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ENM061 - Power Electronic Converters 7.5 ECTS, 2017

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Lecture outline

Multilevel inverter

- Prerequisites for today's lecture
- The Two-level vs Multilevel Inverters
- Neutral Point (Diode) Clamped Inverter (three- and five-level)
- Flying Capacitor Inverter (three- and five-level)
- Modular Multilevel Inverter
- The Half-Bridge vs the Full-Bridge Modular Multilevel Inverter
- Control Strategies
- Summary

Reference:

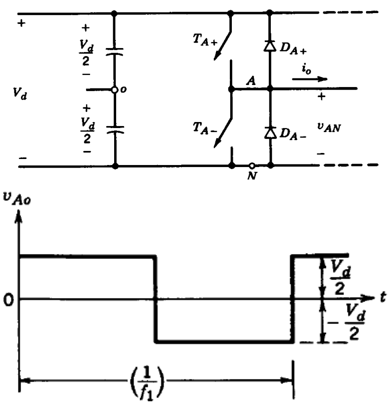
http://web.eecs.utk.edu/~tolbert/publications/multilevel_book_chapter.pdf

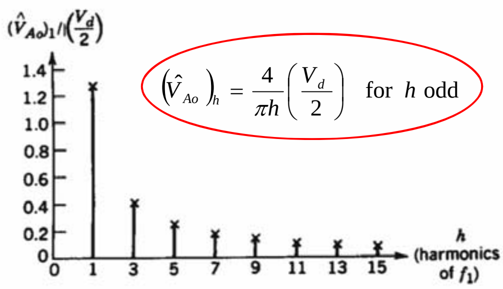
Learning outcomes

- Fourier components and total harmonic distortion (THD) for basic waveforms.
- Operating principles of the most common active components (e.g. diode, thyristor, IGBT, and MOSFET) and passive components (e.g. capacitors, transformers and inductors).
- Operation of a pulse width modulation (PWM), the purpose of controlling the desired quantity and the need for a controller circuit within the power electronic converter.
- Analysis of ideal DC/DC converters (e.g. buck, boost, buck-boost, flyback, the forward, the push-pull, half-bridge and full-bridge converters) in CCM and DCM operation.
- Operating principles of single-phase and three-phase AC/DC inverters with different modulation strategies (e.g. PWM and square wave operation).
- Operation of multilevel inverters (e.g. NPC, flying capacitor and MMC topologies) using current and voltage waveform analysis. Pros and Cons of the converter in terms of harmonics and losses.
- Operation of single- and three-phase diode rectifiers operating with voltage-stiff and current-stiff DC-side. Investigating the impact of line impedance within the converter circuit for current commutation.
- Operation of single- and three-phase thyristor rectifiers operating with a current-stiff DC-side and the impact of line impedance for current commutation. Investigating the use of 6/12-pulse configurations.
- Identify simple power electronic converter schematics. Recognizing the different parts in a physical circuit on which basic wave-shape and efficiency measurements is performed.
- Loss calculation in passive and active components. Evaluating the temperature rise in the active components and choosing an appropriate heat-sink. Gaining a basic understanding of component life time.
- Utilizing the software Cadence PSpice to simulate basic power electronic circuits and the practical labs to have a firsthand experience of how real DC/DC converters operate.

Single-Phase Inverter Square Wave Mode

- The output voltage of an inverter operating in square-wave mode results in a high number of odd harmonics





$$\left(\hat{V}_{Ao}\right)_h = \frac{4}{\pi h}\left(\frac{V_d}{2}\right) \quad \text{for } h \text{ odd}$$

Undeland, Power Electronics
Figure 8-9, page 210

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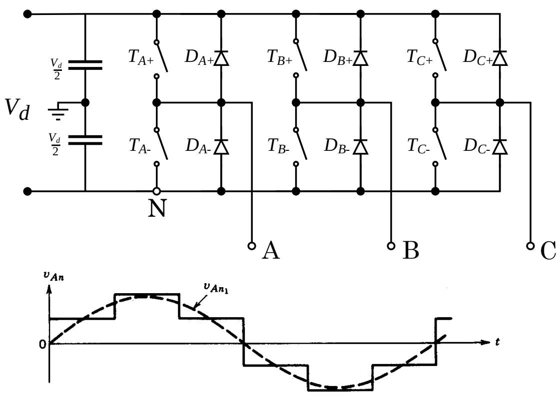
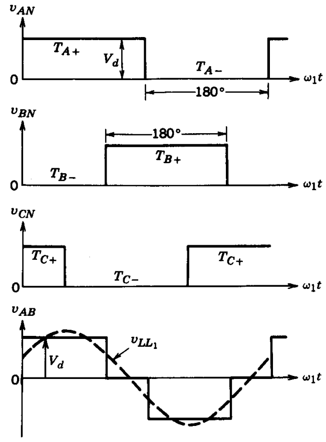
Three-Phase Inverter Square Wave Mode





$$\hat{V}_{An_h} = \left\{ \frac{4}{\pi h} \frac{V_d}{2} \right\} \text{ for } h = 6n \pm 1$$

$$v_{AB} = v_{AN} - v_{BN}$$

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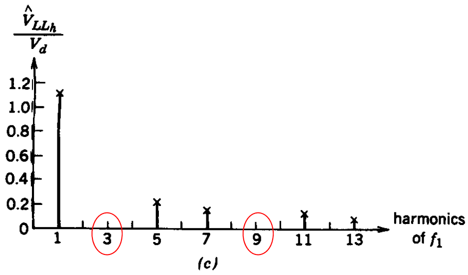
Three-Phase Inverter Square Wave Harmonics

- The line-to-line voltage does not depend on the load
- Contains harmonics (6n±1, n=1,2,…)



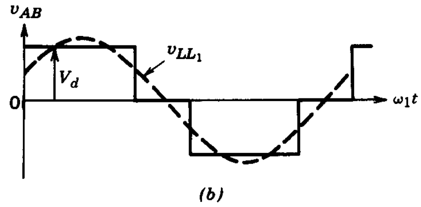


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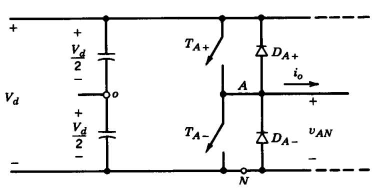
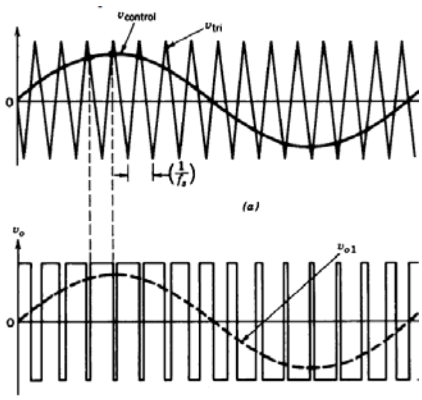
Figure 8-24, page 230

$$\hat{V}_{LL_h} = \frac{4V_d}{\pi h} |\cos(h\pi/6)| = \sqrt{3} \left\{ \frac{4}{\pi h} \frac{V_d}{2} \right\} \text{ for } h = 6n \pm 1$$

Single-Phase Inverter
Bipolar Switching and Voltage Control

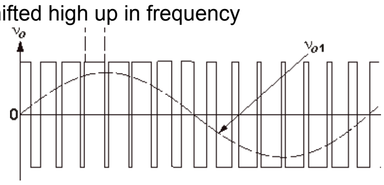
- Compare the reference voltage with a triangular voltage with much higher frequency – bipolar swtiching as for a H-bridge DC/DC-converter

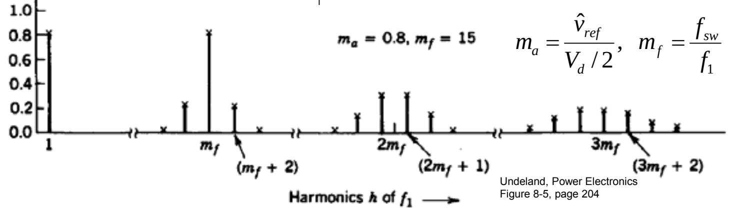




Single-Phase Inverter
Harmonics in Bipolar Switching

- High content of harmonics – shifted high up in frequency





$$m_a = \frac{\hat{v}_{ref}}{V_d/2}, \quad m_f = \frac{f_{sw}}{f_1}$$

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Figure 8-5, page 204

- Synchronous PWM: when the control voltage and the carrier are synched (when $m_f \leq 21$).
- Asynchronous PWM: when m_f is not an integer. Creates unwanted subharmonics of the fundamental frequency component (OK when $m_f \geq 21$)

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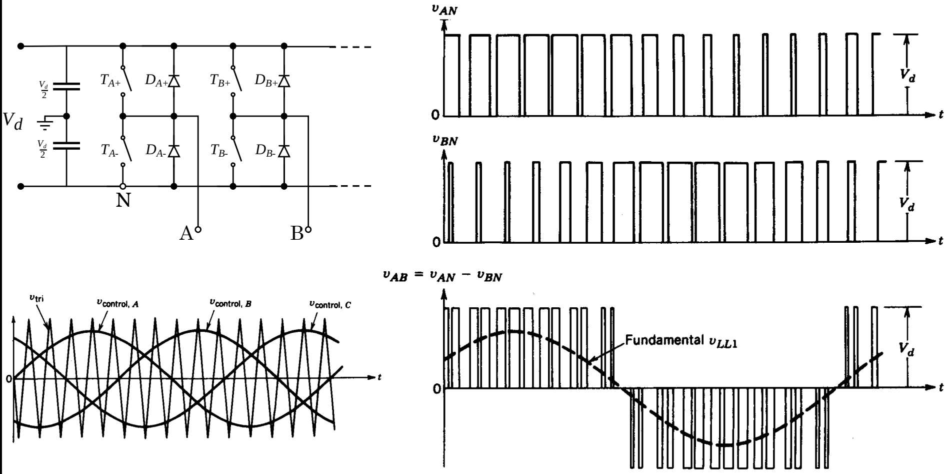
Three-phase Inverter V_{LL} and PWM Operation



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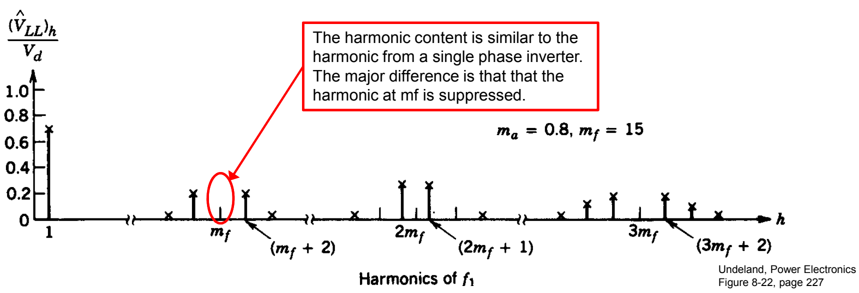
Three-Phase Inverter Harmonics in PWM Operation

- The harmonics in the line-to-line voltage are of concern
- The harmonics at m_f are suppressed in three-phase



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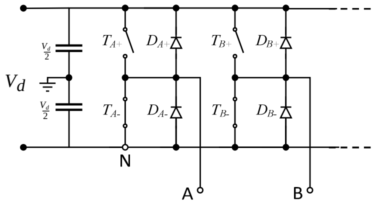
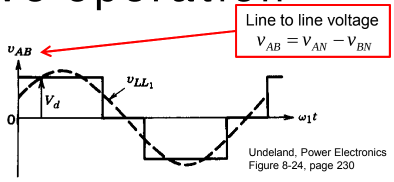
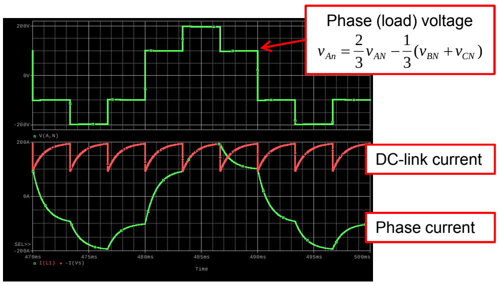
Summary: Three-phase two-level inverter square wave operation

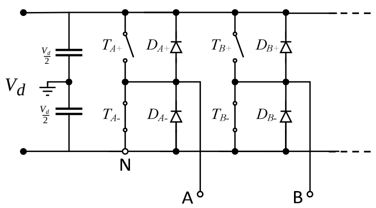


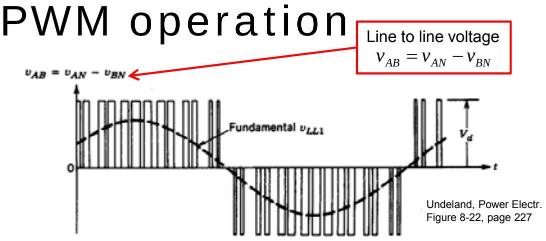


- The resulting phase-to-ground voltage is a 2-level square wave
- The line-to-line voltage is a 3-level quasi-square wave
- The phase-to-nuetral (load) voltage is a 4-level stair-case wave
- For an RL-load, there is a positive average input current and active power is consumed.

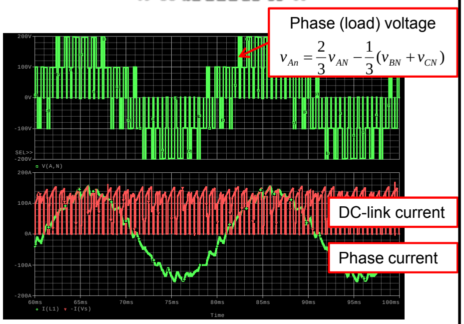


Summary: Three-phase two-level inverter PWM operation





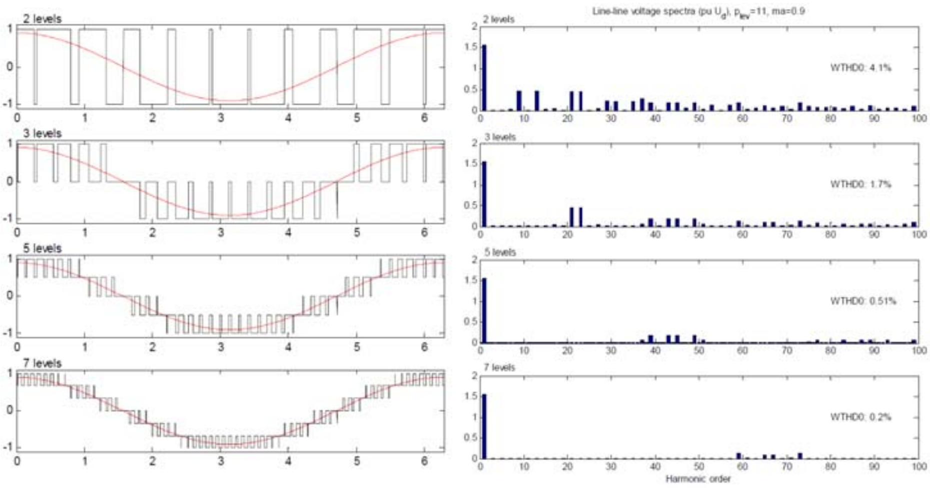
- The resulting phase-to-ground voltage is pulse-width modulated and 2-level
- The line-to-line voltage is pulse-width modulated and 3-level
- The phase-to-nuetral (load) voltage is pulse width modulated and 5-level
- For an RL-load, there is a positive average input current and active power is consumed.



Why Multilevel Inverters?

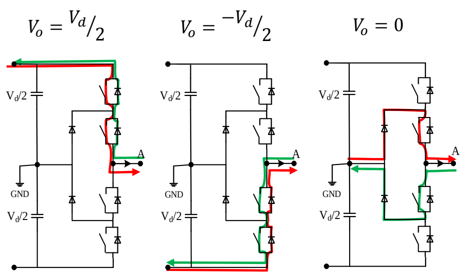
- The phase-to-ground voltages can have more than 2-levels
- By increasing the number of levels, lower effective switching frequency (as low as the fundamental frequency) can be used. This increases the harmonic performance without increasing the switching losses.
- The output voltage swing is reduced – less insulation stress due to high voltage derivatives
- Typical applications are high power converters such as HVDC transmission or large drive systems

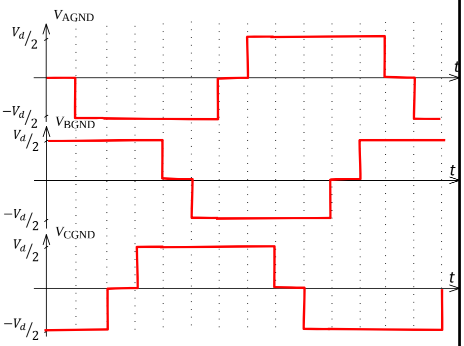
Why Multilevel Inverters?



Neutral Point (Diode) Clamped Inverter (Three-Level)

- Bus-splitting common DC-capacitor and diodes for clamping

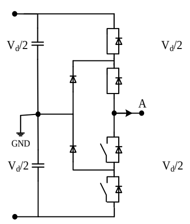




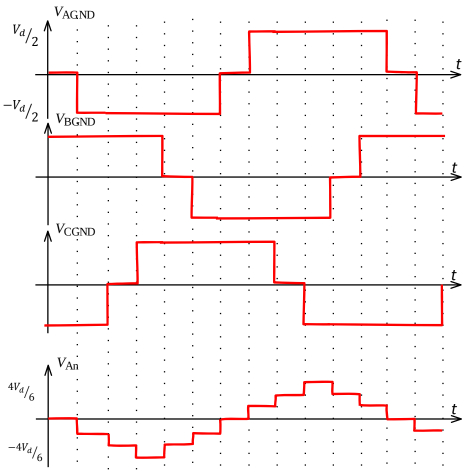
Ex: Show current paths for the three voltage potentials

Neutral Point (Diode) Clamped Inverter (Three-Level)

- Bus-splitting common DC-capacitor and diodes for clamping
- The resulting phase voltage will have 7 levels (unlike 4 in two-level)
- V_n swings between 0 and $\pm V_d/6$



$$v_{An} = \frac{2}{3}v_{AGND} - \frac{1}{3}(v_{BGND} + v_{CGND})$$



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Neutral Point (Diode) Clamped Inverter (Three Level)

- NPC modules for drive systems (600V/75A)

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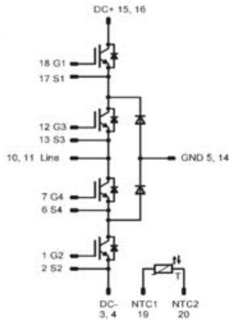

- Traditional module

conduction losses:	36W
switching losses:	118W
total losses:	154W
efficiency:	96,65%
total rating of Si:	720kVA

- NPC module

conduction losses:	62W
switching losses:	28W
total losses:	90W
efficiency:	98,04%
total rating of Si:	900kVA

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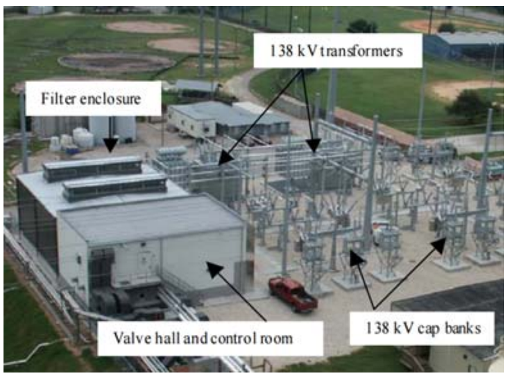
Neutral Point (Diode) Clamped Inverter (Three-Level)

- Static VAR Compensator (STATCOM) in Holly, USA.
- Provides ±95MVAr
- 32kV Converter Voltage
- Series connected IGBTs
- m_f=21
- Designed in 2004 by ABB



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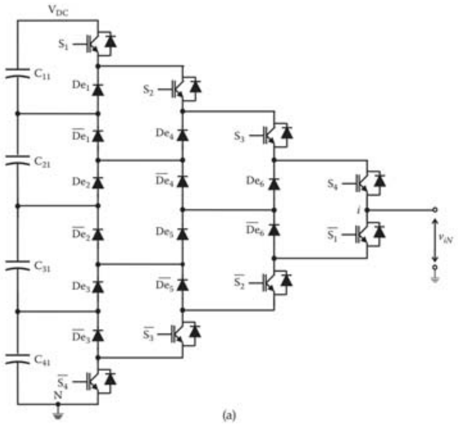
Neutral Point (Diode) Clamped Inverter (Five-Level)

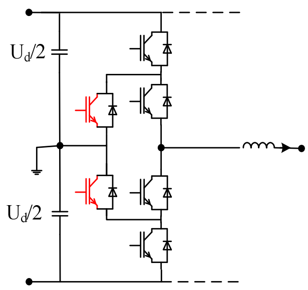
- Complicated design for higher number of voltage levels



© Gonzalez, Fig 2.12

Active Neutral Point Clamped Inverter (Three-Level)

- Active neutral point clamped topology – allows for more even distribution of semiconductor losses
- Gives alternatives for implementing the zero-voltage state
- Used in at least two HVDC projects (Murraylink, USA, and Cross Sound Cable Link, Australia) but difficult to scale up to higher voltages than ±150kV.



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Neutral Point (Diode) Clamped Inverter Pros and Cons

Advantages:

- Any number of levels, but the number of diodes increases
- The capacitors can be pre-charged as a group
- Efficiency is high for the fundamental switching frequency
- Widespread use in MV drives and STATCOMS (mainly 3-level)

Disadvantages:

- The number of clamping diodes required is quadratic ally related to the number of voltage levels.
- For a high number of levels, the commutation mechanisms become complex with many interconnects
- Critical failure propagation with increasing number of levels
- The capacitors at the DC-bus are not minimized/eliminated

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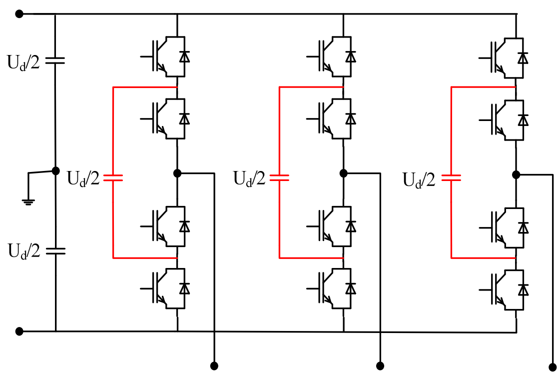
Flying Capacitor Inverter (Three-Level)

- Similar to the diode-clamped inverter but with capacitors instead
- Proven solutions for low number of voltage levels



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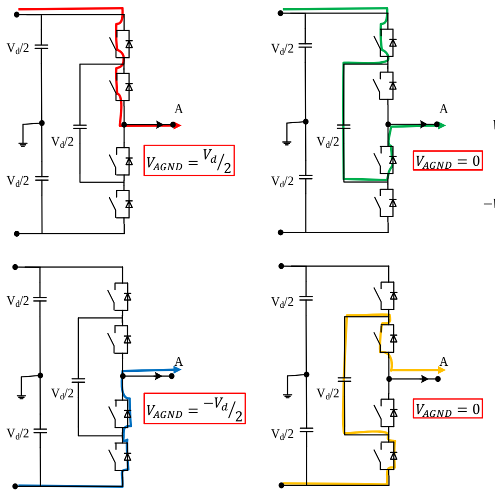
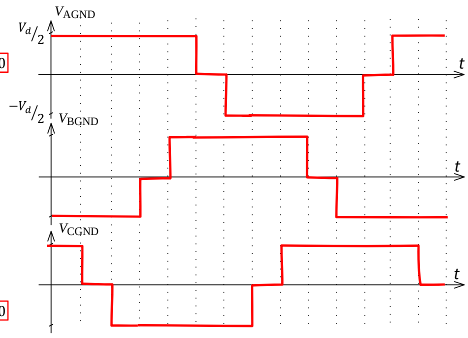
Flying Capacitor Inverter (Three-Level)



Ex: Show current paths for the three voltage potentials



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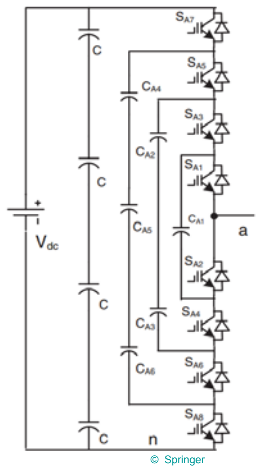
Flying Capacitor Inverter (Five-Level)

- The voltage on each capacitor differs from that of the next capacitor.
- The voltage increment between two adjacent capacitor legs gives the size of the voltage steps in the output waveform.
- Becomes complicated as the number of voltage levels increases



The Flying Capacitor Inverter Pros and Cons

Advantages:

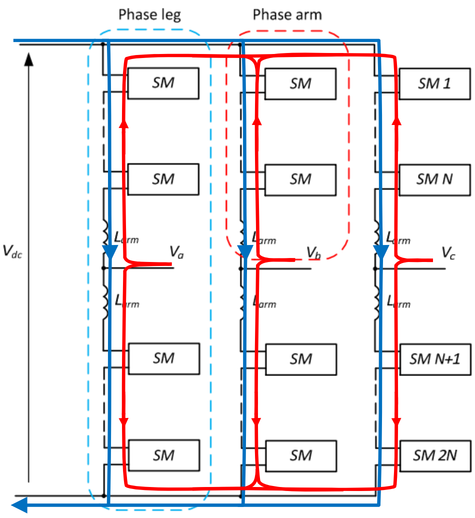
- Redundant states in the phase voltages are available to balance the voltage levels over the capacitors
- Large number of capacitors enables the inverter to ride through voltage sags

Disadvantages:

- Large capacitors are needed since they must be able to handle the fundamental current
- Long commutation path
- Non scalable construction for higher number of voltage levels
- Requires pre-charging of the capacitors which is complicated
- Complicated control needed to track the voltage level over each capacitor
- More expensive and bulky com-pared to a diode clamped inverter

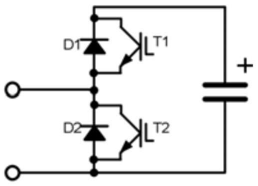
Modular Multilevel Inverter

- Series connection of identical SMs
- Inductors are placed in each phase arm to limit transient currents
- Scalable with regard to voltage levels, power and voltage rating
- Redundancy possible to replace failing cells
- The DC-side current is equally distributed between the legs
- The AC-current is divided equally in the upper and the lower arm in each leg

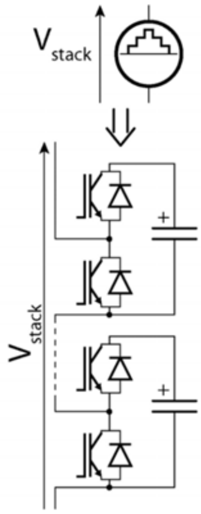


Modular Multilevel Inverter

- Simplest submodule topology for MMC
- Low semiconductor cost and minimized losses
- No possibility for electronic DC-current limitation
- High volume of installed capacitors

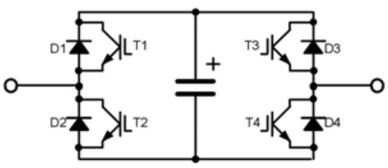


A half-bridge submodule (SM)

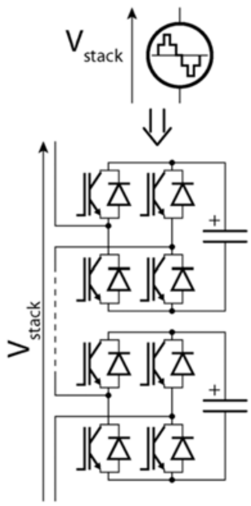


Modular Multilevel Inverter

- For a full-bridge configuration, AC/AC-conversion can be performed
- Double conduction losses in comparison to the half bridge
- Electronic DC-current limitation

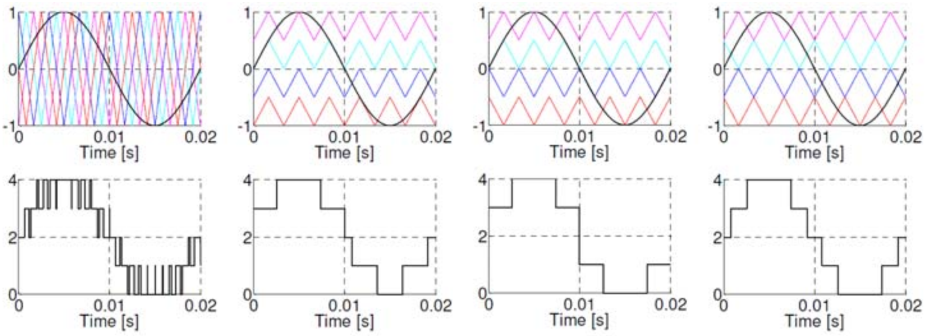


A full-bridge submodule (SM)



Control of the Modular Multilevel Inverter

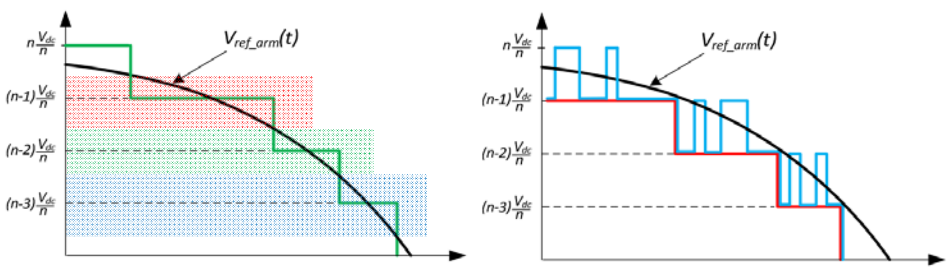
- As for the previous topologies, carrier based modulation methods (PWM) can be used
- Different carriers gives various compromises between swtiching frequency and harmonics



a) PSC b) PDC c) PODC d) APODC

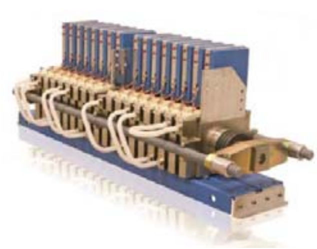
Control of the Modular Multilevel Inverter

- Nearest Level Modulation (NLM) is often used for high voltage applications
- For inverters with large number of cells, cells can be matched so that the output voltage matches the reference with fundamental switching frequency
- With a lower number of voltage levels, one cell in each arm can be modulated which lowers the harmonics



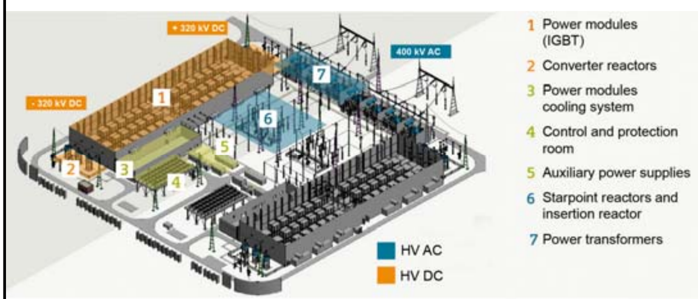
Modular Multilevel Inverters in Power System Applications

- HVDC Light by ABB
- DolWin in the north sea outside Hamburg, commissioned during 2016 (916MW, ±320kV, 45km + 90km cables)



Modular Multilevel Inverters in Power System Applications

- HVDC Plus by Siemens
- Baixas – Sta. Llogaia interconnection (65km, 2000MW, ±320kV)



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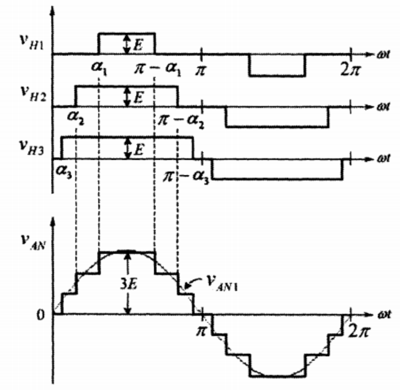
Control of the Cascaded Full Bridge Inverter

- A typical modulation scheme is Selective Harmonic Elimination
- All switches operate with the fundamental frequency which gives low losses
- For each module, the switching angle (α) is controlled.
- For *N* switching angels, *N* independent equations and degrees of freedom can be obtained which can be used to eliminate (*N*-1) harmonics and an adjustable amplitude modulation ratio (m_a)



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The Cascaded Full Bridge Inverter Pros and Cons

Advantages:

- The number of voltage levels is twice the number of DC-sources
- Modularized solution for each cell simplifies packaging and manufacturing
- For an electric vehicle application, the inverter losses can be reduced significantly if MOSFETs are used instead of IGBTs

Disadvantages:

- A separate DC-source is required for each cell
- A large pulsed current is drawn from each DC-source (battery) which gives increased losses and increases the need for filtering

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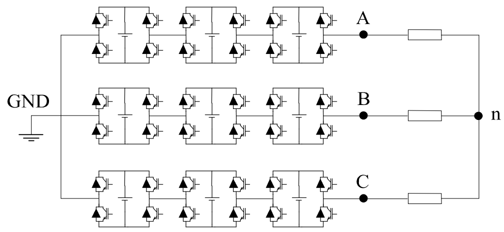
Tutorial 9



Assume 80^o, 140^o and 160^o connection of the cells in a phase per half-cycle

- Plot phase to neutral and ground, the line-to-line and neutral to ground voltages
- THD of the phase to neutral voltage and comparison with two-level case in square-wave operation case
- Average and RMS value of the dc-current from the dc sources and its comparison to two-level square-wave operation case

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Summary

- Pros and cons of the two-level vs multilevel inverters
- Pros and cons of the various multilevel inverters
- Basic operation of a Neutral Point (Diode) Clamped Inverter
- Basic operation of a Flying Capacitor Inverter
- Basic operation of a Modular Multi Level Inverter
- Pros and cons of the Cascaded Half- and Full-Bridge Inverters
- Learning outcome:
  - Operation of multilevel inverters (e.g. NPC, flying capacitor and MMC topologies) using current and voltage waveform analysis. Pros and Cons of the converter in terms of harmonics and losses.