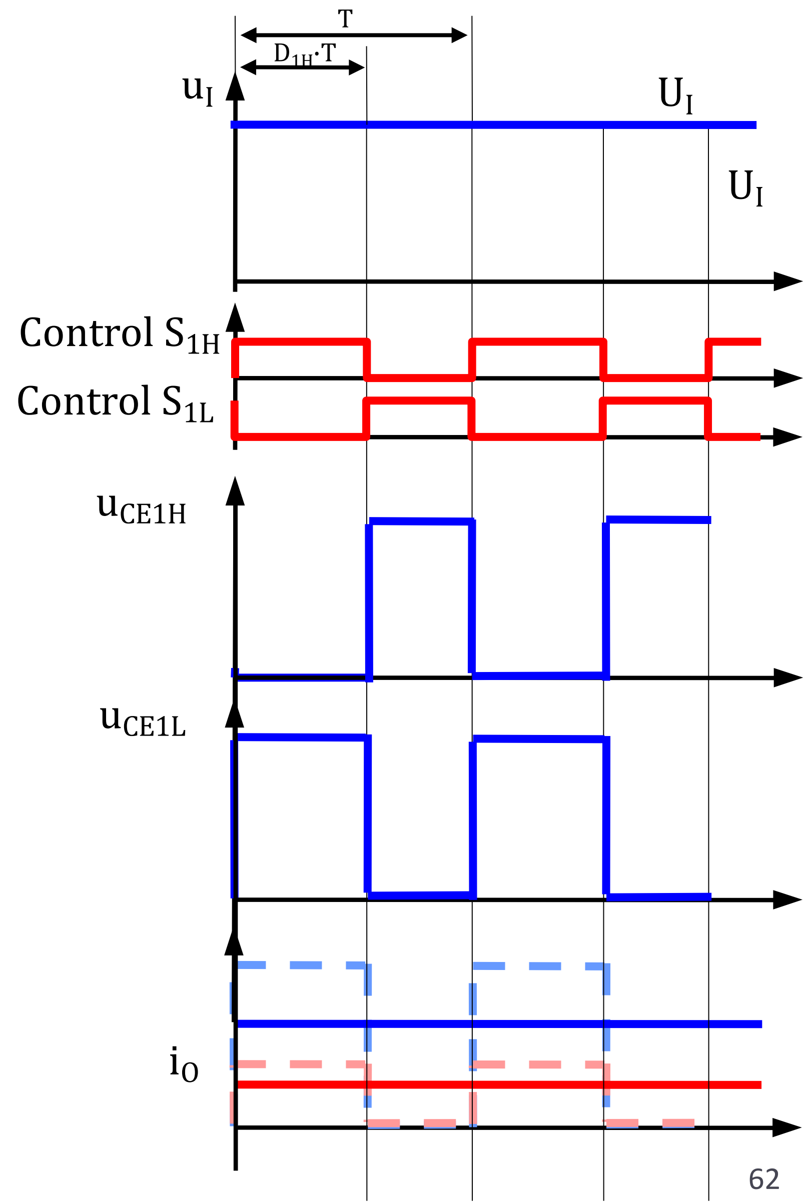


Thus, this converter (under these conditions) can be redrawn:

$$\langle u_O(t) \rangle_T = U_O = D_{1H} \cdot U_I \quad \Rightarrow \quad \frac{U_O}{U_I} = D_{1H}$$

The PWM inverter: 1 leg



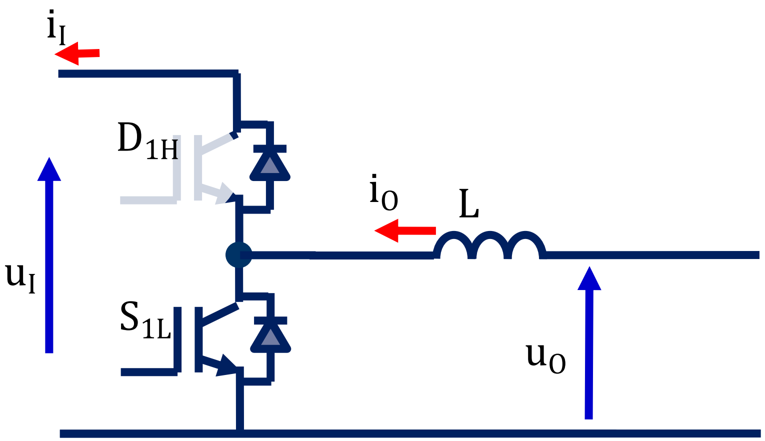


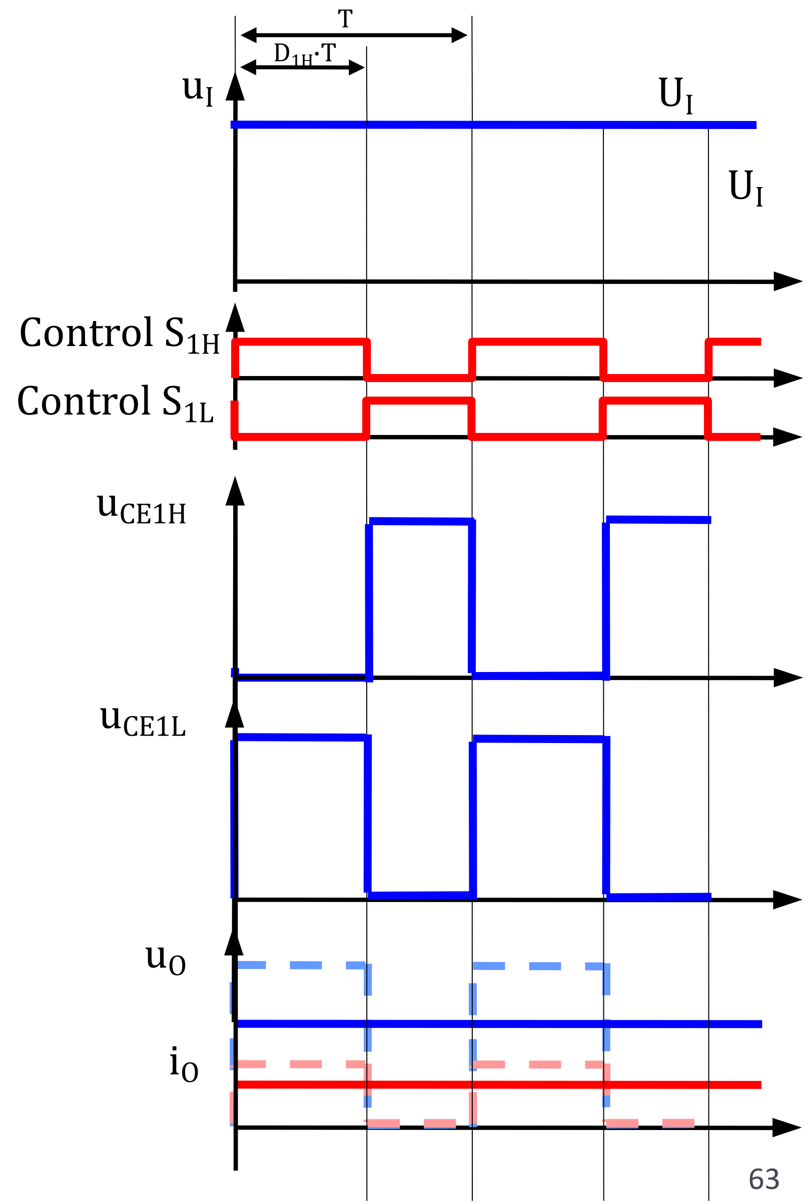
Thus, this converter (under these conditions) can be redrawn:

$$\langle u_O(t)\rangle_T = U_O = D_{1H} \cdot U_I \quad \Rightarrow \quad \frac{U_O}{U_I} = D_{1H}$$

... to find the **BUCK** converter in CCM!!!

The PWM inverter: 1 leg





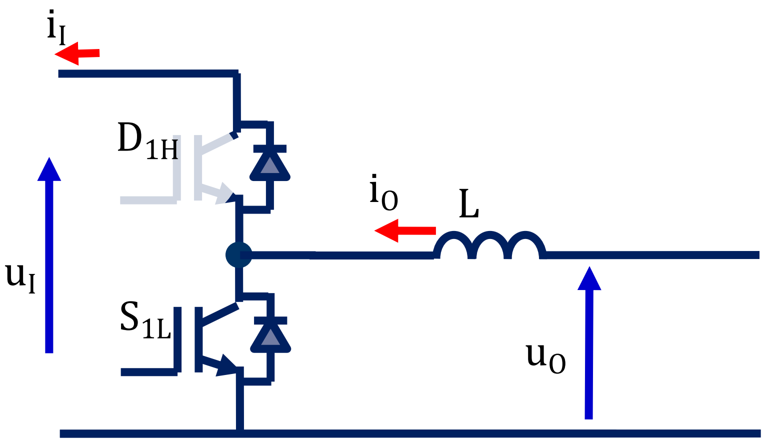
Thus, this converter (under these conditions) can be redrawn:

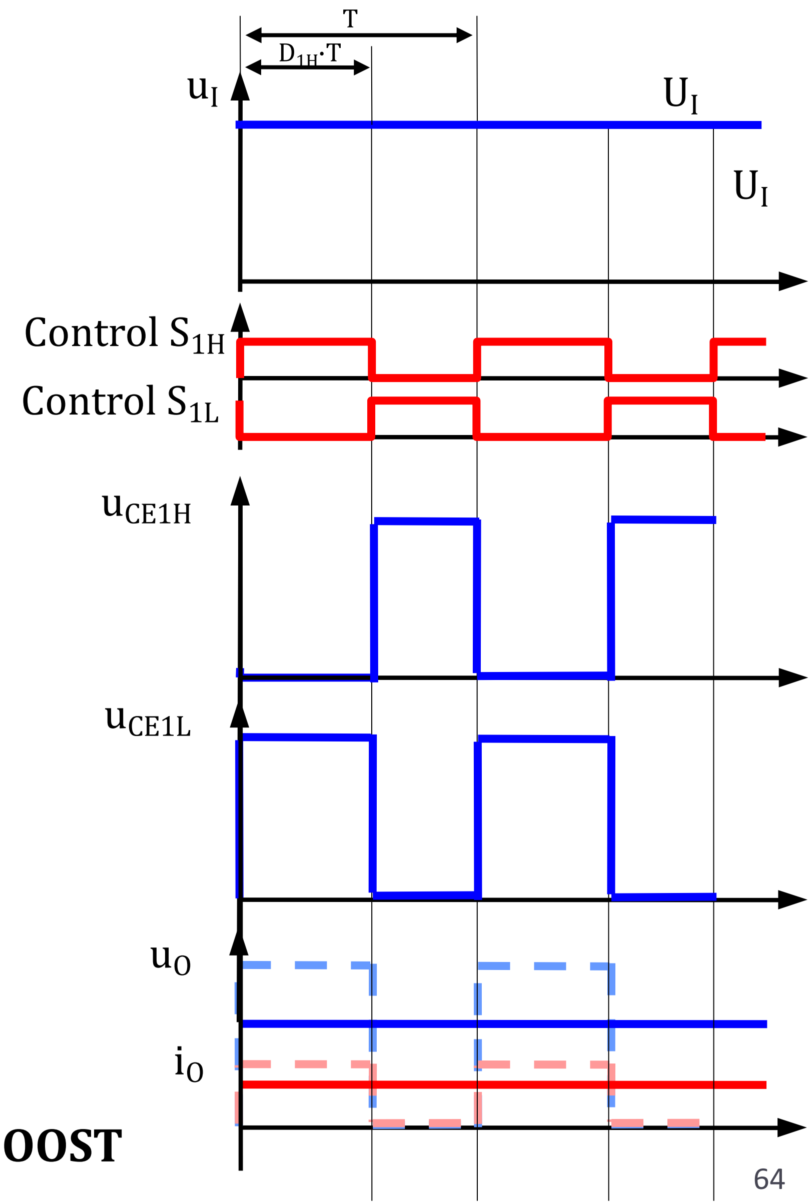
$$\langle u_O(t)\rangle_T = U_O = D_{1H}\cdot U_I \quad \Rightarrow \quad \frac{U_O}{U_I} = D_{1H}$$

... to find the **BUCK** converter in CCM!!!

Furthermore, if we consider the bidirectional converter, (delivering power to u_I),

The PWM inverter: 1 leg





Thus, this converter (under these conditions) can be redrawn:

$$\langle u_O(t) \rangle_T = U_O = D_{1H} \cdot U_I \quad \Rightarrow \quad \frac{U_O}{U_I} = D_{1H}$$

... to find the **BUCK** converter in CCM!!!

Furthermore, if we consider the bidirectional converter, (delivering power to u_I),

$$\frac{U_I}{U_O} = \frac{1}{D_{1H}} = \frac{1}{1 - D_{1L}}$$

... then we have the **BOOST** converter in CCM!!!

References:

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"Power Electronics: Converters, Applications and Design, 3rd edition". Mohan, Undeland, Robbins. John Wiley & Sons, Inc. 2003.
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