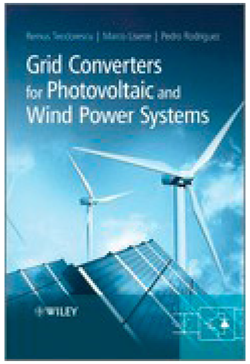

Grid Converters for Photovoltaic and Wind Power Systems

by R. Teodorescu, M. Liserre and P. Rodriguez

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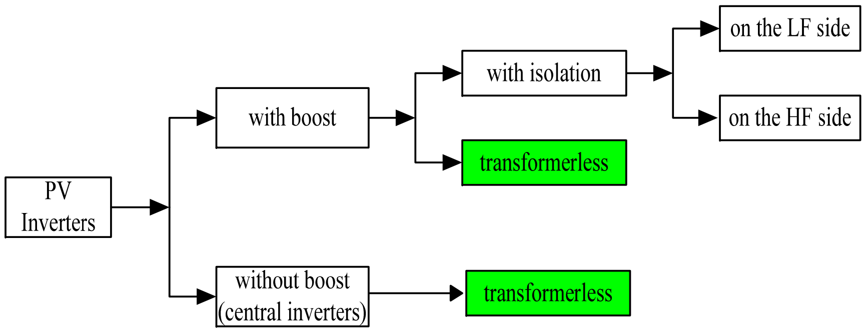
Chapter 2

Photovoltaic Inverter Structures

Outline

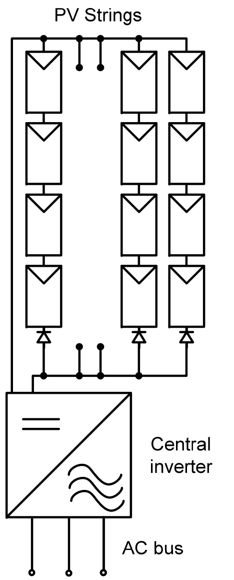
- Structures
- Topologies
- Modulation
- Control

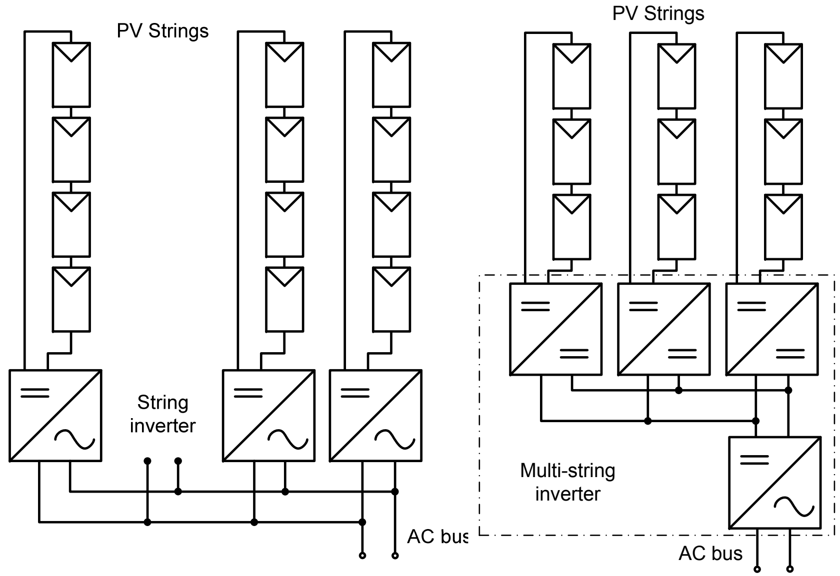
Structures

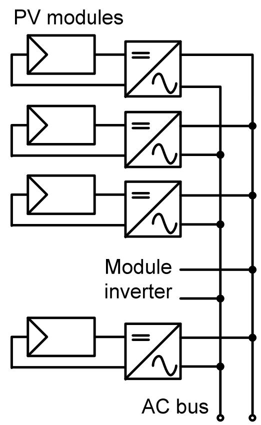


- PV DC voltage typically low for string inverters → boost needed for low power
- For high power (>100 kW) central PV inverters w/o boost, typical three-phase FB topologies with LV-MV transformer)
- Galvanic isolation necessary in some countries
- LF/HF transformer (cost-volume issue)
- A large variety of topologies
- The optimal topology is not matured yet as for drives
- Transformerless topologies having higher efficiency are emerging and the grid regulations are changing in order to allow them

Structures







Central inverters

- 10-250kW, three-phase, several strings in parallel
- High efficiency, low cost, low reliability, not optimal MPPT
- Used for power plants

String (Multi)inverters

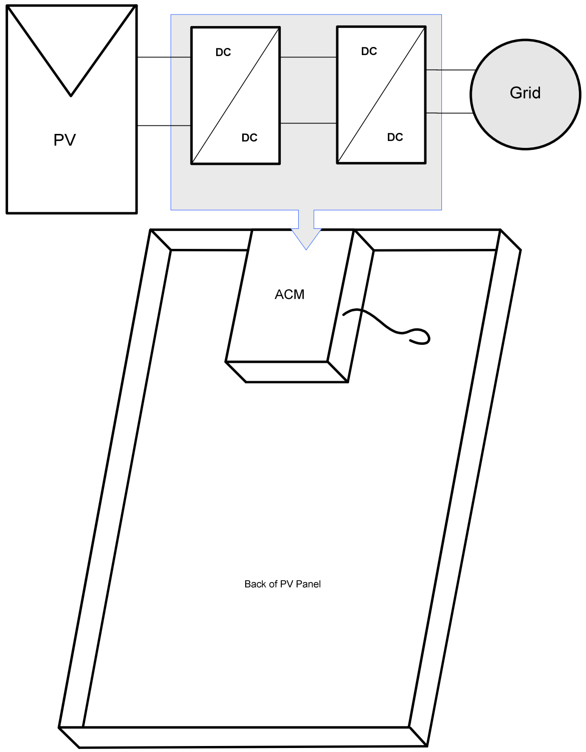
- 1.5-5 kW, typical residential application
- Each string has its own inverter enabling better MPPT
- The strings can have different orientations
- Three-phase inverters for power<5kW

Module inverters

- 50-180W, each panel has its own inverter enabling optimal MPPT
- Lower efficiency, difficult maintenance
- Higher cost/kWp

High efficiency Mini-central PV inverters (8-15 kW) are also emerging for modular configuration in medium and high power PV systems

Structures: PV Modules



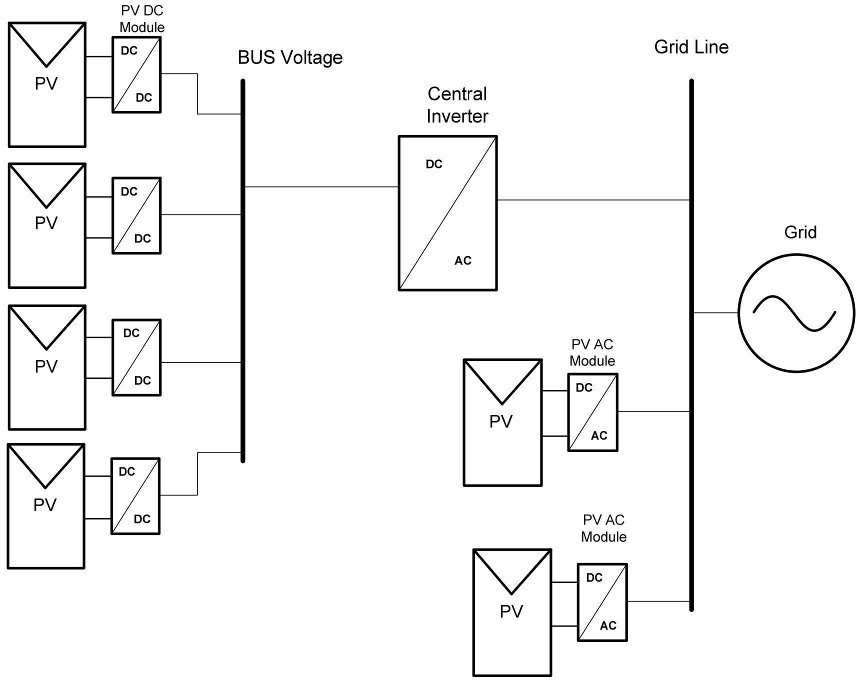
The advantages of PV modules compared to traditional PV systems are:

- Each module works independently
- High modularity allowing easy system expansion
- Use of standard AC installation material, which reduces costs of installation material and system design.
- No mismatch losses at system level as each AC module operates in its own Maximum Power Point (MPP).
- No need for string diodes.
- Low lightning induced surge voltages, because of the compact DC system layout.

Module Inverters manufacturers:

Enphase, Petra Solar with “SunWave”, Greenray, Exeltech, SolarBridge, Enecsys, Xslent Energy Technologies, Sunsil, Xantrex, Mastervolt (Soladin 120), Tigo Energy (Module Maximizer) , National Semiconductor (Solar Magic), SolarEdge (Power Box)

Structures: PV Modules



PV-DC Modules Double Stage

- Buck Converter plus Push-Pull

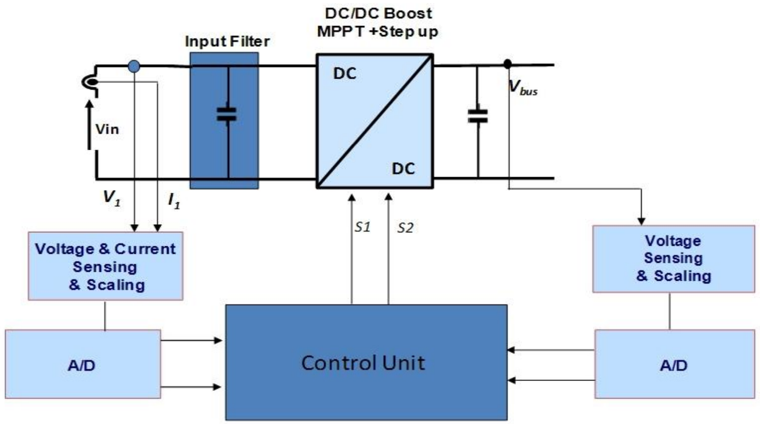
PV-DC Modules Single Stage

- Interleaved Boost with/without Charge pump System or Flyback

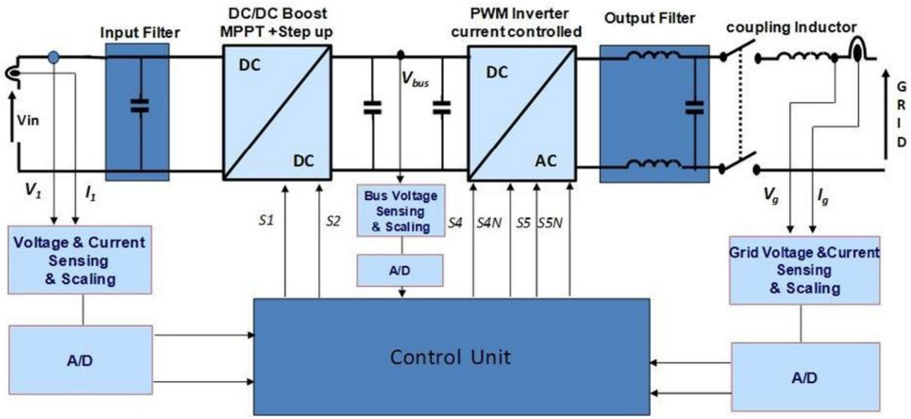
PV-AC Module Double Stage

- Flyback plus Full-Bridge or Flyback (Current COntrol) plus Full Bridge (Low Switching Frequancy operation)

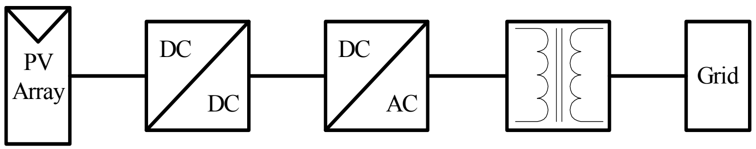
PV-DC Modules Double Stage



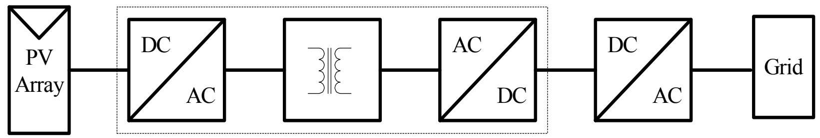
PV-AC Modules Double Stage



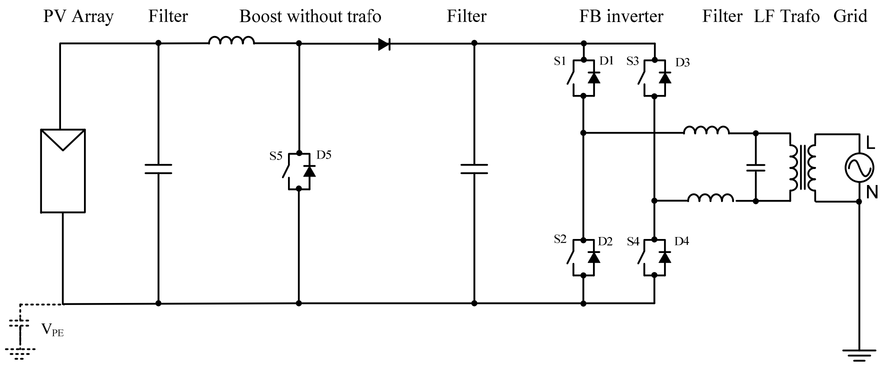
Structures: Transformer-Based



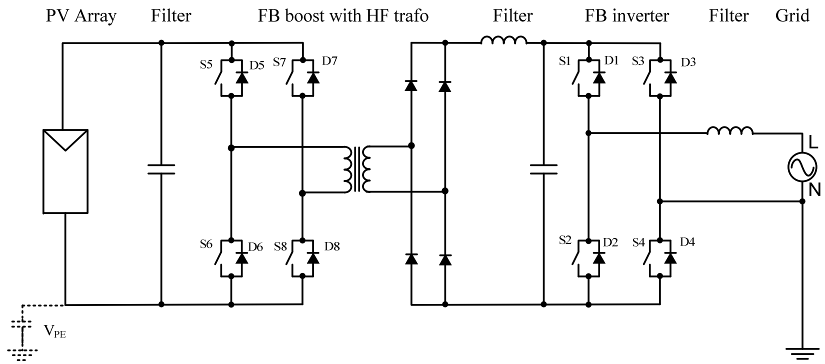
On low frequency (LF) side



On high frequency (HF) side



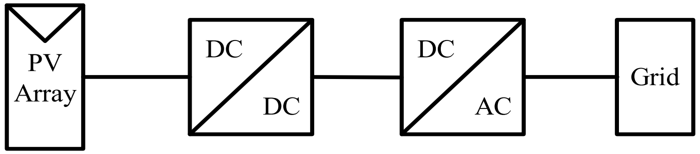
Boosting inverter with LF transformer based on boost converter



Boosting inverter with HF traformer based on FB boost converter

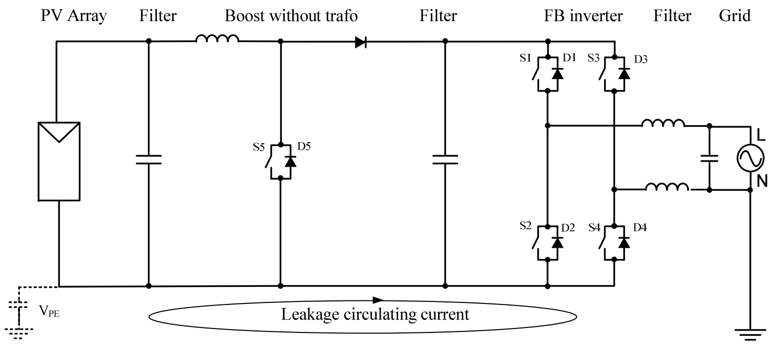
Both technologies are on the market! Efficiency 93-95%

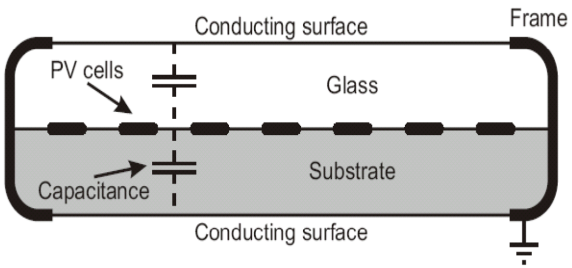
Structures: Transformer-Less



- FB inverter + boost

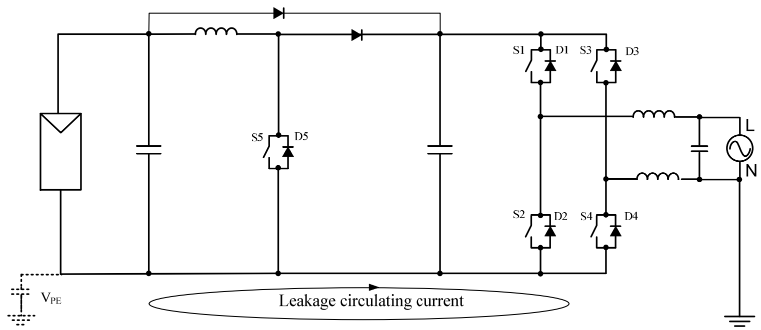
- Typical configuration

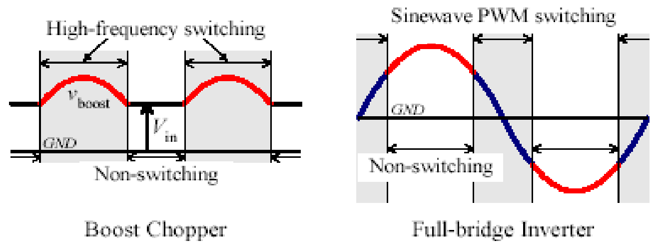




- High efficiency (>95%)
- Leakage current problem
- Safety issue

- Time sharing configuration*

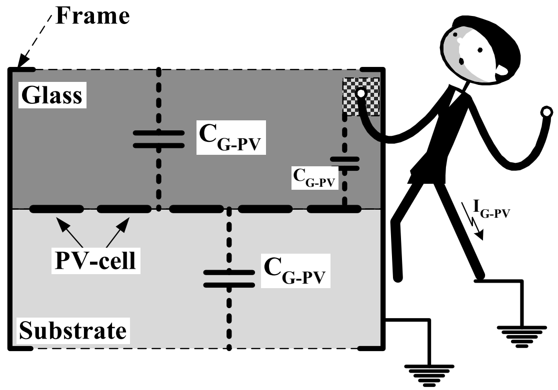




- Efficiency > 96%
- Extra diode to bypass boost when $V_{pv} > V_g$
- Boost with rectified sinus reference

*Source [Ogura, K.; Nishida, T.; Hiraki, E.; Nakaoka, M.; Nagai, S., "Time-sharing boost chopper cascaded dual mode single-phase sinewave inverter for solar photovoltaic power generation system," Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual , vol.6, no., pp. 4763-4767 Vol.6, 20-25 June 2004]

Structures: String Inverters Transformer-Less



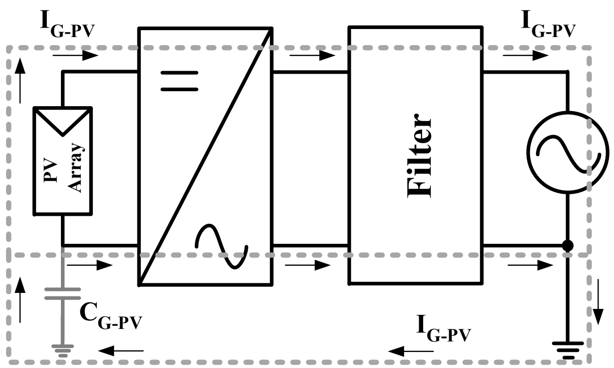
Parasitic capacitance of the PV array

- PV panel array has large surface
- Parasitic capacitance formed between grounded frame and PV cells
- Its value depends on the:
  - Surface of the PV array and grounded frame
  - Distance of PV cell to the module
  - Atmospheric conditions and dust which can increase the electrical conductivity of the panel's surface

Leakage current

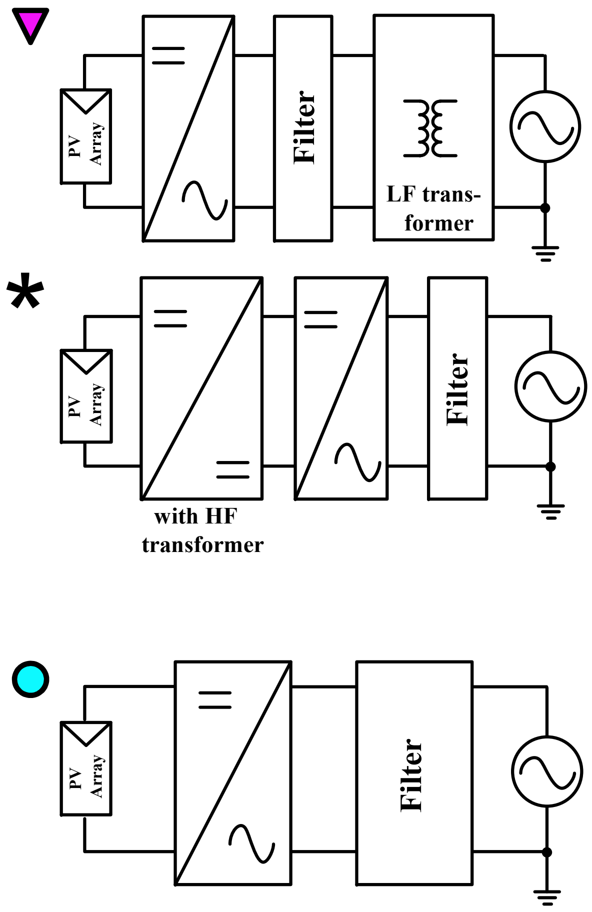
- Charging and discharging this capacitance leads to ground leakage currents (unsafe for human interaction; damage PV panels)
- Amplitude of leakage current depends on
  - Value of parasitic capacitance
  - Amplitude and frequency of imposed voltage
- RCM (Residual Current Monitoring) unit for monitoring

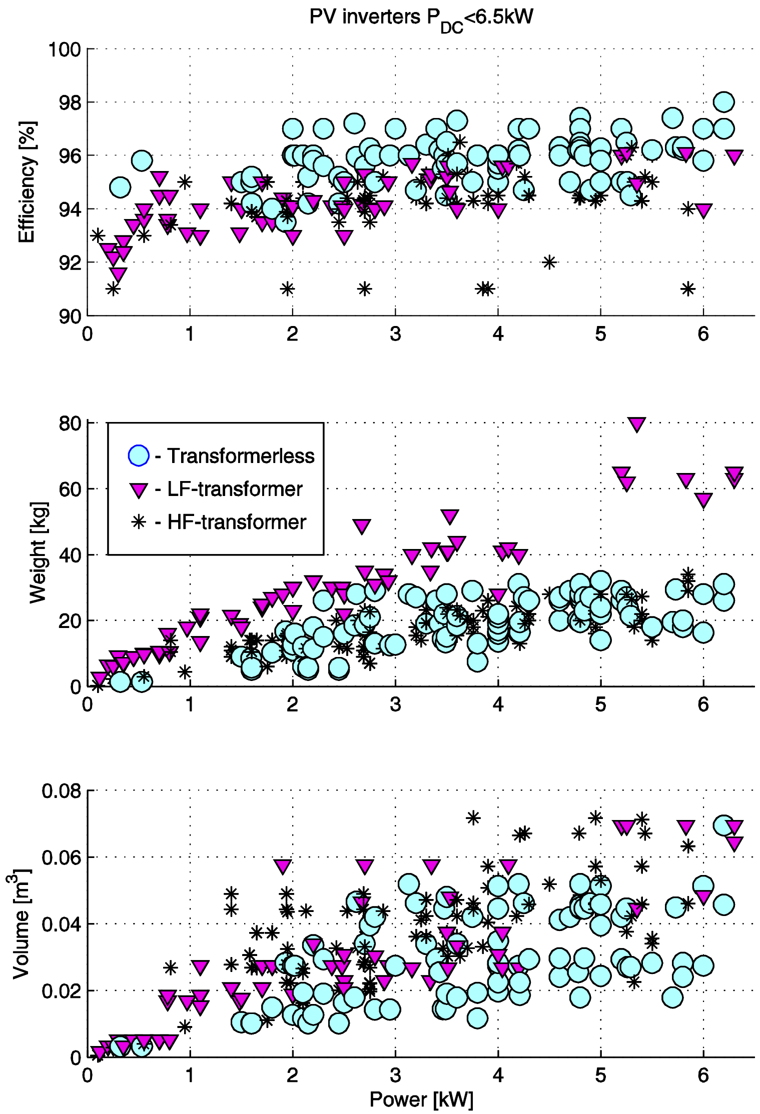
  leakage ground currents



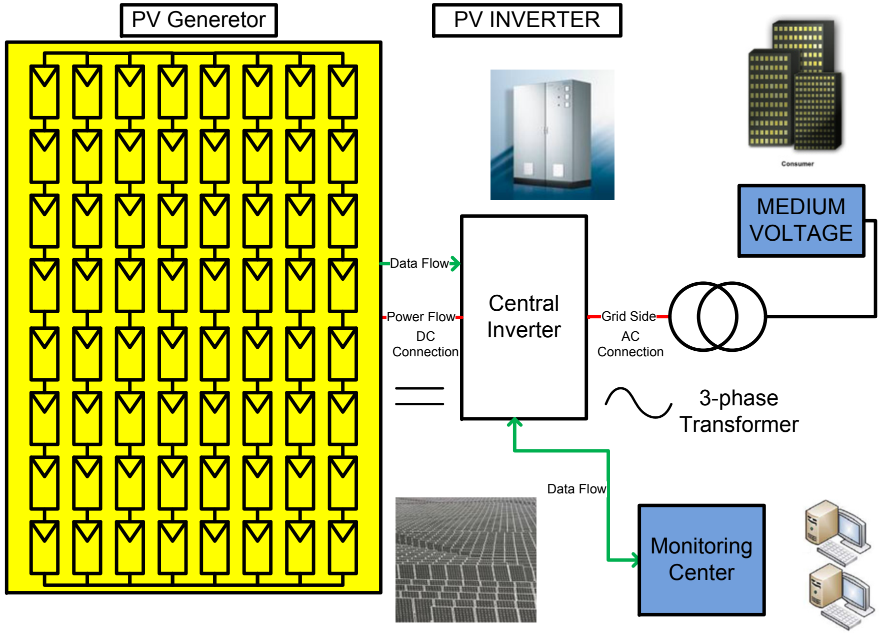
Structures: Comparison

With transformer





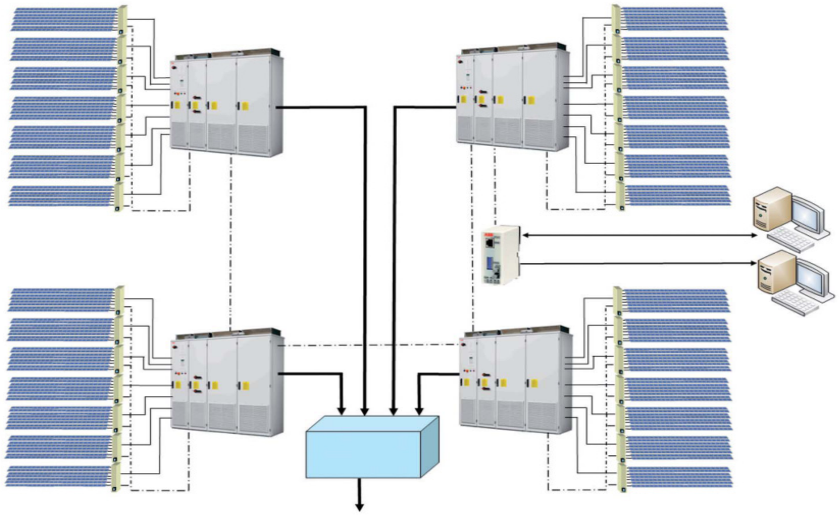
Structures: Central Inverters



- High Performance for Large PV Plant, High Level Monitoring , High Level Intelligence, Reliability
- High Efficiency (up 98+%), Competitive prize/performance ratio.
- Typical structure – String inverter, 3-phase FB proven technology (more parallel) with transformer to MV
- Manufacturers:

  Aero Sharp, Aros (Sirio), Conergy, Control Techniques, EEI - Equipaggiamenti Elettronici Industriali Srl, Eurener, Green Power, Helios System, Hyunday Heavy, Integral Drive Systems AG, Ingeteam, Jema, Kaco, Layer, Leonics, Lti, Padcon, Pairan, Power One, PV Powered, Refu, Elettronica Santerno, SatCon, Schneider Electric, Siel, Siemens, Siliken, SMA, Sputnik, Voltwerk, Zigor

Structures: Central Inverters



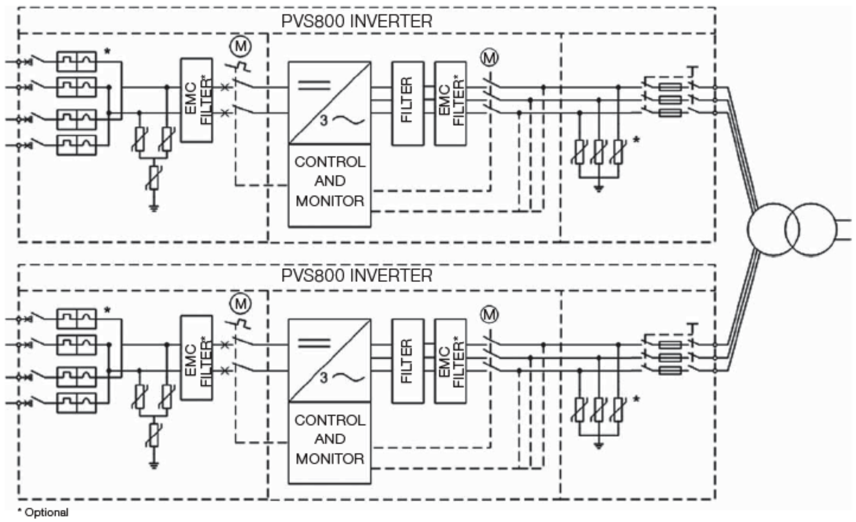


ABB – PVS800*

- Multi-level achieved by dual inverter configuration
- 100-500 kW
- 450-750Vdc input
- 400Vac out
- Efficiency > 97.5%
- Modular design, Long life-time,PF Comp

*Source [www.abb.com]

Structures: Central Inverters

SUNNY CENTRAL up to 1250MV (2x Sunny Central 630HE)*

Efficient

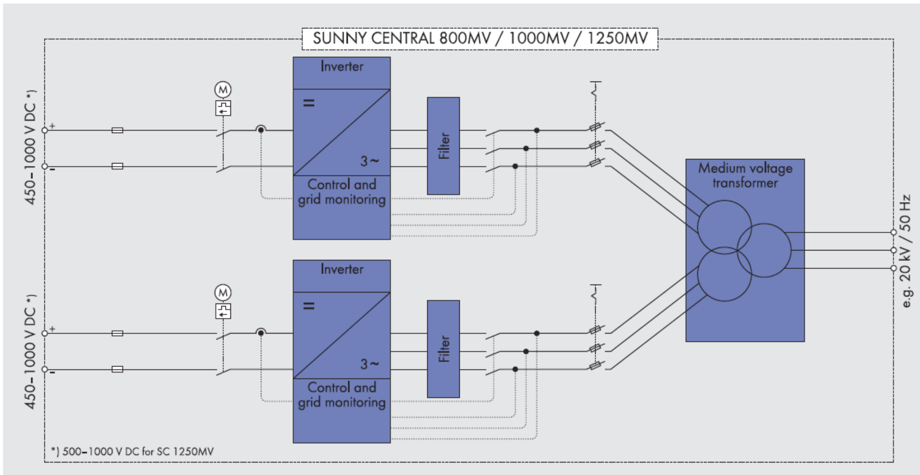
- Without low voltage transformer → Higher system efficiency due to direct connection to the medium voltage Grid

Turnkey Delivery

- With medium-voltage transformer and concrete substation for outdoor installation

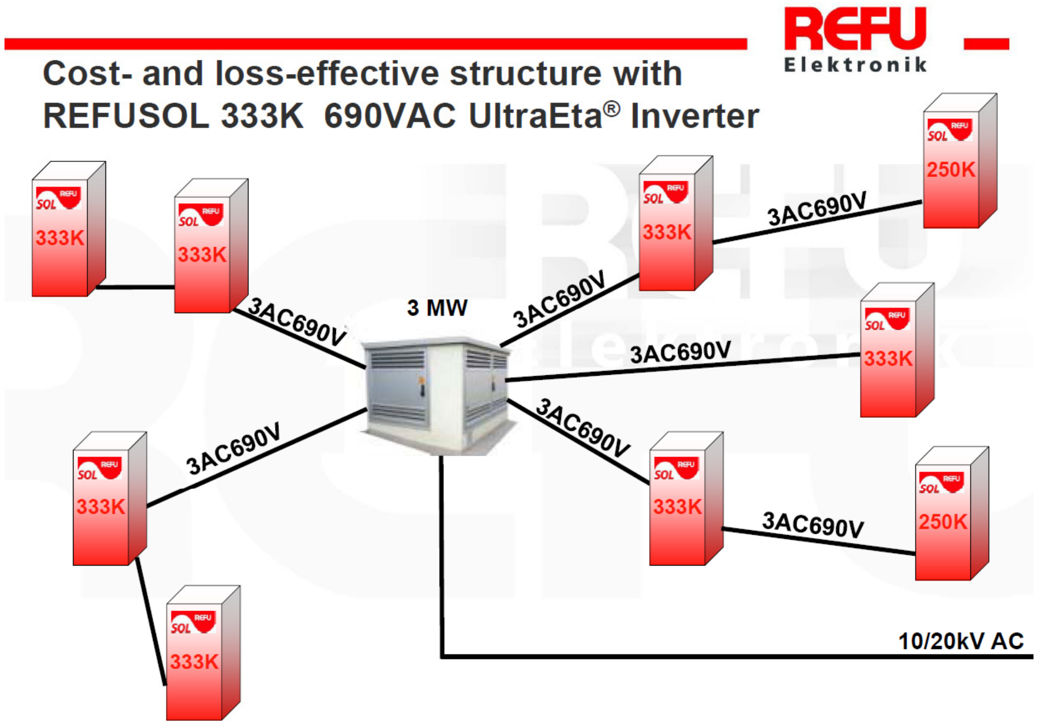
Optional

- Grid management
- Control of reactive power
- Medium-voltage switching stations for a flexible structure of large solar parks
- AC transfer station with measurement
- Medium-voltage transformers for other grid voltages (deviating from 20 kV)



*Source [www.sma.de]

Structures: Central Inverters -Learn from Wind Power*



- Nominal power: 333kW @ 3AC690V+N
- Max. efficiency:>98,5% with UltraEta®topology
- MPP voltage range: 600-1200VDC
- Max. DC Voltage: 1400V
- Weight: approx. 400kg (1,20kg/kW)
- Outdoor-qualified housing

- 690VAC is standard in the wind industry
- Standard-components for up to 3MW + are cost-effective and reliable
- Inverter cost (approx.) proportional to AC current
- Up to 1500VDC is enabled for PV components by DIN VDE0100
- Reduces installation time
- Reduces copper costs and cabling losses

*Source [www.refusol.de]

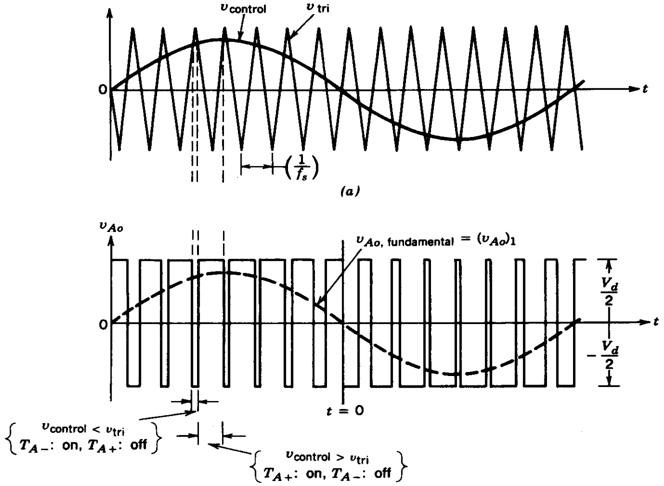
Structures: Conclusions

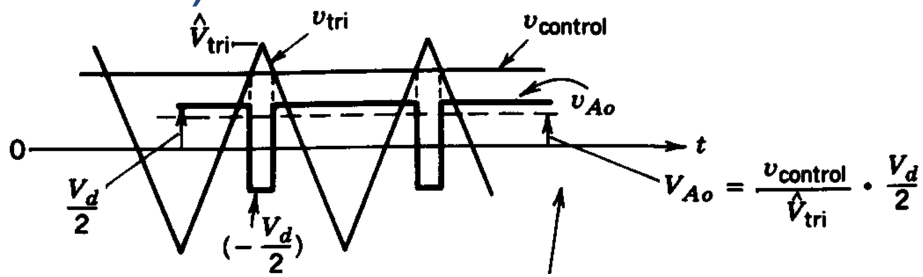
- PV Modules are emerging on the market with more manufacturers
  - Both dc-dc and dc-ac
- Transformerless multistring PV inverters feature in comparison with Transformer Based PV inverters:
  - Higher efficiency
  - Lower volume and weight
  - Today more than 70% of the PV inverters sold on the market are transformerless achieving 98% max conversion efficiency and 97.7% “european” (weighted) efficiency [Photon Magazine]
  - Further improvements in the efficiency can be achieved by using SiC MosFets. ISE Fraunhofer-Freiburg reported recently* 99% efficiency (25% reduction in switching + conduction losses)
- Central inverters are preferred in Large (multi MW) PV power plants
  - 98+% efficiency is achieved with classical 2 level inverters

*Source [Burger, B., Schmidt,H. “25 YEARS TRANFORMLESS INVERTERS” – Proceedings of PVSEC 2007]

Topologies: FB Modulation

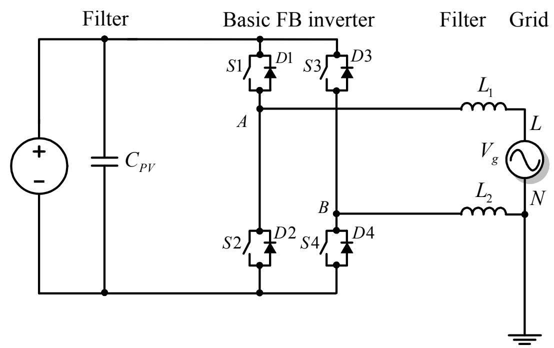
Modulation Basics (recapitulation)





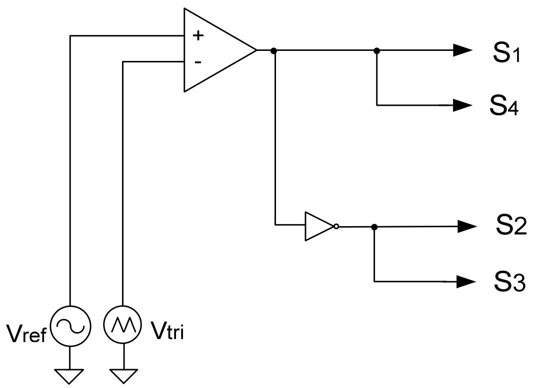
$$V_{Ao} = \overline{v}_{Ao} = \frac{v_{control}}{\hat{V}_{tri}} \frac{V_d}{2} \quad ; \quad v_{control} \le \hat{V}_{tri} ; \quad m_a = \frac{v_{control}}{\hat{V}_{tri}}$$

VSI connected to the grid using an H-Bridge topology

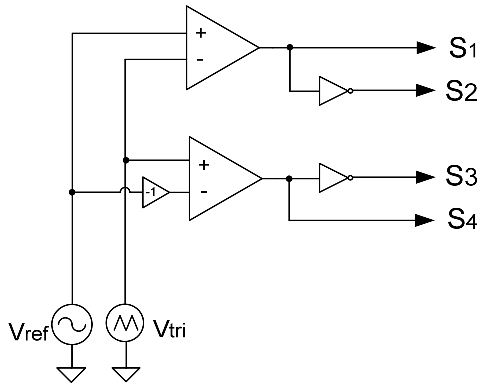


Topologies: FB Modulation

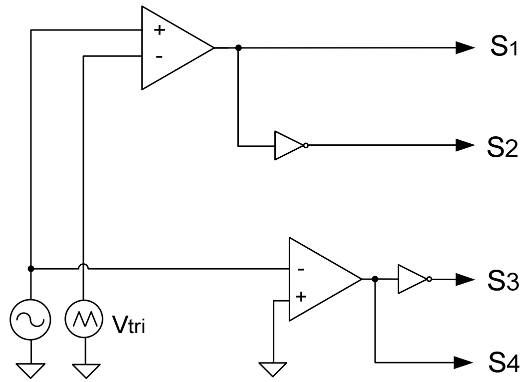
Bipolar PWM
S1 + S4 and S2 + S3 are switched complementary at high frequency



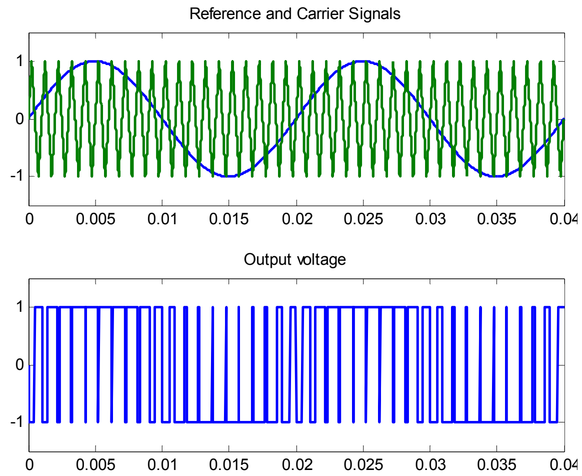
Unipolar PWM
Leg A and B are switched with high frequency with mirrored sinusoidal ref.



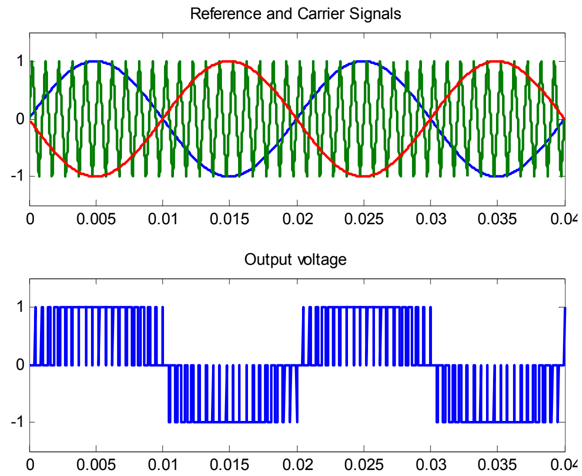
Hybrid PWM
Leg A is switched with high frequency and Leg B is switched with grid frequency



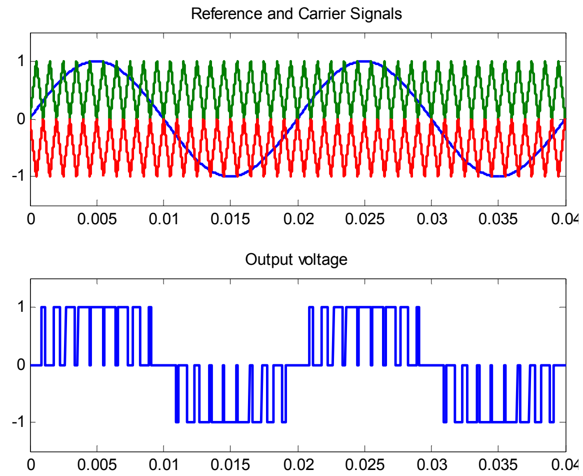
Bipolar PWM



Unipolar PWM

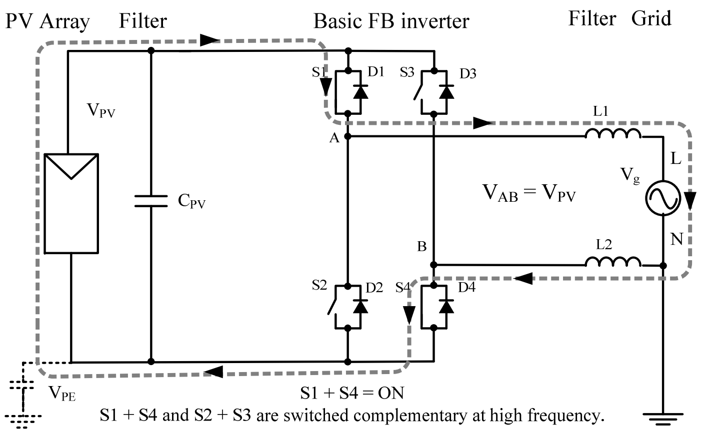


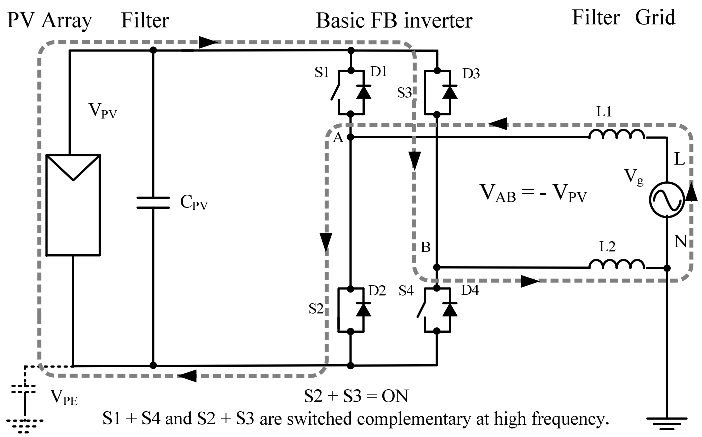
Hybrid PWM



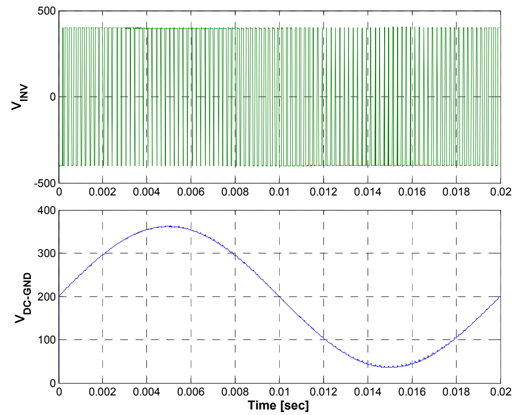
1kHz triangular wave and 50Hz sinusoidal reference

Topologies: FB Bipolar PWM

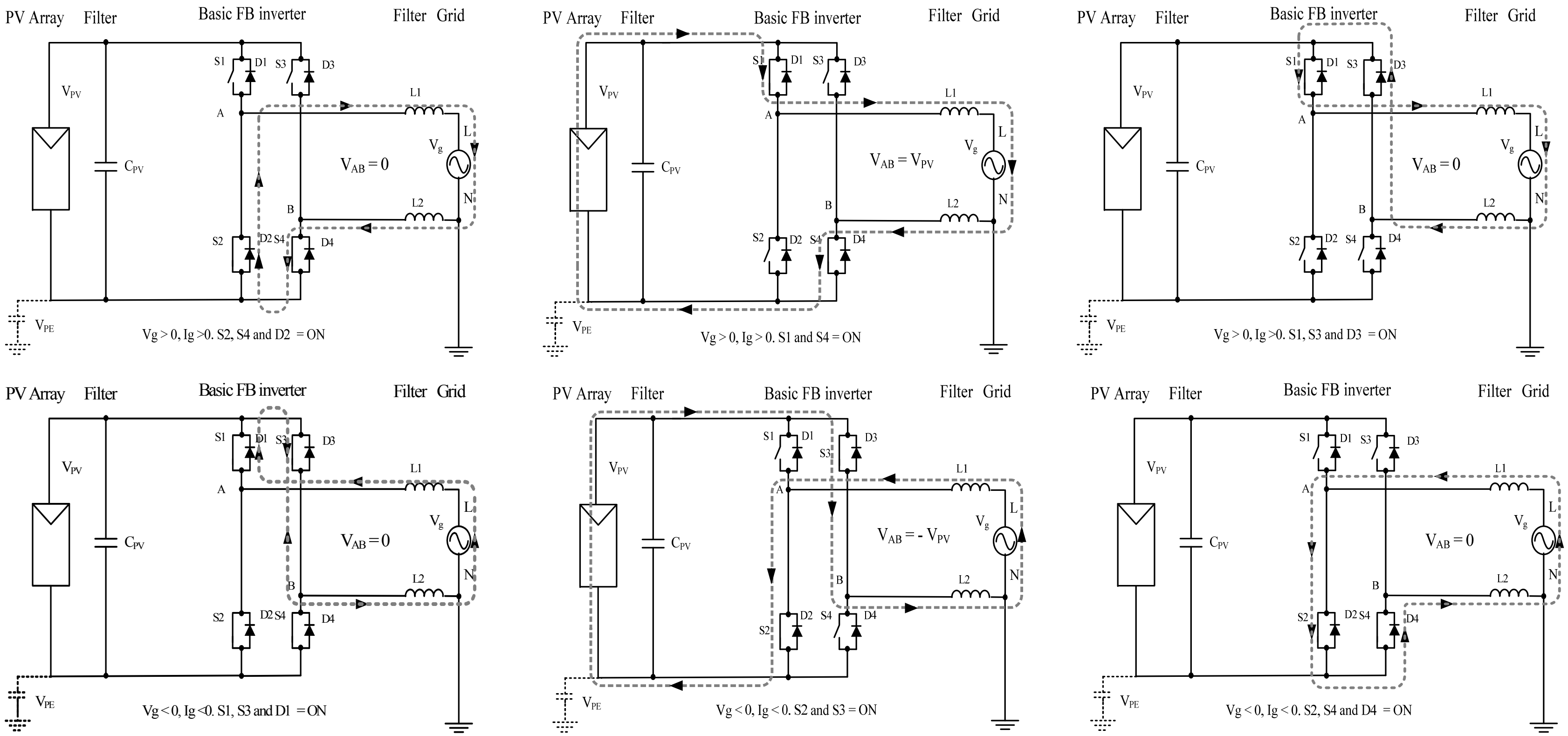




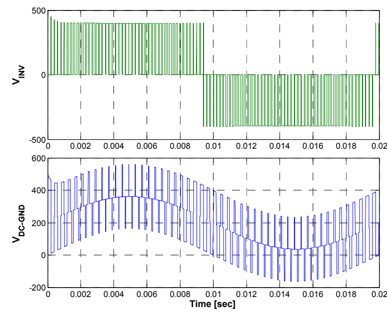
- S1 + S4 and S2 + S3 are switched complementary at high frequency (PWM)
- No 0 output voltage possible
- The switching ripple in the current equals 1x switching frequency → large filtering
- Voltage across filter is bipolar → high core losses
- No common mode voltage → V_{PE} free for high frequency →low leakage current
- Max efficiency 96.5% due to reactive power exchange L1(2)<-> Cpv during freewheeling and that 2 switched are simultaneously switched every switching
- This topology is not suited to transformerless PV inverter due to low efficiency!



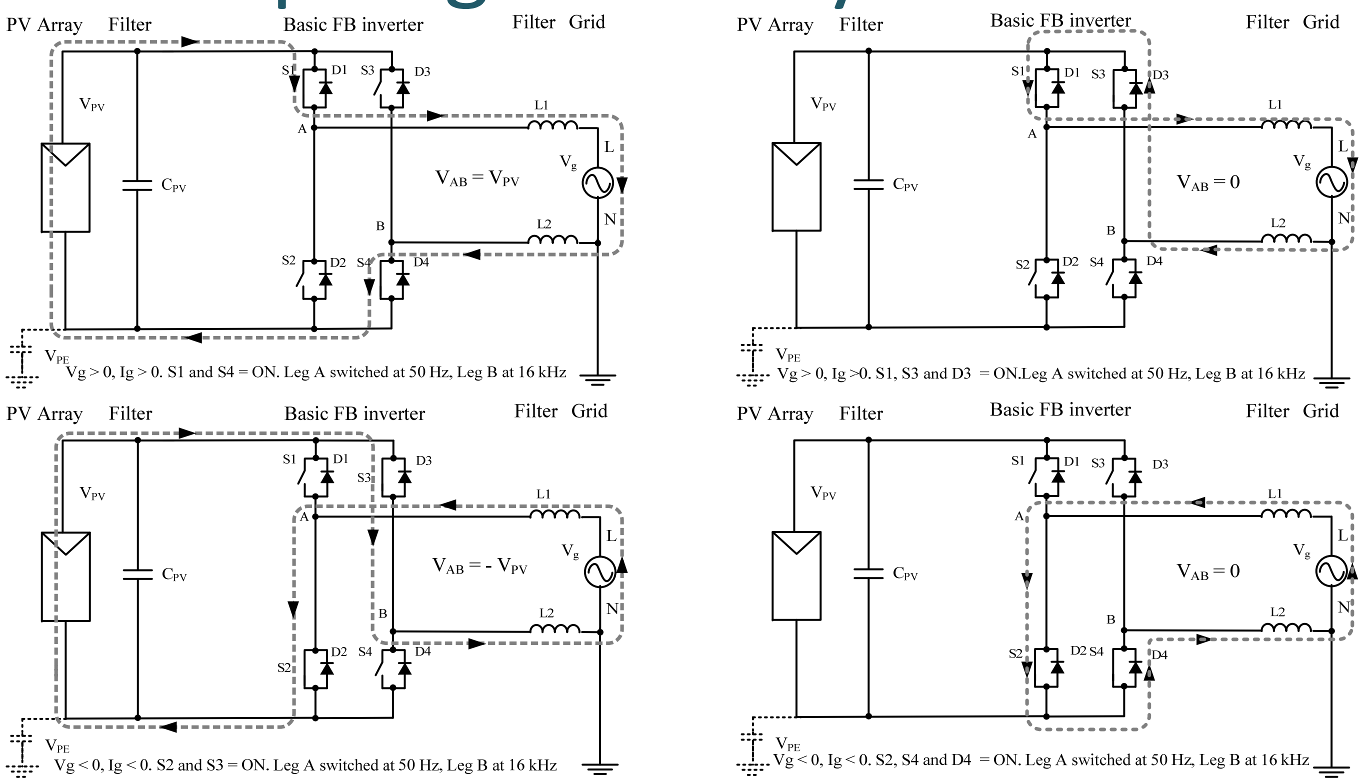
Topologies: FB Unipolar PWM



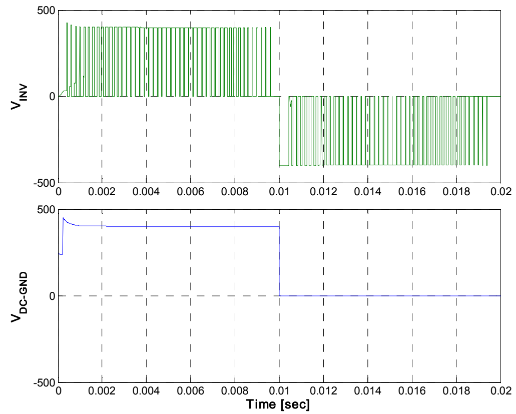
- Leg A and B are switched with high frequency with mirrored sinusoidal reference
- Two 0 output voltage states possible: S1 and S2 = ON and S3 and S4 = ON
- The switching ripple in the current equals <u>2x</u> switching frequency → lower filtering
- Voltage across filter is unipolar → low core losses
- V_{PE} has switching frequency components → <u>high leakage current and EMI</u>
- Max efficiency 98% due to <u>no</u> reactive power exchange L1(2)<-> Cpv during freewheeling
- This topology is not suited for TL PV inverter due to high leakage!



Topologies: FB Hybrid PWM

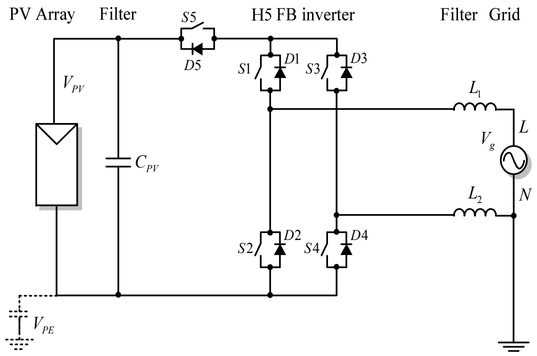


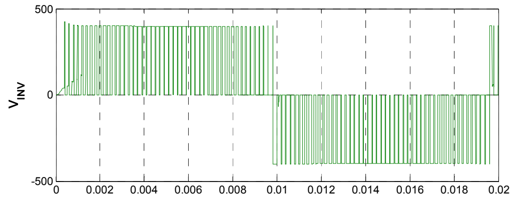
- Leg A is switched with grid low frequency and Leg B is switched with high PWM freq
- Two 0 output voltage states possible: S1 and S2 = ON and S3 and S4 = ON
- The switching ripple in the current equals 1x switching frequency → high filtering
- Voltage across filter is unipolar → low core losses
- V_{PE} has square wave variation at grid frequency → high leakage current and EMI
- High efficiency 98% due to no reactive power exchange L1(2)<-> Cpv during freewheeling and due to lower frequency switching in one leg.
- This topology is not suited for transformerless PV inverter due to high leakage!



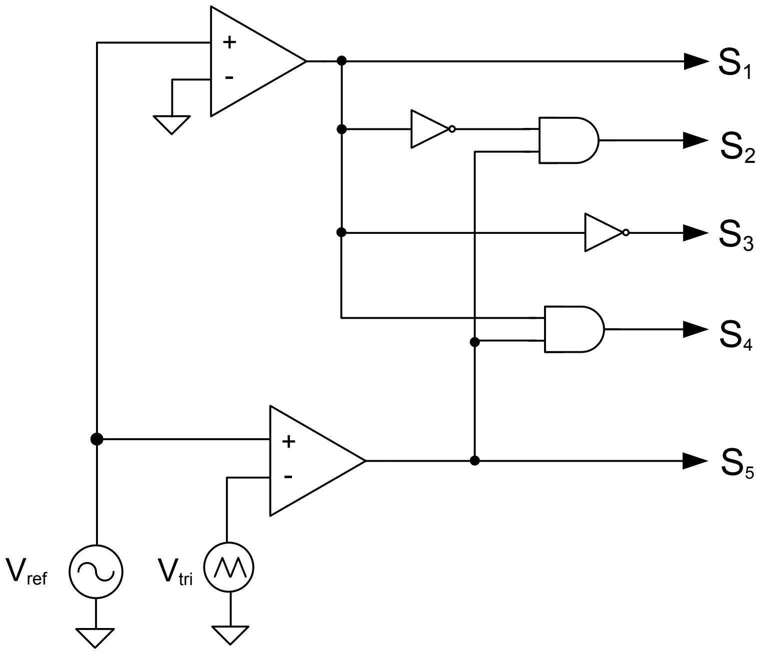
Source [Ray-Shyang Lai; Ngo, K.D.T., "A PWM method for reduction of switching loss in a full-bridge inverter," Power Electronics, IEEE Transactions on , vol.10, no.3, pp.326-332, May 1995]

Topologies: H5 (SMA) Modulation



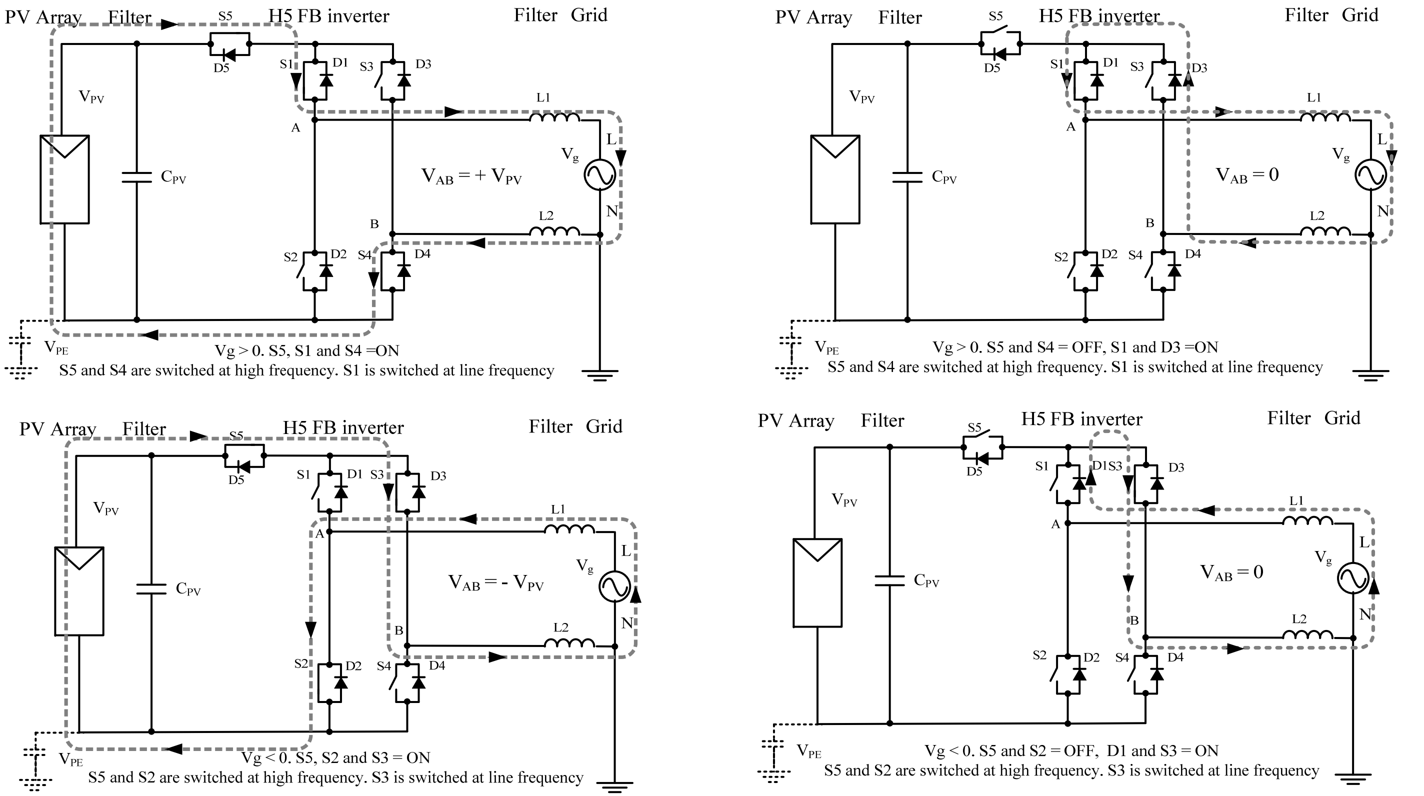


S5 and S4 (S3) are switched with high frequency
S1 (S2) are switched with low grid freq

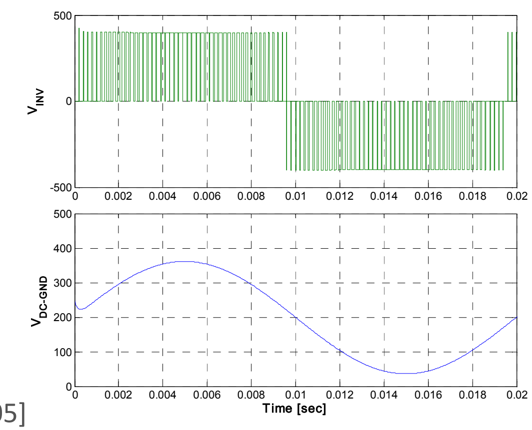


Source [Victor M.et al.- US Patent Application, Pub.No.: US 2005/0286281 A1, Pub. Date: 29.Dec.2005]

Topologies: H5 (SMA)

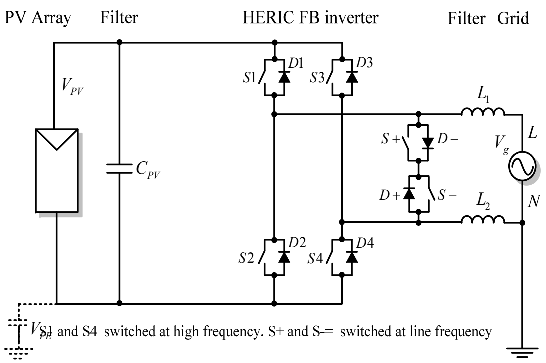


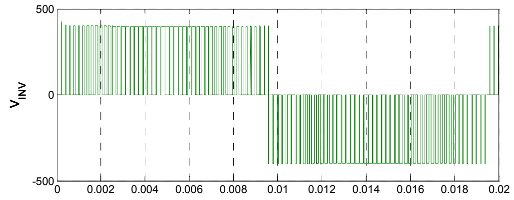
- Extra switch in the dc link to decouple the PV generator from grid during 0 voltage
- Two 0 output voltage states possible: S5 = OFF, S1 = ON and S5 = OFF, S3 = ON
- The switching ripple in the current equals 1x switching frequency → high filtering
- Voltage across filter is unipolar → low core losses
- V_{PE} is sinusoidal with grid frequency component → low leakage current and EMI
- High max. efficiency 98% due to no reactive power exchange as reported by Photon Magazine for SMA SunnyBoy 4000/5000 TL single-phase



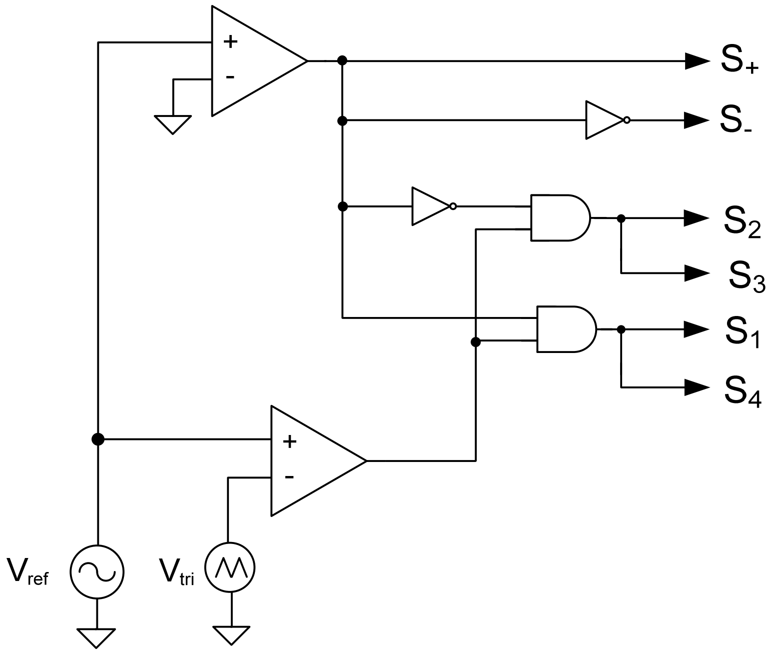
Source [Victor M.et al.- US Patent Application, Pub.No.: US 2005/0286281 A1, Pub. Date: 29.Dec.2005]

Topologies: HERIC Modulation



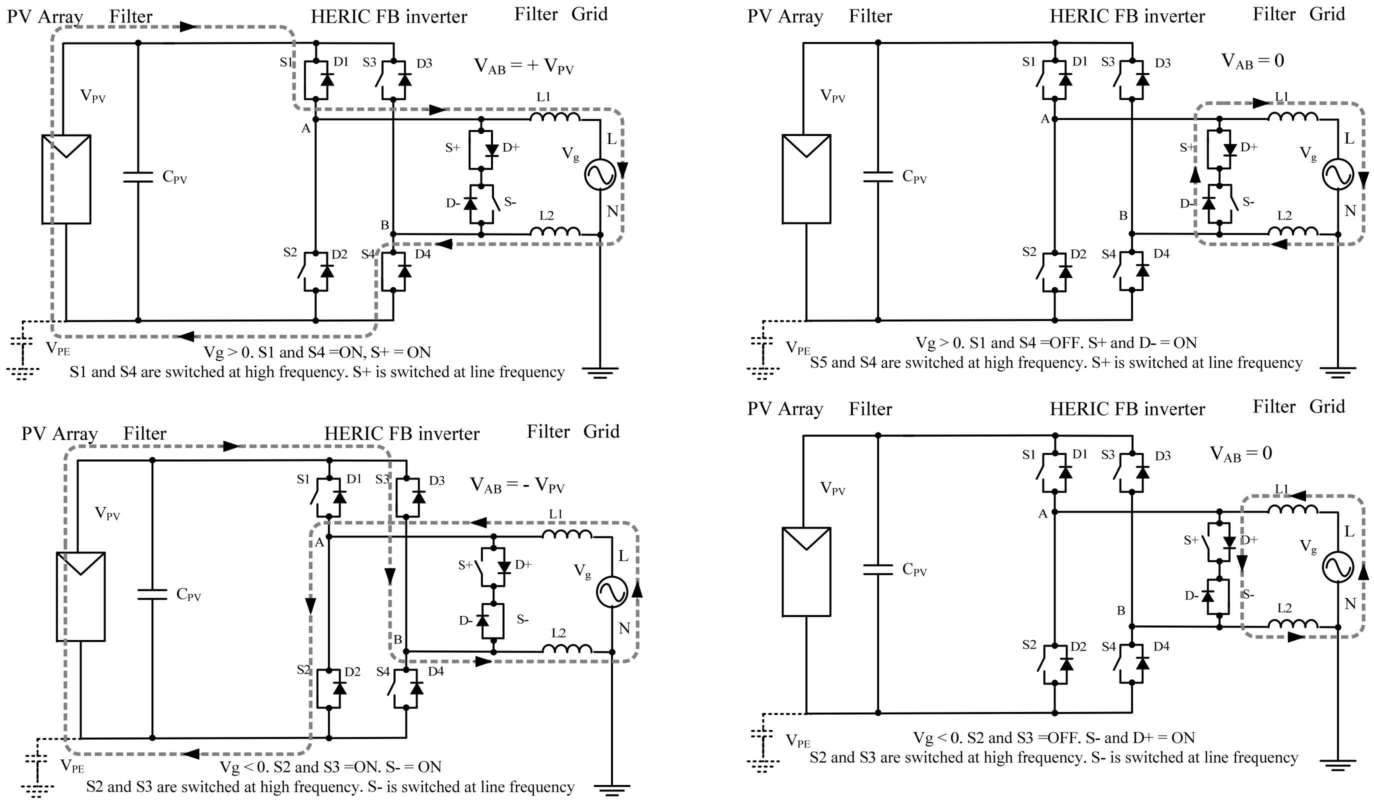


S+ and S- are switched with grid freq
S1&S4 (S2&S3) are switched with high freq

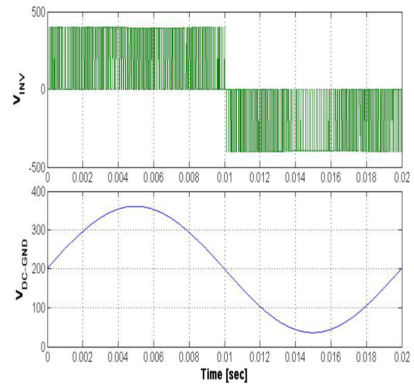


Source [Schmid H. et al. US Patent No: 7046534, issued 16 May 2006]

Topologies: HERIC

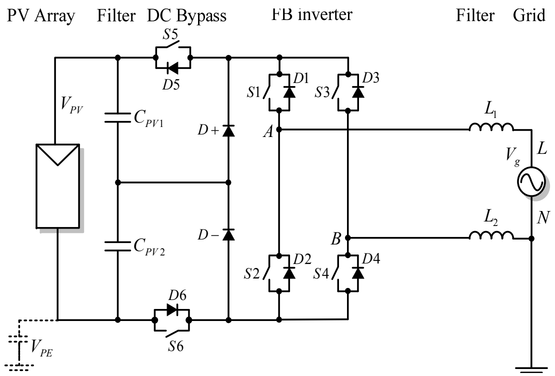


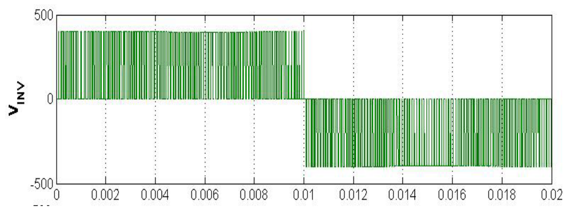
- Two 0 output voltage states possible: S+ and D- = ON and S- and D+ = ON
- The switching ripple in the current equals 1x switching frequency → high filtering
- Voltage across filter is unipolar → low core losses
- V_{PE} is sinusoidal has grid frequency component → low leakage current and EMI
- High efficiency 98% due to no reactive power exchange as reported by Photon Magazine for Sunways AT series 2.7 – 5 kW single-phase



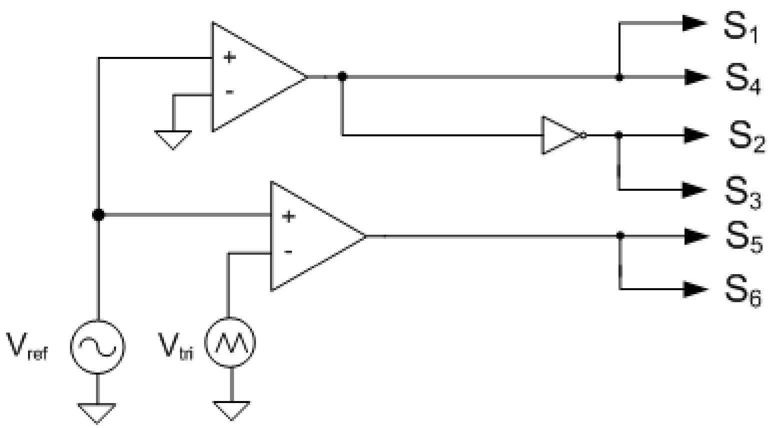
Source [Schmid H. et al. US Patent No: 7046534, issued 16 May 2006]

Topologies: FBDC Bypass (H6)



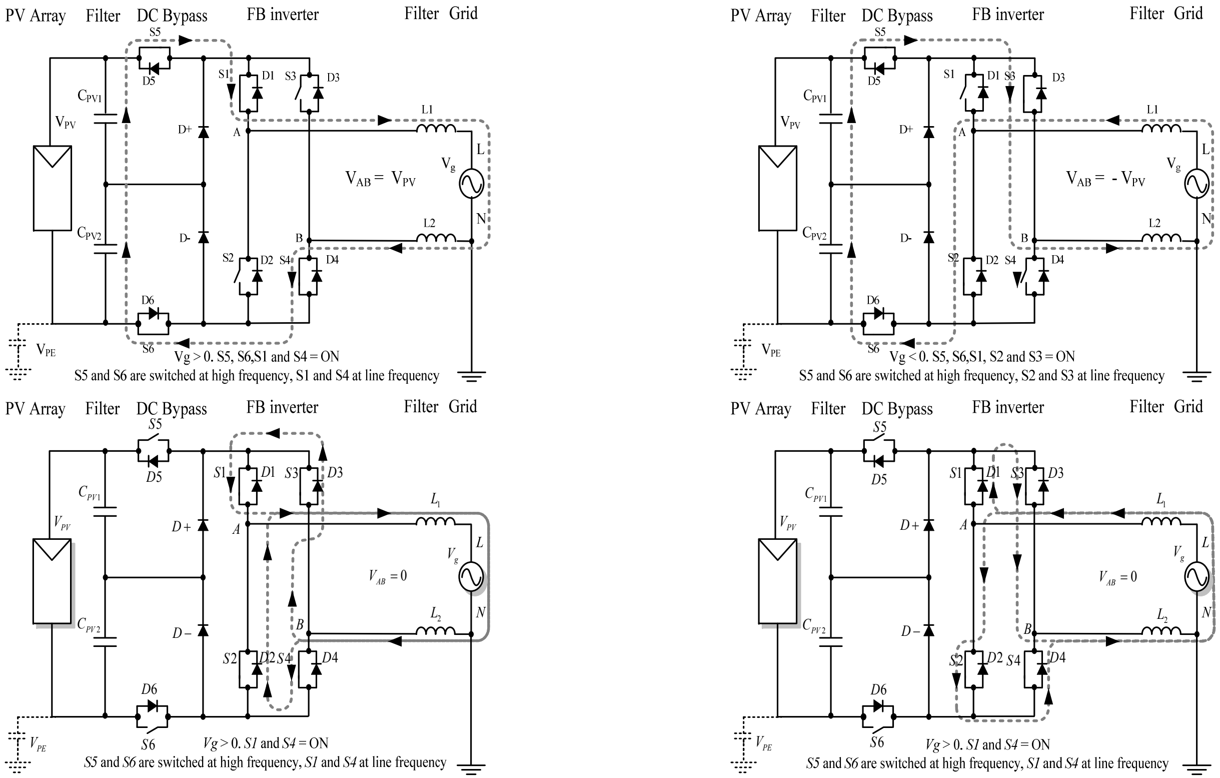


S5 and S6 are switched at high frequency, S1&S4 (S2&S3) at line frequency

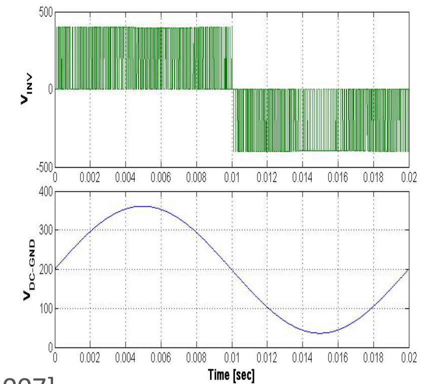


Source [Gonzalez S R, et.al.- International Patent Application, Pub No. WO2008015298, Pub. Date: 2 July 2007]

Topologies: FBDC Bypass (H6)

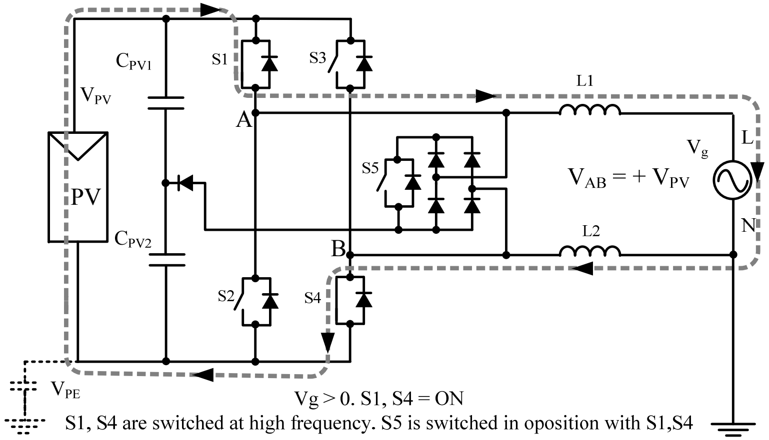


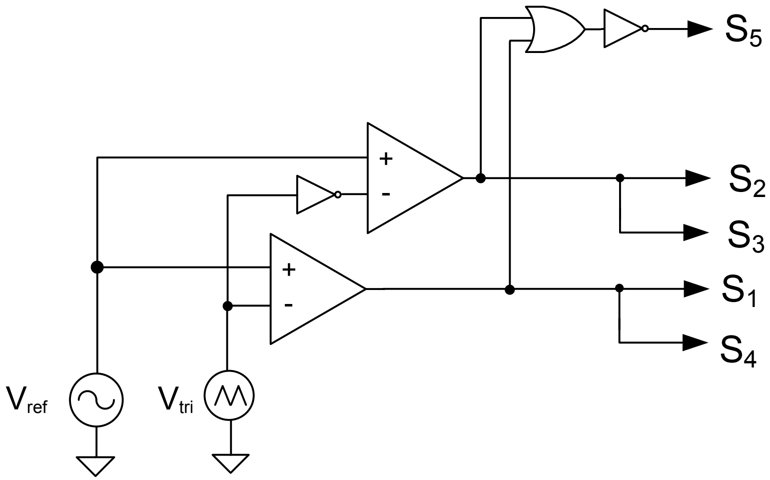
- Two extra switches switching with high frequency and 2 diodes bypassing the dc bus. The 4 switches in FB switch at low fsw
- Two 0 output voltage states possible by "natural clamping# of D+ and D-
- The switching ripple in the current equals 1x switching frequency → high filtering
- Voltage across filter is unipolar → low core losses
- V_{PE} is sinusoidal and has grid frequency component → low leakage and EMI
- High max efficiency 96.5% due to no reactive power exchange as reported by Photon Magazine for Ingeteam Ingecon Sun TL series (2.5/3.3/6 kW, single-phase)

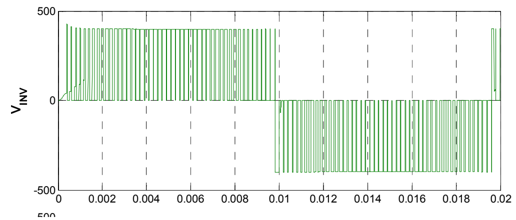


Source [Gonzalez S R, et.al.- International Patent Application, Pub No. WO2008015298, Pub. Date: 2 July 2007]

Modulation: ZVFBR(AAU+UPC)

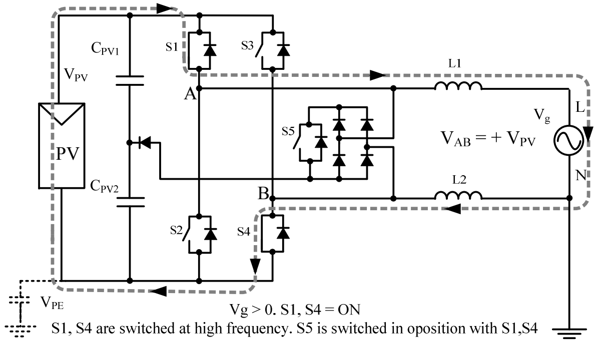


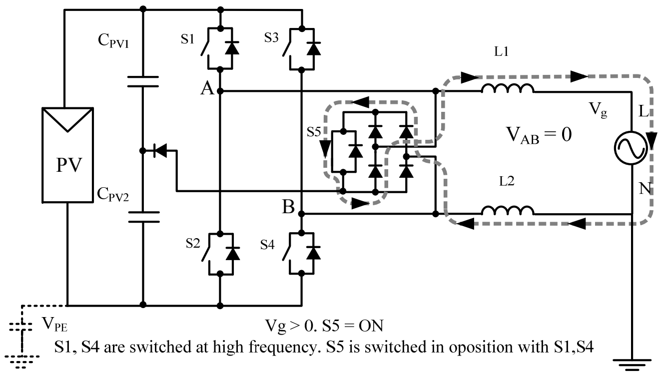


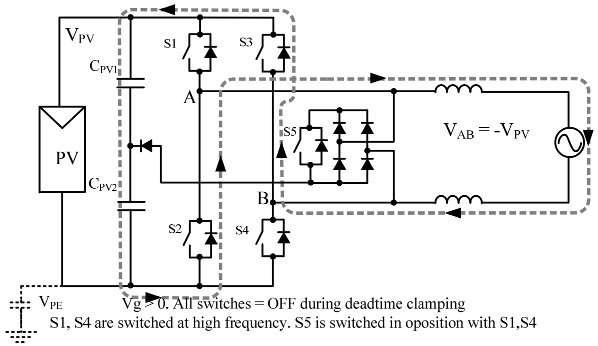


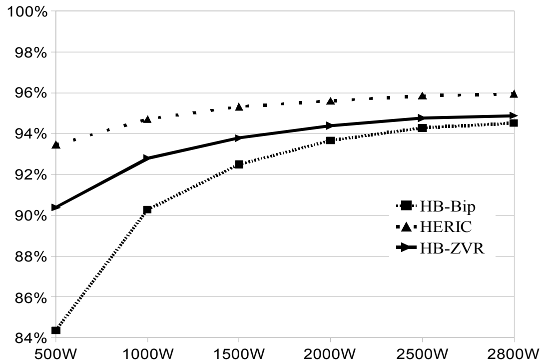
Source [T. Kerekes, R. Teodorescu, P. Rodriquez, G. Vazquez and E. Aldabas, A new high-efficiency single-phase transformerless PV inverter topology; IEEE Transactions on Industrial Electronics]

Topologies: ZVFBR (AAU+UPC)

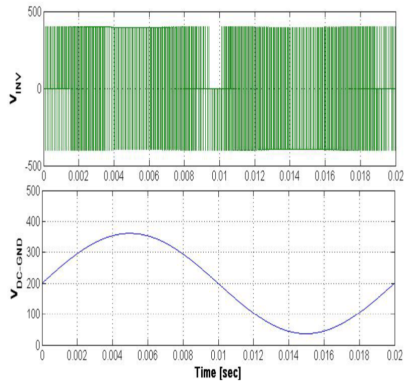






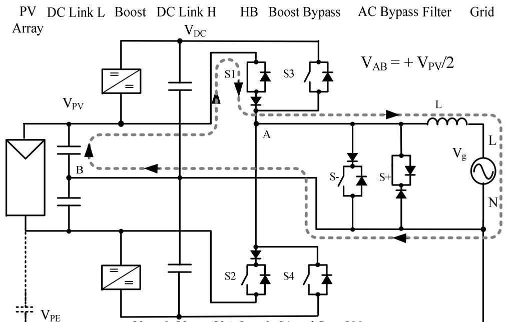


- Derived from HERIC but the bidirectional grid-short-circuiting switch is implemented using a diode bridge and 1 switch
- Zero voltage is achieved by turning the FB off and turning T5 on -> higher losses as HERIC due to high switching frequency of T5
- The switching ripple in the current equals 1x switching frequency → high filtering
- Voltage across filter is bipolar due to deadtime clamping → higher core losses
- V_{PE} is constant → low leakage current and EMI
- High efficiency due to no reactive power exchange during zero voltage

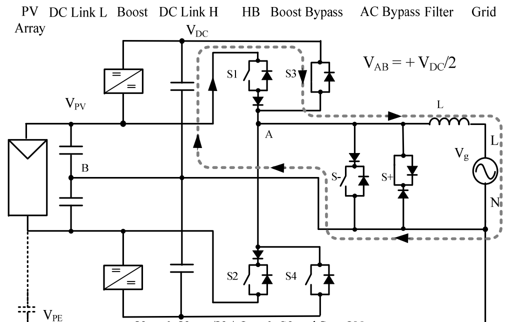


Source [T. Kerekes, R. Teodorescu, P. Rodriquez, G. Vazquez and E. Aldabas, A new high-efficiency single-phase transformerless PV inverter topology; IEEE Transactions on Industrial Electronics]

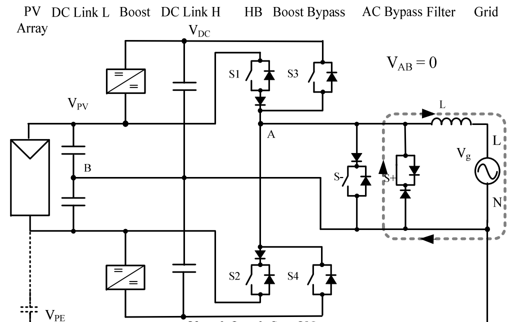
Topologies: UltraEta - REFU



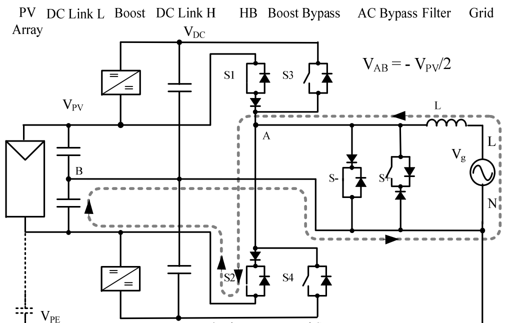
$V_g > 0$, $V_{PV} < |V_g|$, $I_g > 0$. S1 and S+ =ON
S1 is switched at high frequency. S+ is switched at line frequency



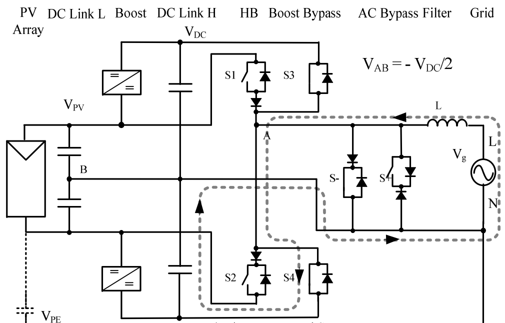
$V_g > 0$, $V_{PV} < |V_g|$, $I_g > 0$. S3 and S+ =ON
S3 is switched at high frequency. S+ is switched at line frequency



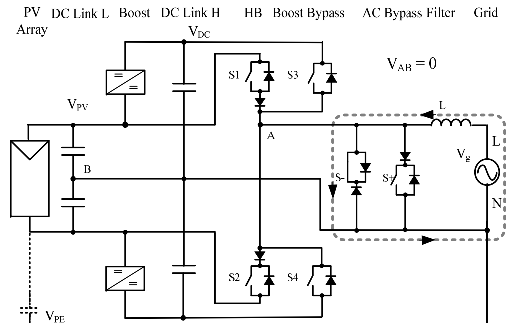
$V_g > 0$, $I_g > 0$. S+ =ON
S+ is switched at line frequency



$V_g < 0$, $V_{PV} > |V_g|$ $I_g < 0$. S2 and S- =ON
S2 is switched at high frequency. S- is switched at line frequency

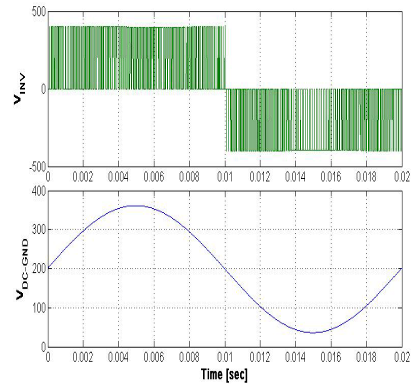


$V_g < 0$, $V_{PV} < |V_g|$ $I_g < 0$. S4 and S- =ON
S2 is switched at high frequency. S- is switched at line frequency



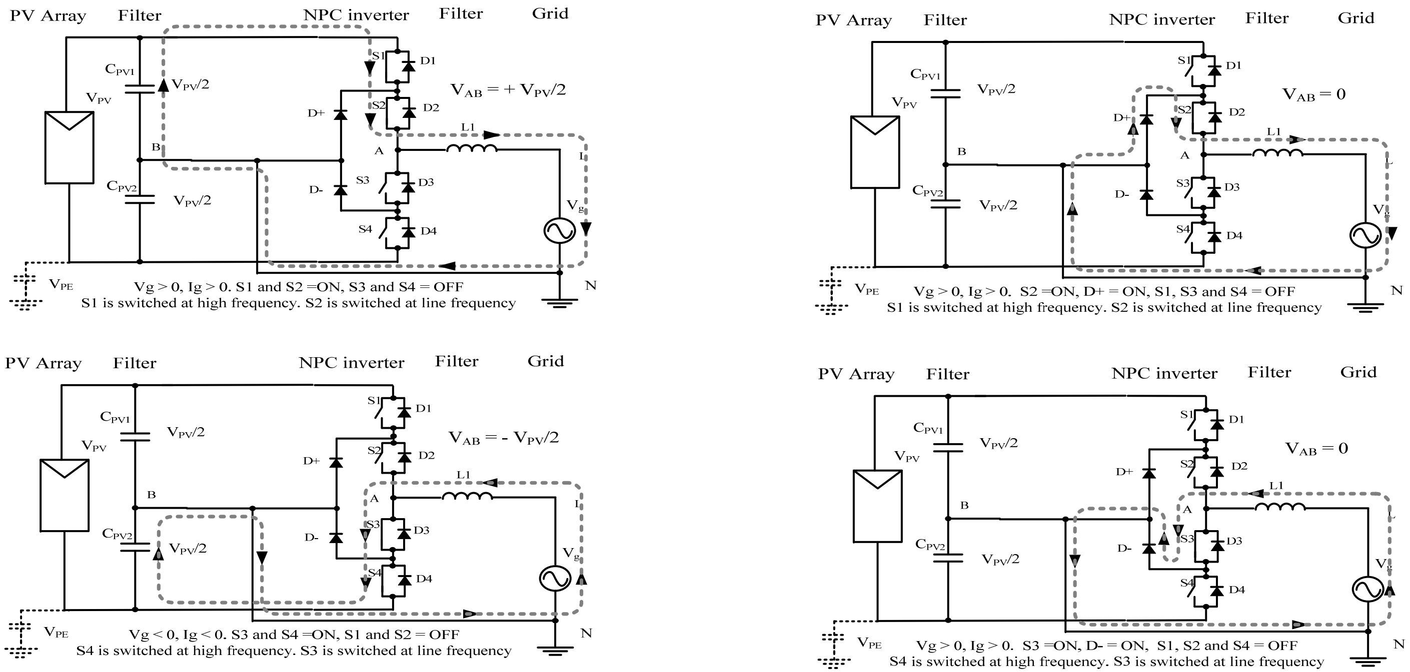
$V_g < 0$, $I_g < 0$. S- =ON
S- is switched at line frequency

- Three-level output. Requires double PV voltage input in comparison with FB but it include time-shared boost
- Zero voltage is achieved by short-circuiting the grid using the bidirectional switch
- The switching ripple in the current equals <u>1x</u> switching frequency → high filtering
- Voltage across filter is unipolar → low core losses
- V_{PE} w/o high freq component → <u>low leakage current and EMI . No L in neutral!</u>
- High max efficiency 98% due to <u>no</u> reactive power exchange, as reported by Photon Magazine for Refu Solar RefuSol (11/15 kW, three-phase)

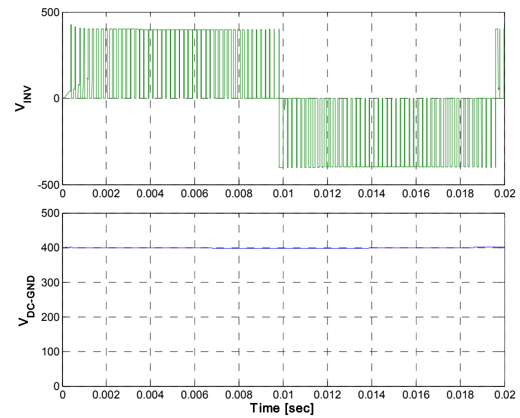


Source [Hantschel J. German Patent Application, Pub. No. DE102006010694 A11, Pub Date: 20 Sep 2007]

Topologies: NPC (Danfoss Solar)

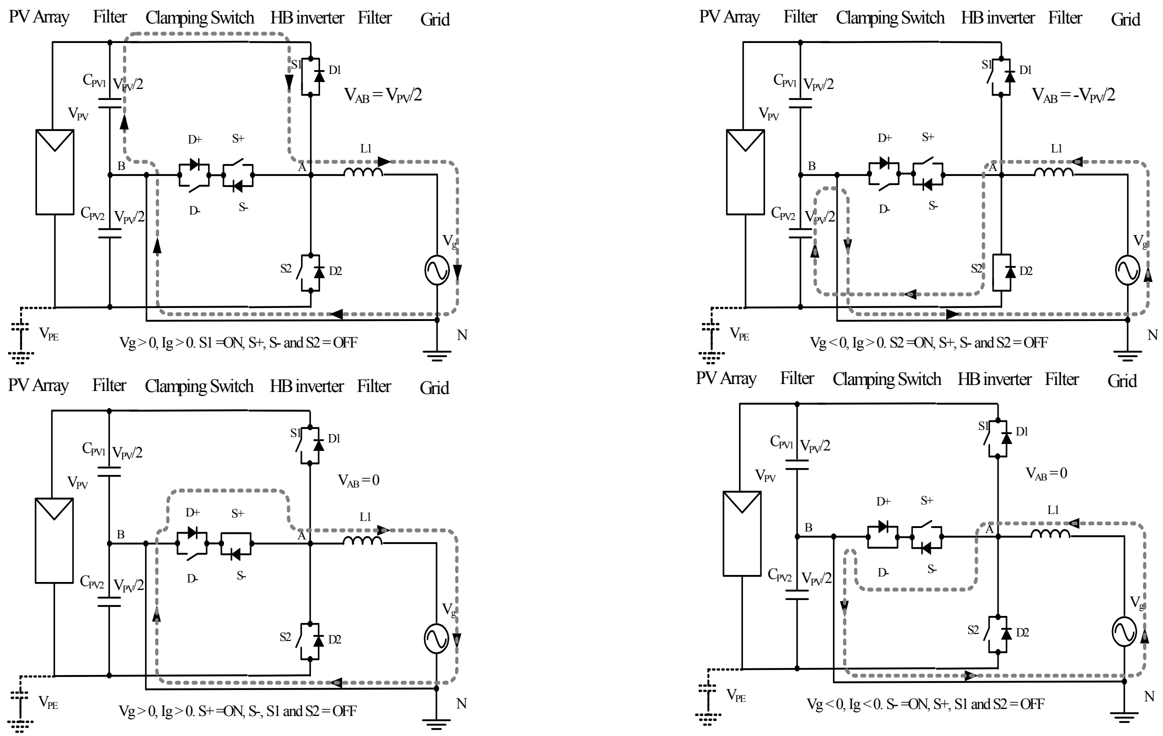


- Three-level output. Requires double PV voltage input in comparison with FB. Typically needs boost.
- Two 0 output voltage states possible: S2 and D+ = ON and S3 and D- = ON. For zero voltage during Vg>0, Ig<0, S1 and S3 switch in opposition and S2 and S4 for Vg<0, Ig>0
- The switching ripple in the current equals 1x switching frequency → high filtering
- Voltage across filter is unipolar → low core losses
- V_{PE} is equal –Vpv/2 w/o high freq comp → low leakage and EMI . No L in N!
- High max efficiency 98% due to no reactive power exchange, as reported by Danfoss Solar TripleLynx series (10/12.5/15 kW)

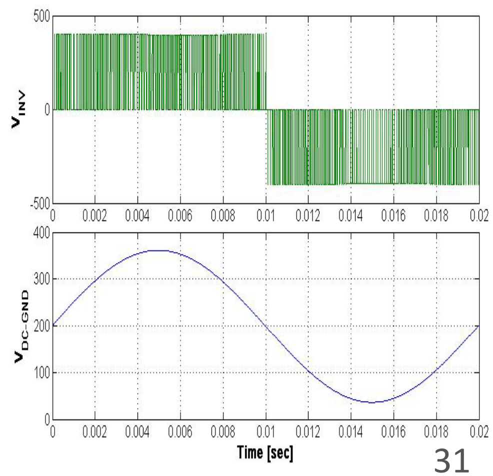


Source [A. Nabae, I. Takahashi, and H. Akagi; "A New Neutral-Point-Clamped PWM Inverter"; IEEE Transactions on Industry Applications, vol. IA-17, no. 5, 1981, pp. 518-523]

Topologies: CONERGY



- Only 4 switches needed with 2 of them (S+ and S-) rated only Vpv/4
- Three-level output. Requires double PV voltage input in comparison with FB. Typically needs boost.
- Two 0 voltage states using the bidirectional clamping switch (S+ and S-)
- The switching ripple in the current equals 1x switching freq → high filtering
- Voltage across filter is unipolar → low core losses
- V_{PE} is equal –Vpv/2 w/o high freq comp → low leakage and EMI . No L in N!
- High max efficiency 96.1% due to no reactive power exchange, as reported by Conergy IPG series (2-5 kW single-phase)



Source [Knaup P – International Patent Application, Pub No. WO 2007/048420 A1, Pub. Date: 3 May 2007]

Topologies: TL Comparison

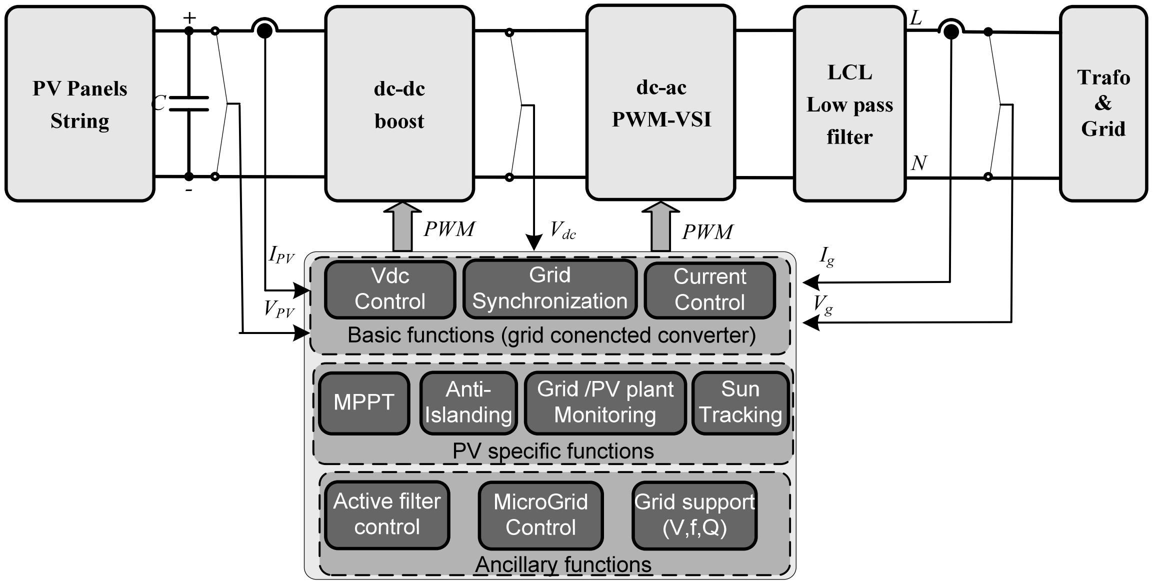
Topologies derived from FB

- Actually both HERIC, H5, REFU and FB-DCBP topologies are converting the 2 level FB (or HB) inverter in a 3 level one
- This increases the efficiency as both the switches and the output inductor are subject to half of the input voltage stress
- The zero voltage state is achieved by shorting the grid using higher or lower switches of the bridge (H5) or by using additional ac bypass (HERIC or REFU) or dc bypass (FB-DCBP)
- H5 and HERIC are isolating the PV panels from the grid during zero voltage while REFU and FB-DCBP is clamping the neutral to the mid-point of the dc link
- Both REFU and HERIC use ac by-pass but REFU uses 2 switches in anti- parallel and HERIC uses 2 switches in series (back to back). Thus the conduction losses in the ac-bypass are lower for the REFU topology
- REFU and H5 have slightly higher efficiencies as they have only one switch switching with high-frequency while HERIC and FB_DCBP have two
- FB-ZVR derives from HERIC but uses a different implementation of the bidirectional switch using a diode bridge and one switch. Constant Vpe but moderate high efficiency (lower than HERIC but higher than FB-UP). Can also work with non-unitary PF

Topologies derived from NPC

- The classical NPC and its “variant” Conergy-NPC are both three-level topologies featuring the advantages of unipolar voltage across the filter, high efficiency due to disconnection of PV panels during zero-voltage state and practical no leakage due to grounded DC link mid-point
- Due to higher complexity in comparison with FB-derived topology, these structures are typically used in three-phase PV inverters with ratings over 10 kW (mini-central)

Control Structure Overview



Basic functions – common for all grid-connected inverters

- Grid current control
  - THD limits imposed by standards
  - Stability in case of grid impedance variations
  - Ride-through grid voltage disturbances (not required yet!)
- DC voltage control
  - Adaptation to grid voltage variations
  - Ride-through grid voltage disturbances (optional yet)
- Grid synchronization
  - Required for grid connection or re-connection after trip

PV specific functions – common for PV inverters

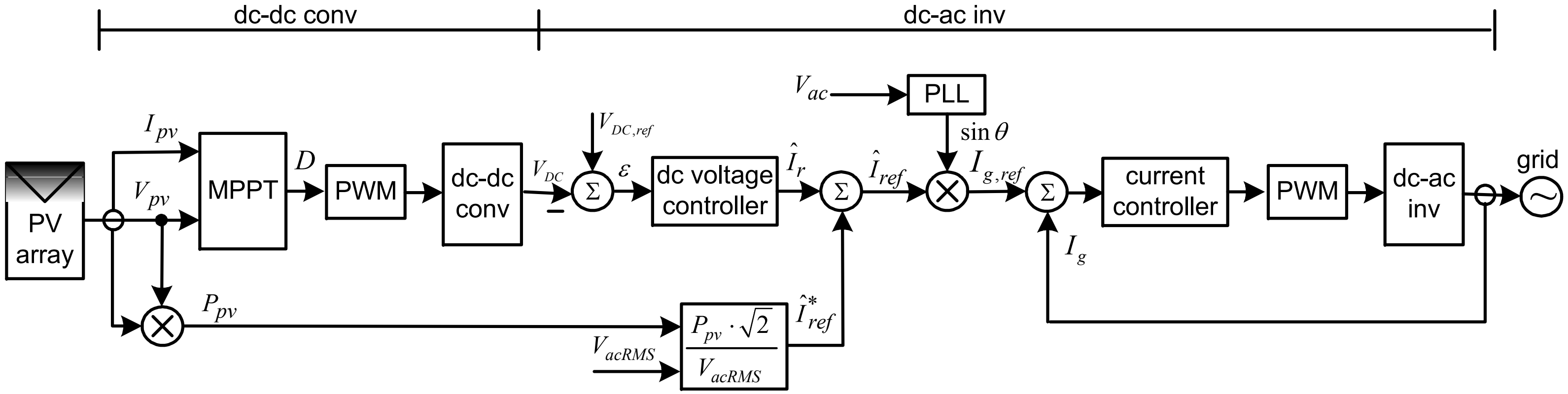
- Maximum Power Point Tracking – MPPT
  - Very high MPPT efficiency in steady state (typical > 99%)
  - Fast tracking during rapid irradiation changes (dynamical MPPT efficiency)
  - Stable operation at very low irradiation levels
- Anti-Islanding – AI as required by standards (VDE0126, IEEE1574, etc.)
- Grid Monitoring
  - Operation at unity power factor as required by standards
  - Fast Voltage/frequency detection
- Plant Monitoring
  - Diagnostic of PV panel array
  - Partial shading detection
- Sun Tracking (mechanical MPPT)
  - 1-2 axis motion controller tracking of Sun

Ancillary Support – (future?)

- Voltage Control
- Fault Ride-through
- Power Quality
  - Harmonics
  - Unbalance

Control Structure for Dual-Stage

Typical control structure for dual-stage PV inverter

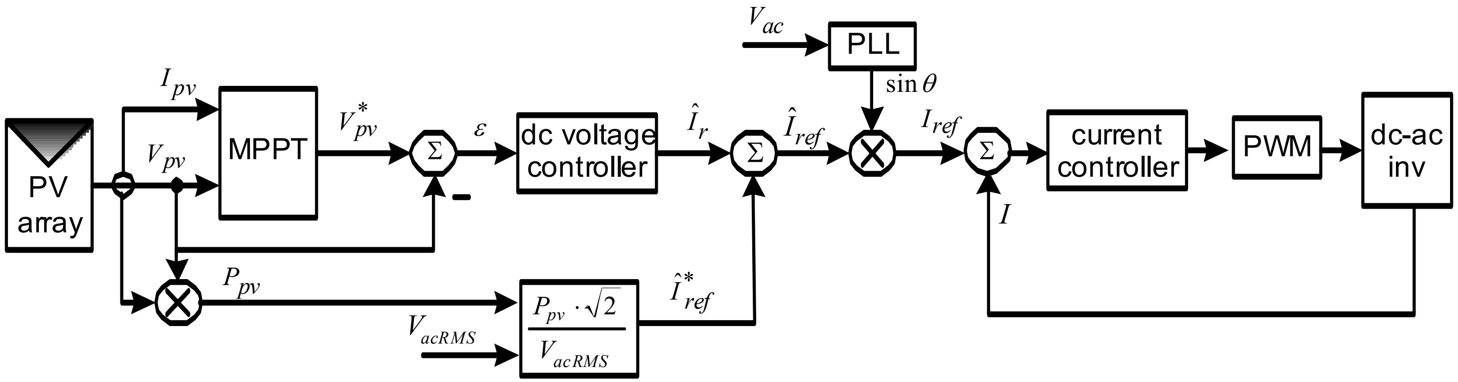


- The MPPT is implemented in the dc-dc boost converter.
- The output of the MPPT is the duty-cycle function. As the dc-link voltage V_{DC} is controlled in the dc-ac inverter the change of the duty-cycle will change voltage at the output of the PV panels, V_{PV} as:

$$V_{DC} = K \frac{V_{PV}}{1 - D}$$

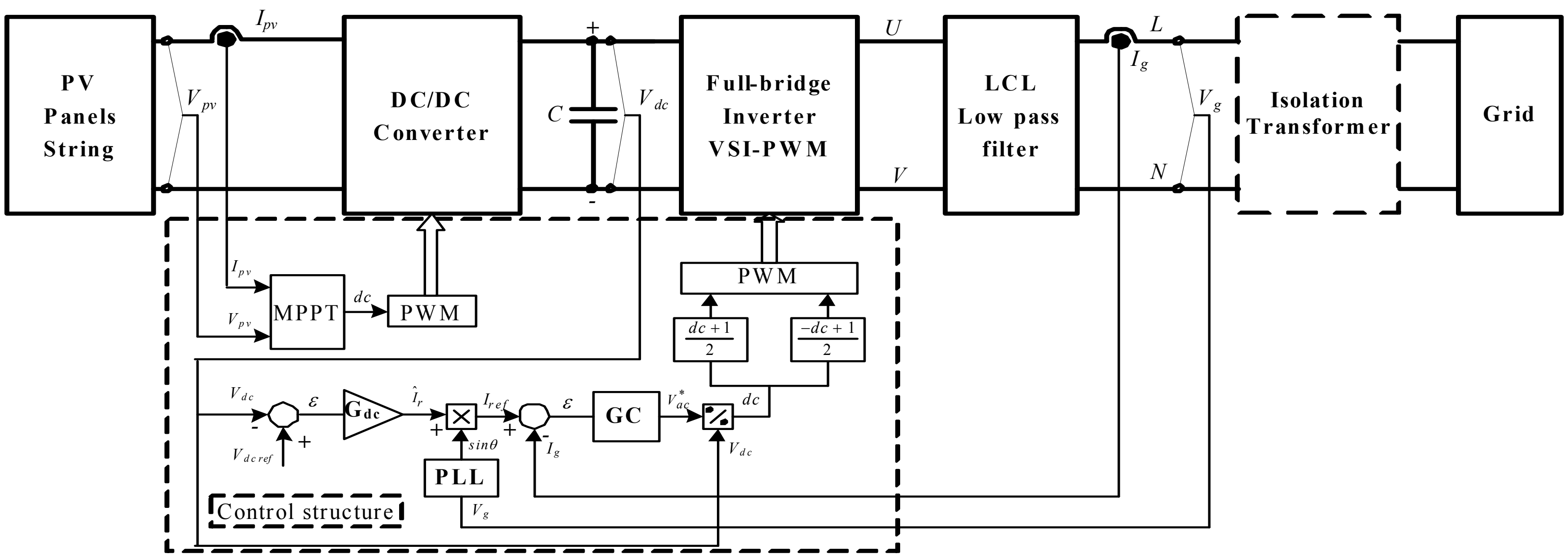
- The dc-ac inverter is a typical current controlled voltage source inverter (VSI) with PWM and dc-voltage controller.
- The power feed-forward requires communication between the two stages and improves the dynamics of MPPT

Control Structure for Single-Stage



- In these topologies -which are becoming more and more popular in countries with low grid voltage (120V) like Japan and thus the voltage from the PV array is high enough - the MPPT is implemented in the dc-ac inverter
- Also in topologies with boost transformer on AC side
- The output of the MPPT is the dc-voltage reference. The output of the dc-voltage controller is the grid current reference amplitude. The power feed-forward improves the dynamic response as MPPT runs at a slow sampling frequencies (typ. 1 Hz)
- A PLL is used to synchronize the current reference with the grid voltage

Control Implementation



- The current controller GC can be of PI or PR (Proportional Resonant) type
- Other non-linear controllers like hysteresis or predictive control can be used for current control
- The DC voltage controller can be P type due to the integration effect of the typical large capacitor

Conclusion

- The “race” for higher efficiency PV inverters has resulted in a large variety of “novel” transformerless topologies derived from H-Bridge with higher efficiency and lower CM/EMI (H5, HERIC)
- Equivalent high-efficiency can be achieved with 3-level topologies (ex NPC)
- Today more than 70% of the PV inverters sold on the market are transformerless achieving 98% max conversion efficiency and 97.7% “european” (weighted) efficiency
- Further improvements in the efficiency can be achieved by using SiC MosFets. ISE Fraunhofer-Freiburg reported recently* 99% efficiency (25% reduction in switching + conduction losses)
- For 3-phase systems the trend is to use 3 independent controlled single-phase inverters like 3xH5 or 3xHERIC but 3FB-SC and 3NPC (not proprietary) are also present on the market. 3NPC achieve higher efficiency 98%
- The general trend in PV topologies is “More Switches for Lower Losses”

*Source [Burger, B., Schmidt,H. “25 YEARS TRANFORMLESS INVERTERS” – Proceedings of PVSEC 2007]