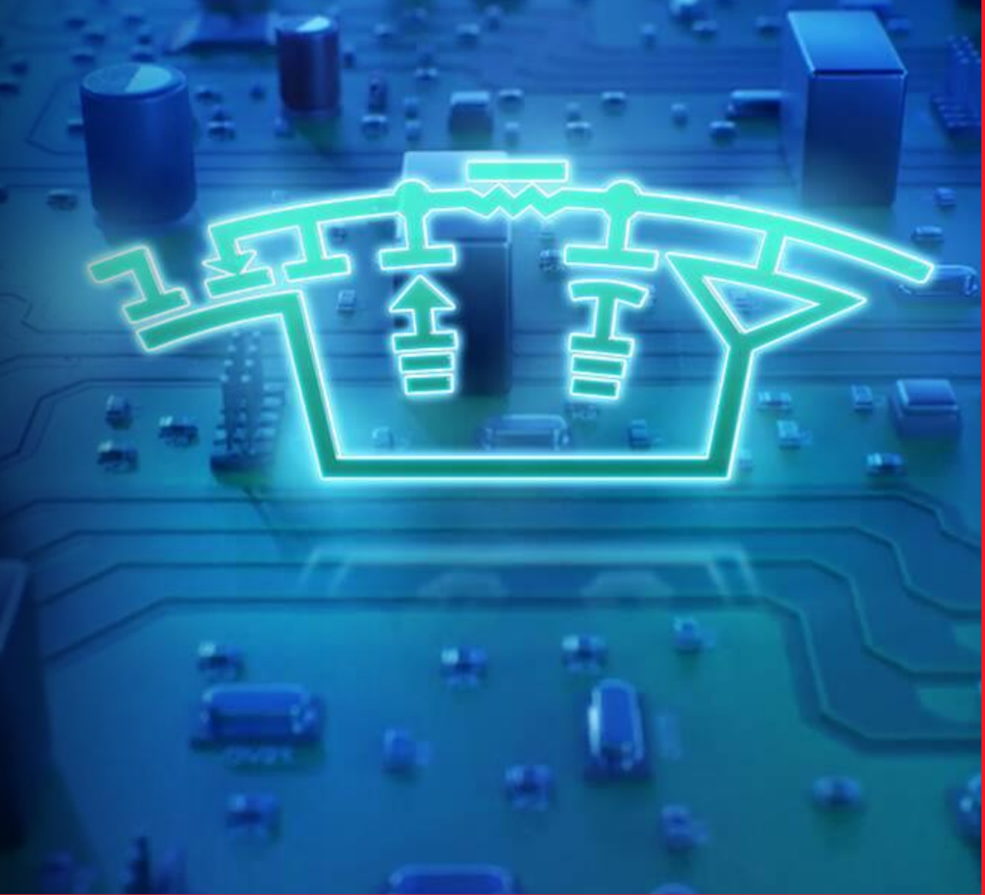
Power Supply Design Seminar

Comparing AC/DC power-conversion topologies for three-phase industrial systems



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Agenda

- Overview of power-conversion systems
- Three-phase boost-converter topology overview and operating principles
- Power losses, common-mode noise and capacitor stress comparisons
- Experimental results (two level, T type, Vienna, active neutral point clamped [ANPC])
- Conclusions

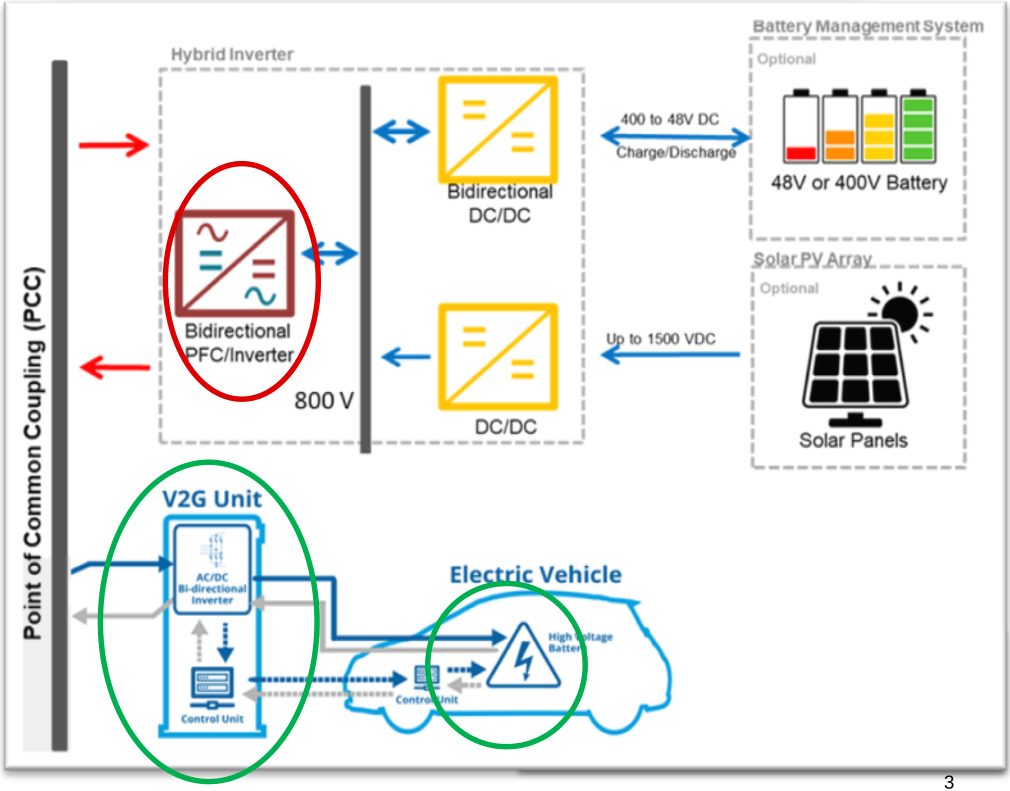
Overview: End Equipment with AC/DC Converter

Energy sustainability and security are accelerating demands for:

- Renewable Energy: Wind and Solar
- Energy storage systems
- Electric Vehicles (EV) & Chargers

Key End Equipment Challenges:

- Grid stability / reliability
- Power quality
- Fast & Efficient EV charging



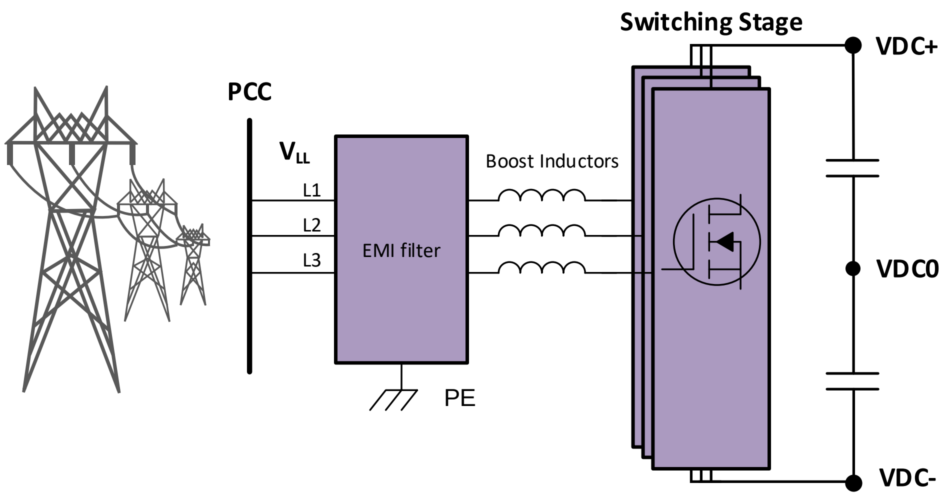
Overview: Existing AC/DC topologies

AC/DC boost converter benefits:

- Higher efficiency (lower currents)
- Less electromagnetic interference (EMI) noise injected into the grid
- Able to handle better surges from the grid

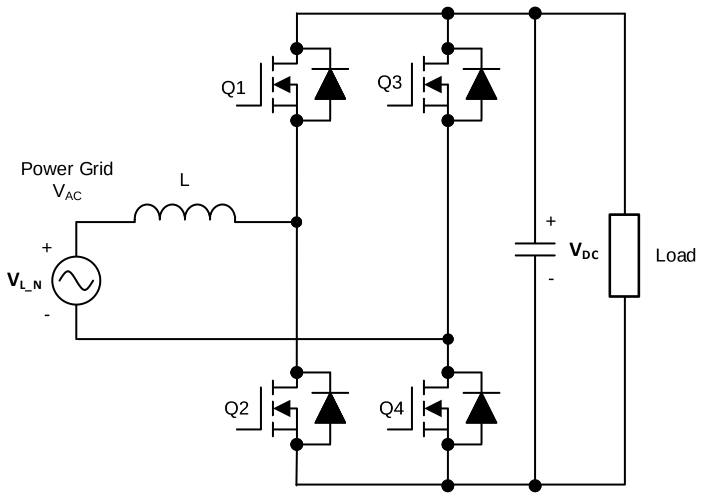
An AC/DC boost converter requires:

- Boost power factor correction (PFC) ($V_{DC} \gg \sqrt{2}\, V_{LL}$)
- Inductive behavior on the grid side
- Capacitive behavior on the DC side
- Three-phase benefits: current, size, power ripple

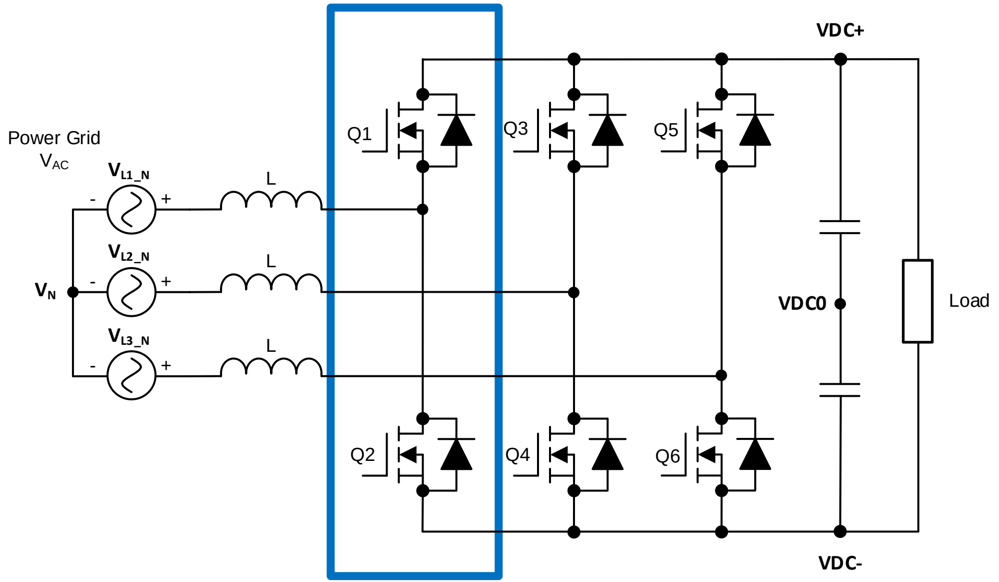


Overview

Single-phase, two-level PFC



Three-phase, two-level PFC

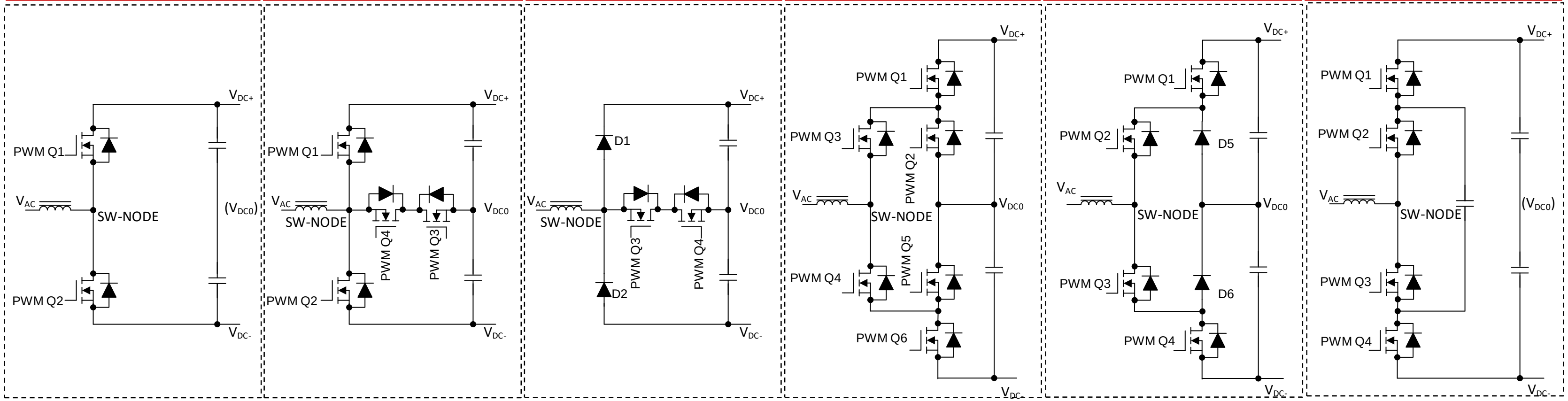


Switching cell

Note: Neutral of grid is virtually connected to the middle point at high frequency

Multilevel topology overview on AC/DC power stages

2L two-level converter	3L three-level T-type	3L Vienna rectifier	3L ANPC	3L neutral-point clamped (NPC)	FC3L flying capacitor

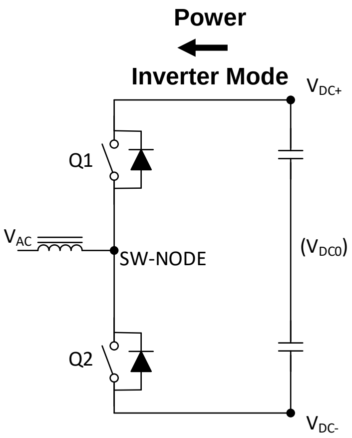


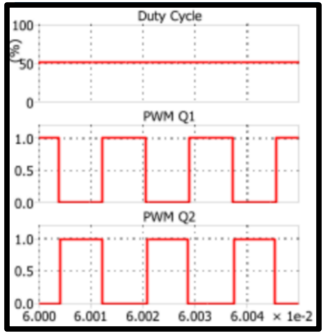
Requires two connections to the DC link

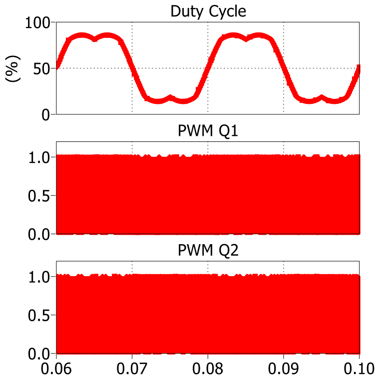
Requires three connections to the DC link

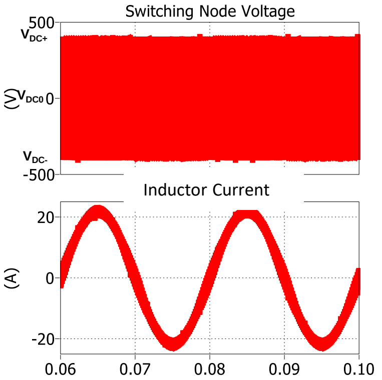
Requires two connections to the DC link

2L converter: Basic operating principles









For a positive sine wave ($V_{DC0} \leq V_{AC} \leq V_{DC+}$), duty cycle >50%:

- Q1 and Q2 are switching f_{PWM}
- Output voltage is defined by duty cycle of the pulse-width modulator (PWM) (Q1 is on more often than Q2)
- Dead time between Q1 and Q2

For a negative sine wave ($V_{DC-} \leq V_{AC} \leq V_{DC0}$), duty cycle <50%:

- Q1 and Q2 are switching f_{PWM}
- Output voltage again defined by duty cycle of PWM (Q1 is more often OFF than Q2)

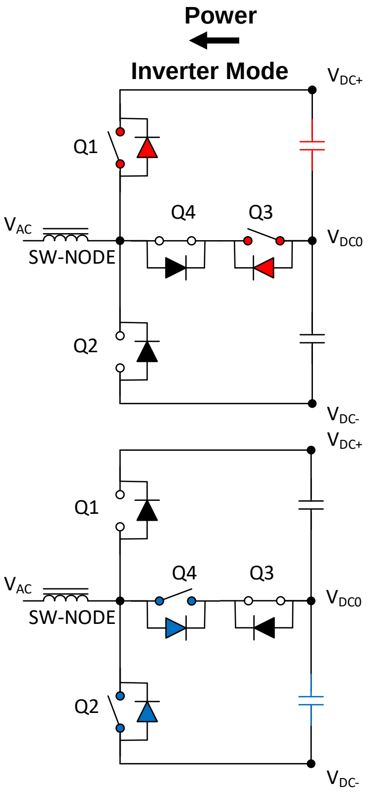
At zero crossing, the duty cycle is 50%

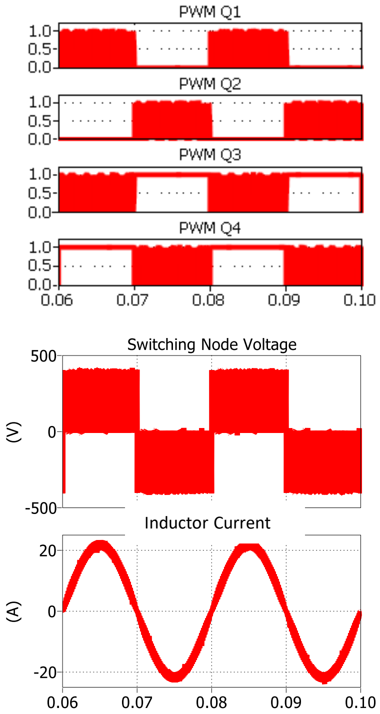
When the output ripple frequency $f_{HF\text{-}RIPPLE}$ is equal to f_{PWM}:

- f_{RIPPLE} defines sizes of filtering components (magnetics and capacitors)

Q1 and Q2 need be V_{DC} rated (for V_{DC} = 800 V, **1,200-V rated**)

3L T-type: Basic operating principles





For a positive sine wave ($V_{DC0} \leq V_{AC} \leq V_{DC+}$):

- Q4 is permanently in the on-state; Q2 is permanently off
- Q1 and Q3 in red are switching f_{PWM}
- The dead time between Q1 and Q3 needs to be accounted for

For a negative sine wave ($V_{DC-} \leq V_{AC} \leq V_{DC0}$):

- Q3 is permanently in the on-state, Q1 is permanently off
- Q2 and Q4 in blue are switching f_{PWM}
- The dead time between Q2 and Q4 needs to be accounted for

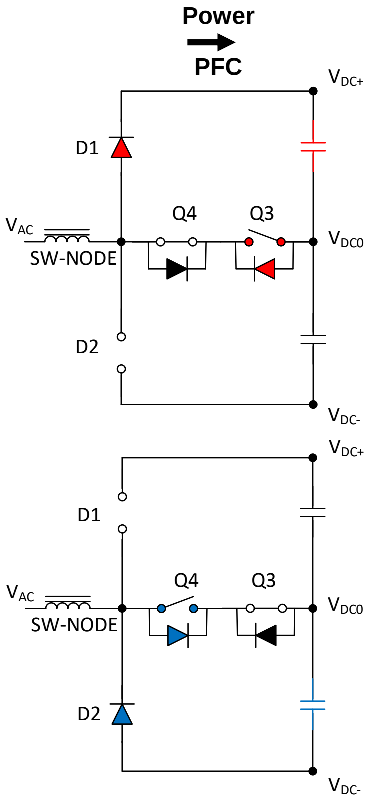
When the output ripple frequency $f_{HF\text{-}RIPPLE}$ is equal to f_{PWM}:

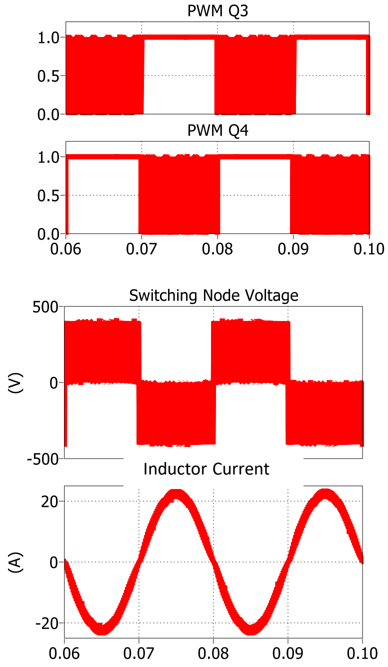
- $f_{HF\text{-}RIPPLE}$ defines the size of filter components (magnetics and capacitors)

Q1 and Q2 need be V_{DC} rated (for V_{DC} = 800 V, 1,200-V rated)

Q3 and Q4 can be 1/2 V_{DC} rated (for V_{DC} = 800 V, 600-V rated)

3L Vienna rectifier: Basic operating principles





For a positive sine wave ($V_{DC0} \leq V_{AC} \leq V_{DC+}$):

- Current is negative because of PFC operation
- Q4 is permanently in the on-state
- Q3 in red is switching at f_{PWM}

For a negative sine wave ($V_{DC-} \leq V_{AC} \leq V_{DC0}$):

- Current is positive because of PFC operation
- Q3 is permanently in the on-state
- Q4 in blue is switching at f_{PWM}

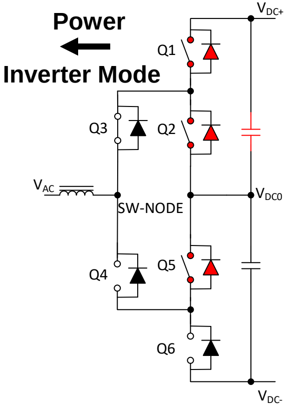
When the output ripple frequency $f_{HF\text{-}RIPPLE}$ is equal to f_{PWM}:

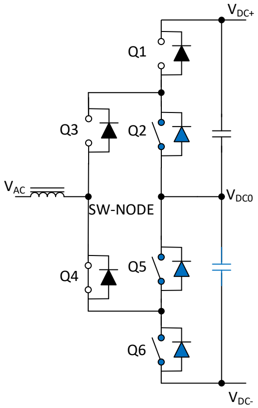
- $f_{HF\text{-}RIPPLE}$ defines the size of filter components (magnetics and capacitors)

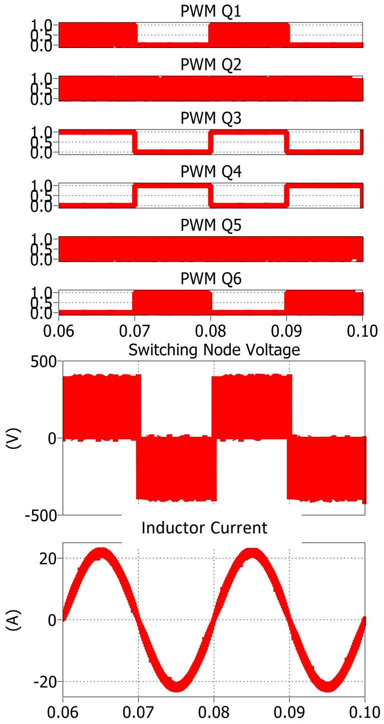
D1 and D2 need be V_{DC} rated (for V_{DC} = 800 V, 1,200-V rated)

Q3 and Q4 can be 1/2 V_{DC} rated (for V_{DC} = 800 V, 600-V rated)

3L ANPC: Basic operating principles







For a positive sine wave ($V_{DC0} \leq V_{AC} \leq V_{DC+}$):

- Q3 is permanently in the on-state, Q4 is off
- Q1 and Q2 in red are switching f_{PWM}
- Additionally, Q5 is switching with Q1

For a negative sine wave ($V_{DC-} \leq V_{AC} \leq V_{DC0}$):

- Q4 is permanently in the on-state, Q3 is off
- Q5 and Q6 in blue are switching f_{PWM}
- Additionally, Q2 is switching with Q6

When the output ripple frequency $f_{HF\text{-}RIPPLE}$ is equal to f_{PWM}:

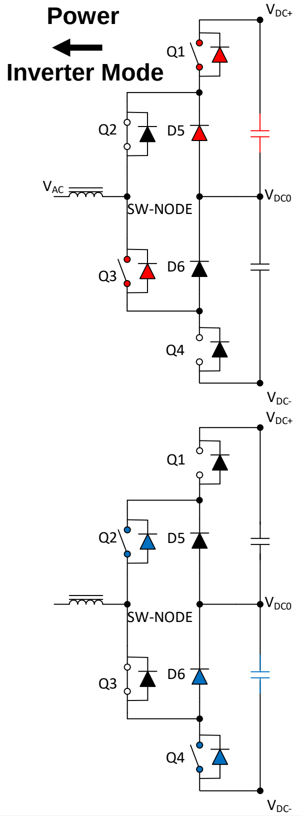
- Again, $f_{HF\text{-}RIPPLE}$ defines the size of filter components

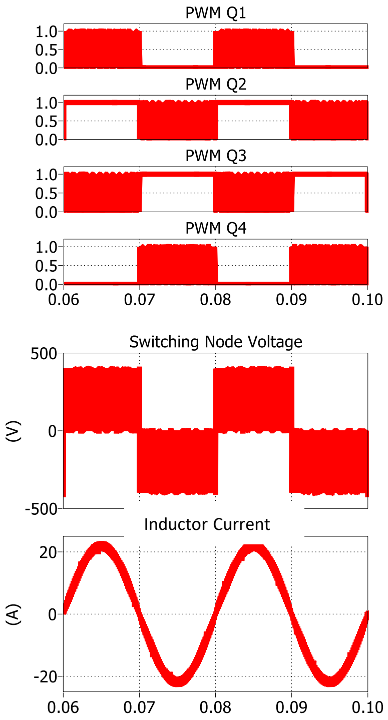
All switches can be 1/2 V_{DC} rated (for V_{DC} = 800 V, 600-V rated)

Q3 and Q4 are switching at f_{AC} (50 or 60 Hz)

Critical shutdown sequencing – balancing of voltages to 1/2 V_{DC}

3L NPC: Basic operating principles





For a positive sine wave ($V_{DC0} \leq V_{AC} \leq V_{DC+}$):

- Q2 is permanently in the on-state; Q4 is off
- Q1 in red is switching f_{PWM}
- Q3 operates complementary to Q1

For a negative sine wave ($V_{DC-} \leq V_{AC} \leq V_{DC0}$):

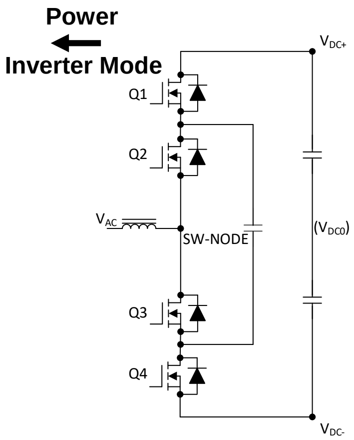
- Q3 is permanently in the on-state; Q1 is off
- Q4 in blue is switching f_{PWM}
- Q2 operates complementary to Q4

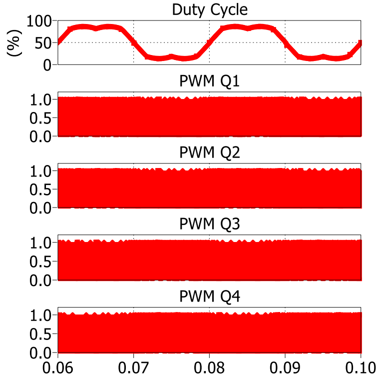
When the output ripple frequency $f_{HF\text{-}RIPPLE}$ is equal to f_{PWM}:

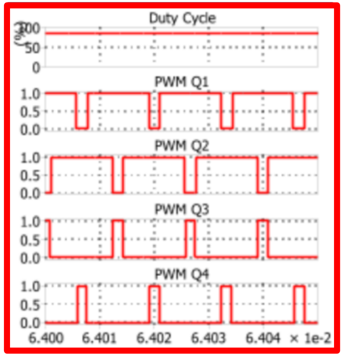
All switches can be 1/2 V_{DC} rated (for V_{DC} = 800 V, 600-V rated)

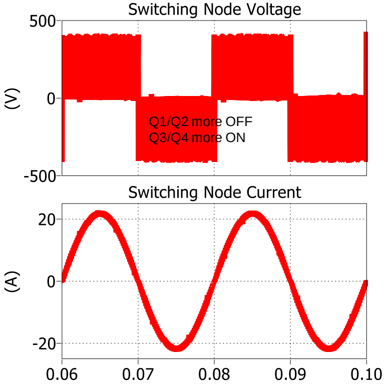
Critical shutdown sequencing – balancing of voltages to 1/2 V_{DC}

FC3L: Basic operating principles









All FETs are switching f_{PWM}

Pairs Q1 and Q4 and Q2 and Q3 complement each other

For a positive sine wave ($V_{DC0} \leq V_{AC} \leq V_{DC+}$):

- At the +peak, Q1 and Q4 and Q2 and Q3 are 180 degrees phase-shifted to each other and Q1 and Q2 are more in the on-state than Q3 and Q4

For a negative sine wave ($V_{DC-} \leq V_{AC} \leq V_{DC0}$):

- At the –peak, Q1 and Q4 and Q2 and Q3 are 180 degrees phase-shifted to each other and Q1 and Q2 are more in the off-state than Q3 and Q4

At zero crossing:

- The duty cycle of Q1 and Q4 and Q2 and Q3 are each 50%

When the output ripple frequency $f_{HF\text{-}RIPPLE}$ is equal to $2 \times f_{PWM}$:

- Defines a smaller size of filter components (magnetics and capacitors)

All switches can be 1/2 V_{DC} rated (for V_{DC} = 800 V, 600-V rated)

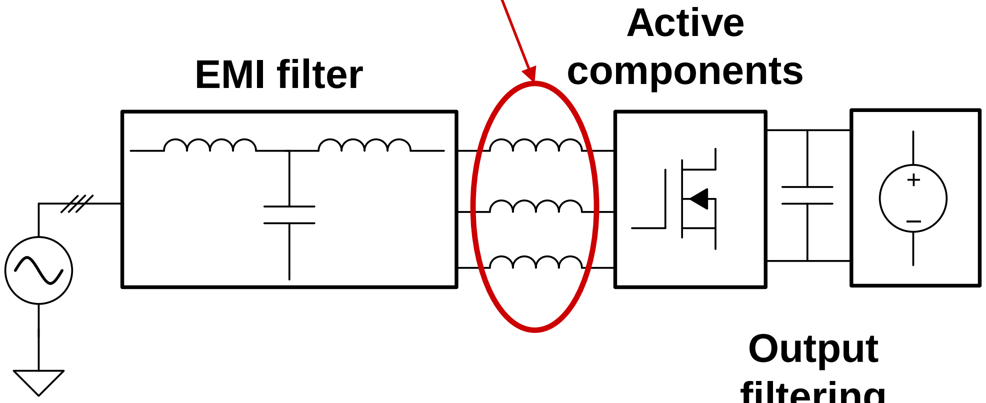
Initial charging of flying capacitor to 1/2 V_{DC} is critical

Critical shutdown sequencing – balancing of voltages to 1/2 V_{DC}

Comparison overview

- When designing a three-phase converter, you need to consider:
  - Input filtering
  - Output filtering
  - Active component selection
  - Control
  - Drivers
  - Measurements
- Converter size, efficiency and cost are at first approximation driven by:
  - **Active components and cooling**
  - **Output filtering (capacitors)**
  - **Input filtering (EMI filtering)**

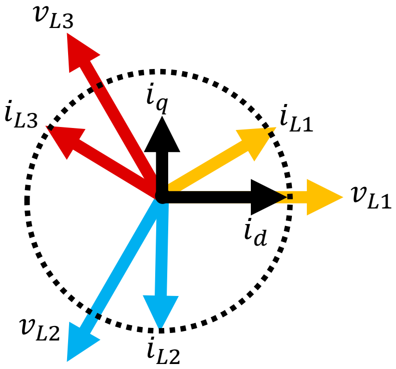
Required inductance is half when using a three-level converter



- **Study done for an 11-kVA system**
- **Maximum allowable power loss is 130 W**

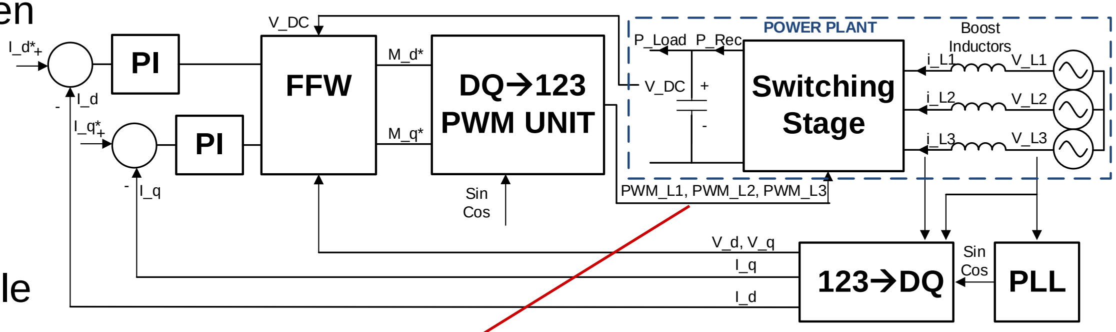
Power-loss comparison: Applied methodology

- Three-phase converters can operate as a PFC or as an inverter
- What are the differences in losses when operating as a PFC or an inverter?
- How are the power losses distributed within the components?
- Target inverter 11 kW: keep constant the current amplitude and change angle

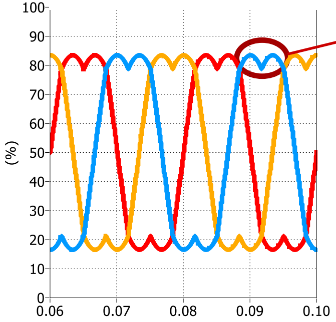


DC link voltage measurement

Voltage and current grid measurements



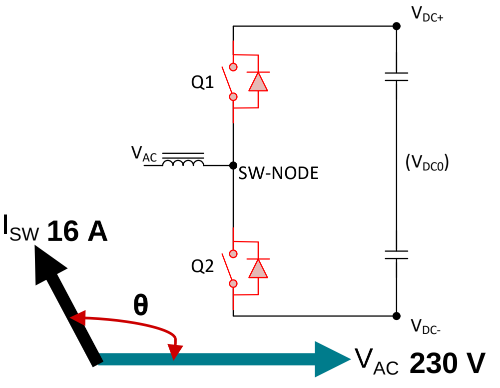
Duty cycles applied to the switching stage



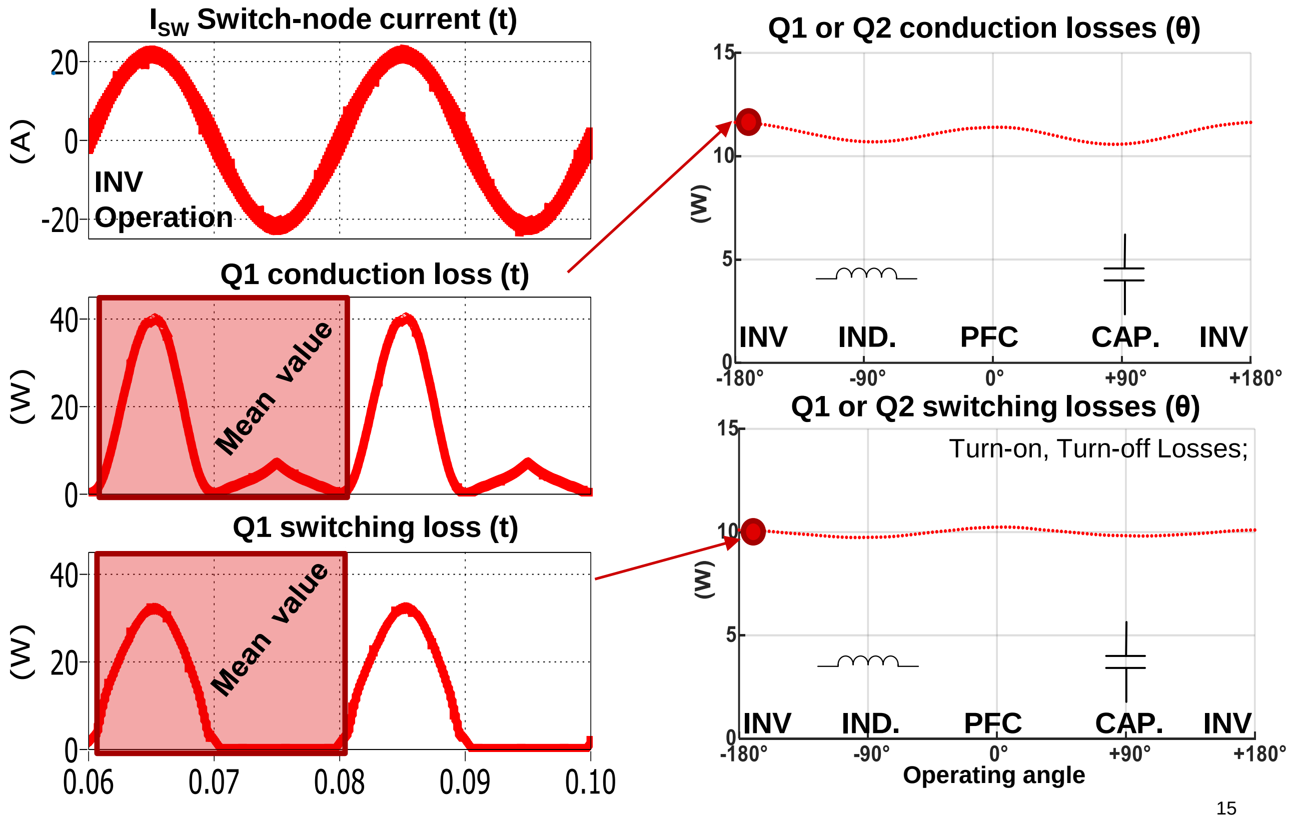
Shape is not sinuosidal because of the third harmonic introduced by space vector modulation

Design Considerations for Current Sensing in DC EV Charging Applications

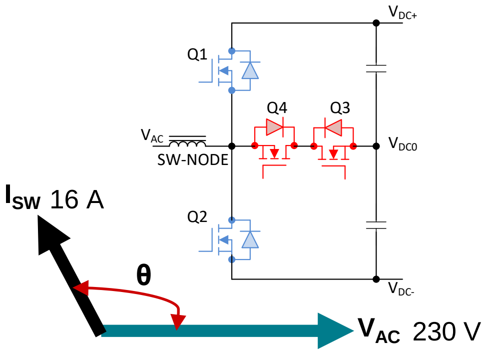
Power-loss comparison: Two-level converter



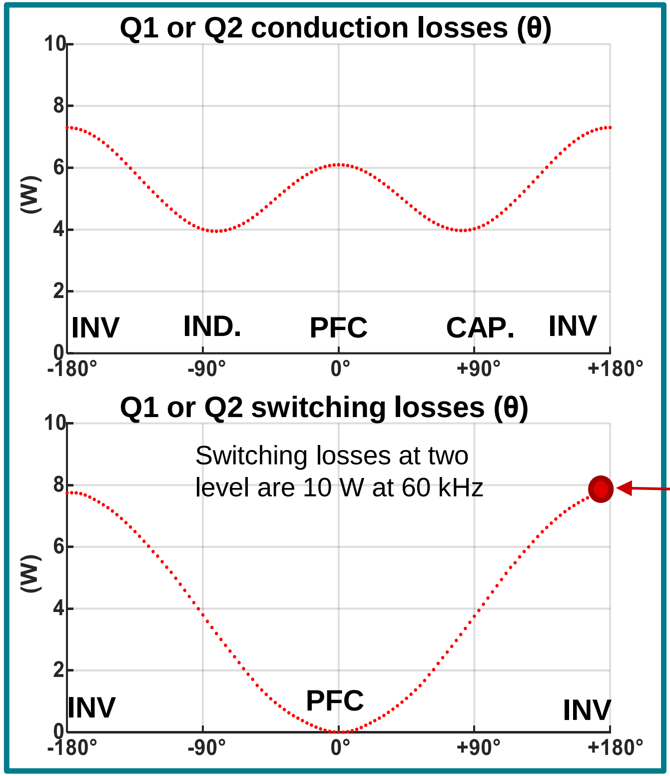
- Bidirectional (11 kVA)
- 75 mΩ, 1.2 kV, silicon carbide (SiC)
- Conduction and switching losses are extrapolated
- Switching losses during half cycle are null
- Losses in function of the angle are not changing
- Total loss: 130 W at 60 kHz

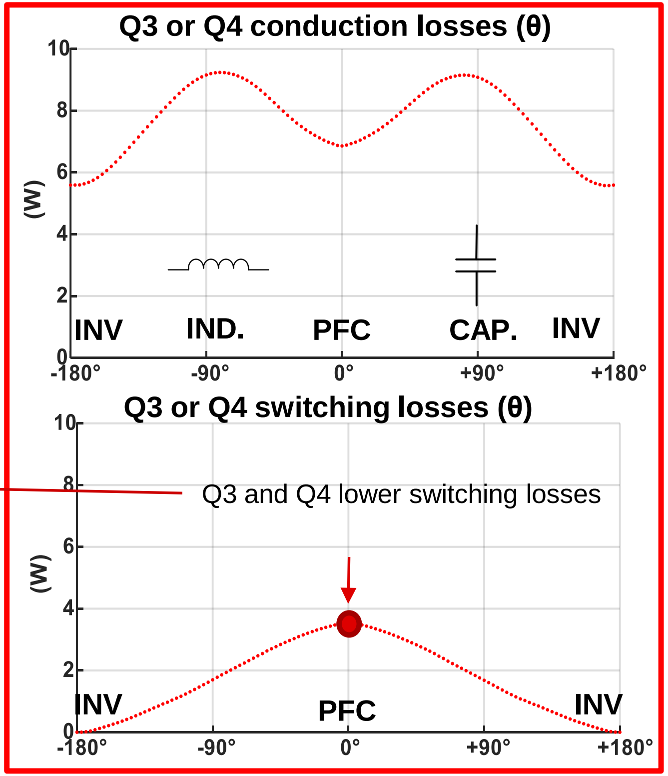


Power-loss comparison: T-type

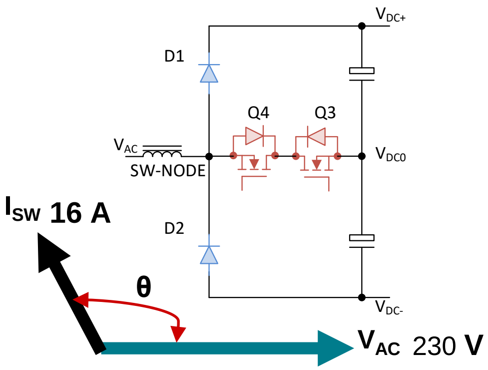


- Bidirectional (11 kVA)
- 75 mΩ, 1.2 kV, SiC
- 60 mΩ, 650 V, SiC
- No switching losses of Q1 and Q2 at 0 degrees
- No switching losses of Q3 and Q4 at ±180 degrees
- Total loss: 130 W at 100 kHz

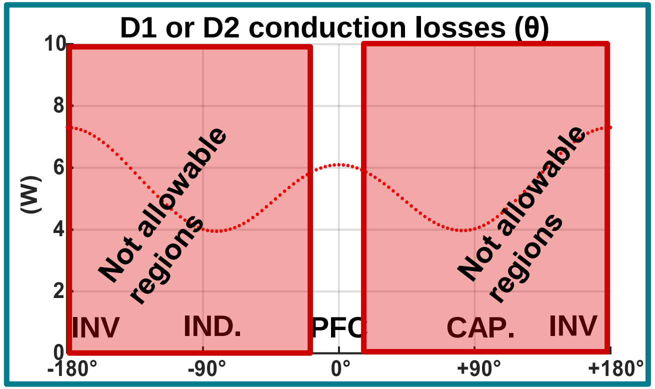


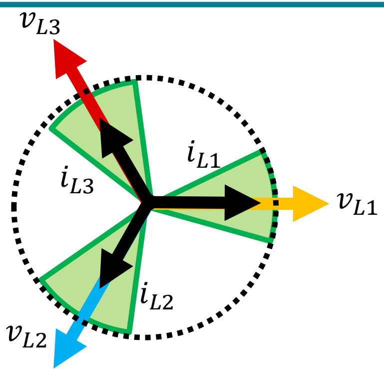


Power-loss comparison: Vienna rectifier

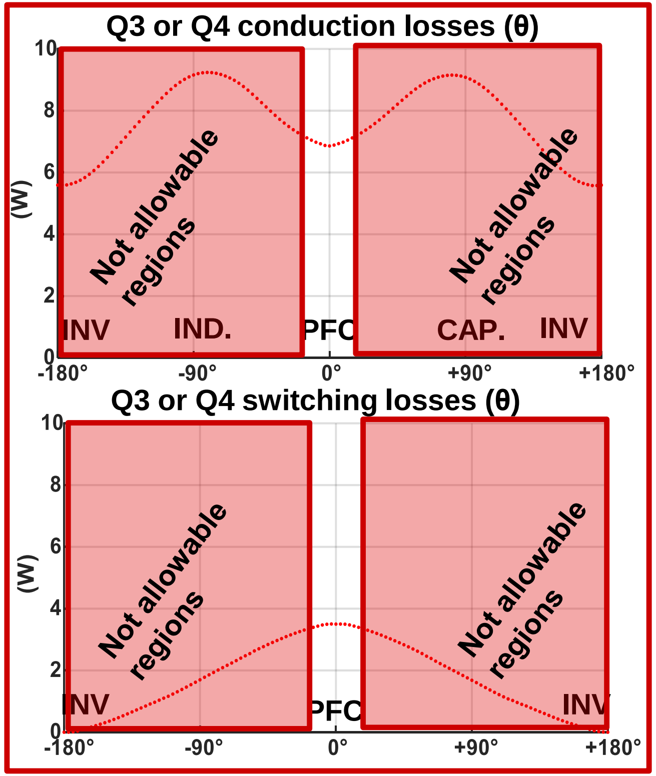


- Unidirectional (11 kVA)
- Schottky barrier diode, 30 A, 1.2 kV, SiC
- 60 mΩ, 650 V, SiC
- Q3 and Q4 always have switching losses
- Converter operating limit angles are ±30 degrees
- Total loss: 130 W at 95 kHz

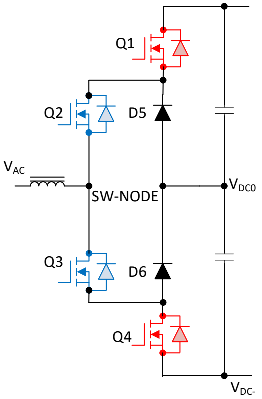


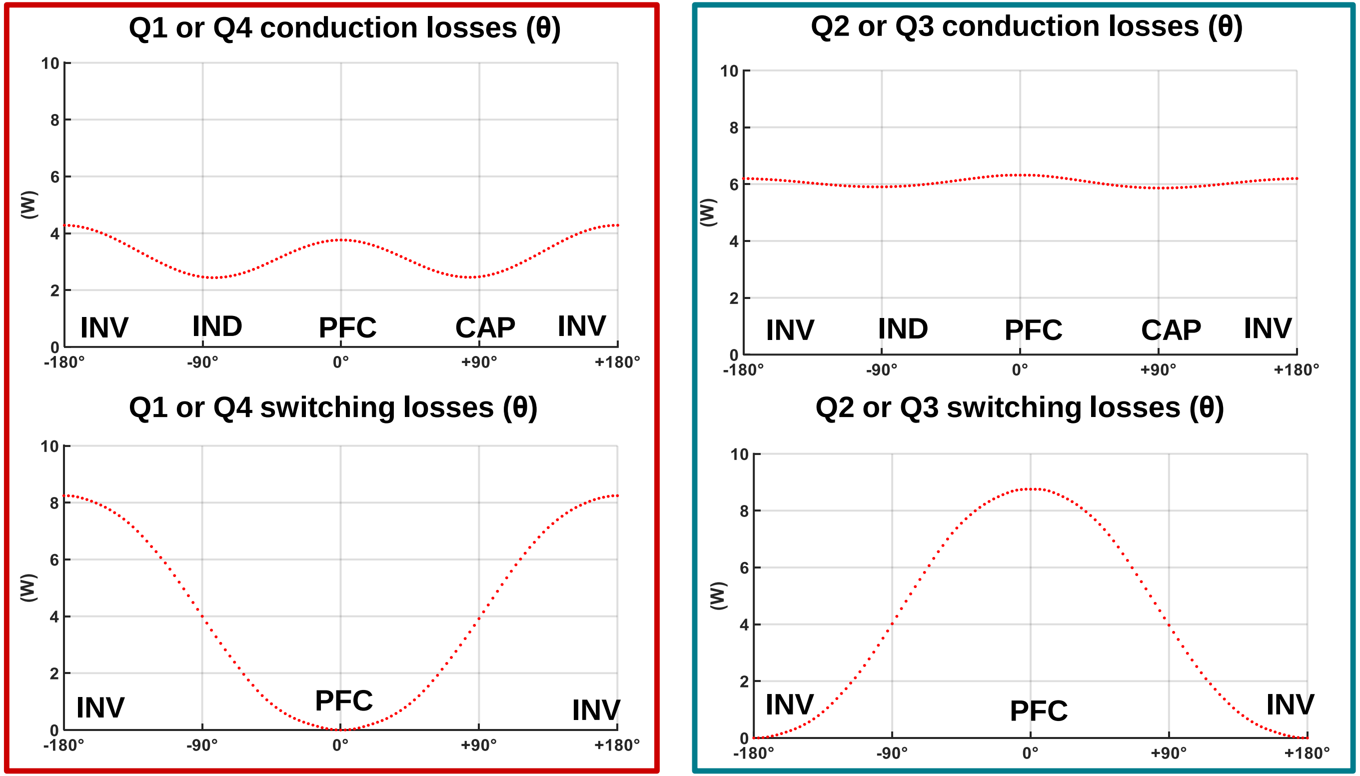


PFC operation



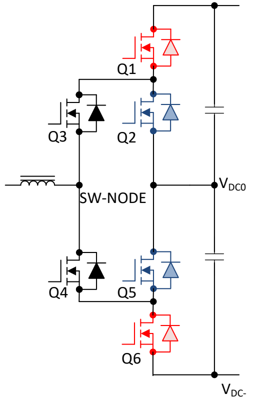
Power-loss comparison: NPC



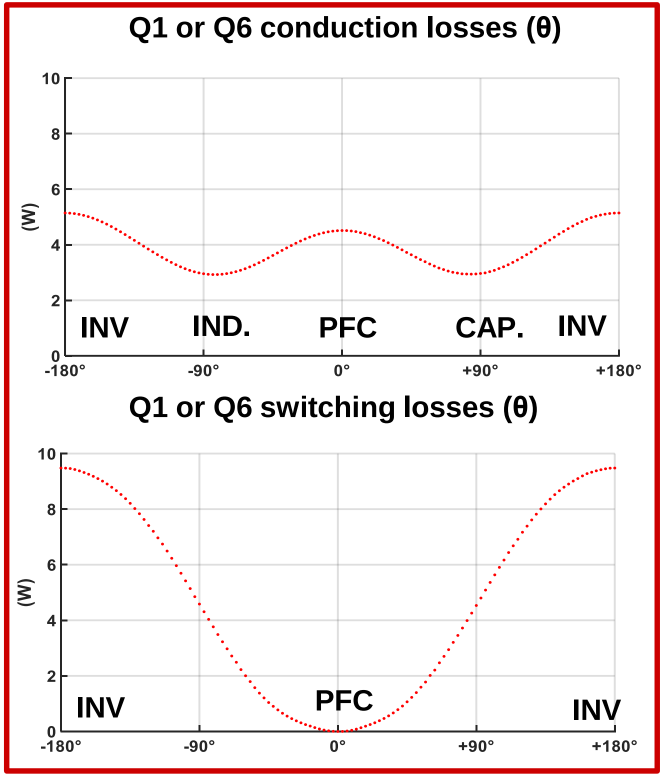


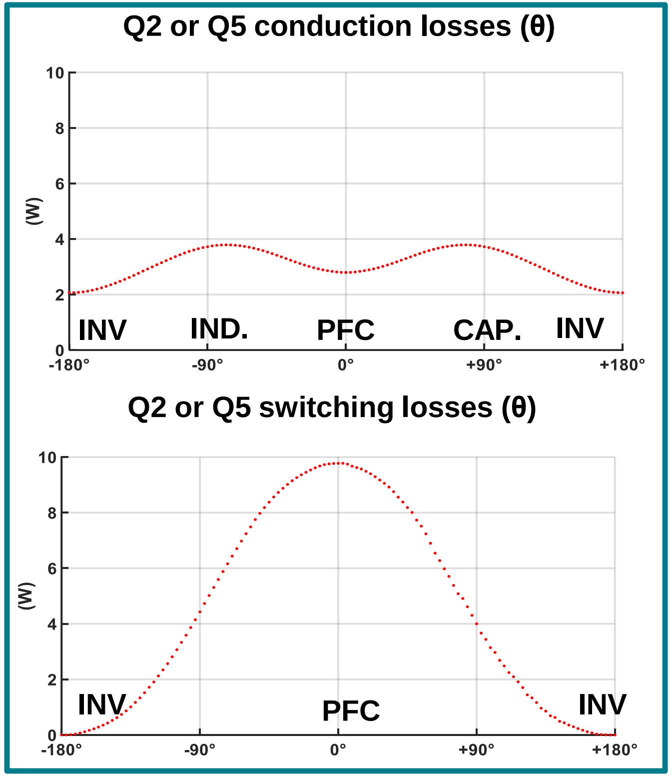
- Bidirectional (11 kVA)
- SBD, 30 A, 650 V, SiC
- 35 mΩ, 650 V, SiC
- No switching losses of Q1 and Q4 at 0 degrees
- No switching losses of Q2 and Q3 at ±180 degrees
- Total loss: 130 W at 98 kHz

Power-loss comparison: ANPC

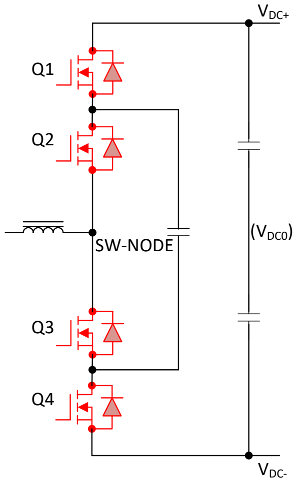


- Bidirectional (11 kVA)
- 35 mΩ, 650 V, SiC
- 35 mΩ, 650 V, silicon
- No switching losses of Q1 and Q4 at 0 degrees
- No switching losses of Q5 and Q6 at ±180 degrees
- Total loss: 130 W at 108 kHz

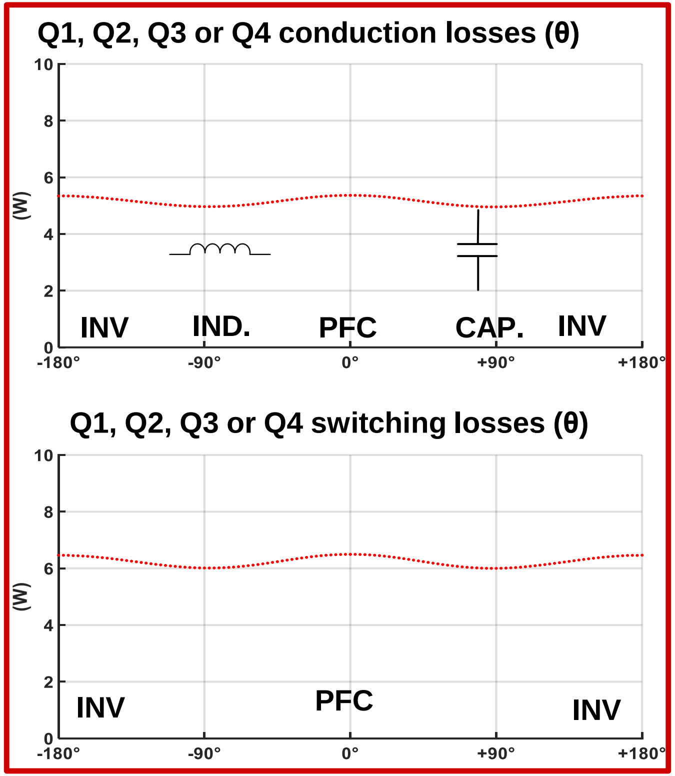




Power-loss comparison: Flying capacitor

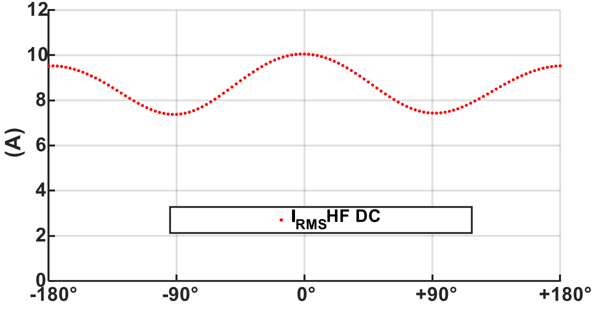


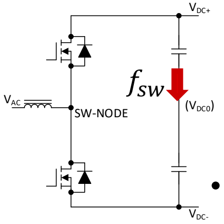
- Bidirectional (11 kVA)
- 35 mΩ, 650 V, SiC
- Conduction and switching losses are mostly constant in function of the angle
- In general, this topology is more efficient thanks to double-frequency out
- Total loss: 130 W at 69 kHz



Current-ripple comparison in three-phase AC/DC

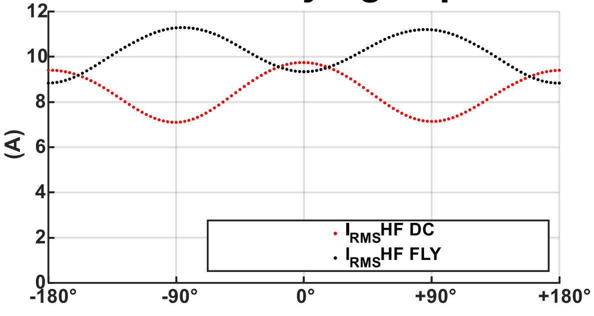
Two-level converter

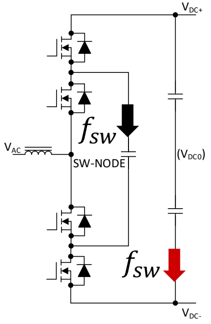




- DC power coming out from three-phase AC does not lead power ripple when grid is symmetric
- Minimum quantity of electrolytic capacitors
- Film capacitors filter the ripple current

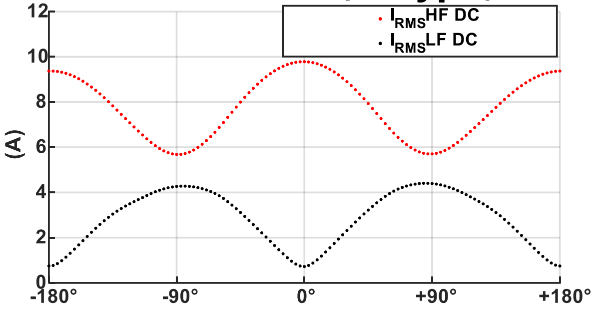
Three-level flying capacitor

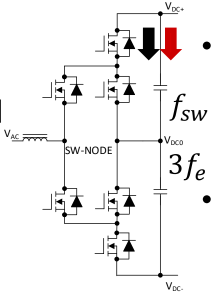




- DC power coming out from three-phase AC does not lead power ripple when grid is symmetric
- Minimum quantity of electrolytic capacitors
- Film capacitors filter the ripple current
- Flying capacitor only seen at switching frequency

Three-level ANPC, T-type, NPC



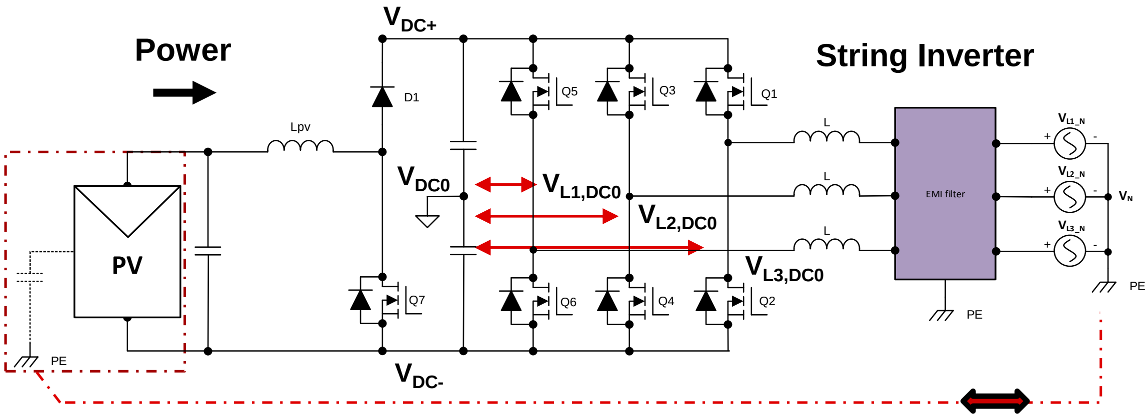


- Low-frequency power ripple caused by charging and discharging of capacitor during half period
- Electrolytic capacitor necessary with reactive power
- Film capacitors filter the ripple current

Common-mode noise comparison: Introduction

Depending on the application, the common-mode voltage can become very critical:

- Panels are presenting high surfaces exposed to ground
- When raining, parasitic capacitance of the photovoltaic (PV) panel can be as high as 200 nF/kWp (kilowatt power peak installed)
- When three-phase inverter switches, it generates a common-mode voltage that creates parasitic currents
- Issues related to safety and possible unwanted triggering of the residual current detector may occur

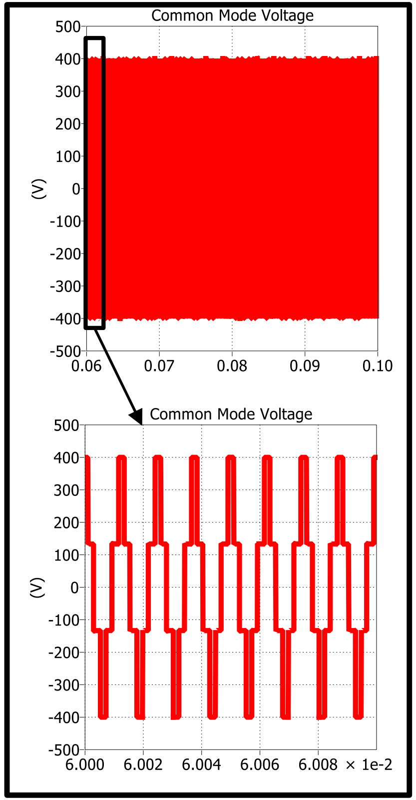


$$V_{CM} = (V_{L1,DC0} + V_{L2,DC0} + V_{L3,DC0}) / 3$$

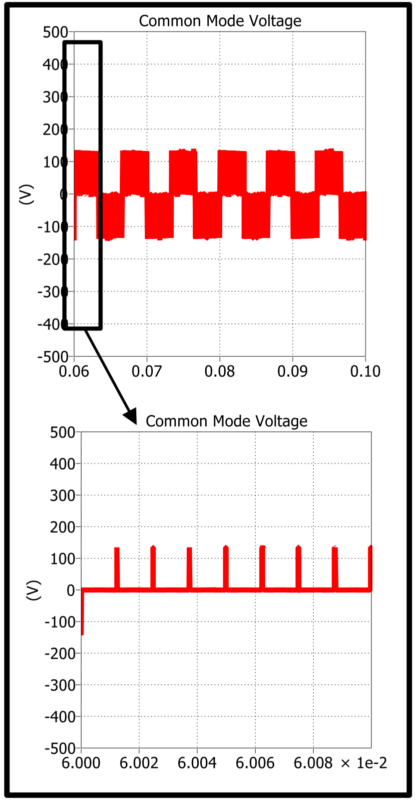
Common-mode noise comparison: Results

- At first approximation, three-level converters are always presenting the same common-mode noise (Vienna, T-type, ANPC, NPC)
- Peak common-mode voltage applied at two levels is three times higher than three levels. At 800 V_{DC}:
  - 400-V peak with a two-level AC/DC
  - 400-V/3 peak with a three-level AC/DC
- RMS common-mode voltage applied at two levels is three times higher than three levels. At 800 V_{DC}:
  - 310 V_{RMS} with a two-level AC/DC
  - 74 V_{RMS} with a three-level AC/DC
- Significant attenuation effort required by the EMI filter in a two-level converter for PV applications

Two level

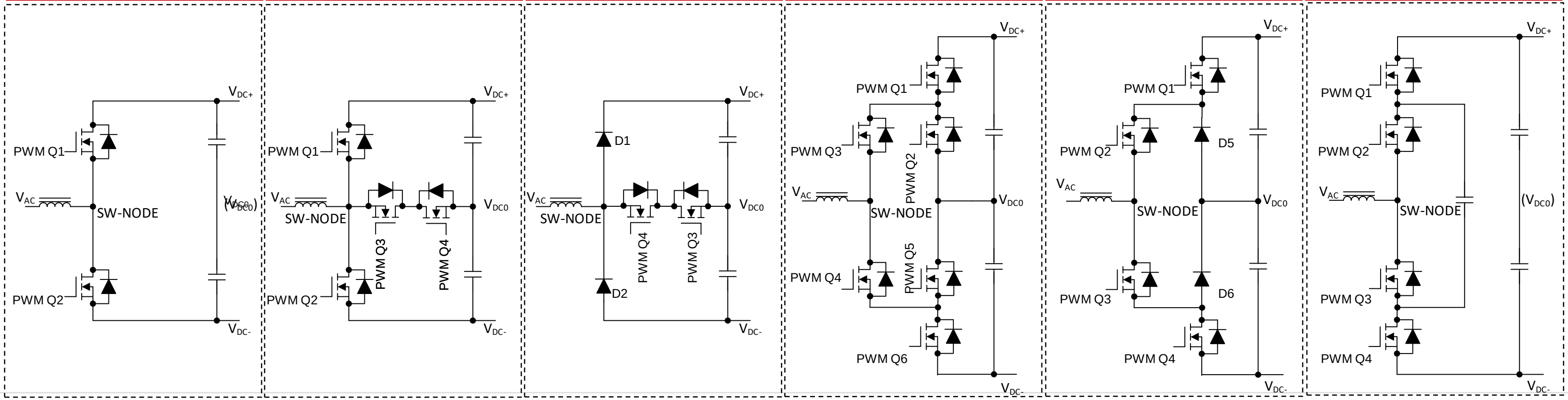


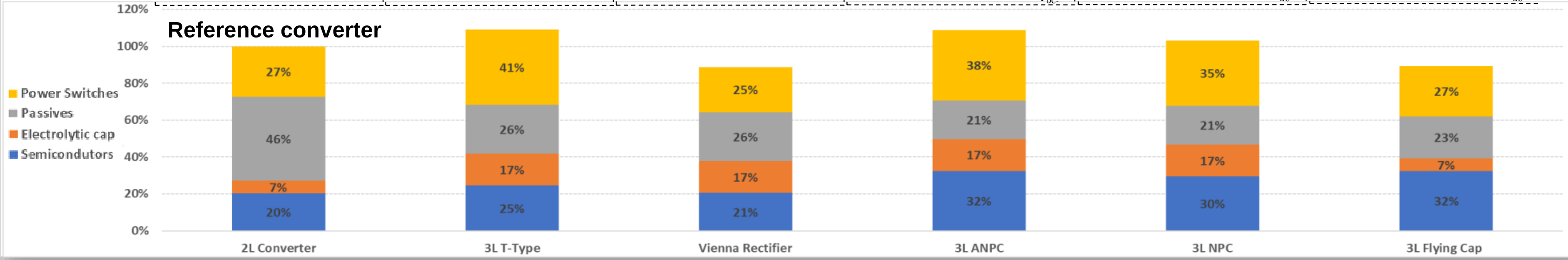
Three level



Bill-of-materials comparison

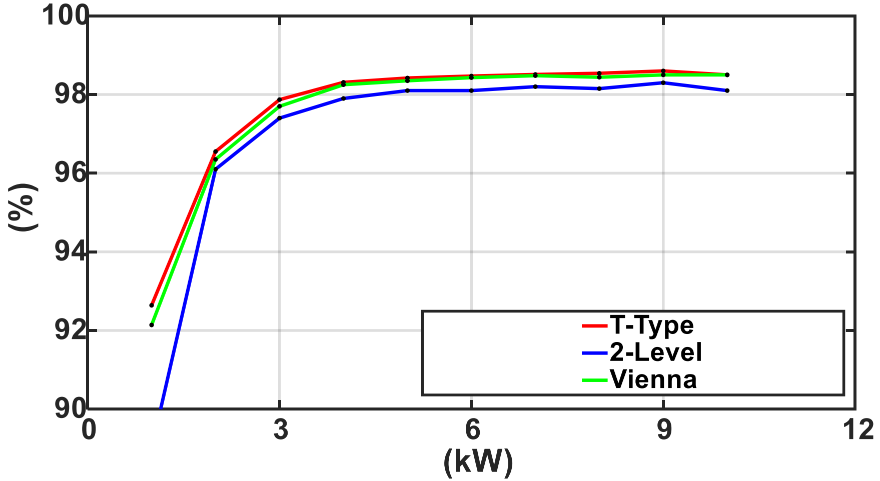
2L two-level converter	3L three-level T-type	3L Vienna rectifier	3L ANPC	3L NPC	FC3L flying capacitor

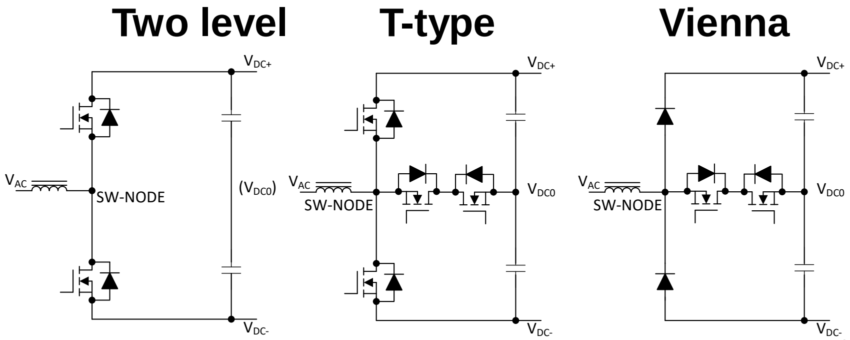




Experimental results: TIDA-01606

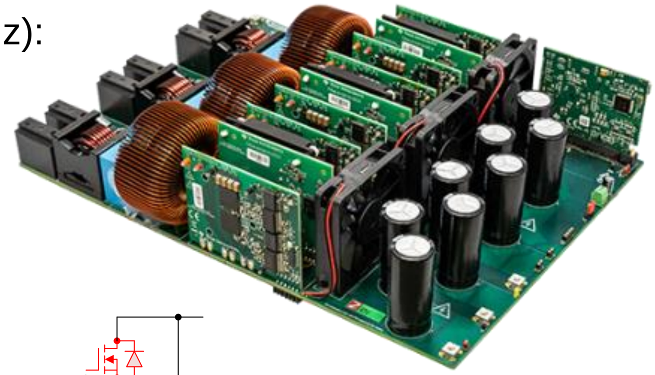
- The 10-kW, Bidirectional Three-Phase Three-Level (T-type) Inverter and PFC Reference Design includes an 11-kW converter based on SiC devices (50 kHz):
  - When operating as a T-type, 650 V 60 mΩ (SiC) and 1,200 V 75 mΩ (SiC)
  - When operating as a two-level converter, 1,200 V 75 mΩ (SiC)
  - When operating as a Vienna rectifer, 1,200 V 40 A SBD (SiC), 650 V 60 mΩ (SiC)

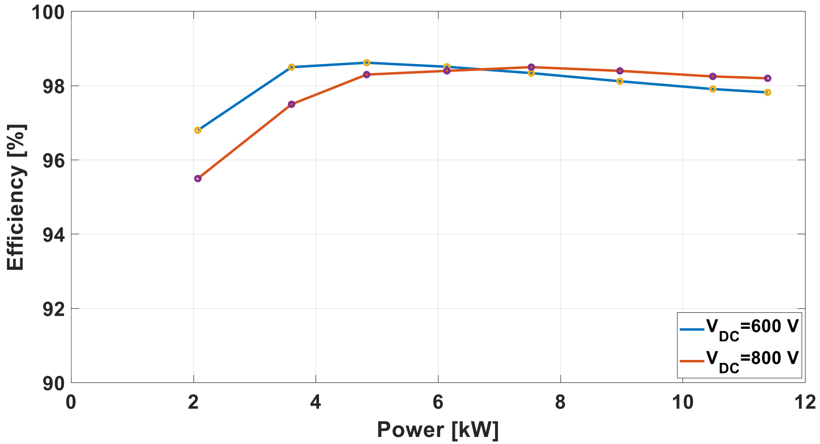


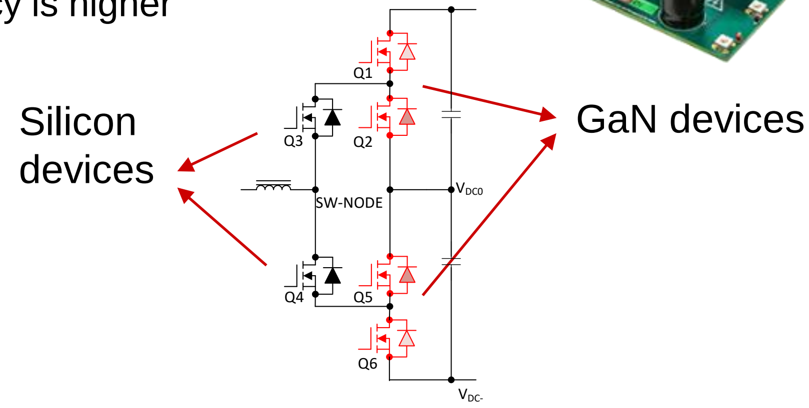


Experimental results: TIDA-010210

- The 11-kW, Bidirectional, Three-Phase ANPC Based on GaN Reference Design includes an 11-kW converter based on GaN devices (100 kHz):
  - Low-frequency 40 mΩ, 600 V silicon superjunction metal-oxide semiconductor field-effect transistor (MOSFET)
  - High-frequency 30-mΩ, 600-V GaN
- At a higher DC link voltage and low load, efficiency is lower
- At a higher DC link voltage and high load, efficiency is higher







Conclusions

- Multilevel topologies:
  - Smaller passives offer up to **50% reduction in size** for a three-level inverter vs. a two-level inverter
  - A multilevel topology enables FETs with **significantly lower switching and conduction losses**, which improves efficiency by using FETs with half the blocking voltage for the same DC bus voltage
  - Three-level topologies keep the switching voltage to half of a two-level inverter, which **reduces overall EMI**

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