FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Basics of Inverter Technology and Grid Integration

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Fraunhofer Institute for Solar Energy Systems ISE

European Summer Campus 2013
'Energy on all scales'

Freiburg, 02/09/2013

www.ise.fraunhofer.de

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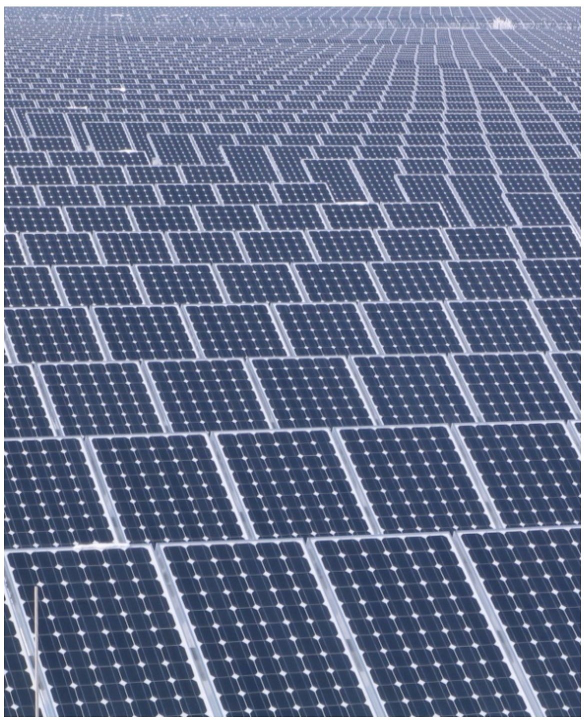
AGENDA

- PV Inverter Technology
  - Definition and Classification
  - Principle Requirements
  - Fundamentals of Switching Inverters
  - Basic Topologies
    - Transformer/Transformerless
    - Singel-/Three-Phase
  - Efficiencies
  - Development Trends
  - Large PV Power Plants (Optional)
- Grid Integration
  - Background
  - Today's Requirements and Experiences
  - Future Challenges

Definition and Classification
What are Inverters?

- PV Generator
  (DC Source)



- Inverter

- DC/AC conversion
- Maximum Power Point Tracking (MPPT)

- AC Grid

Definition and Classification
Classification of PV Inverters

Micro Inverters:

- < 1 kW
- Input: < 100 V
- Typically connected to only one PV-panel
- MPPT on panel level
- Max. Efficiencies: ~96 %
- Cost/Watt: high

String Inverters:

- < 30 kW
- Input: 150 V … 1000 V
- Connected to one or few strings of PV-Panels
- MPPT on string level
- Max. Efficiencies: ~98 %
- Cost/Watt: medium

Central Inverters:

- > 30 kW, up to 1 MW
- Input: 450 V … 1500 V
- Connected to multiple parallel PV-Strings
- MPPT in PV-array level
- Max. Efficiencies: ~99 %
- Cost/Watt: low

MPPT: Maximum Power Point Tracking

Definition and Classification
Typical Applications for Different Inverter Types

Micro Inverters:

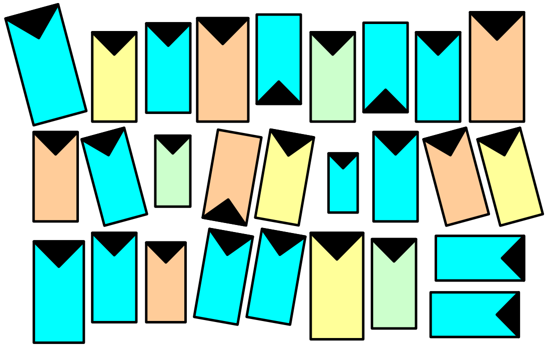
- Small PV installations
- Inhomogeneous PV-panel situations, like
  - Partial shading
  - Different orientations
  - Different size or types
- Cabling on AC-Level

String Inverters:

- Residential PV installations
- Sometimes large PV power plants
- Cabling on DC-Level

Central Inverters:

- Large, utility-scale PV power plants
- Cabling on DC-Level



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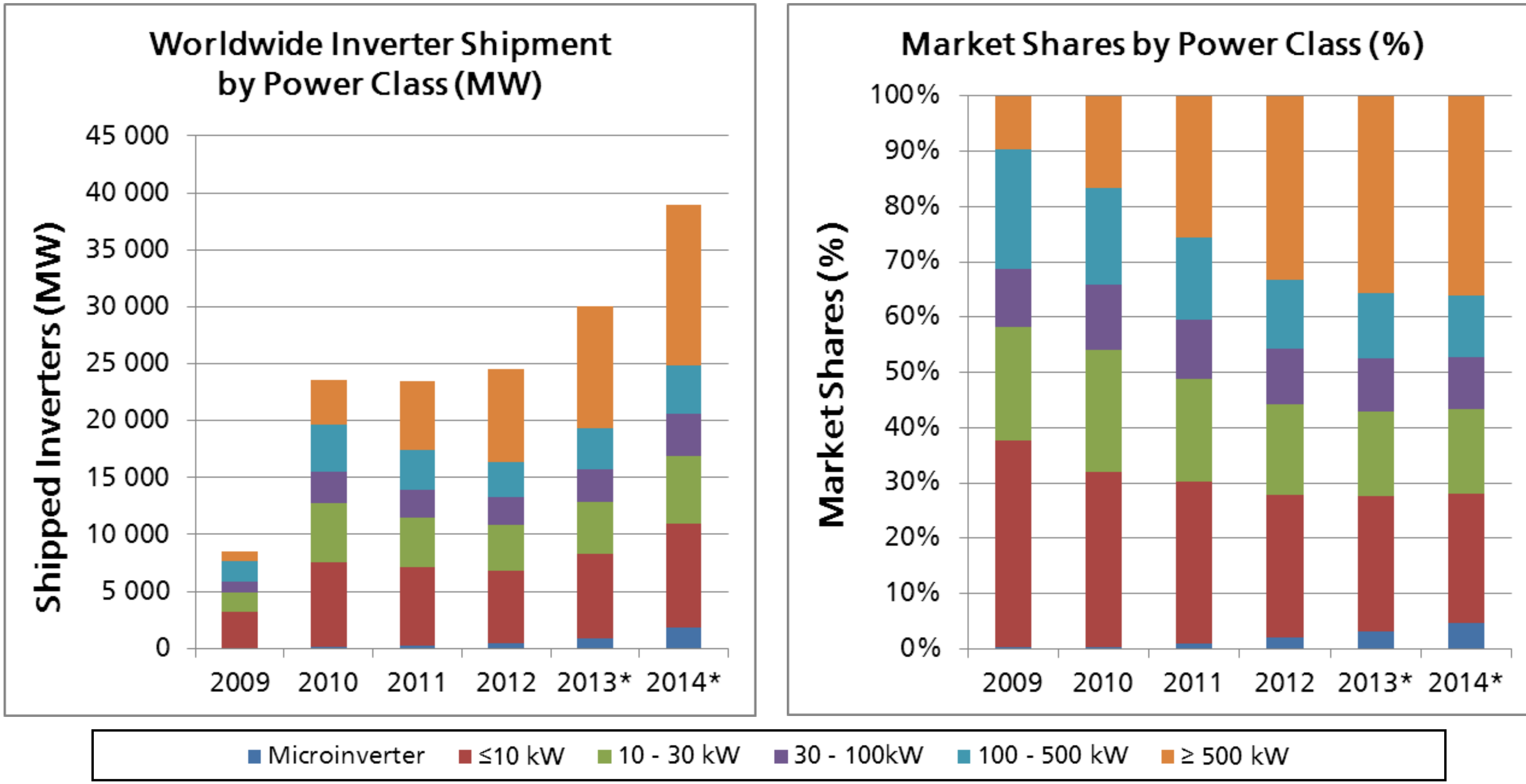
Definition and Classification
Inverter Market Share by Power Class



Data: IHS: PV Inverters – World Market Report 2013

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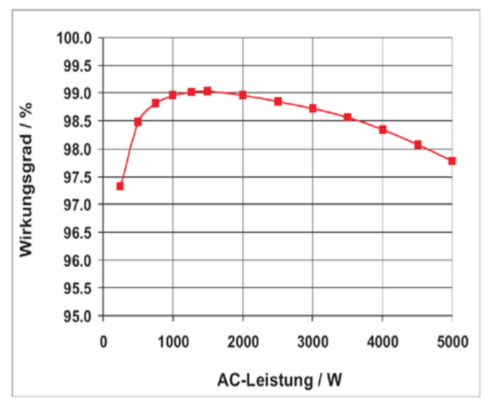
Requirements for PV Inverters
General Requirements for PV inverters

- High overall efficiency
- Cost effectiveness (costs per watt)
- Small size and lightweight
- Reliability and lifetime
- Low audible noise (not relevant for central inverters)
- Integrated monitoring / Monitoring interface / Smart phone apps
- Conformity with international standards and grid codes
- Fast reacting support
- Local content requirements for production



Sources: SMA and Fraunhofer ISE, Germany; Sunpower, USA

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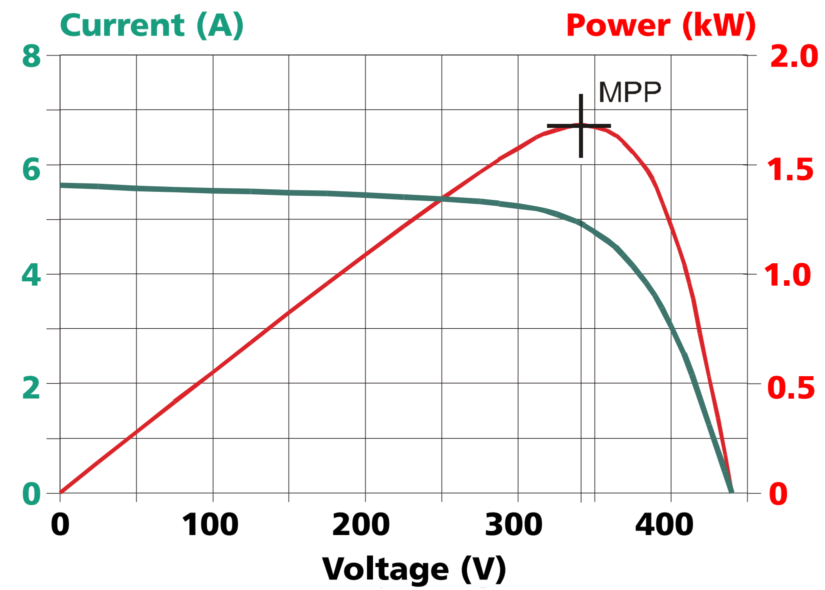
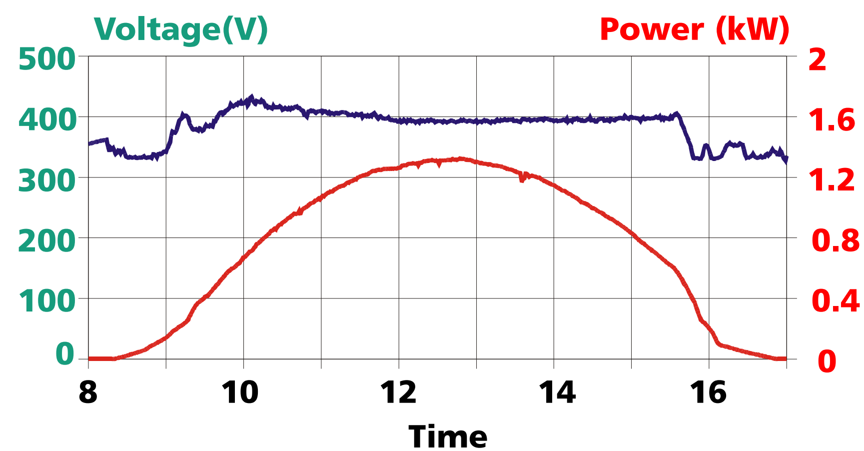
Requirements for PV Inverters
DC Input Requirements

- Large input voltage range
- Reliable MPP-Tracker (e.g. shadings, irradiance transients)
- Low DC voltage ripple (otherwise mismatch losses)
- Low common mode voltage (otherwise fault currents)
- Protections against over-voltage, over-load and over-temperature
- Low turn-on and -off thresholds with hysteresis (max. yield)
- Arc detection (required by NEC when wires inside building; not yet mandatory in Europe)





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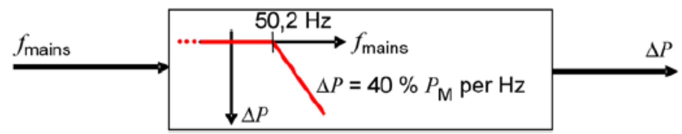
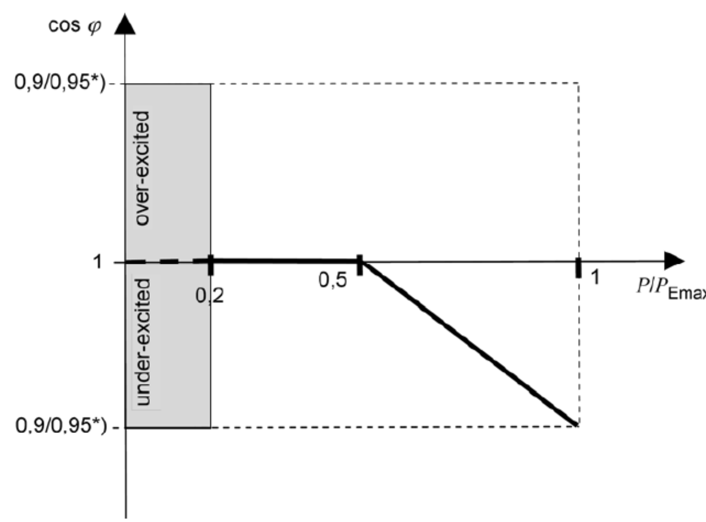
Requirements for PV Inverters
AC Output Requirements

- Sine wave output current
- Low current distortion (THD < 3%)
- Compliance to low/medium/high voltage grid codes
- Active power derating (e.g. at over-frequency)
- Reactive power control (e.g. cos(phi): 0.95_{ind} to 0.95_{cap})
- Disconnection in case of large voltage or frequency deviations (e.g. $0.80*U_0 < U < 1,15*U_0$; 47.5 Hz < f < 51.5 Hz)
- Grid stabilization during grid faults
- Anti-islanding detection



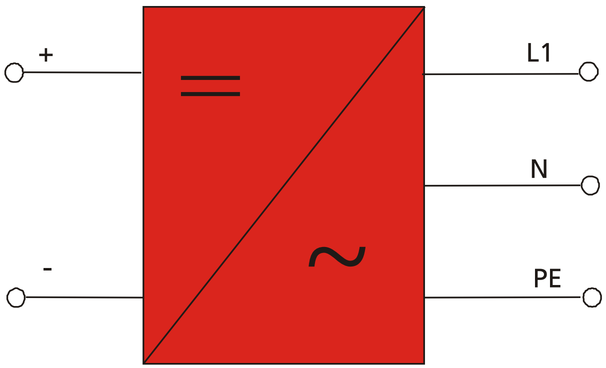
$$\Delta P = 20\, P_M \frac{50{,}2\text{ Hz} - f_{mains}}{50\text{ Hz}} \quad \text{for } 50{,}2\text{ Hz} \le f_{mains} \le 51{,}5\text{ Hz}$$

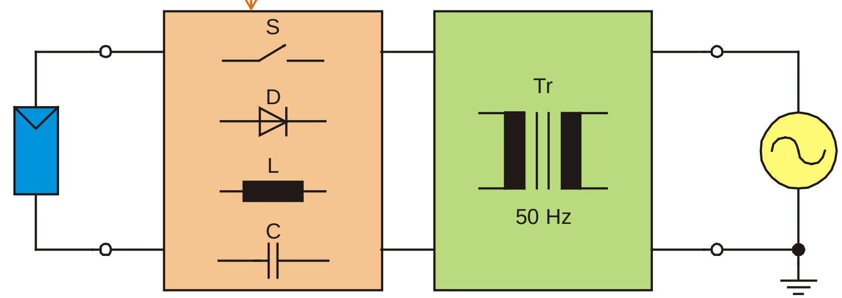


Fundamentals of Switching Inverters

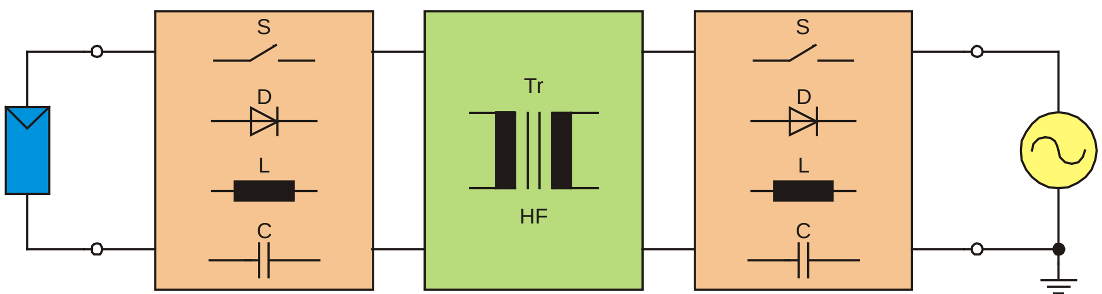
Most popular inverter circuits

- Switches (transistors)
- Diodes
- Inductors
- Capacitors

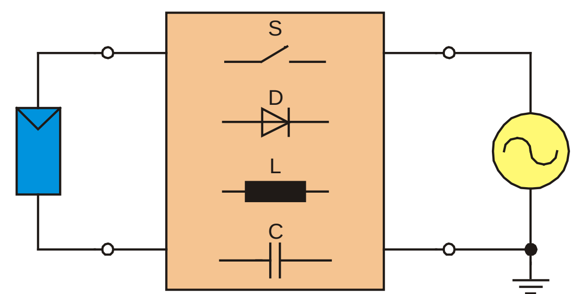




a) With 50/60 Hz transformer



b) With HF-transformer



c) Transformerless

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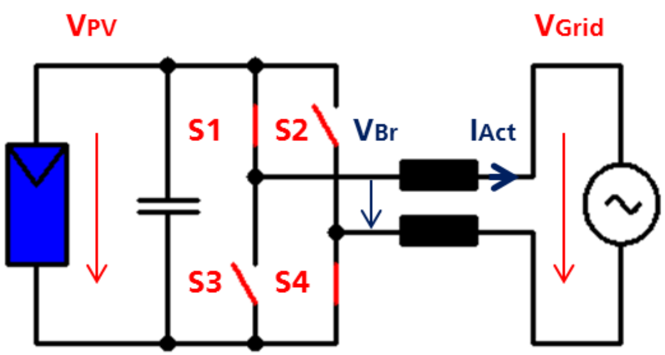
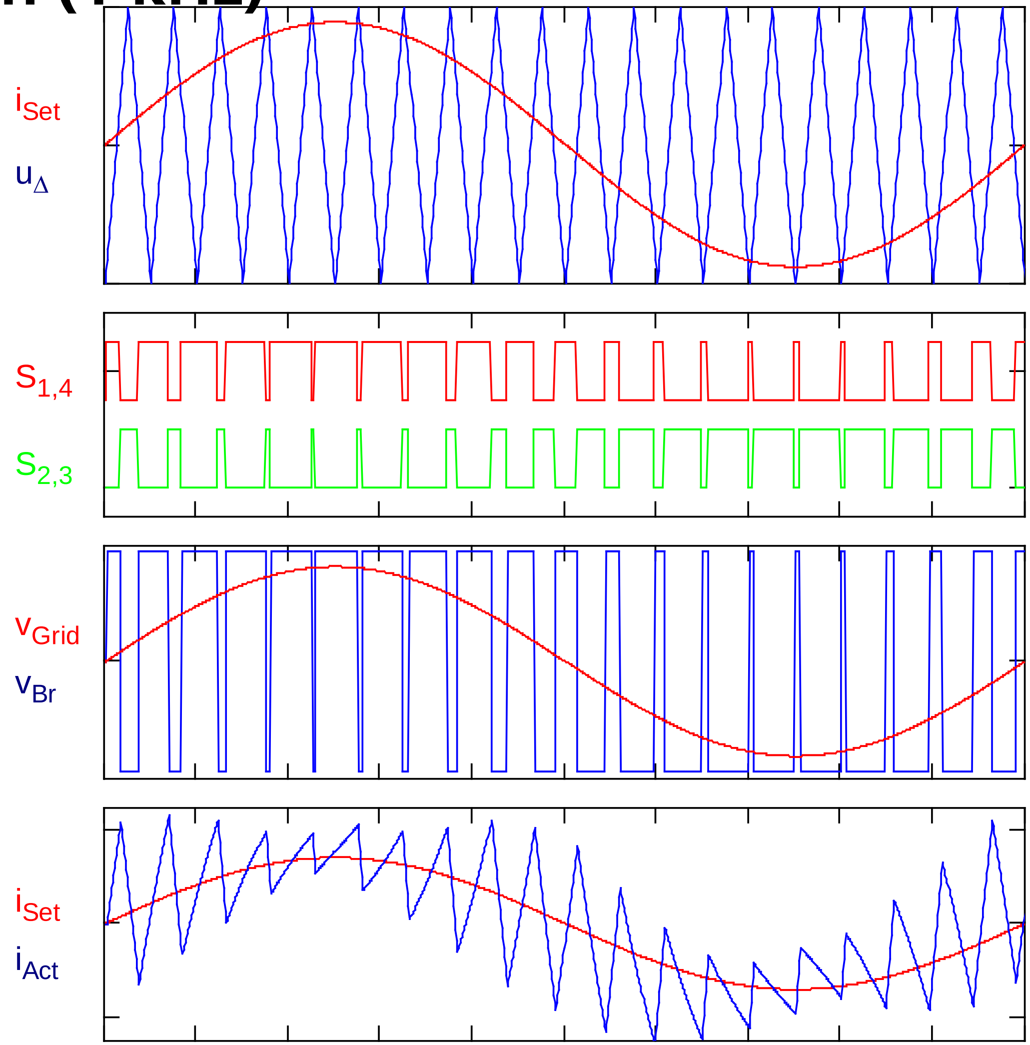
Fundamentals of Switching Inverters
Pulse Width Modulation (1 kHz)





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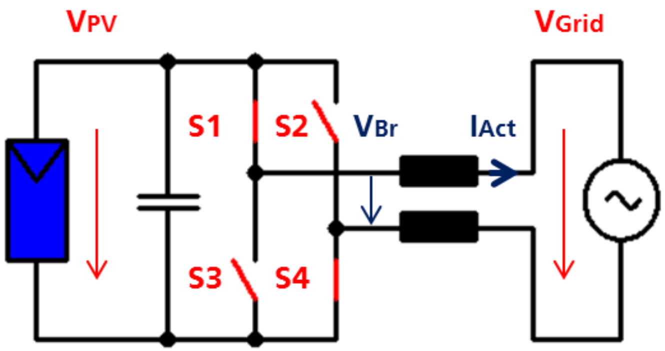
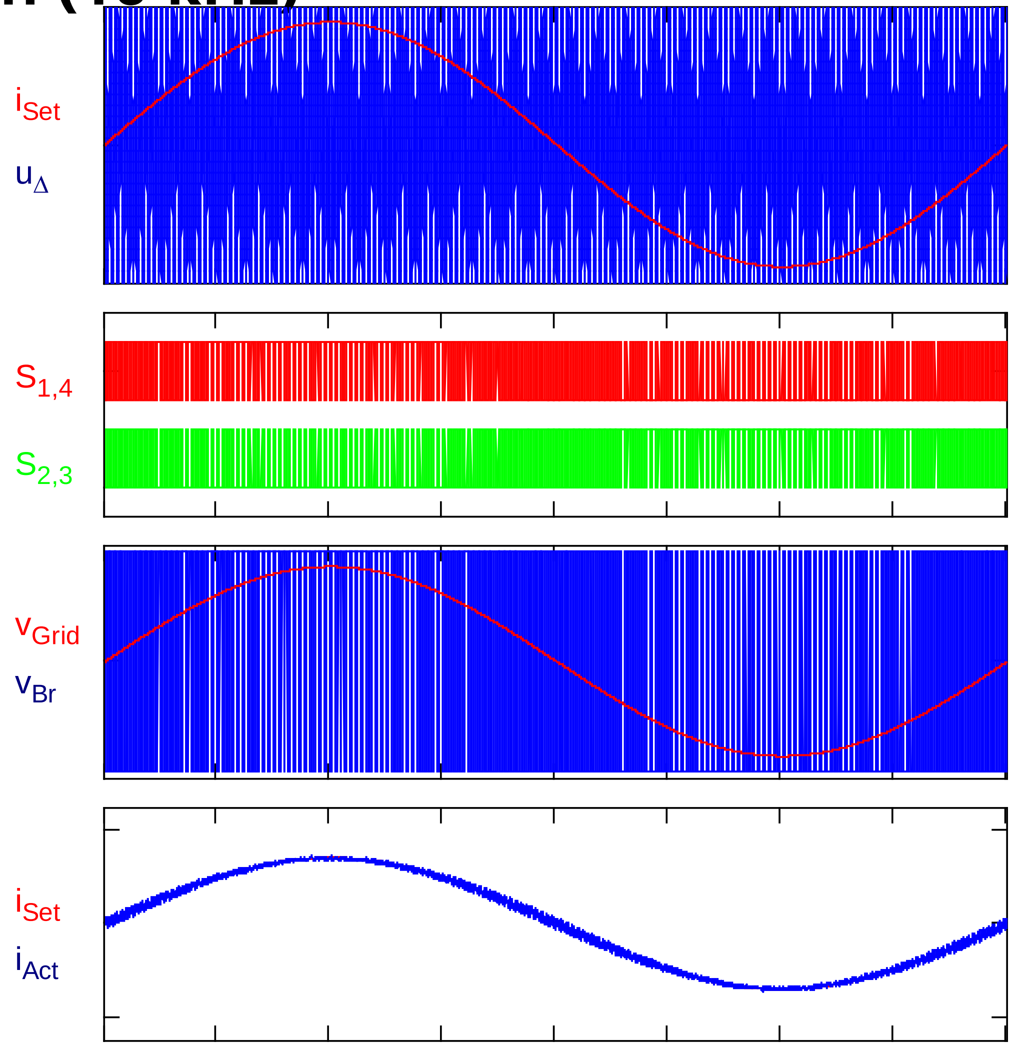
Fundamentals of Switching Inverters
Pulse Width Modulation (16 kHz)





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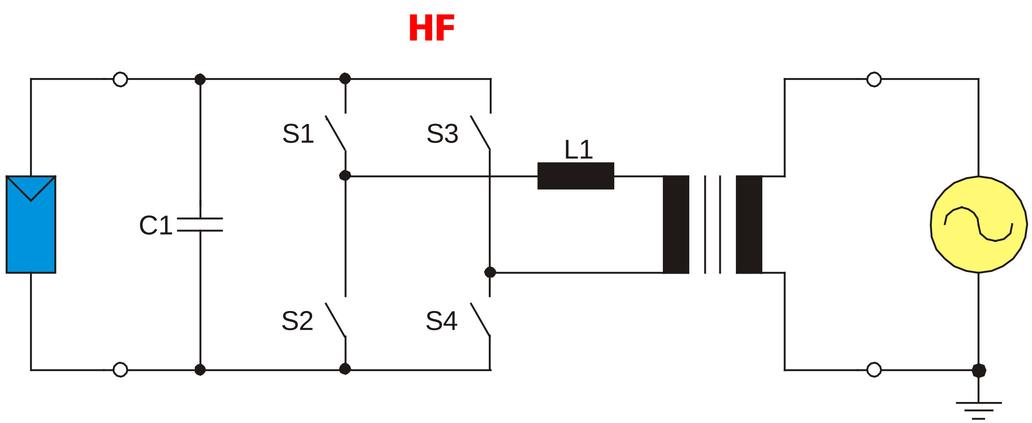
Basic Topologies

Inverter with 50/60 Hz transformer (LF-T inverter)



full-bridge inverter with LF transformer

Diehl	Platinum 2100, 2800, 3100 and 3800S (P_{DC})
G&H	POWER-TRAP® SO-1500, 2000, 2500, 3000
Ingeteam	Ingecon SunLite 2.5, 3.3 and 5 (P_{AC})
SMA	Sunny Boy 3300 & 3800 SMC 4600, 5000, 6000 and 7000HV (S_{AC})

+ Galvanic isolation
+ Wide input voltage range

- High weight (transformer)
- Low efficiency (91 … 96%)
- Not all compliant to VDE-AR-N 4105

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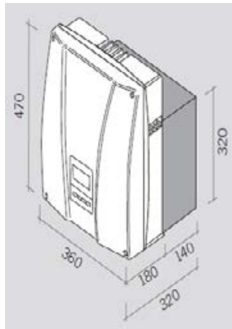
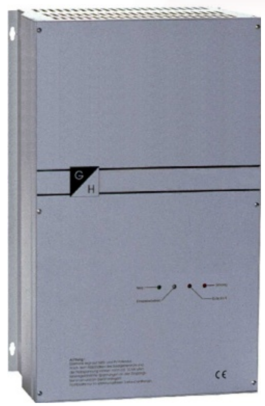
Basic Topologies
LF-T inverter





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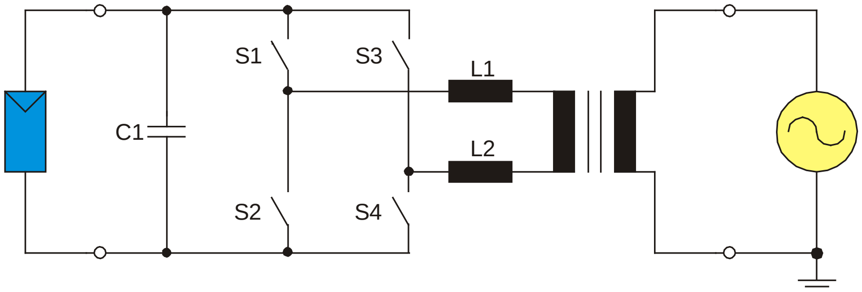
SMA	Sunny Boy 3300 & 3800 SMC 4600, 5000, 6000 and 7000HV (S_{AC})

Power-Trap uses master-slaver principle (old device). SunLite uses same platform as TL family, LF transformer located at the rear in additional box. Diehl has internal data-logger. Sunny Mini Central operate on 250 … 600 V and 7000HV goes up to 800 V_{DC}.

Basic Topologies
Micro Inverter, LF transformer



Dorfmüller DMI 150, 250

- robust
- no communication
- weight 6,3 kg
- European efficiency 87% to 90%

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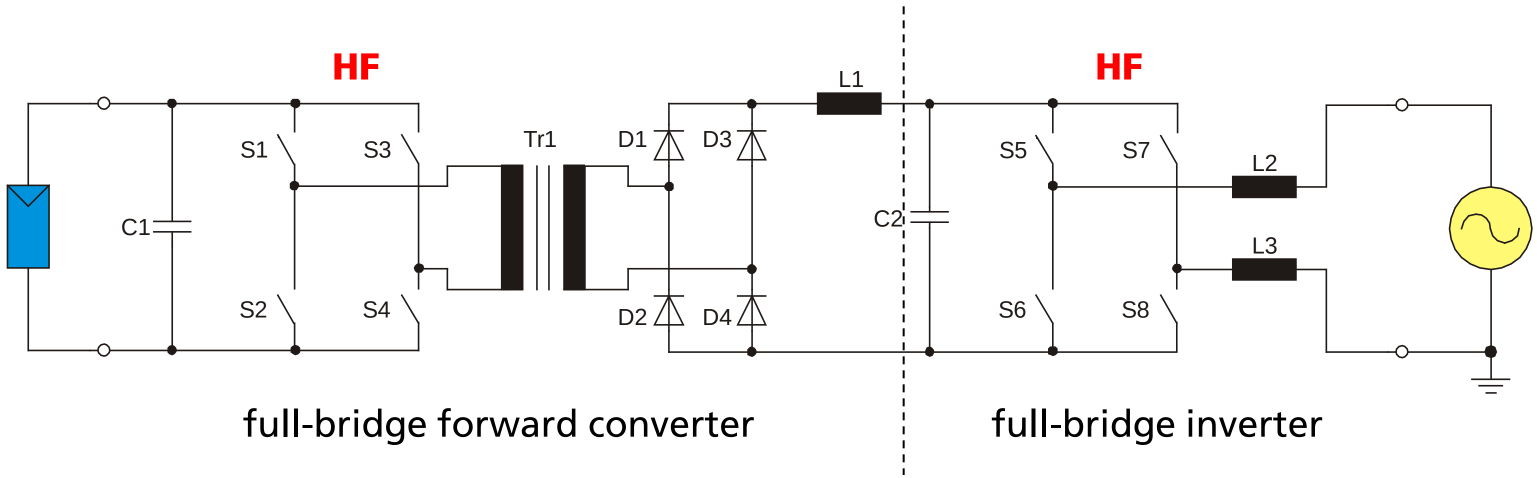
Basic Topologies
HF-T inverter with full-bridge forward converter



Fronius IG 15, 20, 30, 40 and 60 HV (P_{AC})

+ Input voltage on 150 … 500 V
+ Lightweight (12 kg / 20 kg for HV)
+ Capability of reactive power

- Two conversion stages
- High number of components
- Efficiency on 92 … 94%

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Basic Topologies
HF-T inverter with full-bridge forward converter

Fronius IG 15, 20, 30, 40
and 60 HV (P_{AC})

Different housings for indoor (IP21, 9 kg, left) and outdoor (IP45, 12 kg, middle)

Source: Fronius, Austria

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Basic Topologies
Do PV inverters really need transformers?

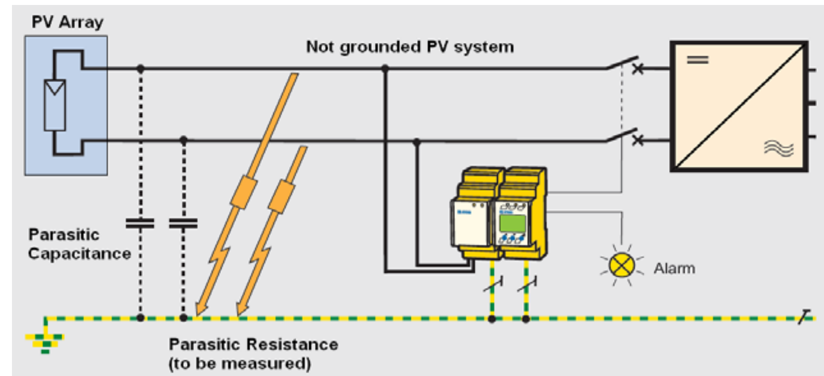
- PV modules are fully isolated through use of glass, back sheet and frame
- PV modules have safety class II up to 1000 V (similar to drilling machine, no grounding)
- Junction boxes are isolated (plastic material)
- PV modules comply to IEC 61215, IEC 61730 (conservation of electrical performance)
- PV modules use double insulated wires (double jacket for better UV resistance)
- PV modules use insulated connectors (MultiContact, Tyco …)

… no they don't!

Basic Topologies
Safety mechanisms of Transformer-Less (TL) inverters

According to VDE 126-1-1:

- Measurement of DC insulation resistance to ground (PE)
- Residual Current Detector Type B (AC+DC) to trip if step >30 mA (static limit higher due to $C_{parasitic}$)
- Limitation of DC current injection into public grid (e.g. <1% of I_N)
- Two mechanical relays in series to guarantee disconnection
- Redundant control circuits to prevent software malfunctions



Isolation Measurement, Source: Bender, Germany

RCD-Circuit

Decoupling Relays

→ TL inverters are even safer than inverters with transformer!

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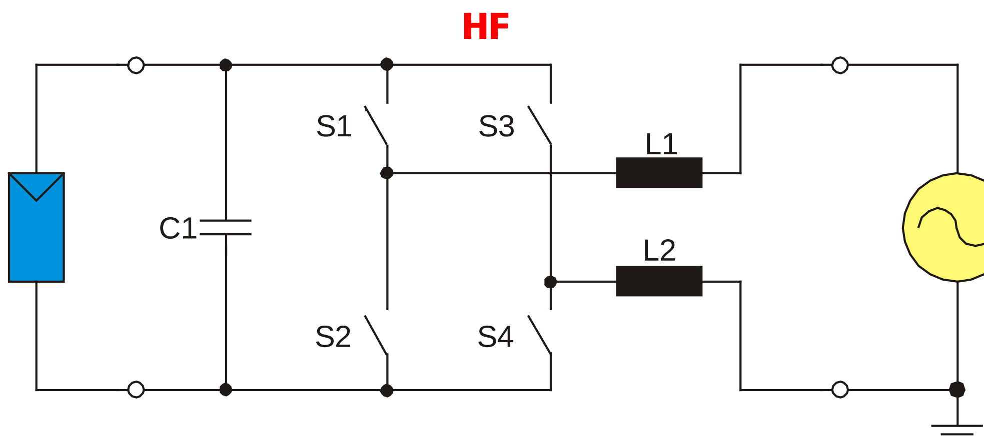
Basic Topologies
TL inverter



KACO	Powador 3200, 4400, 5300, 5500 & 6600 (P_{DC})
Santerno	Sunway™ M XS 2200, 3000, 3800, 5000, 6000, 7500 (P_{AC})
SolarEdge	SE2200, 3000, 3500, 4000 and 5000 (P_{AC})
Solutronic	SOLPLUS 25,35 50 and 55 (P_{AC})

+ Few components, small and light
+ Cost-effective and reliable
+ Efficiency on 96-98%
+ Reactive power capability

- Min. input voltage > 350 V

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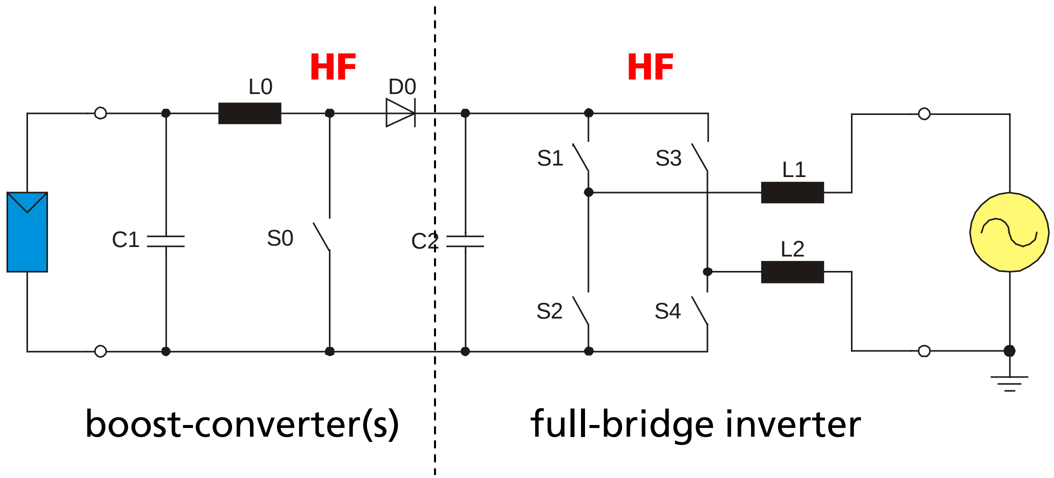
Basic Topologies
TL inverter

KACO	Powador 3200, 4400, 5300, 5500 & 6600 (P_{DC})
Santerno	Sunway™ M XS 2200, 3000, 3800, 5000, 6000, 7500 (P_{AC})
SolarEdge	SE2200, 3000, 3500, 4000 and 5000 (P_{AC})
Solutronic	SOLPLUS 25,35 50 and 55 (P_{AC})

Powador uses hardware downsizing and allows ‘power-boost’ (9 kHz switching frequency) for 5300 *supreme* version. SolarEdge inverters are designed to operate with module maximizers (DC/DC converters).

Sources: KACO, Solutronic, Germany; Santerno, Italy: SolarEdge, Israel.

Basic Topologies
TL inverter with boost-converter(s)



Chint Power Systems :	SCE Series
Ingeteam :	Sun Lite TL Series
Kostal:	Piko Series
Power-One:	PVI-TL-OUTD Series
Solutronic:	SOLPLUS Series
SMA:	SB1300, 1600, 2100 TL
Sputnik:	SolarMax 2000, 3000, 4200 and 6000S
Steca:	StecaGrid 300/500

+ Wide(r) input voltage range
+ Efficiency on 94 … 97%
+ Reactive power capability

- Additional components
- Larger size and higher weight
- Lower efficiency

Basic Topologies
TL inverter with boost-converter(s)

Chint Power Systems :	SCE Series
Ingeteam :	Sun Lite TL Series
Kostal:	Piko Series
Power-One:	PVI-TL-OUTD Series
Solutronic:	SOLPLUS Series
SMA:	SB1300, 1600, 2100 TL
Sputnik:	SolarMax 2000, 3000, 4200 and 6000S
Steca:	StecaGrid 300/500

CPS SCE 4.6, Solutronic SSOLPLUS 40S2 and Power-One PVI-TL-OUTD family offer 2 MPP-Trackers. SolarMax is very lightweight (13 kg). StecaGrid has input voltage on 45 … 230 V and uses master-slave principle.

Sources: Chint Power Systems, China; Ingeteam, Spain; SMA, Solutronic and Steca, Germany; Sputnik, Switzerland; Power-One, USA

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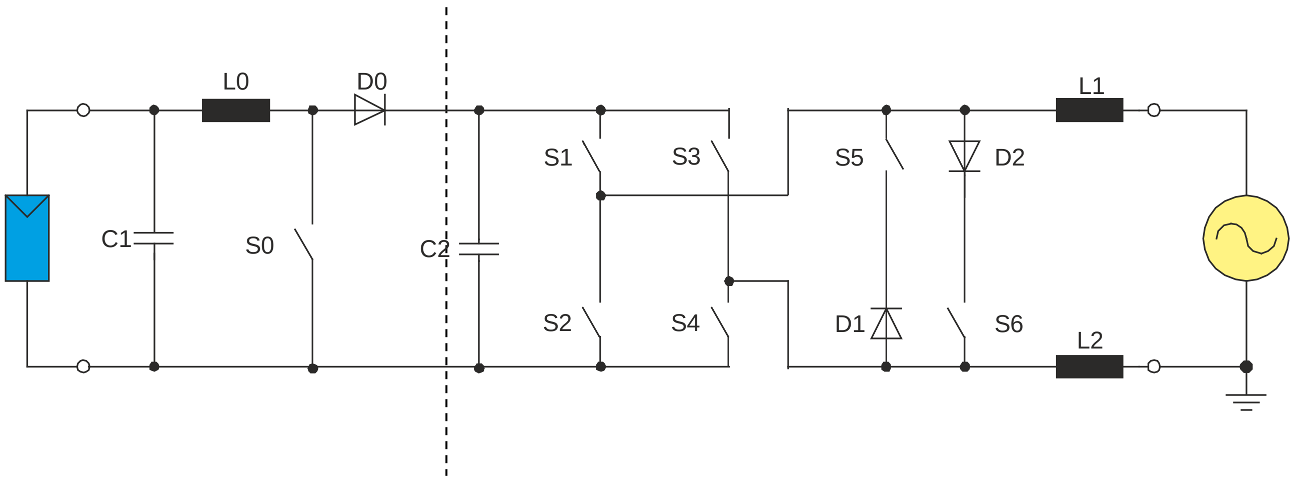
Basic Topologies
TL inverter with HERIC® topology



1 … 2 boost-converters
(not for Sunways)

full-bridge inverter with HERIC®

Sputnik:
SolarMax 2000
3000, 4000, 4600
& 5000P

Sunways
NT 2500, 3000,
3700, 4200 and
5000

+ Input voltage on 100 … 600 V
+ Higher efficiency 97 … 98 %
+ Lightweight (17 … 19 kg)
+ Reactive power capability

- Add. semiconductors and control

HERIC = Highly Efficient & Reliable Inverter Concept

Patents: EP 1 369 985 B1, US 7 046 534 B2
Patent Application: DE 102 21 592 A1

Basic Topologies
TL inverter with HERIC® topology

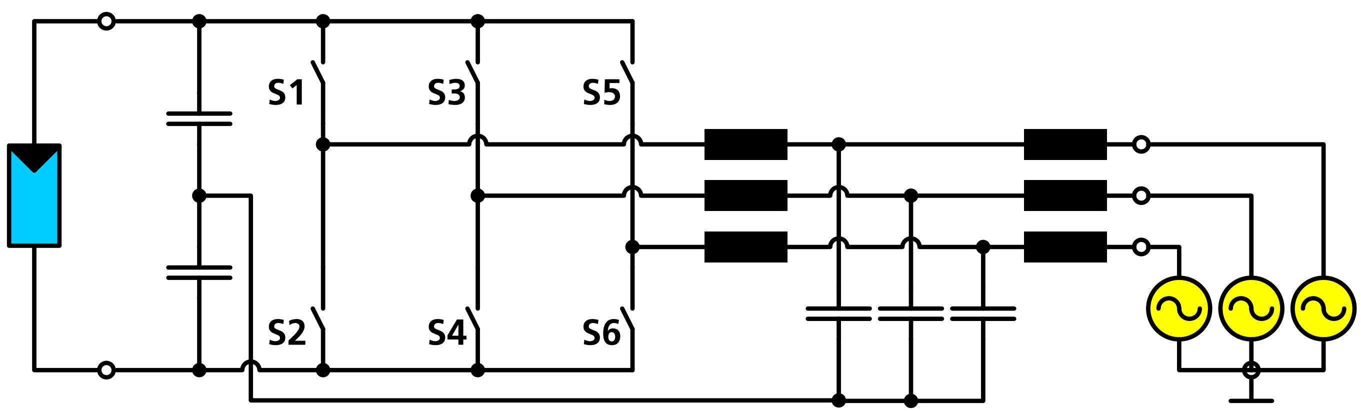
Sputnik:
- SolarMax 2000 3000, 4000, 4600 & 5000P

Sunways
- NT 2500, 3000, 3700, 4200 and 5000 (all w/o booster)

Source: Sunways, Germany; Sputnik Engineering, Switzerland

Basic Topologies
3-Phase Inverters

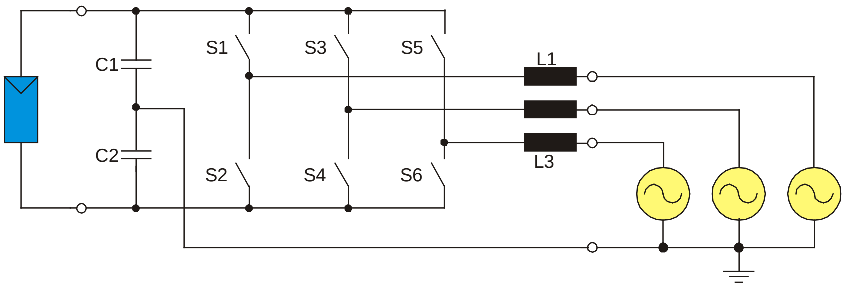
- Symmetrical feed-in in all three phases
- Required for devices with > 4.6 kVA (Germany)
  → (Multi-)String Inverters, Central Inverters
- Constant power flow
  → less input capacitance required
- Cost effective

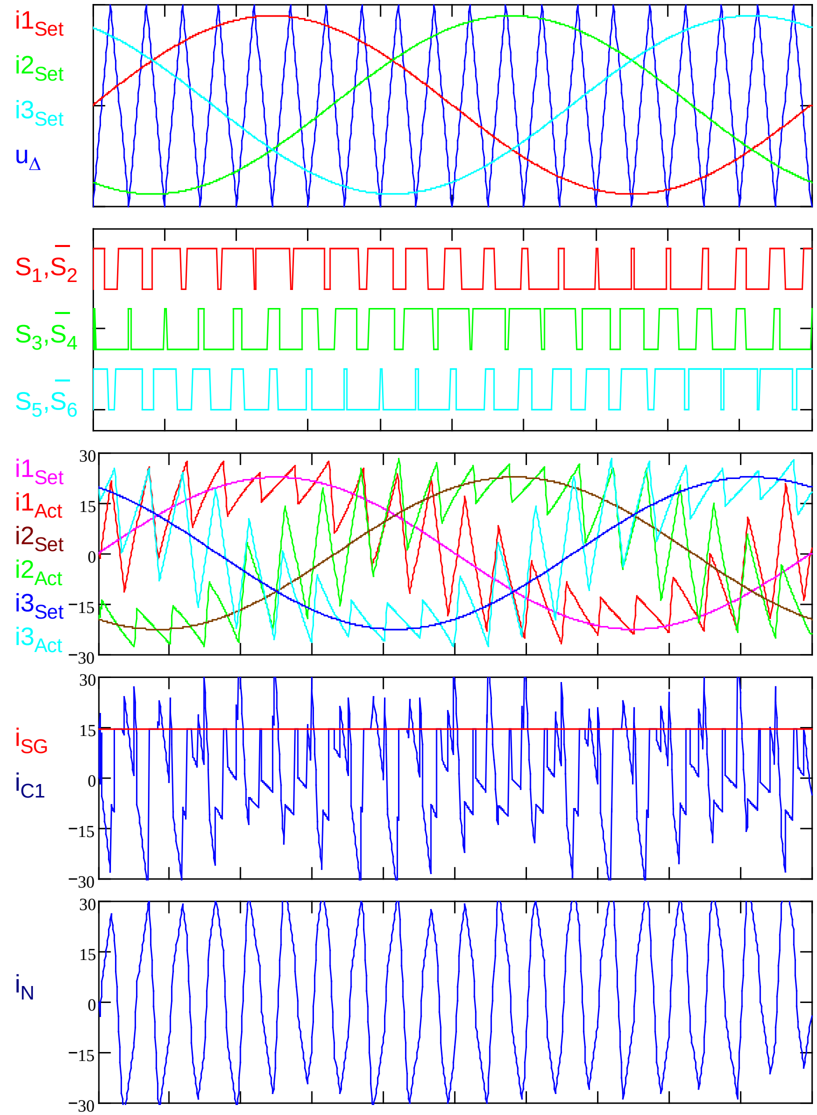


Basic 3-phase topology: B6-bridge

Basic Topologies
Bipolar switching (B6-bridge)

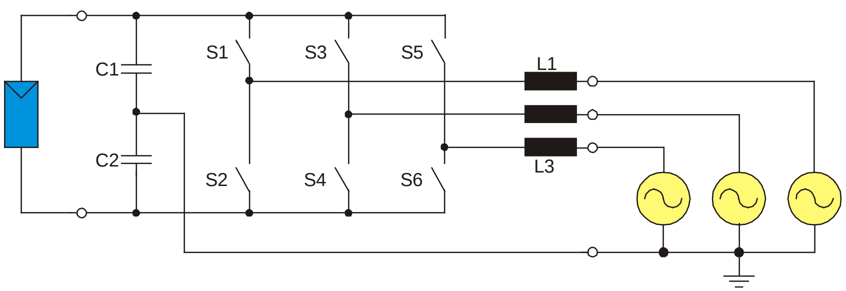
switching frequency 1 kHz

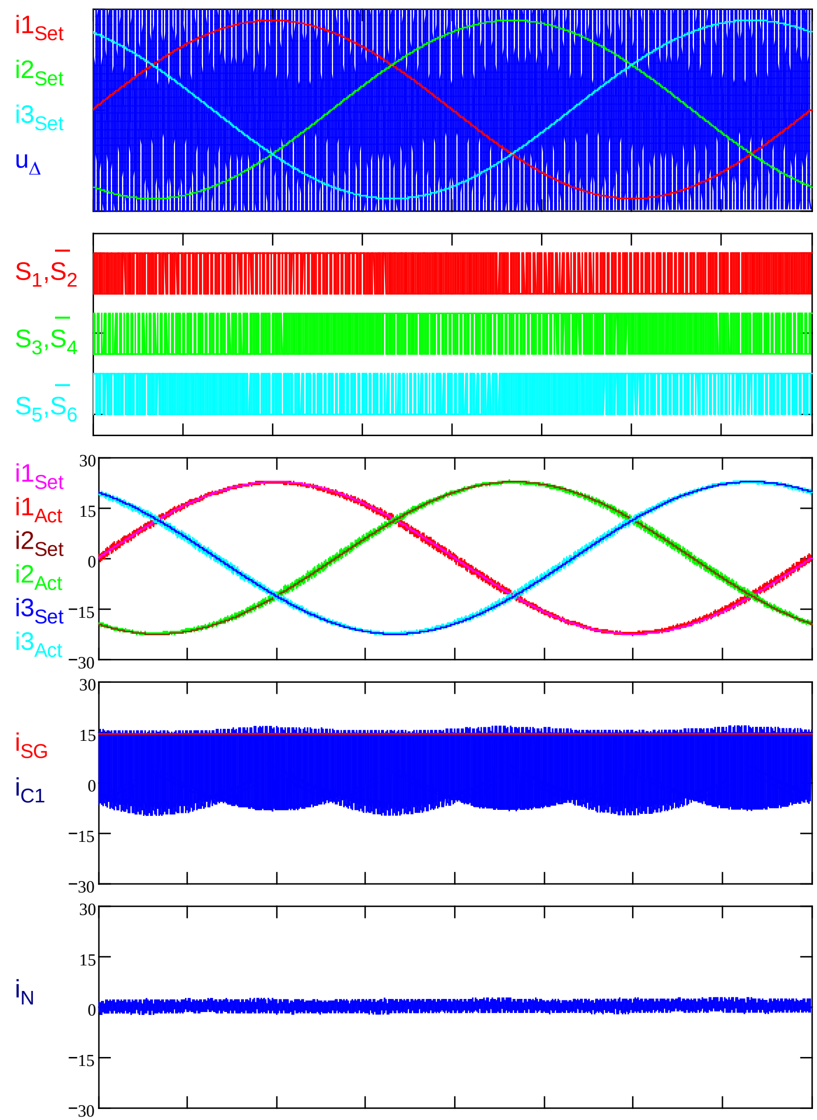




Basic Topologies
Bipolar switching (B6-bridge)

switching frequency 16 kHz





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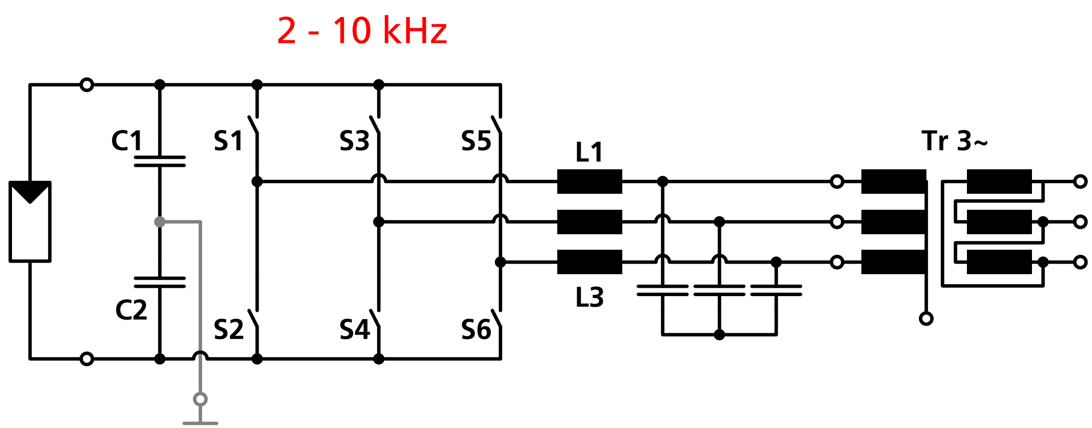
Basic Topologies
Examples for 3ph-inverters

Kostal	PIKO 4.2, 5.5, 8.3, and 10.1
SolarFabrik	Convert 4T, 6T, 8T and 10T
Steca	StecaGrid 8000, 9000 and 10000 3ph

Sources: Steca, Kostal Solar Electric, Germany

Basic Topologies
Central Inverters Based on B6-Bridge



AEG: Protect PV.250/500
Bonfiglioli Vectron: RPS 450
Kaco: XP200 … 350
Refu: Refusol 100k … 630k
Santerno: TG 600 … 800
Siemens: SINVERT PVS500…700
SMA: Sunny Central
Sputnik: Solarmax C Series
Voltwerk: VC110 … VC300
Gefran: Radius Inverter
…

+ robust, reliable
+ high power
+ efficiency up to 98%
+ PV generator can be grounded

- Low switching frequencies
- Jumping potential on AC-side
- No parallel connection of multiple inverters on AC-side

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Basic Topologies
Central Inverters Based on B6-Bridge

Sources: SMA, Voltwerk, Kaco

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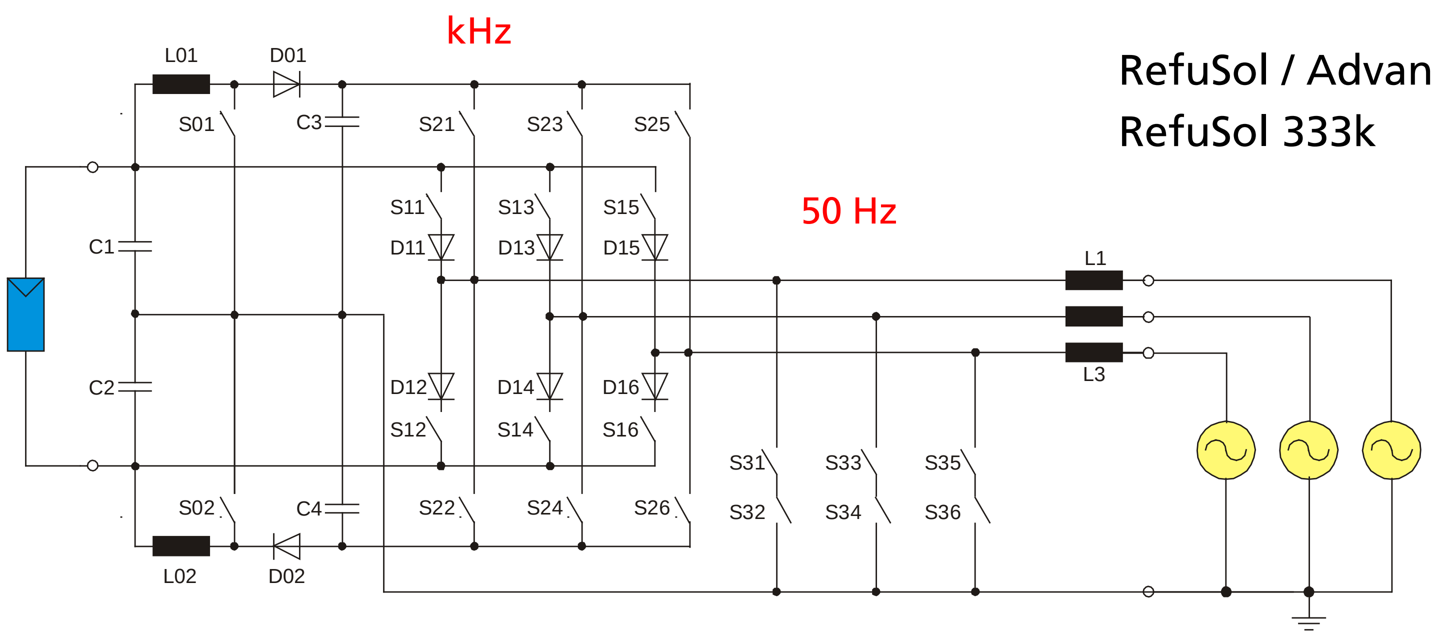
Basic Topologies
Five level TCC with symmetric boosters



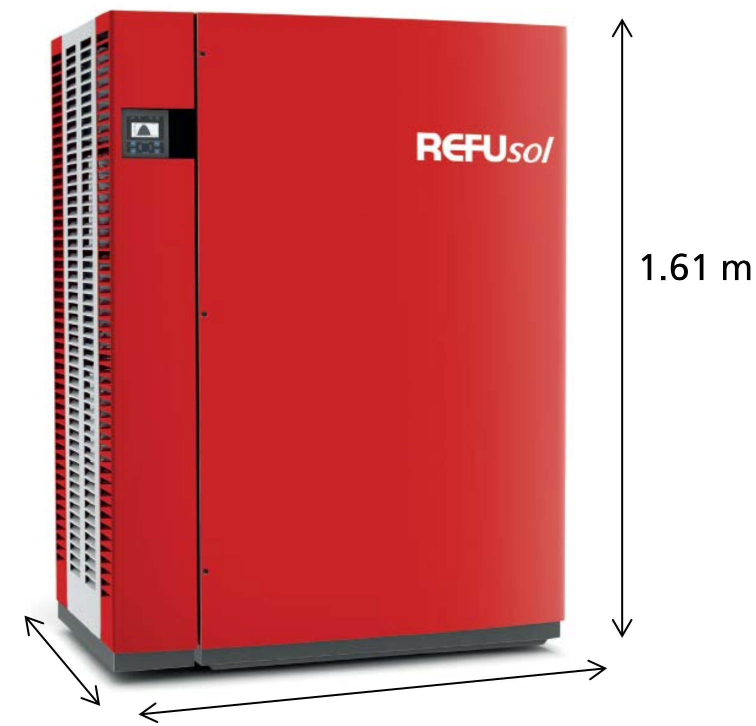
RefuSol / Advanced Energy:
RefuSol 333k

- \+ input voltage range up to 1400 V
- \+ Output voltage: 690 V
- \+ efficiency > 98%
- \+ Very compact

- \- many components
  (28 power semiconductors)
- \- complex control

Patent: DE 10 2006 010 694 B4

Basic Topologies
Five level TCC with symmetric boosters



RefuSol 333K	
nom. power	333 kVA
max. DC-voltage	**1500 V**
AC-voltage	690 V
no. of MPPT	1 (3 /MVA)
weight	0.85 t (2.6 t/MVA)
volume	1.6 m³ **(4.8 m³/MVA)**
type of protection	IP 65
efficiency	98.5%
weighted effiencies	98.2% (EU) -% (CEC)
Cooling	Forced air

Source: www.refusol.de

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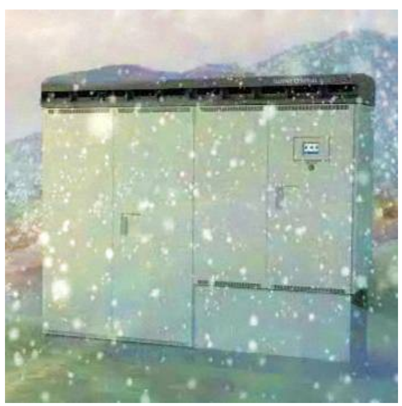
Basic Topologies
Outdoor Cabinets





- Type of protection: IP65
- Outdoor installation
- No additional buildings for inverters
- Minimizing footprint, resources and costs
- No heavy load transportation
  → remote places
- Use of standard compact stations (transformer, MV switch gear)

Sources: www.refusol.de, www.aesolaron.com, www.satcon.com, www.sma.de

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Basic Topologies
Inverter Stations

- Power up to 2.5 MW
- Station includes pre-assembled
  - Inverter(s)
  - Transformer(s)
  - Medium-voltage switch gear
- No additional buildings required
- Types
  - Concrete Stations
  - Container Station

Sources: www.kaco-newenergy.com, www.padcon.com

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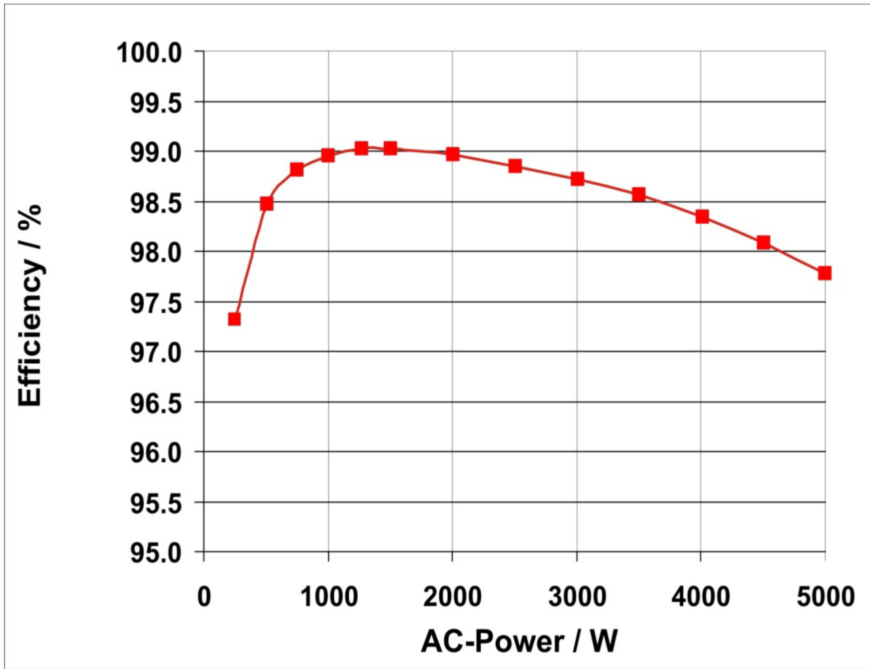
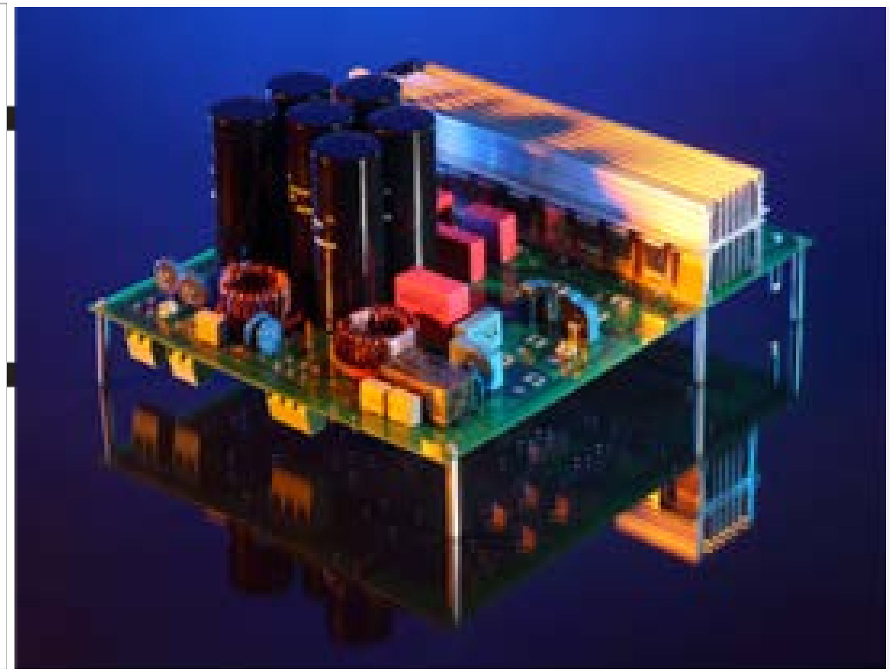
Efficiency
PV Inverter with SiC Transistors





+ 99% Efficiency
+ Small heatsinks
+ Passive cooling

solar awards 2009

- Availability of SiC-transistors
- Costs of SiC

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Efficiency

Efficiency Range for Single-Phase Inverters

Transformer-less, unipolar, with SiC transistors

(HERIC, H5, H6, 3-level)

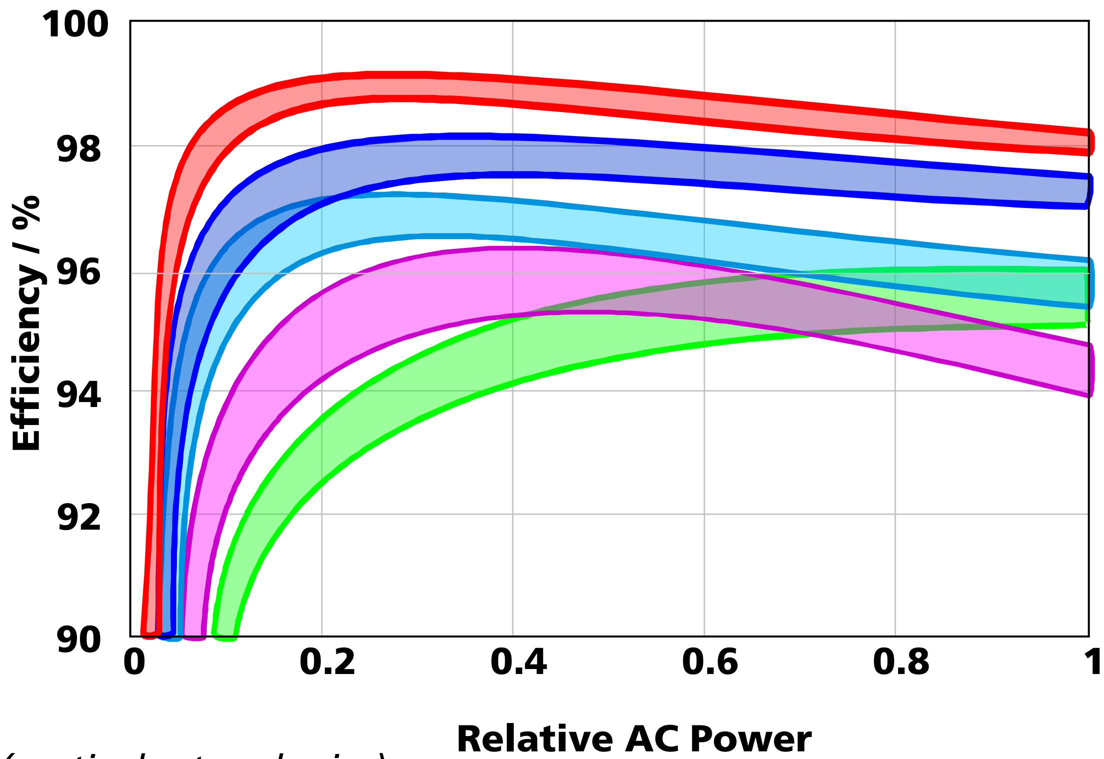
Transformerless, unipolar (HERIC, H5, H6, 3-level)

Transformer-less, bipolar

(full-bridge)

HF Transformer (16 kHz)

LF Transformer (50/60 Hz)



NB = Exceptions do not fit the rule (particular topologies)
Efficiency range of a single-phase 5 kW inverter with 16 kHz switching frequency

Development Trends for PV Inverters

Weight – Efficiency – Costs

- Transformerless inverters
- Highly efficient special topologies
- Multi-level topologies
- Higher switching frequencies
- Higher Voltages
- New semiconductors
- Higher dynamic controllers

Reliability – Lifetime

- Learning from after-sales
- Smarter designs without over-sizing

Generator and user friendliness

- Diagnostic functions
- Multi-string with separate MPPTs
- Fast interfaces
- Yield control: PC and smart phone software
- Easy to maintain

Grid compliance

- Active filtering (power quality)
- Fault Ride Through
- P- and Q- control

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Utility-Scale PV Power Plants

Example:

Solarpark Waldpolenz, Germany

Power: 40 MWp
Area: 110 ha

Constructed: 2007/2008

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Utility-Scale PV Power Plants
Top-6 (Power)

Power	Location	Description	Commis sioned
250 MW	USA, Yuma County, AZ	Agua Caliente Solar Project I	2012
214 MW	India, Charanka	Charanka Park, Patan district PV power plant	2012
200 MW	China, Golmud	Golmud PV power plant	2011
166 MWp	Germany, *Meuro*	Solarpark Meuro	2011-2012
150 MW	USA, Sonoran desert, AZ	Mesquite Solar I	2011-2012
145 MWp	Germany, Neuhardenberg	Solarpark Neuhardenberg	2012

Source: PV power plant ranking www.pvresources.com (18/05/2013)

- PV Power Plants up to 250MW are already realized
- Projects >>100 MW are under construction
- Large-scale power plants have been installed in more than 30 countries
  → global issue
- Future projects will not require FITs*
  → PV power plants pay-off!

*) http://www.photon.info/photon_news_detail_en.photon?id=76664

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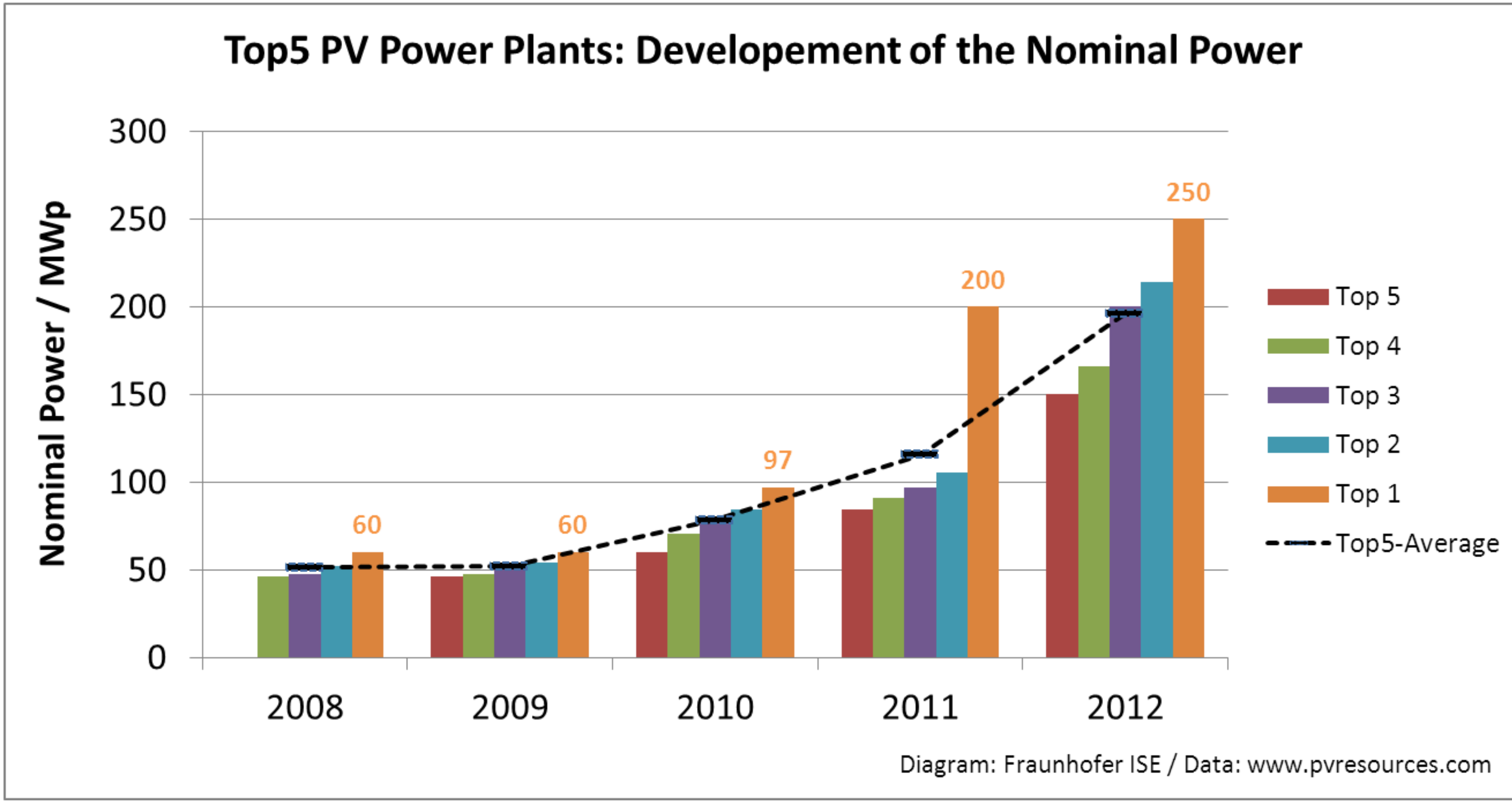
Utility-Scale PV Power Plants
Development of Top-5 PV Power Plant



Utility-Scale PV Power Plants
Characteristics and Requierments

5 MW PV Power Plant "Dürbheim"
Photo: M. Buhlinger

- Utility-scale power plants are investment-driven
- PV power plants:
  - fit well into the utilities' generation systems
  - can deliver expansive peak-power
  - must be controllable by the utilities
  - play a crucial role in the electricity networks
  - must participate in the grid stabilization process

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AGENDA

- PV Inverter Technology
  - Definition and Classification
  - Principle Requirements
  - Basic Topologies
  - Safety Issues and Transformerless Inverters
- Grid Integration
  - Background
  - Today’s Requirements and Experiences
  - Future Challenges

Background
Requirements for Selling Inverters

Product

Requirements

- National and international standards
- Legal regulations for feed-in tariffs
- Grid codes and technical guidelines

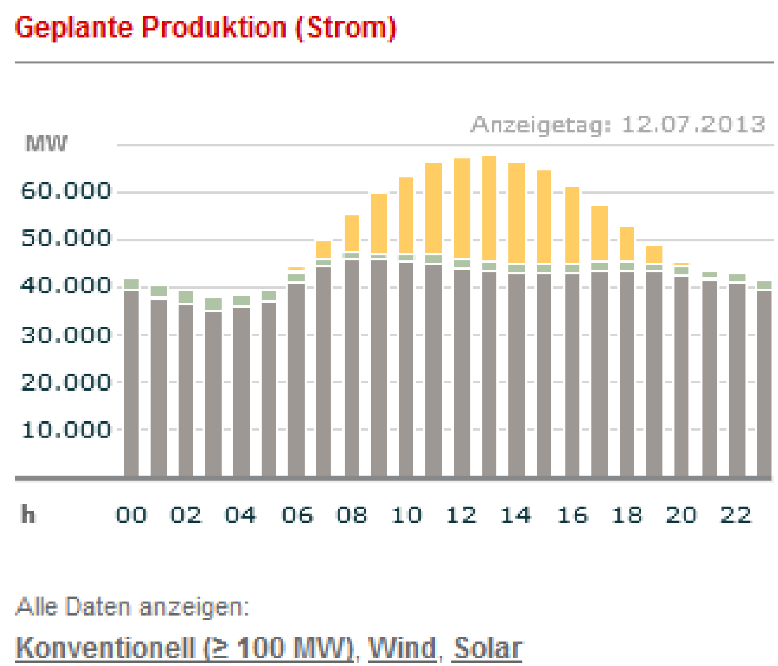
Market

Background
Why are new grid codes necessary?

- Strong expansion of renewable energies
- Replacement of conventional power plants (synchronous generators) by power electronics
- Temporarily high share of renewables
- Renewables already play a crucial role in the networks

→ Renewables must participate in the grid stabilization process

→ Grid codes should regulate their electrical properties



Germany (12.7.2012):
Peak-power is generated by PV power plants
Source: www.transparency.eex.com

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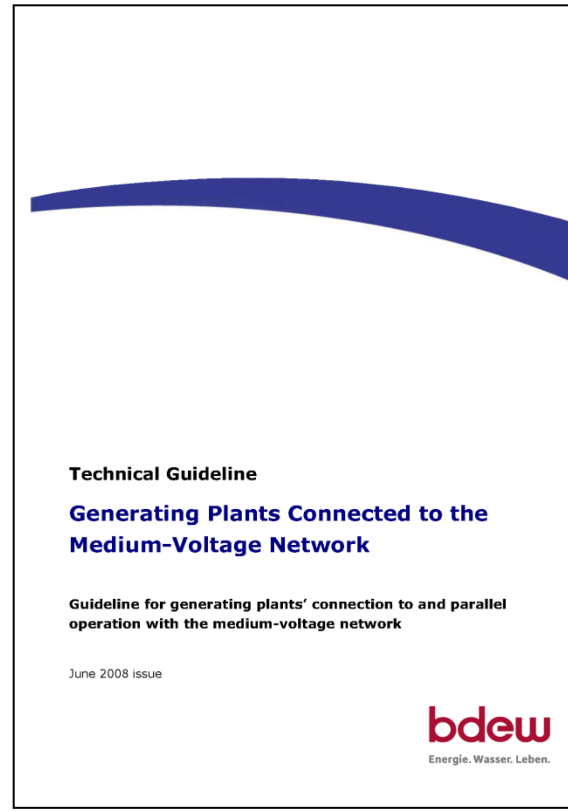
Today's Requirements
The German BDEW Medium Voltage Guideline

- German BDEW Medium Voltage Guideline (2008) requires:
  - Active and reactive power control
  - Limits for harmonics and flicker
  - Network/plant protection
  - Low Voltage Ride Through (LVRT) and Dynamic Network Support

  → PV power plants must show a similar behavior like conventional power plants
- Certificates are required
- In the meantime: Many international guidelines similar to BDEW MV Guideline, e.g. in Spain, Italy, China, …



Technical Guideline

Generating Plants Connected to the Medium-Voltage Network

Guideline for generating plants' connection to and parallel operation with the medium-voltage network

June 2008 issue

bdew

Energie. Wasser. Leben.

German BDEW Medium Voltage Grid Code, June 2008

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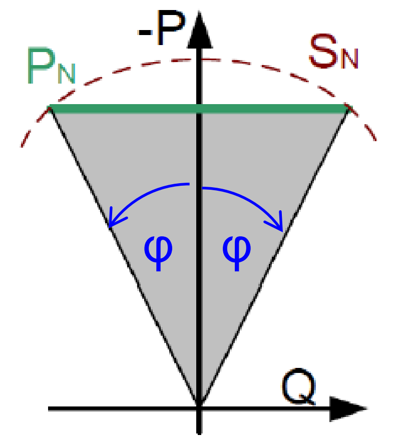
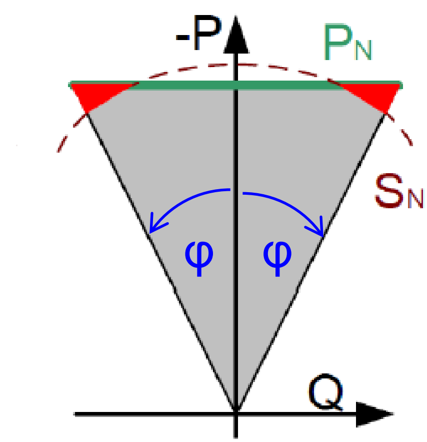
Today’s Requirements and Experiences
Active and Reactive Power Control

- Requirements:
  - Required range for reactive power (Q): cos φ = 0.95_{ind} … 0.95_{cap}
  - Inverters should provide Q(V)- and cosφ(P)-characteristics
  - P-reduction on demand of the utility
  - P-reduction at over-frequencies





- Experiences:
  - Q-Requirements lead to oversizing of the inverter
  - cos φ - accuracy requirements are challenging
  - P- and Q-control is not a principle issue for PV-inverters

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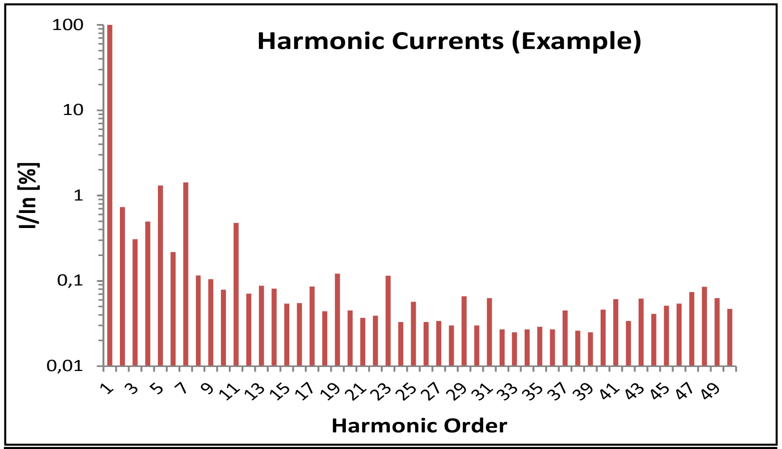
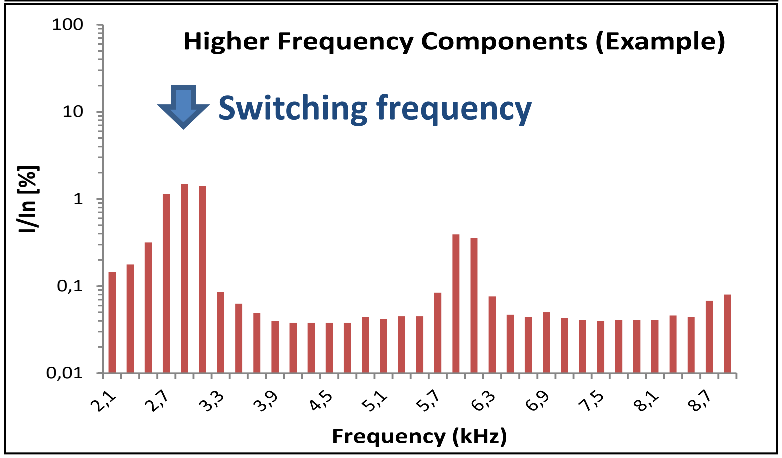
Today's Requirements and Experiences
Limits for harmonics and flicker

- Measurements:
  - Flicker
  - Harmonics of the injected current up to 9 kHz
  - Limits depend on the short-circuit power of the point of interconnection (POI)
- Experiences:
  - Flicker is not a problem for PV inverters
  - Problems with low-order harmonics (filter resonance) are unusual
  - Switching frequency is dominant

    → might lead to a limitation of the installable power for certain POIs





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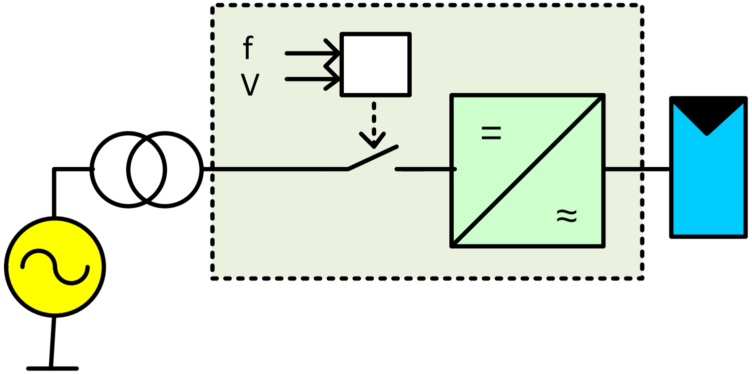
Today's Requirements and Experiences
Network/plant protection

- Requirements:
  - Protective disconnection in the event of:
    - Over-/under-frequency or
    - Over-/under-voltage
- Experiences:
  - Protective disconnection functionality typically integrated into the inverter control

→ Type-testing inside the lab possible

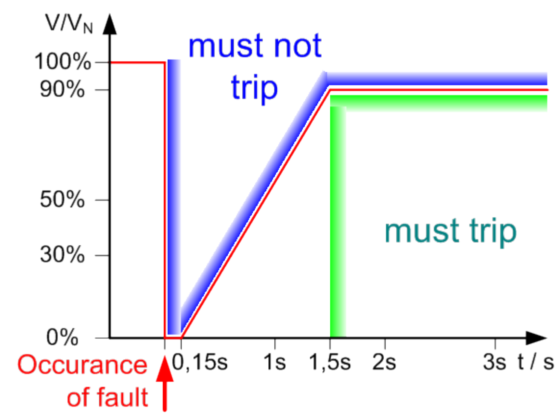
→ Periodical rechecks in the field can be difficult



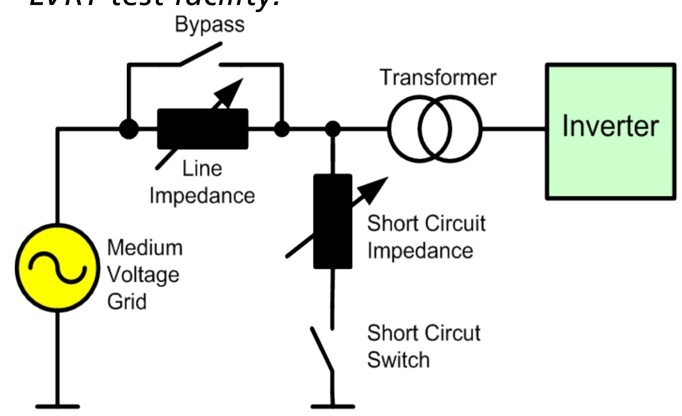
Today’s Requirements and Experiences
Low Voltage Ride Through (LVRT)

- Background:
  - Inverters must stay grid connected during short-term faults
  - Avoidance of unintentional disconnections of large amounts of feed-in power
    → may lead to a network collapse
- Requirements:
  - Inverters must proof their LVRT-capability for:
    - Voltage dips with variable depth & duration
    - Symmetrical and unsymmetrical faults
    - Full load and part load operation
  - Standard LVRT test facility:
    Inductive voltage divider (IEC 61400-21)

LVRT boundary line:

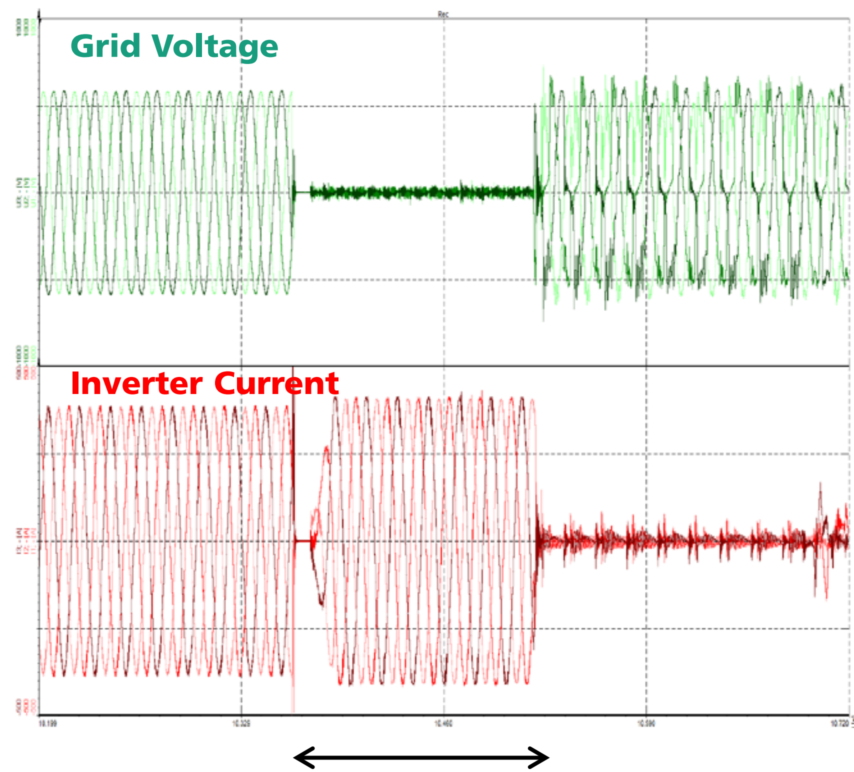


LVRT test facility:



Today's Requirements and Experiences
Dynamic Network Support

- Background:
  - Renewables should support the faulty grid by injecting reactive current
- Requirements:
  - Fast control of reactive current depending on the grid voltage
- Experiences:
  - Setting the required reactive current is no general problem
  - Typically no dynamic network support for unsymmetrical faults so far



Grid Fault Event (150 ms)

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Future Challenges
Full Grid Integration

- Future Demands:
  - Full dynamic network support also for unsymmetrical faults → negative sequence controller required!
  - Power electronics can react within milliseconds (no inertia)
    - Useful definition of settling times for P- and Q-control
    - Synthetic inertia required?
  - Grid stabilization vs. active anti-islanding
  - Power quality functionalities, active filtering
  - Black-start capability
- Conclusions:
  - Transformation of energy system is in progress
  - Renewables must participate in grid control and stabilization
  - Full capabilities of power converters must be used to control the future grid supplied through 100% power electronics!

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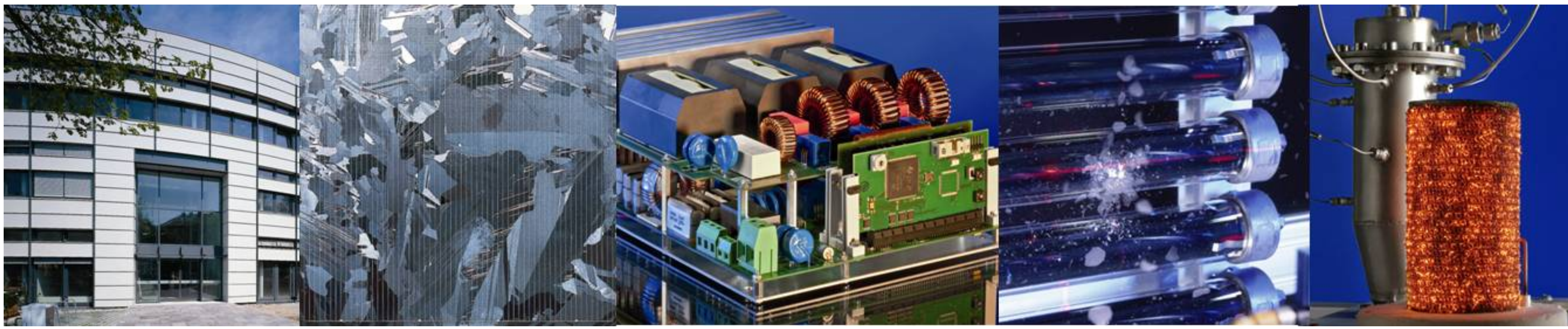
Thank you for your attention!



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