# EE-465 - W5
# 3-PHASE VSI
# CARRIER BASED PWM

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We will look into:

- 2L VSI operating principles
- Carrier-based PWM
- Zero-sequence injection principles
- Other multilevel topologies

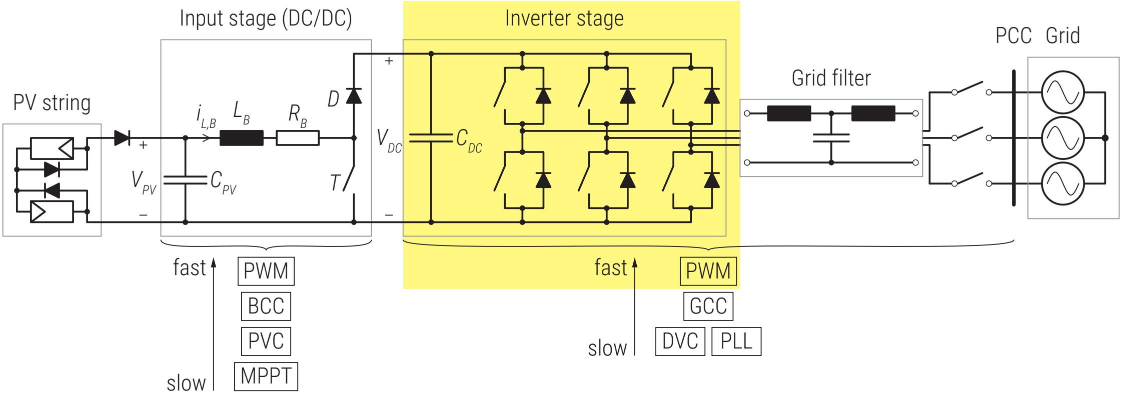



**Figure 1** PV double-stage grid connected converter.

# 3-PHASE 2-L INVERTER

- Obtained by combining $3\times$ 2-L phase-legs
- $N$ and $O$ are not connected together! - but can be used as references for various calculations
- 3-phase load can be brought in only a limited number of configurations
- 3-phase 2-level inverter has only 8 switching states (configurations)

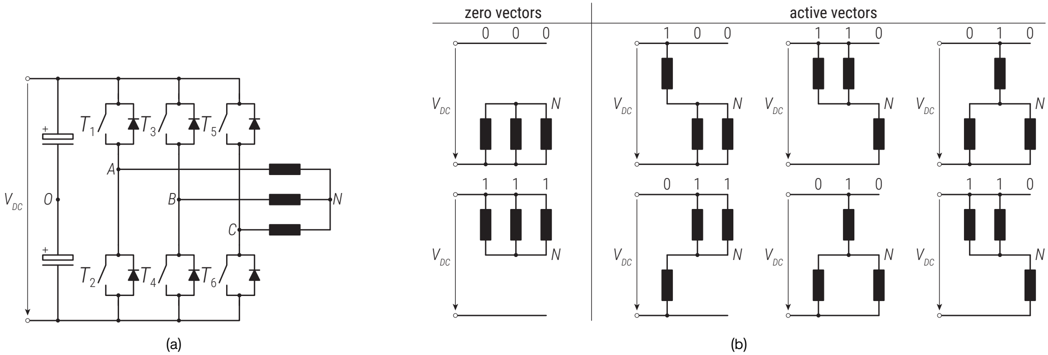



**Figure 2** (a) 2L three-phase inverter scheme and (b) $2^3 = 8$ switch combinations.

**Table 1** Instantaneous phase to neutral and common mode voltages for all 8 space vectors, assuming identical phase impedances $Z$.

| | $s_A$ | $s_B$ | $s_C$ | $v_{AN}$ | $v_{BN}$ | $v_{CN}$ | $v_{NO}$ |
|---|---|---|---|---|---|---|---|
| $\mathbf{V}_0$ | 0 | 0 | 0 | 0 | 0 | 0 | $-V_{\text{DC}}/2$ |
| $\mathbf{V}_1$ | 1 | 0 | 0 | $2V_{\text{DC}}/3$ | $-V_{\text{DC}}/3$ | $-V_{\text{DC}}/3$ | $-V_{\text{DC}}/6$ |
| $\mathbf{V}_2$ | 1 | 1 | 0 | $V_{\text{DC}}/3$ | $V_{\text{DC}}/3$ | $-2V_{\text{DC}}/3$ | $V_{\text{DC}}/6$ |
| $\mathbf{V}_3$ | 0 | 1 | 0 | $-V_{\text{DC}}/3$ | $2V_{\text{DC}}/3$ | $-V_{\text{DC}}/3$ | $-V_{\text{DC}}/6$ |
| $\mathbf{V}_4$ | 0 | 1 | 1 | $-2V_{\text{DC}}/3$ | $V_{\text{DC}}/3$ | $V_{\text{DC}}/3$ | $V_{\text{DC}}/6$ |
| $\mathbf{V}_5$ | 0 | 0 | 1 | $-V_{\text{DC}}/3$ | $-V_{\text{DC}}/3$ | $2V_{\text{DC}}/3$ | $-V_{\text{DC}}/6$ |
| $\mathbf{V}_6$ | 1 | 0 | 1 | $V_{\text{DC}}/3$ | $-2V_{\text{DC}}/3$ | $V_{\text{DC}}/3$ | $V_{\text{DC}}/6$ |
| $\mathbf{V}_7$ | 1 | 1 | 1 | 0 | 0 | 0 | $V_{\text{DC}}/2$ |

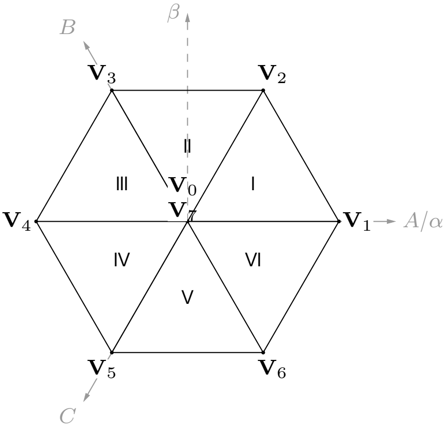


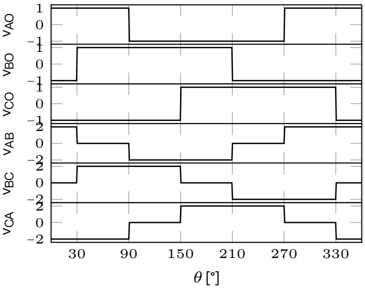

**Figure 3** Voltage synthesis capability for a 2-L 3-ph inverter.

# SQUARE-WAVE (SIX-STEP) OPERATION FOR 2-L INVERTERS

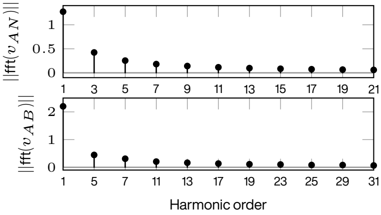
- Leg voltage is a simple square-wave type - contains all odd harmonics
- Only the active vectors are used (6 out of 8)
- Each leg is driven by 180° pulse, 120° delay between the phase-legs
- It is described by a geometric progression. In phase $a$, the voltage with respect to the negative bus terminal is:

$$v_A(t) = V_{DC}\frac{2}{\pi}\left(\frac{\pi}{4} + \frac{1}{3}\sin(3\omega_0 t) + \frac{1}{5}\sin(5\omega_0 t) + \dots\right)$$

- The magnitudes of the harmonics are $||v[k]||_{\text{phase}} = V_{DC}\frac{2}{\pi}\frac{1}{k}, k \in \{1,\ 3,\ 5,\ \dots\}$
- Line-to-line voltage can be determined by subtracting phase voltages, leading to cancelation of triplen harmonics: $v_{AB}(t) =$ $V_{DC}\frac{2\sqrt{3}}{\pi}\left(\sin(\omega_0 t + \pi/6) + \frac{1}{5}\sin(5\omega_0 t - \pi/6) + \frac{1}{7}\sin(7\omega_0 t + \pi/6) + \dots\right)$
- The magnitudes of the harmonics are $||v[k]||_{\text{line}} = V_{DC}\frac{2\sqrt{3}}{\pi}\frac{1}{k}, k \in \{1,\ 5,\ 7,\ \dots\}$
- Inverter does frequency control / voltage control through external DC link control
- $M = 4/\pi \simeq 1.27$




(a)




(b)

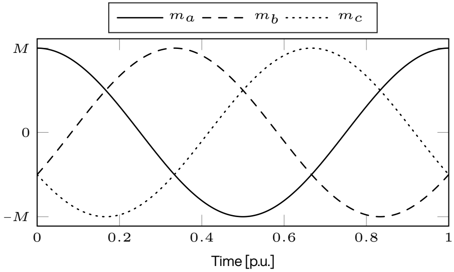
# SINUSOIDAL PWM - SPWM

- Normally, we want sinusoidal line-to-line voltages
- Fundamental three-phase reference signals:

$$\begin{cases} v_a^\star = V_m \cos(\omega t) \\ v_b^\star = V_m \cos(\omega t - 2\pi/3) \\ v_c^\star = V_m \cos(\omega t + 2\pi/3) \end{cases}$$

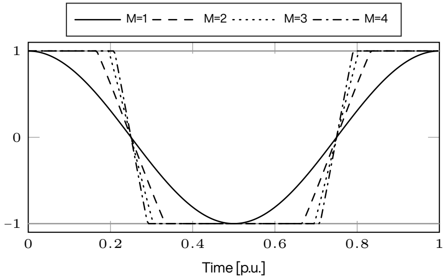
- The modulation index is defined as $M = \frac{V_m}{V_{DC}/2}$
- It relates the output peak phase voltage and $V_{DC}$
- Reference normalization:

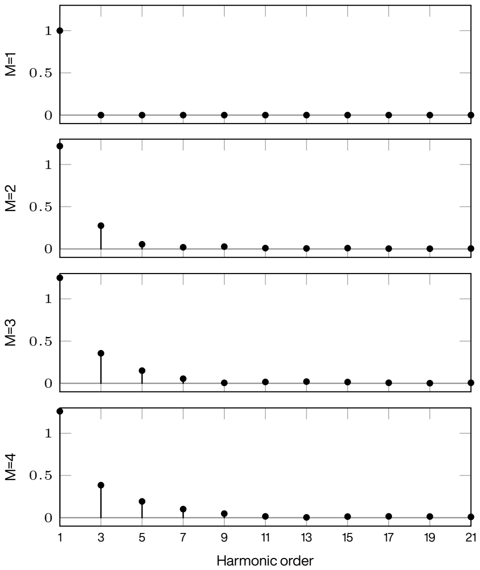
$$\begin{cases} m_a^\star = M \cos(\omega t) \\ m_b^\star = M \cos(\omega t - 2\pi/3) \\ m_c^\star = M \cos(\omega t + 2\pi/3) \end{cases}$$



# OVERMODULATION

- Normally, we have carrier bounded to $\pm 1$ range
- SPWM is bounded by $M_{\text{max}} = 1$, else low-order harmonics appear
- Non-triplen harmonics are difficult to filter out (low filter cut-off frequency required, means large filters!)
- In the worst case, it becomes six-step (square-wave) modulation



# ZERO-SEQUENCE INJECTION

- From power systems theory for three-phase system (if $\omega$ = cst): there exists a linear decomposition into positive, negative and zero sequence of balanced (with same amplitude) symmetrical components (with $\pm$120° shift)
- In star-connected systems, no zero-sequence current can flow $\rightarrow$ degree of freedom to be used for extending the DC bus utilization, i.e. allow $M_{\text{max}} > 1$
- Zero-sequence component is obtained as: $m_{zs} = (m_a + m_b + m_c)/3$

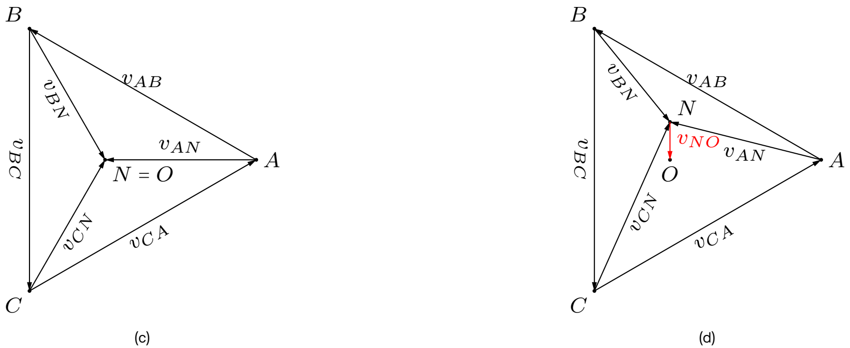



**Figure 4** (a) no zero-sequence signal and (b) zero sequence signal, with line-to-line voltage preservation.

- The zero-sequence injection is defined as:

$$\begin{cases} m_a = M\cos(\omega t) + m_{zs} \\ m_b = M\cos(\omega t - 2\pi/3) + m_{zs} \\ m_c = M\cos(\omega t + 2\pi/3) + m_{zs} \end{cases}$$

- The harmonic distortion will be reduced, as no low-order non triplen harmonics are injected, contrary to the six-step modulation
- The zero-sequence signal doesn't appear in the line-to-line voltages as the triplen harmonics cancel each other: $v_{AB} = v_{AN} - v_{BN}$
- No zero-sequence current will flow in star-connected loads

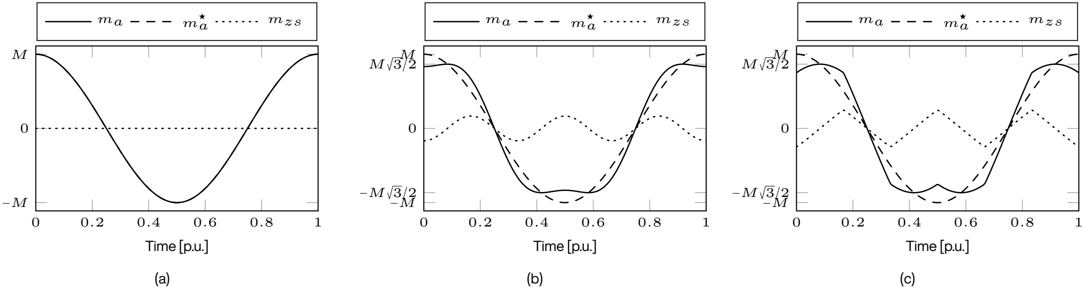


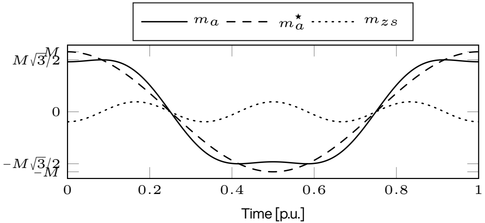

**Figure 5** Zero-sequence injection methods illustration: (a) sinusoidal PWM, (b) third harmonic injection and (c) min/max injection.

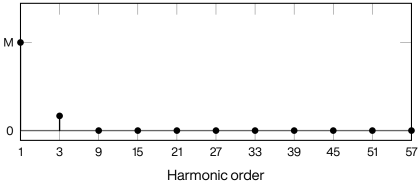
- The third harmonic is the lowest triplen harmonic. It might very likely have the largest impact.
- Let $b$ the relative amount of third harmonic that we want to add to the fundamental
- Taking phase $a$ as exampled:
  $m_a^\star = M\cos(\omega t) + bM\cos(3\omega t)$
- Extreme of the function is found by equalizing the derivative to 0:

$$\frac{\mathrm{d}m_a}{\mathrm{d}t} = -M\omega\sin(\omega t) - b3M\omega\sin(3\omega t) = 0$$

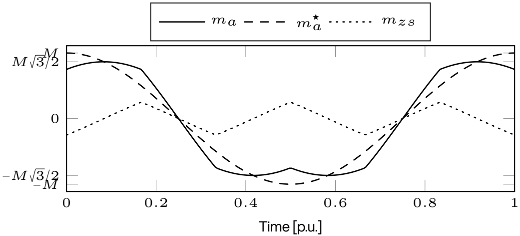
$$b = -\frac{\sin(\omega t)}{3\sin(3\omega t)}$$

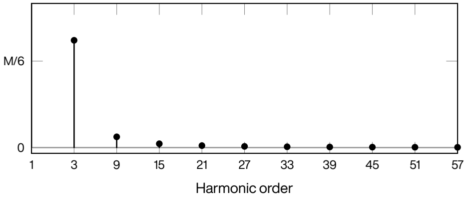
- The peak of the modulating signal is found at $\omega t = \pi/6$
- Result: $b = -\frac{\sin(\pi/6)}{3\sin(3\pi/6)} = -\frac{\sin(\pi/6)}{3} = -1/6$
- At peak value:
  $M_{\text{max}}\cos(\omega t) + bM_{\text{max}}\cos(3\omega t) = 1 \rightarrow M_{\text{max}} = \frac{1}{\cos(\pi/6)}$
- The increase is around 15 %: $M_{\text{max}} = \frac{1}{\cos(\pi/6)} = \frac{2}{\sqrt{3}} \approx 1.15$



- It is not convenient to inject a third harmonic, as the magnitude and frequency of the reference signal cannot be directly determined from the instantaneous sampled modulation index references
- The harmonic content is an infinite sum of odd triplen harmonics!



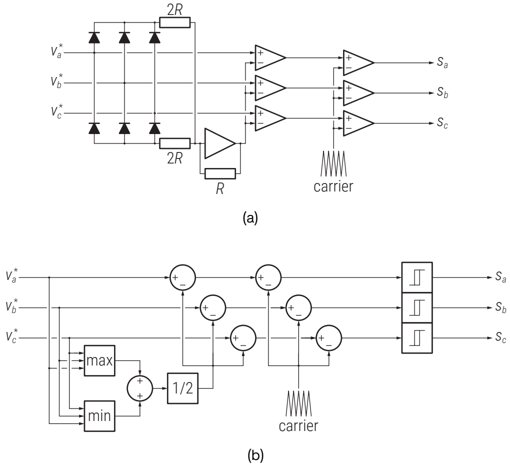




**Figure 6** Min/max zero-sequence injection: (a) analog scheme and (b) digital PWM.

- Depending on the load type (resistive, inductive, capacitive), switching losses ($\sim v \cdot i$) are high when the load current is large
- Discontinuous PWM avoids switching for a certain time in a period ($2\times$ 60°)
- That region has to be adapted depending on the load type
- $M_{\text{max}} = 2/\sqrt{3}$
- Not switching = clamping one phase voltage to $V_{DC}$ or $0$

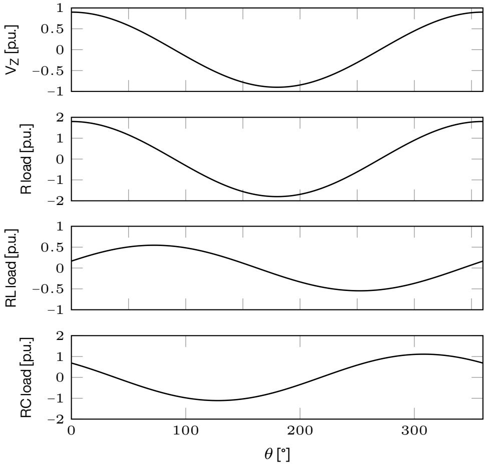



**Figure 7** Load types: resistive (current in phase), inductive (current lagging) and capacitive (current leading).

# DISCONTINUOUS PWM - DPWM

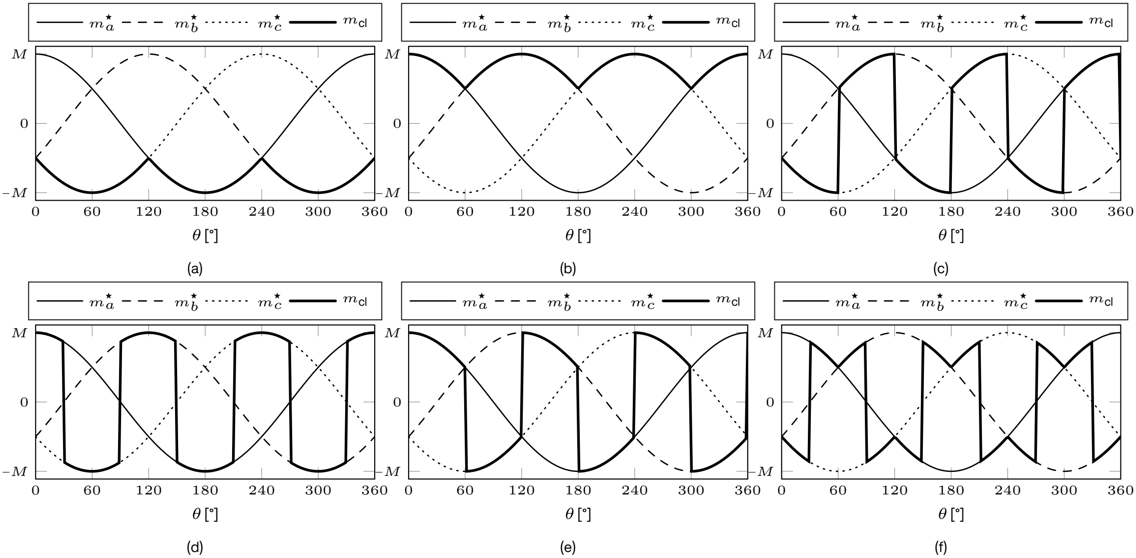



**Figure 8** Discontinuous PWM clamping regions: (a) DPWMMIN, (b) DPWMMAX, (c) DPWM0, (d) DPWM1, (e) DPWM2 and (f) DPWM3.

# DISCONTINUOUS PWM - DPWM

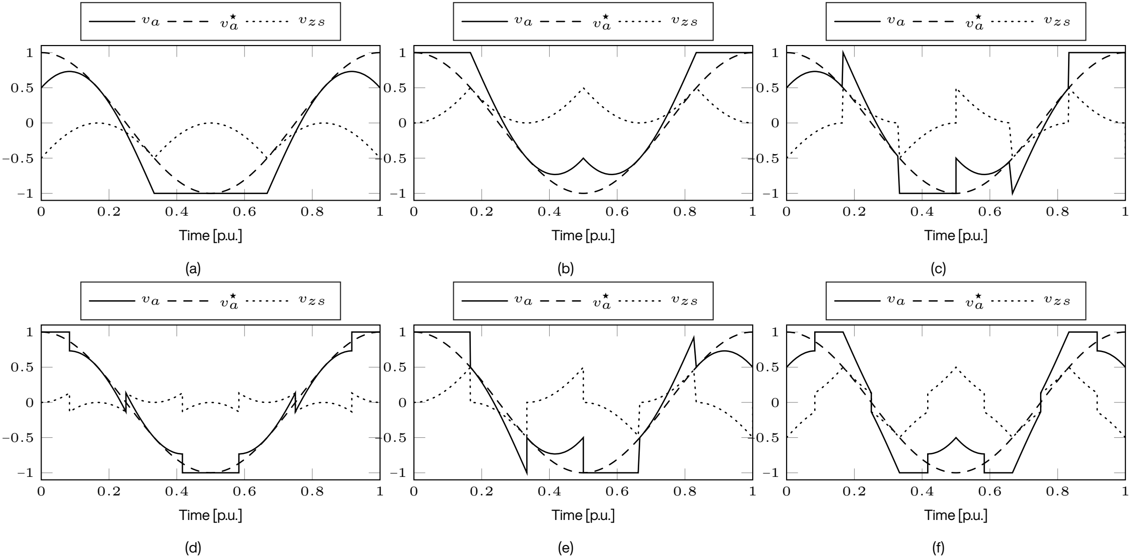



**Figure 9** Discontinuous PWM, $M = 1$: (a) DPWMMIN, (b) DPWMMAX, (c) DPWM0, (d) DPWM1, (e) DPWM2 and (f) DPWM3.

# HARMONIC DISTORTION FACTOR - HDF

- Figure of merit for harmonic losses caused by switching harmonics
- DPWM schemes allow for effective increase of switching frequency of 1.5 times of CPWM
- Switching losses of CPWM and DPWM can be maintained at the same level

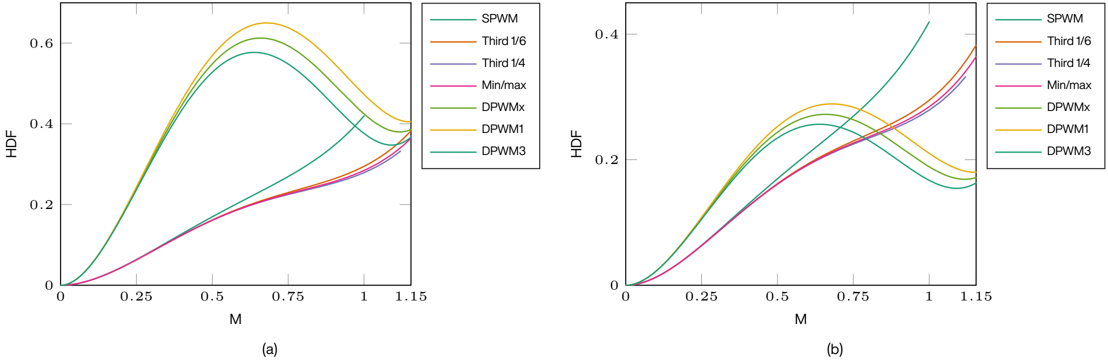



**Figure 10** HDF plot for: (a) $f_{\text{sw,CBPWM}} = f_{\text{sw,DPWM}}$ and (b) $f_{\text{sw,CBPWM}} = 2f_{\text{sw,DPWM}}/3$.

# EFFECTIVE MODULATION INDEX

- In overmodulation region ($M > 1$ for SPWM or $M > 2/\sqrt{3}$ for zero-sequence injection methods), the real modulation index (i.e. fundamental term of the Fourier series) is not anymore given by a linear expression
- The effective modulation index saturation at $4/\pi$ (six-step modulation)

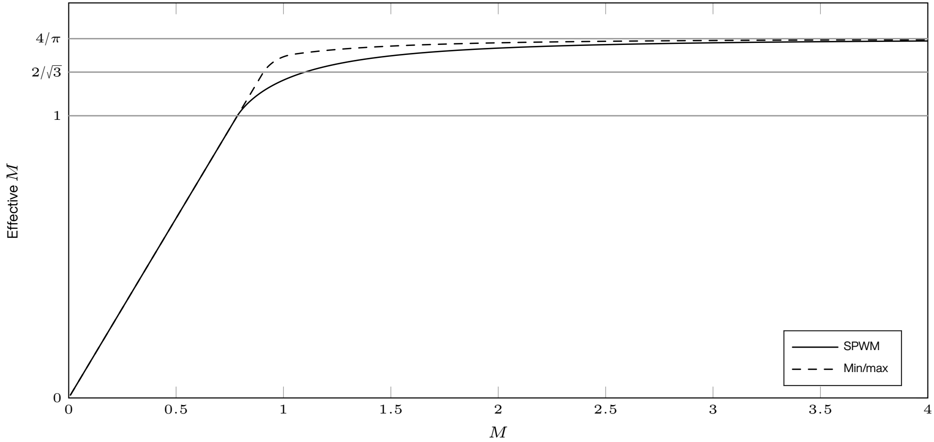



**Figure 11** Effective modulation index in linear and overmodulation regions.

# MULTILEVEL CONVERTERS

- Advantages
  - Higher DC link voltage accessible with same semiconductor technology
  - Improved resolution/quality of the output voltage with lower $f_{sw}$
- Drawbacks
  - Higher complexity in the modulator
  - Device failure

- Examples of three-level topologies
  - 3L Neutral Point Piloted (Holtz 1977)
  - 3L Neutral Point Clamped (Nabae 1981)
  - 3L Flying Capacitor (Meynard 1992)
- Can be extended to > 3-L
- Intermediate voltage levels must be kept balanced

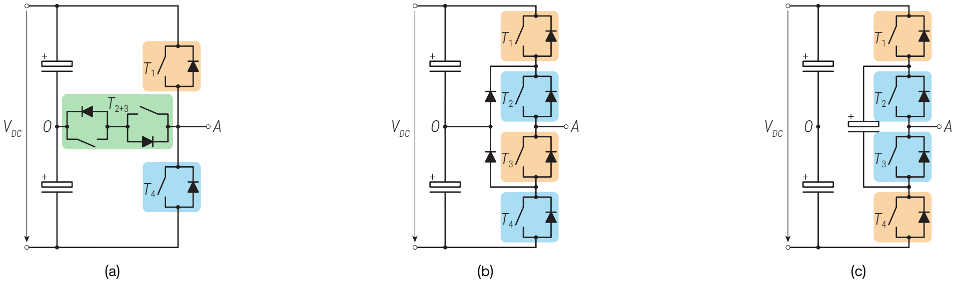
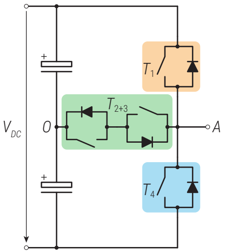



**Figure 12** Multilevel phase-legs: (a) 3L NPP, (b) 3L NPC and (c) 3L FC.

# MULTILEVEL CONVERTERS

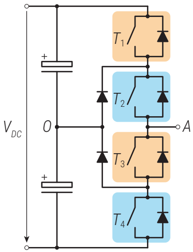
## 3-L NPP




| $s_1$ | $s_4$ | $v_{AO}$ |
|---|---|---|
| 0 | 1 | $-V_{DC}/2$ |
| 1 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | $V_{DC}/2$ |

- Switching logic
  - $s_{2+3}$ = and $(\bar{s}_1, \bar{s}_4)$
- Can operate as 2L

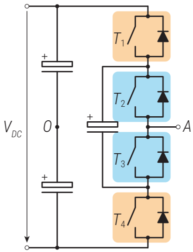
## 3-L NPC




| $s_1$ | $s_2$ | $v_{AO}$ |
|---|---|---|
| 0 | 0 | $-V_{DC}/2$ |
| 1 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 1 | $V_{DC}/2$ |

- Switching logic
  - $s_3 = \bar{s}_1$
  - $s_4 = \bar{s}_2$

## 3-L FC




| $s_1$ | $s_2$ | $v_{AO}$ |
|---|---|---|
| 0 | 0 | $-V_{DC}/2$ |
| 1 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 1 | $V_{DC}/2$ |

- Switching logic
  - $s_3 = \bar{s}_2$
  - $s_4 = \bar{s}_1$

- One carrier assigned per pair of complementary switches

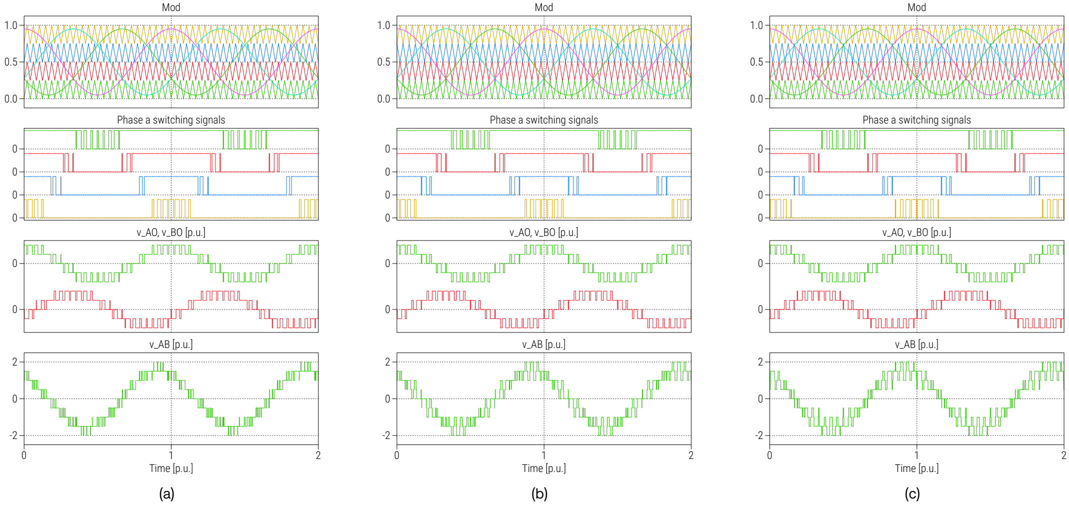



**Figure 13** Multilevel PWM methods illustrated for the 5L case for $f_{\text{sw}} = 24 f_g$: (a) PD-PWM → all carriers in phase, (b) APOD-PWM → 180° shift between carrier bands and (c) POD-PWM → 180° shift between the carrier above and below 0.5.

- PD-PWM is the best multilevel PWM method (cf. line-to-line voltage waveforms)

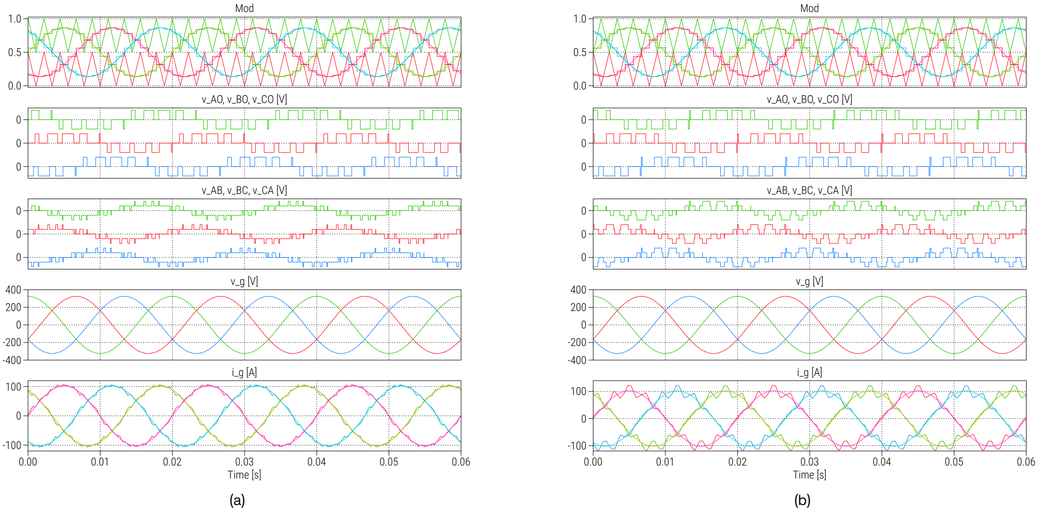



**Figure 14** Typical waveform for a 3L NPC inverter, $V_{DC} = 800$ V, $f_{\text{sw}} = 450$ Hz, $S = 50$ kVA, $\phi = \pi/6$, asymmetrical sampling: (a) PD-PWM and (b) APOD-PWM (POD-PWM is identical to APOD-PWM for 3L).

- Enhanced reliability (operation with failed cells possible)
- Extension to higher voltages
  - Series-connection of LV cells
  - Externally supplied series-connected cells (McMurray 1969)

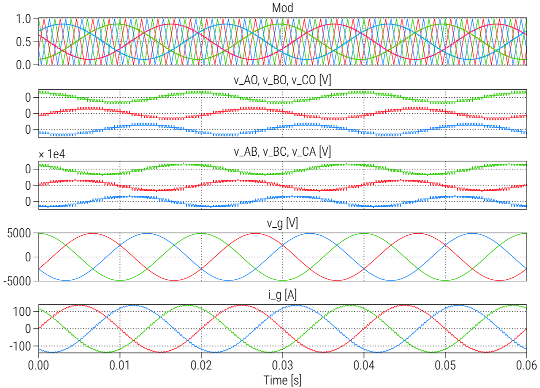



**Figure 15** Operation waveforms for $v_{g,ll} = 6$ kV, $S = 1$ MVA, $\phi = \pi/6$, $N_{\text{cells}} = 3$, $f_{\text{sw,IGBT}} = 500$ Hz, PS-PWM, bipolar modulation for the cell.

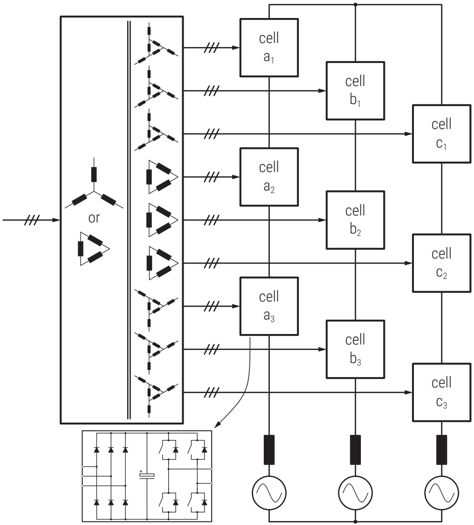



**Figure 16** Cascaded H-bridge with externally supplied cells (Robicon drive). Unidirectional power flow!

# MODULAR MULTILEVEL CONVERTER

- Avoid large bulky transformer(s) of CHB
- For MV and HV applications
  - HVDC, grid support & frequency support (STATCOM), frequency conversion (rail interties), MV drives, shaft generator, etc.

**Figure 17** HVDC hall from Siemens.

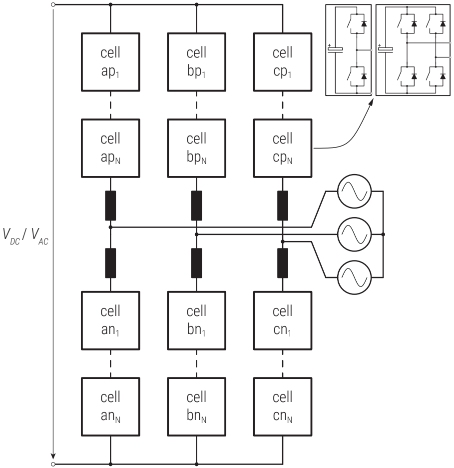



**Figure 18** Double-star modular multilevel converter (Marquardt 2002).