PV INVERTER TECHNOLOGY AND DEVELOPMENTS

SMA Solar Technology AG

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THIS LITTLE LUMP OF SILICON CAN DO AMAZING THINGS

› 2000 times less material to generate the same amount of electricity compared to coal

WHO OR WHAT IS SMA?

Best

efficiency worldwide

99%

More than 1,000 professionals in R&D

Global manufacturer of inverters

Founded in Germany 1981

Over 36GW SMA installed globally

Sales 2015 (exp) €900 million

1 in 3 inverters on the planet is SMA

1 in 4 inverters in Australia is SMA

WHAT DOES SMA STAND FOR?

System Mess Anlagentechnik

Computer Control +

Measuring Technology +

Plant System Technology

1981

1988

1990

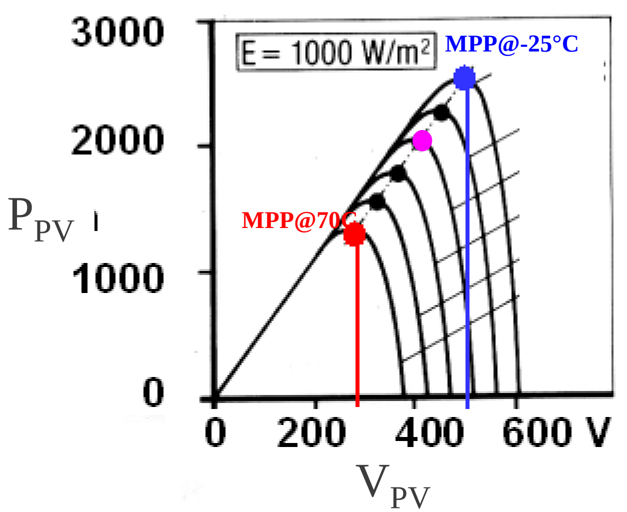
2008

WHAT ARE THE CRITICAL FUNCTIONS OF AN INVERTER AND HOW DOES AN INVERTER WORK

MAIN TASKS OF PV INVERTER CONTROL

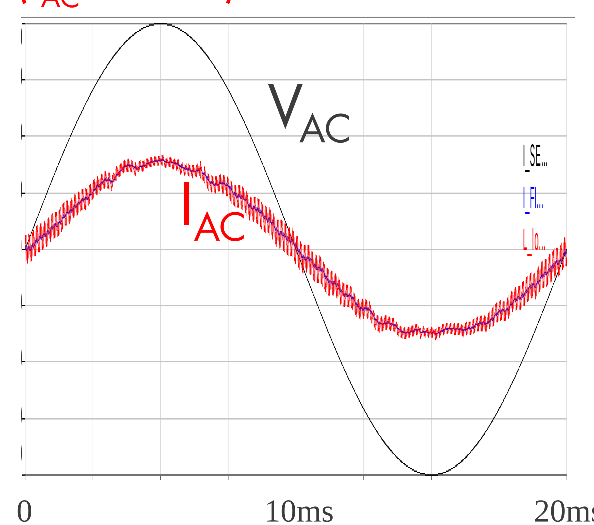
- Control and operational management of the PV inverter has 2 main tasks:

1. PV-generator shall be operated in the way that Maximum Power can be delivered to the grid (MPP-Tracker)

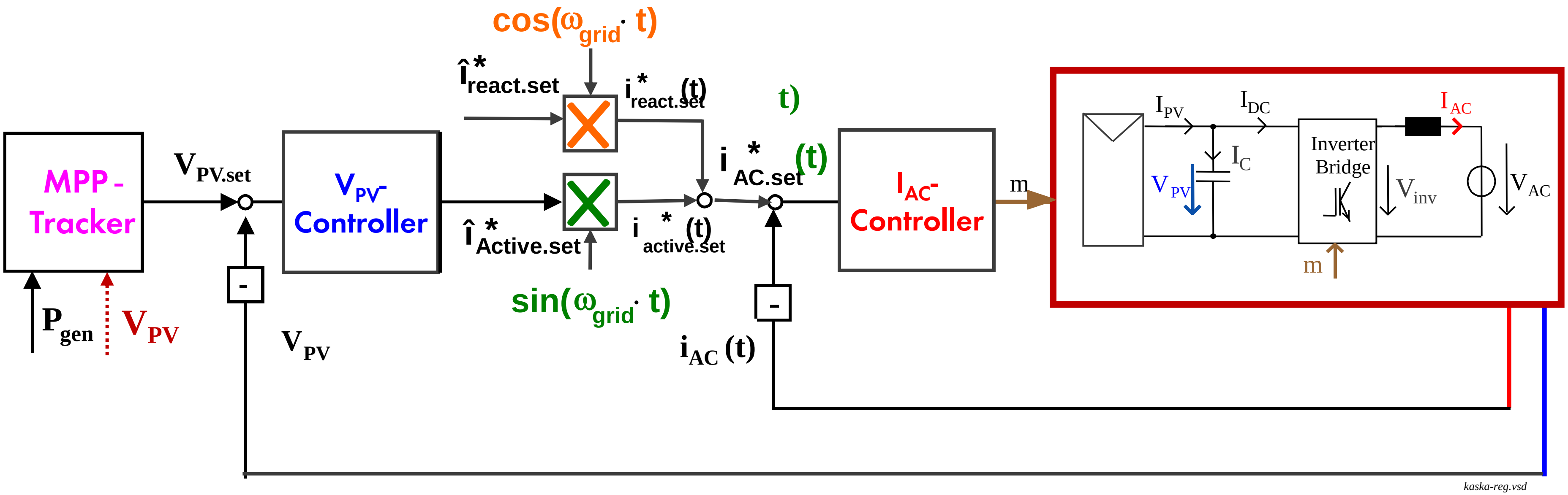


J – solar cell temperature

2. The line current shall be sinusoidal and have a given phase displacement (to deliver reactive power if needed) (I_{AC}-Control)



GENERAL STRUCTURE OF PV INVERTER CONTROL



Cascaded Control:

MPP-Tracker:

Task: $dP_{PV}/dV_{PV}= 0$, Output: V_{PVset}, Cycle time: 1…10s

PV voltage (V_{PV}) -Controller:

Task: $V_{PV}=V_{MPP}$ and limit V_{PV}; Output: $\hat{\imath}_{AC.set}$; Cycle time: 10ms or 20ms (for 50Hz grid)

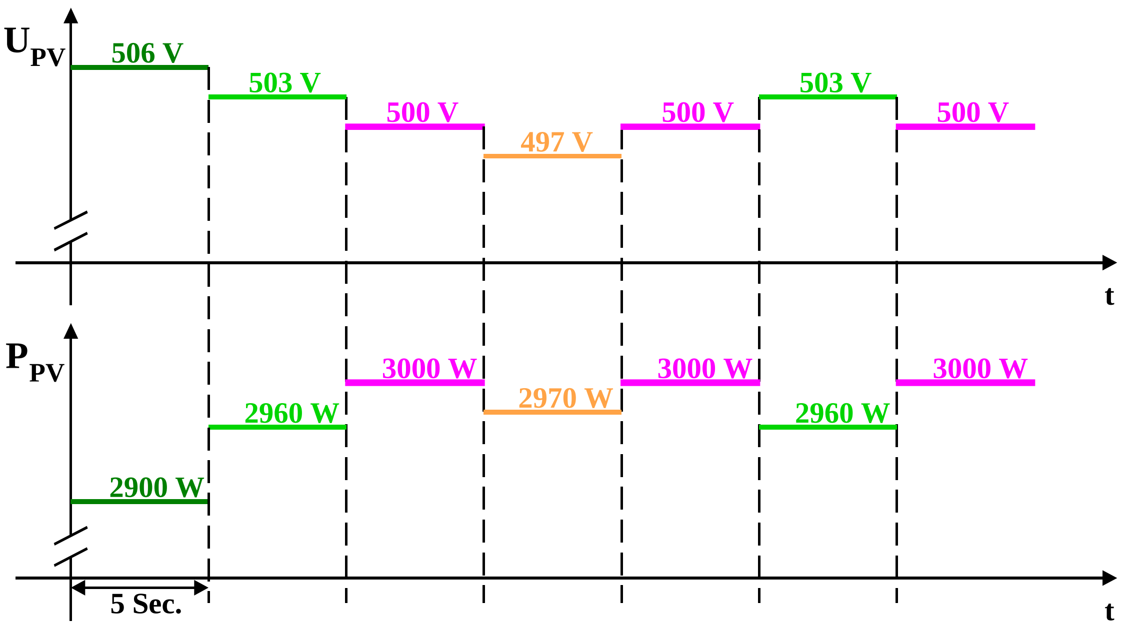
Multiplication with line frequent sinusoidal function gives $i_{AC.active}(t)$

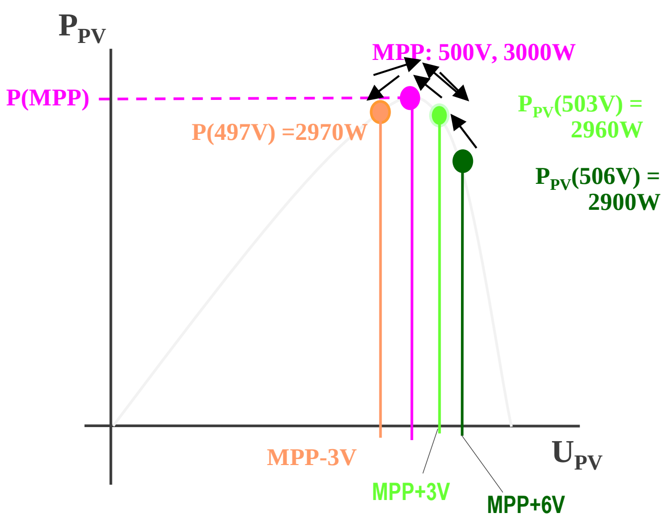
Multiplication with line frequent **cos**inusoidal function gives $i_{AC.reactive}(t)$

Line current (I_{AC}) -Controller:

Task: sinusoidal current, Output: PWM duty cycle m, Cycle time: ~ 50us @ 20kHz f_{switch}

MODE OF OPERATION OF MPP TRACKER

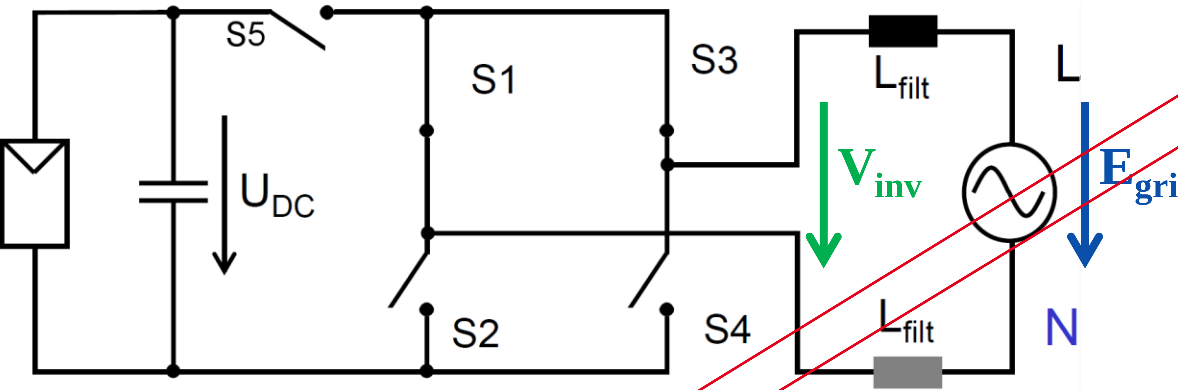


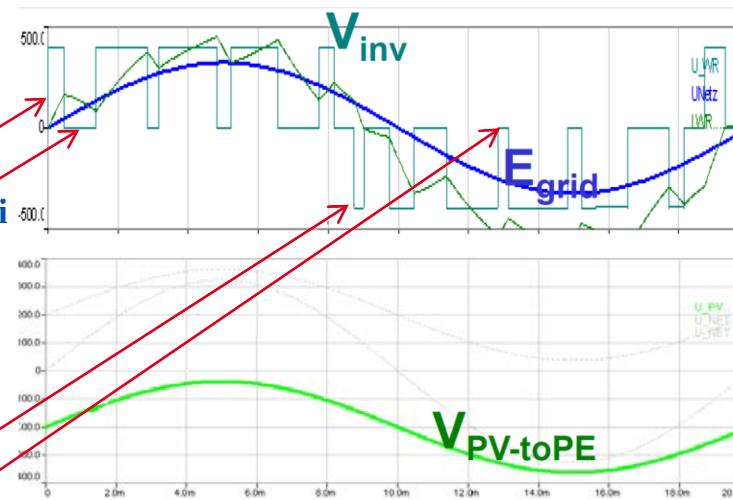


- There are many MPP-tracking algorithms (e.g. P&O-type = "perturb and observe")
- Aim of the MPP-Tracker: To load the PV-generator by variation of V_{PV} in the way that the generator can deliver max possible power $P_{PV}=P_{MPP}$ for given irradition and cell temperature
- In case of cascaded control the output of MPP-tracker is setpoint for V_{PV}-controller $V_{PV.set}$
- Usually realised in a µ-controller (cycling time 1 ... 10 s)

- Example for P&O-type MPP-algorithm:
  - Rule1: Alter V_{PV} by dV (e.g. - 3V)
  - Rule2: Measure the instantaneous value of PV-generator power (=$P_{PV}(i)$),
    - if $P_{PV}(i) > P_{PV}(i-1)$, keep sign of dV
    - if $P_{PV}(i) < P_{PV}(i-1)$, invert sign of dV

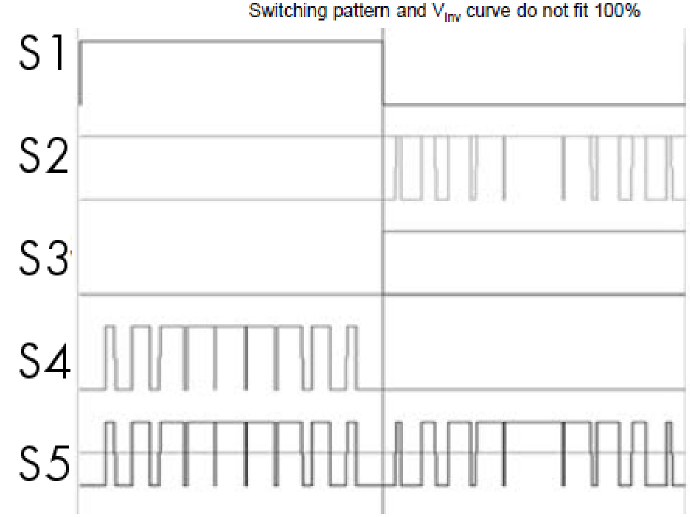
H5 BRIDGE – CONVERTING DC INTO AC SINE WAVE





- $E_{grid} > 0$ (Positive half wave)
  - V_{inv} = + VDC:
    S1, S4, S5 = ON; S2, S3 = OFF
  - V_{inv} = 0:
    S1, S3 = ON; S2, S4, S5 = OFF
- $E_{grid} < 0$ (Negative half wave)
  - V_{inv} = - VDC:
    S2, S3, S5 = ON; S1, S4 = OFF
  - V_{inv} = 0:
    S1, S3 = ON; S2, S4, S5 = OFF

Switching pattern and V_{inv} curve do not fit 100%



- **IGBTs are represented as switches for simplicity of explanation**

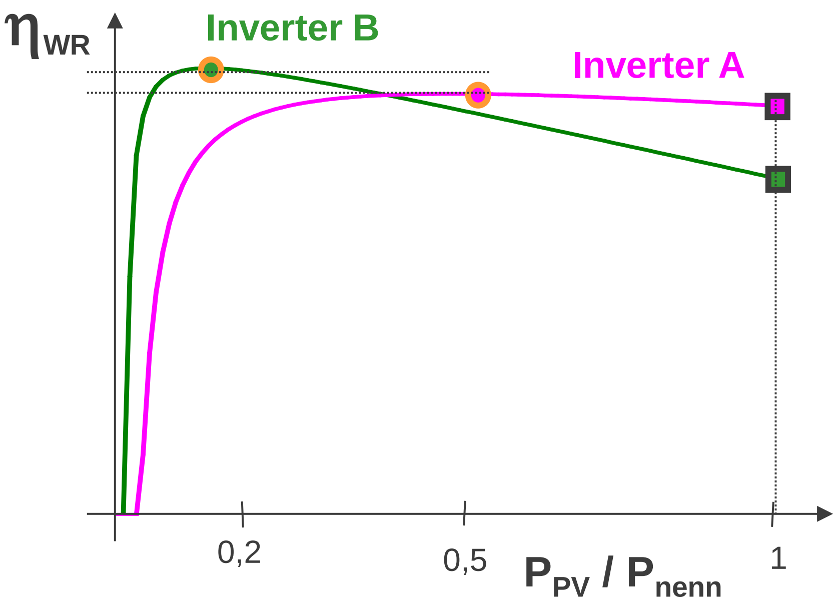
PV INVERTER EFFICIENCY - INTRODUCTION

Importance of the PV inverter efficiency

> Optimum yield of expensive PV energy

> Criteria for purchase decision

> Indicator for innovation capability of the inverter manufacturer



PV inverters have very high efficiencies

> Higher than most off-the-shelf power electronic products

Definitions

> Nominal efficiency

> Maximum efficiency

> "European efficiency"

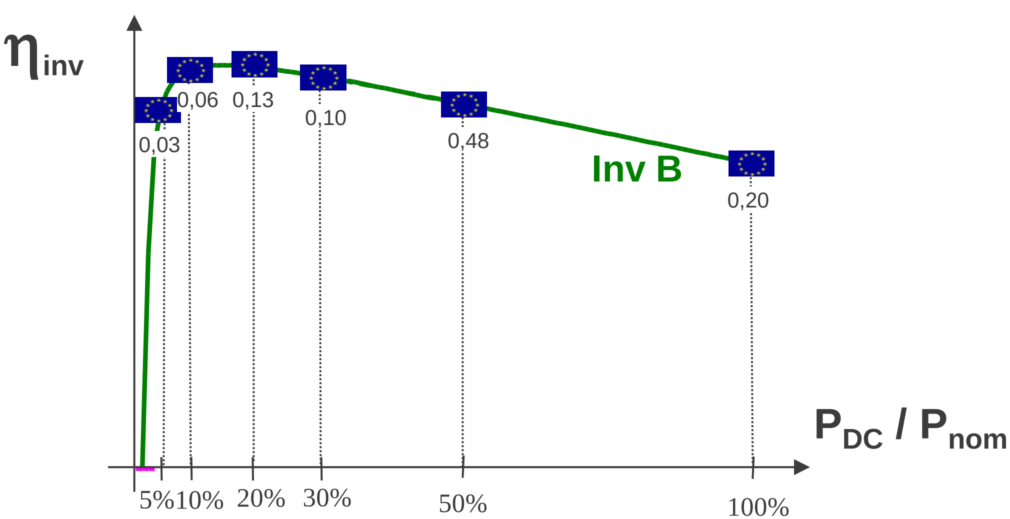
> CEC-Efficiency (California Energy Commission)

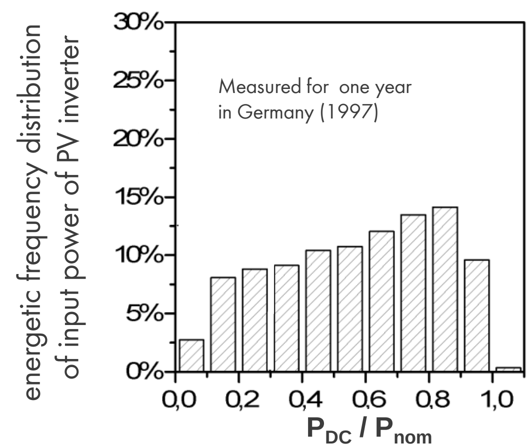
EUROPEAN EFFICIENCY II

- European Efficiency
  - combines the weighted inverter efficiency
  - at six points of operation
  - η_{inv} at P = (5%, 10%, 20%, 30%, 50%, 100% P_{nom})
  - at nominal DC voltage ($V_{DC.nom}$)

$$\eta_{euro} := \sum_{i=1}^{6} g_{euro.i} \cdot \eta_{inv}\left(P_{euro.i}, V_{DC.nom}\right)$$

i	$P_{euro.i}/P_{nom}$	$g_{euro \cdot i}$
1	5%	0,03
2	10%	0,06
3	20%	0,13
4	30%	0,10
5	50%	0,48
6	100%	0,20





CEC-EFFICIENCY: H_{CEC}

CEC-Efficiency η_{CEC}

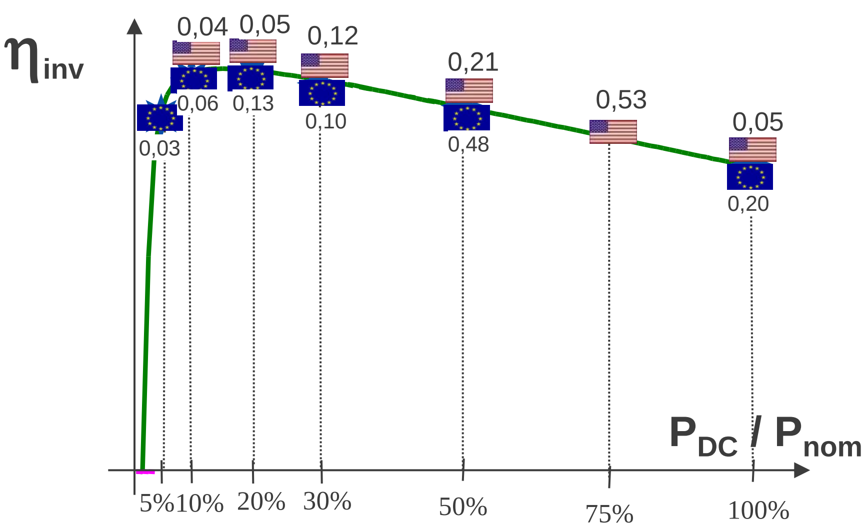
> Californian Energy Commision

> Weighted inverter efficiency at 18 (=6x3) points of operation

> η_{inv} at P = (10%, 20%, 30%, 50%, 75%, 100%) P_{nom} Higher weighting factor for P > 50% P_{nom}

> η_{CEC} includes impact of DC voltage on efficiency

> $\eta_{inv}(V_{DC}) = \eta_{inv}(V_{mpp.min}), \eta_{inv}(V_{mpp.nom}), \eta_{inv}(V_{mpp.max})$



$$\eta_{CEC} := \frac{1}{3} \cdot \sum_{k=1}^{3} \sum_{j=1}^{6} g_{CEC.j} \cdot \eta_{inv}(P_{CEC.j}, V_k)$$

j	$P_{CEC.j}/P_{nom}$	$g_{CEC.j}$
1	10%	0,04
2	20%	0,05
3	30%	0,12
4	50%	0,21
5	75%	0,53
6	100%	0,05

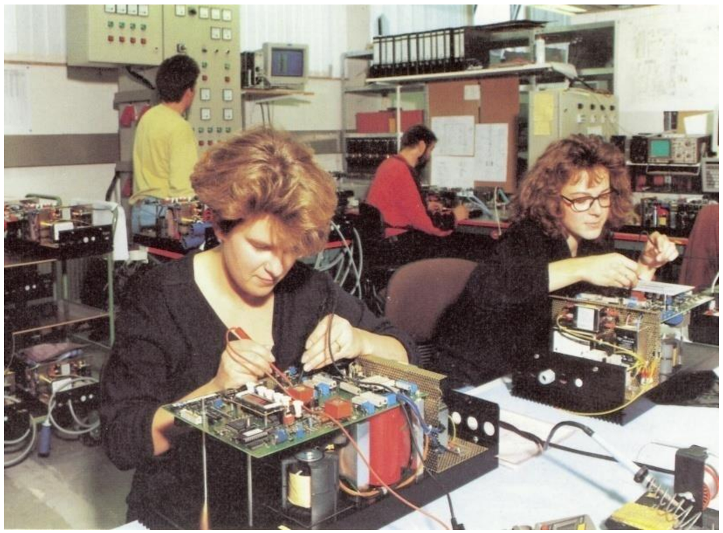
k	V_k
1	$U_{mpp.min}$
2	$U_{mpp.nenn}$
3	$U_{mpp.max}$

MASS PRODUCTION OF PV INVERTERS

PROGRESS IN MANUFACTURING TECHNOLOGY 1991 / TODAY

SMA

1991



- < 1000 pcs./a
- “Work-shop” manufacturing
- Many Hand-soldering connections
- Every inverter a masterpiece

Today

- > 1.000.000 pcs./a (in 2011)
- In-line manufacturing
- Various integrated components
- Assembly time reduced by 85%!

PROCESS OF THE INVERTER MANUFACTURING - OVERVIEW

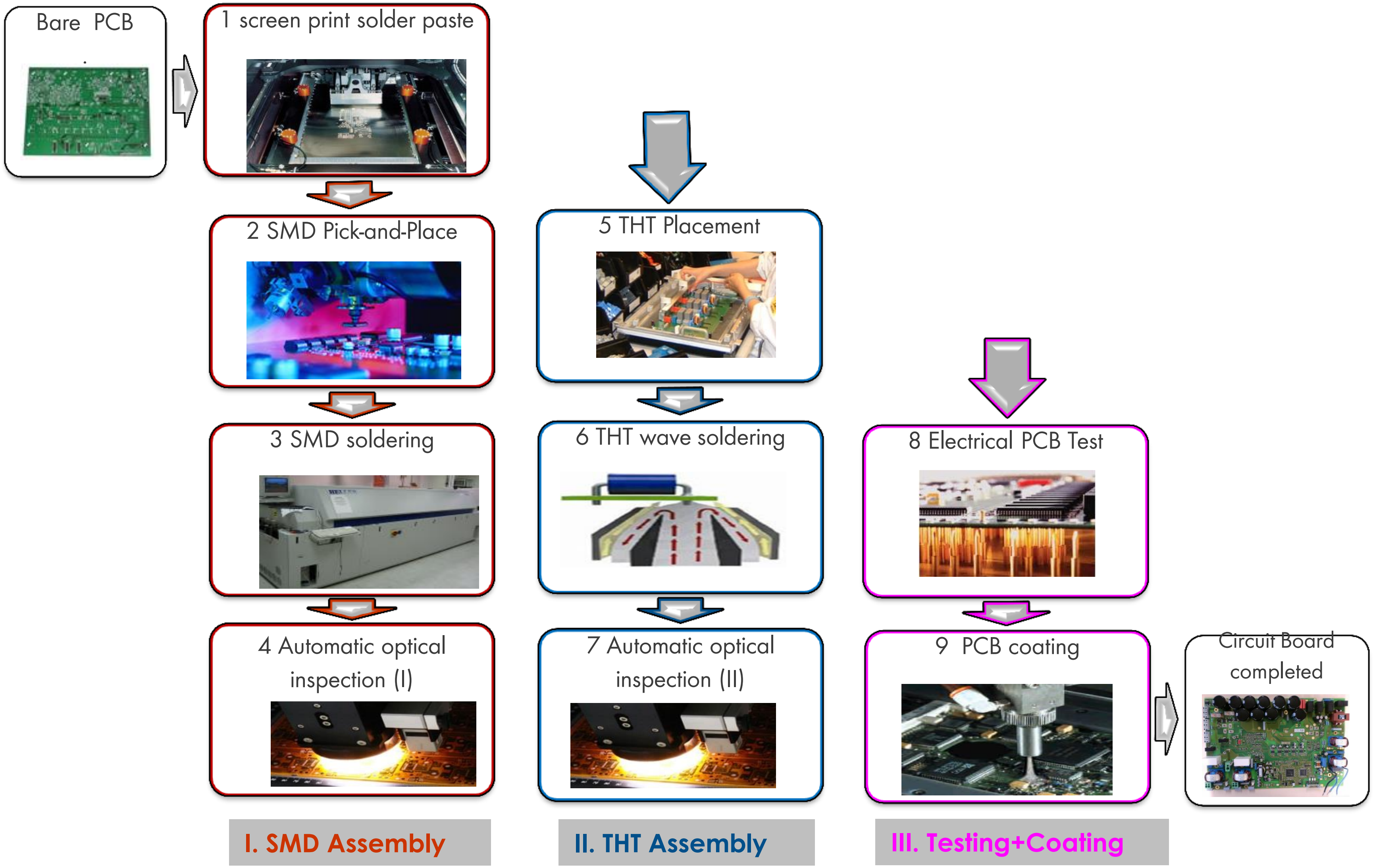
A Printed Circuit Board Assembly

B Inverter Assembly

C Inverter Testing

D Finishing and Shipping

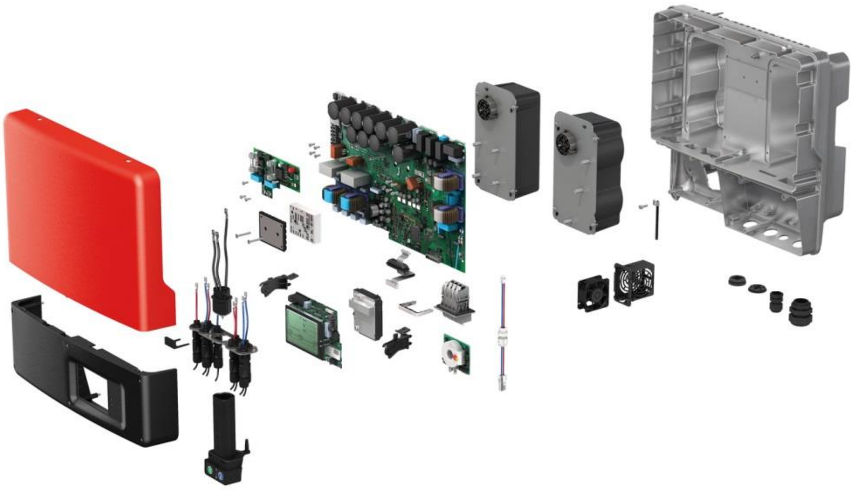
A: PRINTED CIRCUIT BOARD (PCB) ASSEMBLY



→ see also film @SMA youtube channel: http://www.youtube.com/watch?v=2qk5vxWY46A

B. INVERTER ASSEMBLY

- All parts incl. PCB (Step I) are put together in
  5 – 10 manufacturing steps
- Following: High-Voltage (kV) Safety Test
- Rule of thumb: 1 min labour costs 1 €
  (in Germany) (in China 10%-20%)



C. INVERTER TESTING

- Every inverters is functionally tested
- In particular: safety and protection functions

D. FINISHING AND SHIPPING

[Quelle: SMA]

- Finally inverters are finished, packaged and shipped

> e.g. user and installation manual, mounting material ...

HOW HAS INVERTER TECHNOLOGY CHANGED OVER THE PAST 25 YEARS

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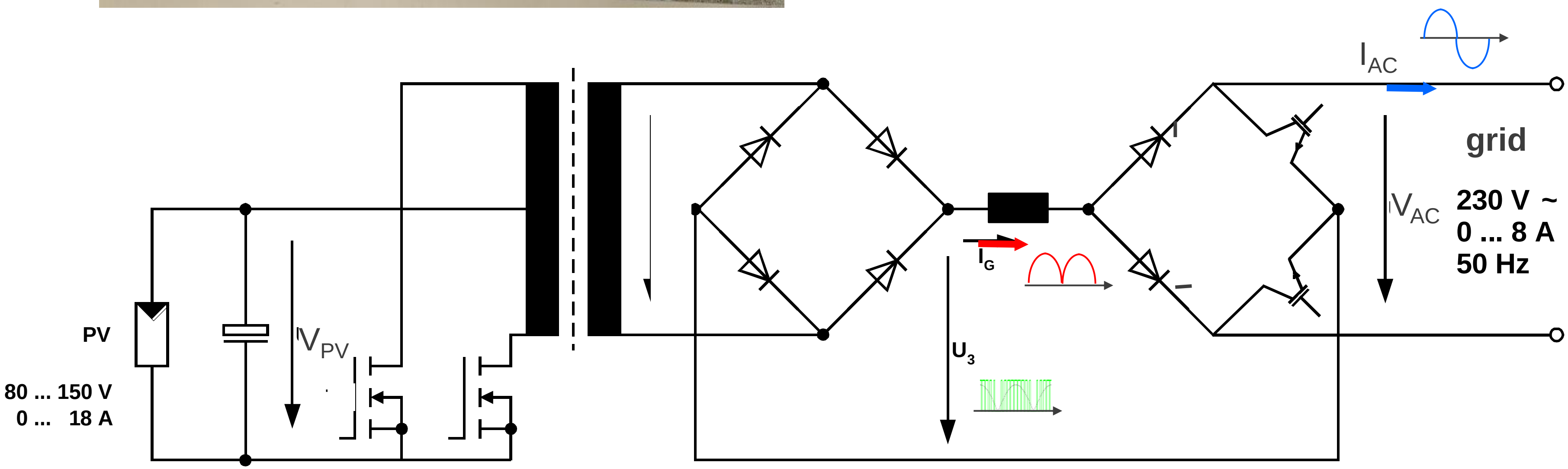
SINGLE PHASE TECHNOLOGIES

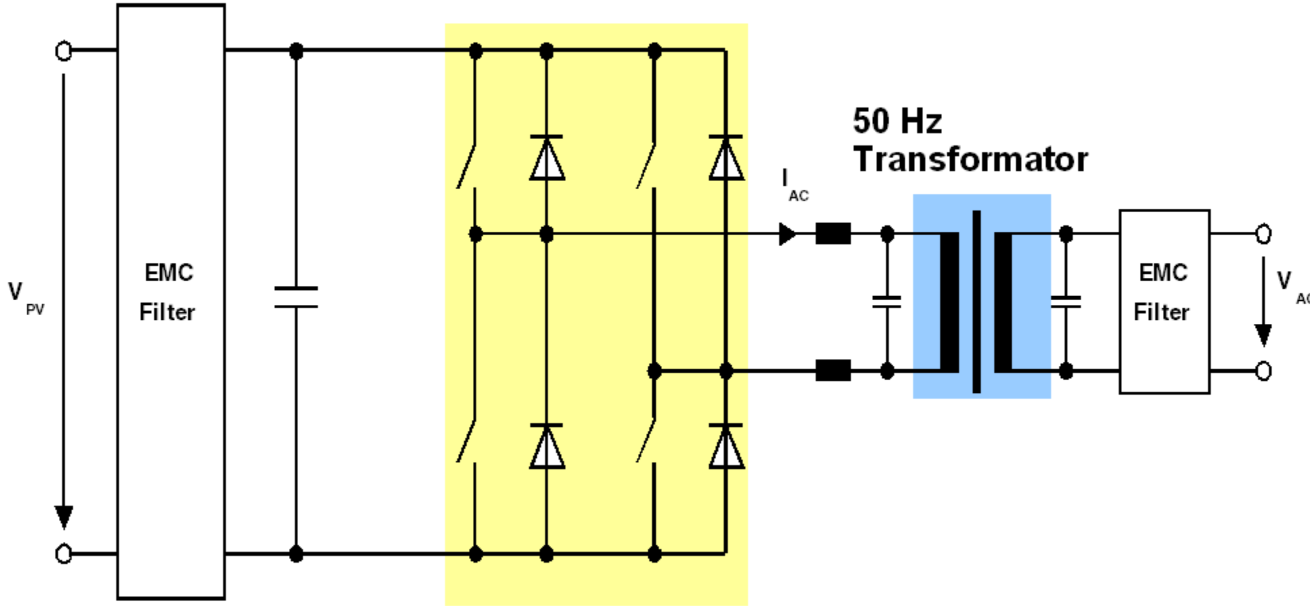
1991 FIRST PV-INVERTER IN SERIES PRODUCTION FOR THE GERMAN 1000-ROOF-PROGRAM

- η_{max}: 90.5 %
- Topology:
  - HF transformer concept
- Power semiconductors:
  - Mosfet, IGBT and thyristors



1995 TRANSFORMER BASED STRING INVERTER

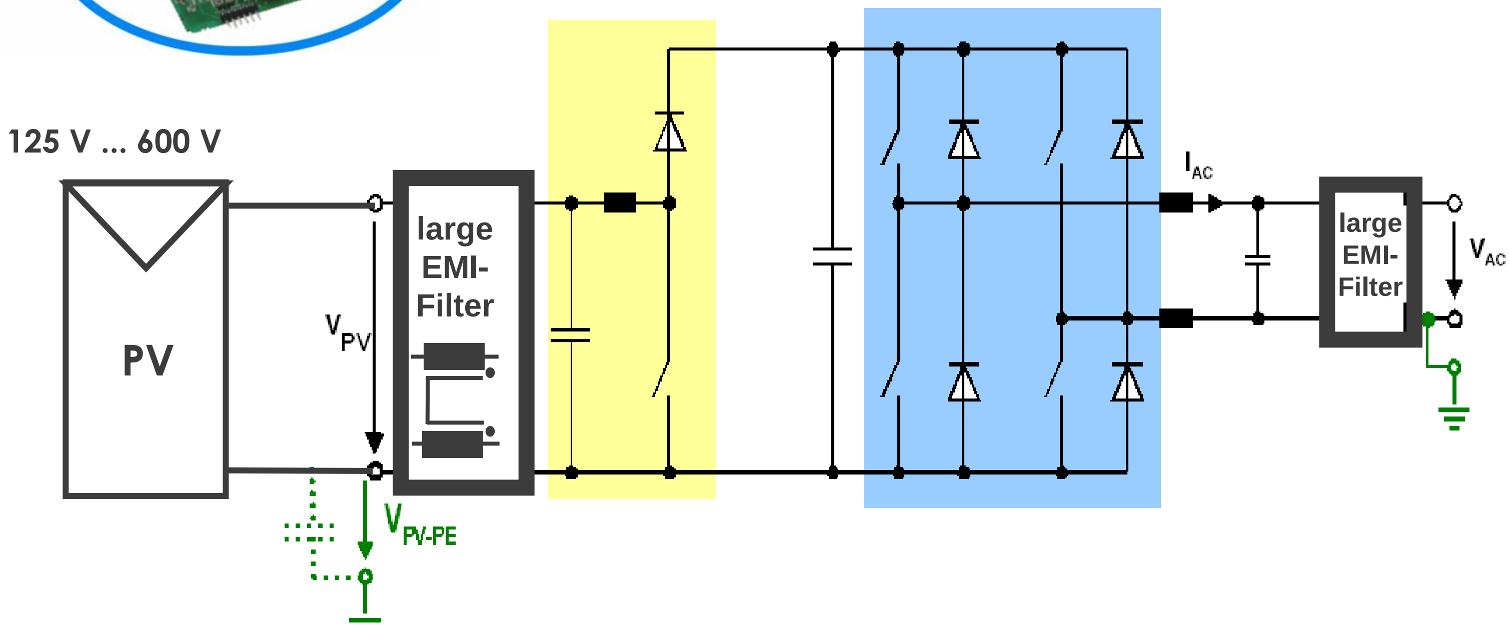
75 V ... 250 V



- η_{max}: 93,5 %
- Nominal Power: 700W
- Reduced Number of components (50Hz-Transformer)
- Smaller DC input current (Higher DC Voltage)
- Mosfet (later IGBT)
- Internal Power supply from DC-Side

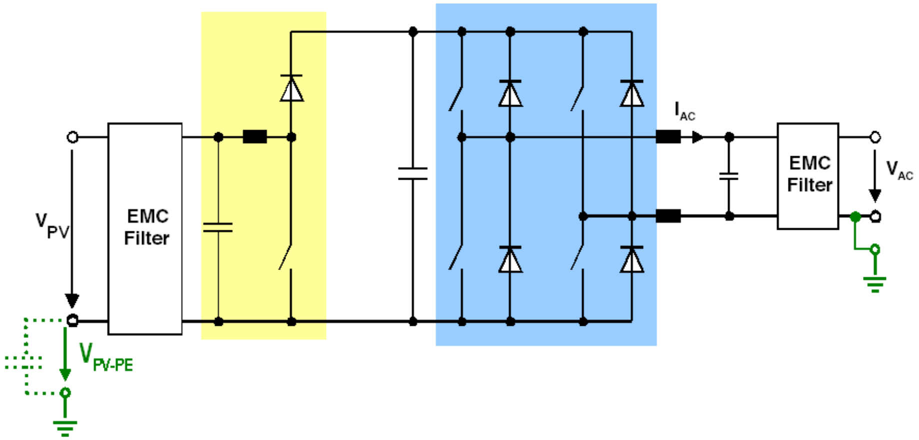
1999 TRANSFORMERLESS STRING INVERTER

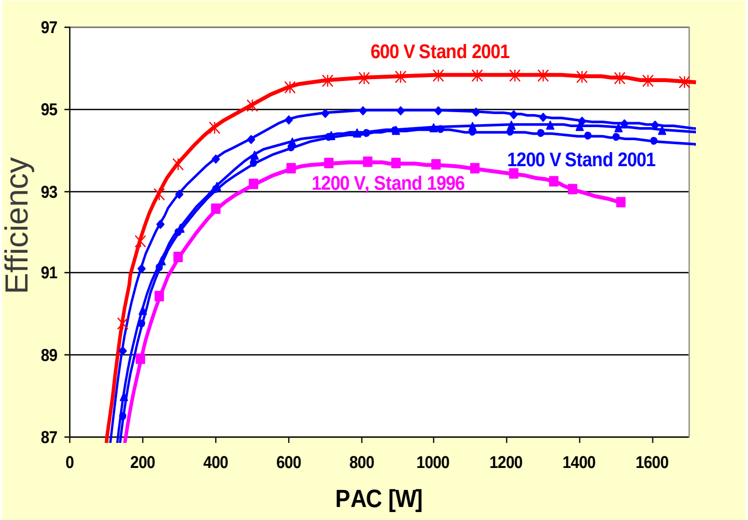
- η_{max}: 95.6 %
- Topology:
  - Transformerless + DC converter
    - for wide DC-voltage range
- Integrated RCD (FI-Schutzschalter) for safety
- IGBT, Mosfet
- Smaller DC input current



2001 TRANSFORMERLESS STRING INVERTER WITH NEW CONTROL ALGORITHM

- η_{max}: 96.1 %
- New generation IGBT
- New control algorithm
  - improved EMI
- Reduced effort for EMI components
  - Lower losses in EMI filter

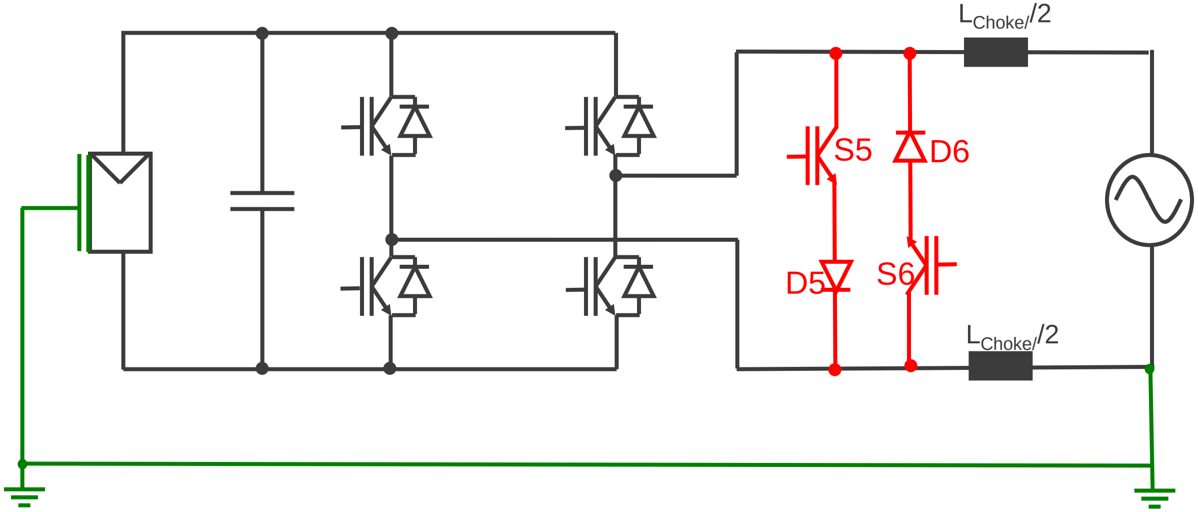




2003 ADVANCES IN TOPOLOGIES FOR TRANSFORMERLESS STRING INVERTER

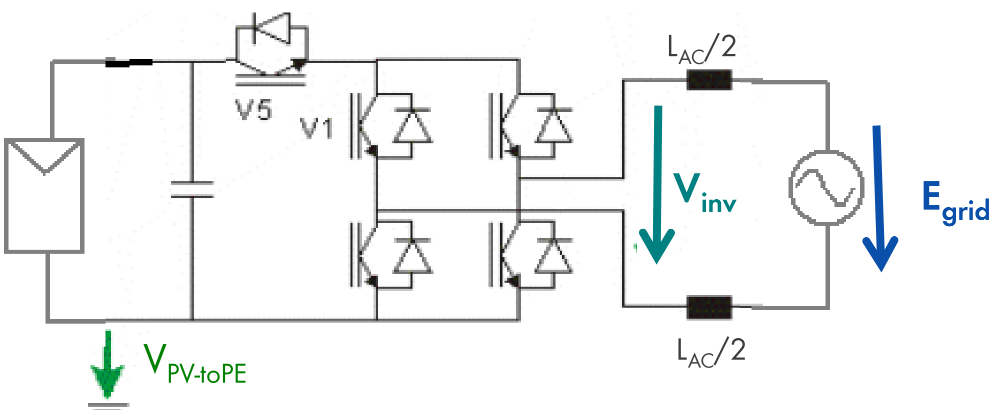
- η_{max}: 97 %
- Max Power: 6000 W
- Transformerless HERIC-Topology
- Additional Components S5/D5, S6/D6 for freewheeling phase in order to
- Minimize losses in magnetic components (L_{Choke})
- for good EMC

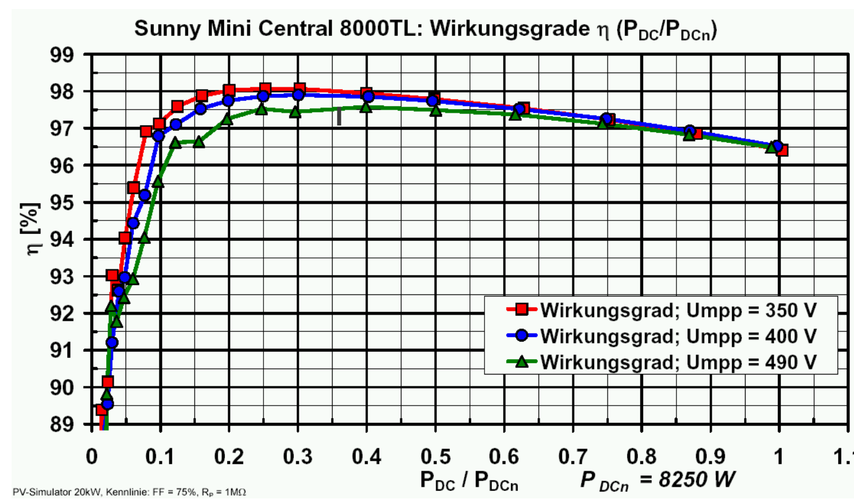
350 V ... 650 V



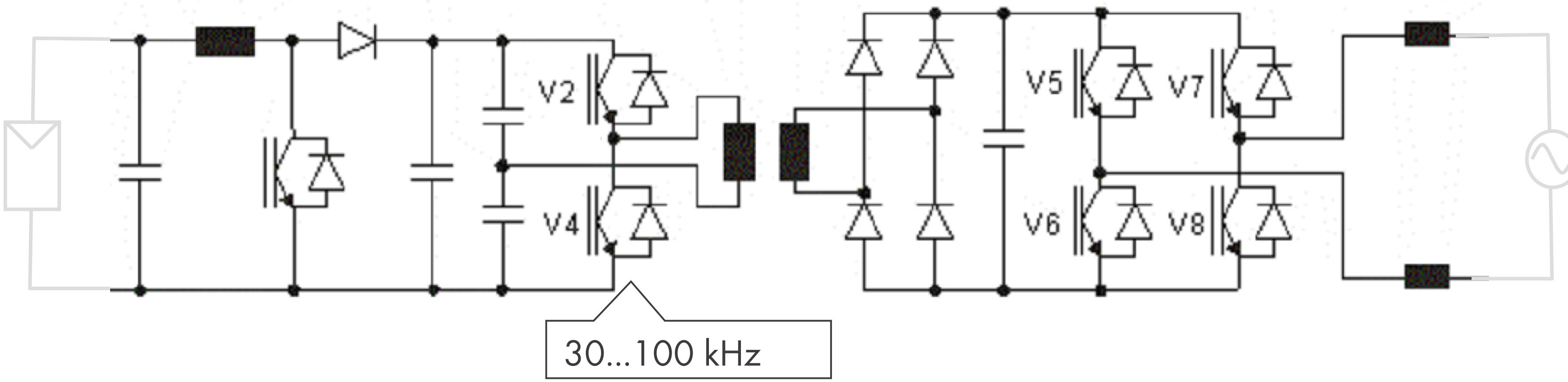
2005 TRANSFORMERLESS H5 TOPOLOGY

- η_{max} > 98.0 %, η_{euro}: 97.7 %
- New transformerless topology
- Without DC converter
- Higher inverter power
- OptiCool®
  power electronic packaging and cooling concept





2009 INVERTER TOPOLOGY WITH HF-TRANSFORMER



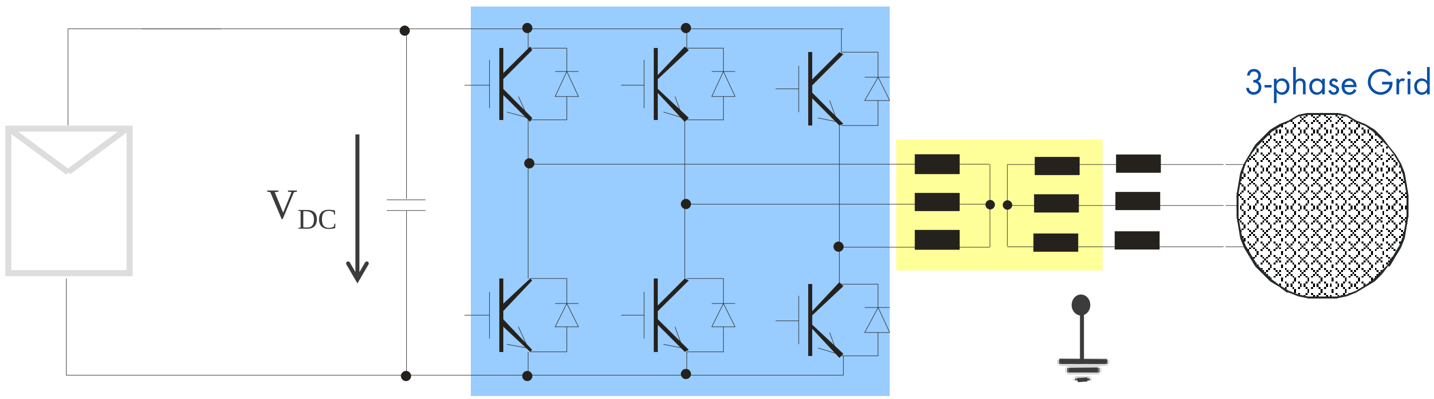
- Max. efficiency: >96%
- Input voltage range: 80V ... 500V (1 : 6,25)
- Cost,
- Weight
- Galvanic isolation / PV-grounding
- PV leakage currents
- 5 converter stages

Sunny Boy 3000 U

Sunny Boy 3000

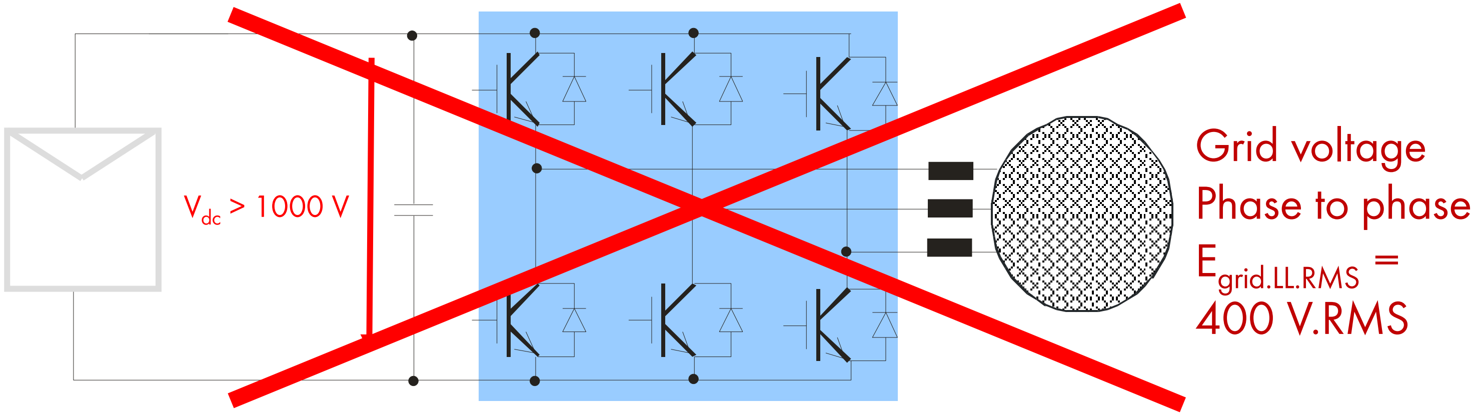
THREE PHASE TECHNOLOGIES

1995 3-PHASE B6-TOPOLOGY WITH 50 HZ-TRANSFORMER



- Max. efficiency: 97 %
- Input voltage range: 450V ... 950V (1 : 2,1)
- Cost, Weight
- Galvanic isolation / PV-grounding
- PV leakage currents
- 2 converter stages

TRANSFORMERLESS 3-PHASE STANDARD-B6-TOPOLOGY FOR GRID FEEDING?



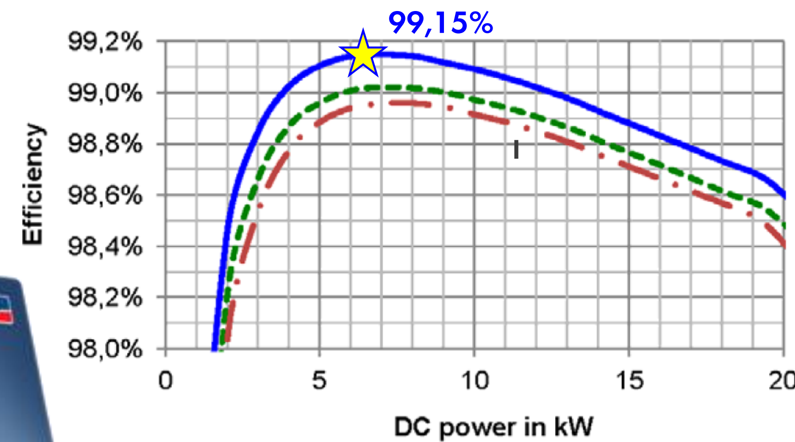
„Killer criteria" (1) for use of Standard-B6-Topologie as transformerless Inverter:

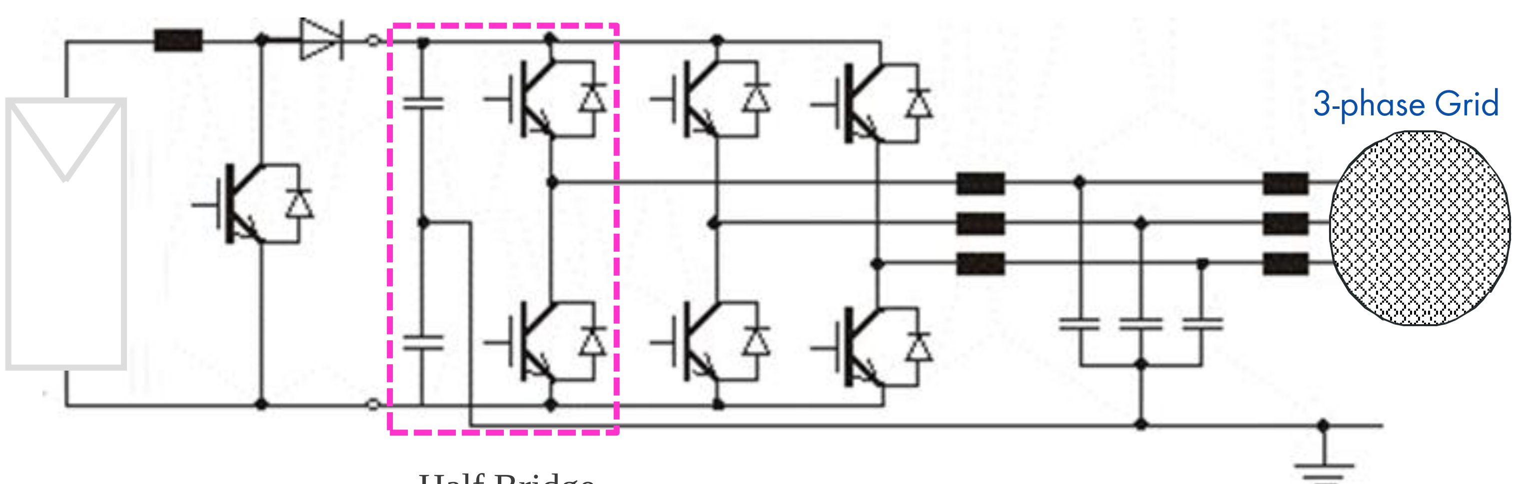
PV inverter would have poor efficiency, because 1700 V IGBTs must be used, because:

- V_{dc} must be higher than amplitude of phase-to-phase grid voltage $\hat{e}_{grid.LL.max}$
- $\hat{e}_{grid.LL.max}$ = 400V * 1.414 * 110% = 622 V
- Number of cells (module) must be selected, so that for hot solar cell generator voltage is higher than $V_{dc.min} = V_{PV.MPP@70C} > \hat{e}_{grid.LL.max} = 622$ V
- Open Circuit voltage of PV-generator on cold days is $V_{PV.OC@-10C} = 2*V_{PV.MPP@70C}$
- $V_{dc.max}$=2*622V=1244 V, therefore 1200 V IGBT can not be used → 1700 V.
- Typical blocking voltage of IGBT: 600 V, 1200 V, 1700 V , …
- 1700 V IGBT has substantial higher switching and conduction losses than 1200 V IGBT.

2011 TRANSFORMERLESS SINGLE-STAGE TOPOLOGY (3 PHASE)

- Max. efficiency: 96% (with 3-level-Inverter 98%)
- Input voltage range: 150V ... 850V (1 : 5,6)
- Cost, Weight
- Galvanic isolation / PV-grounding
- PV leakage currents
- 2 converter stage

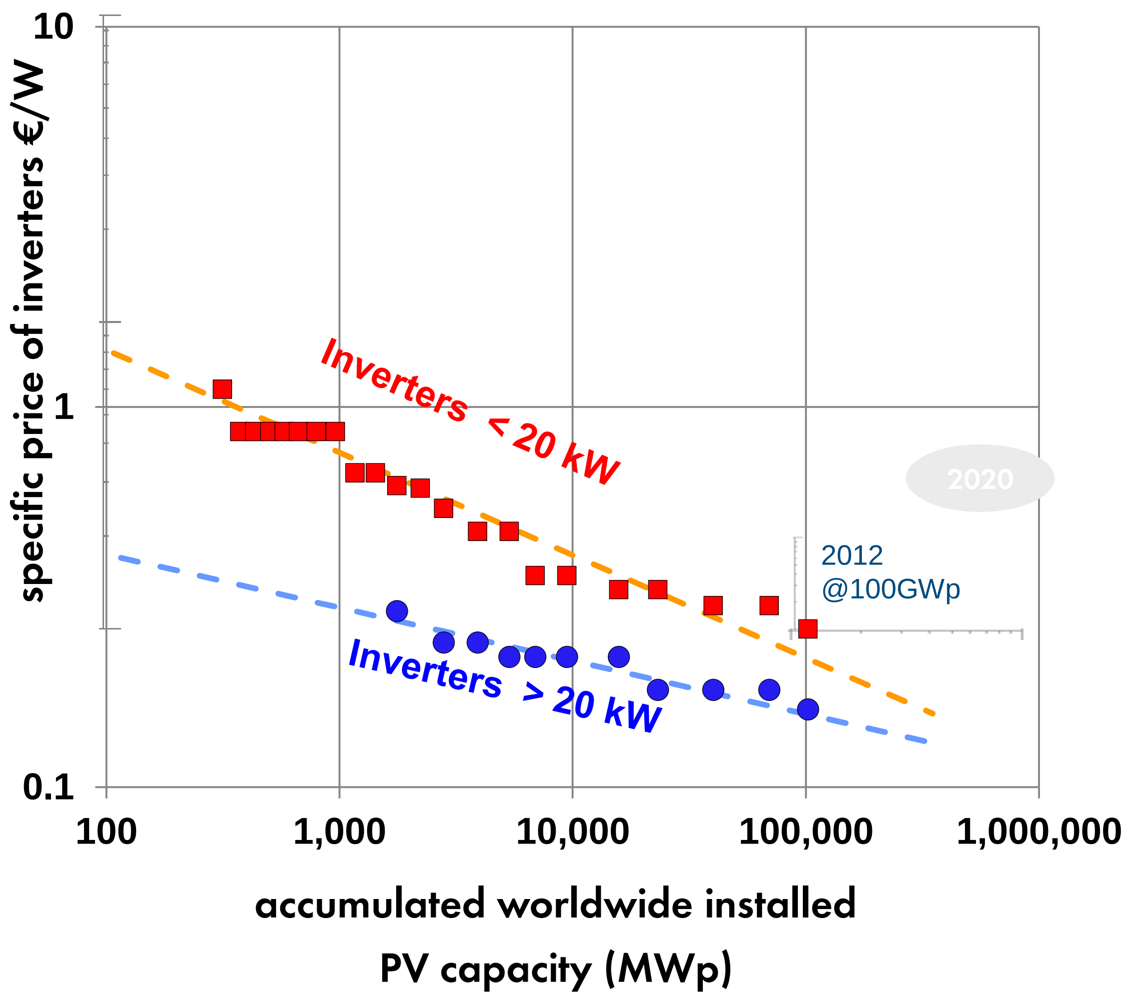




Half Bridge
(2-Level)

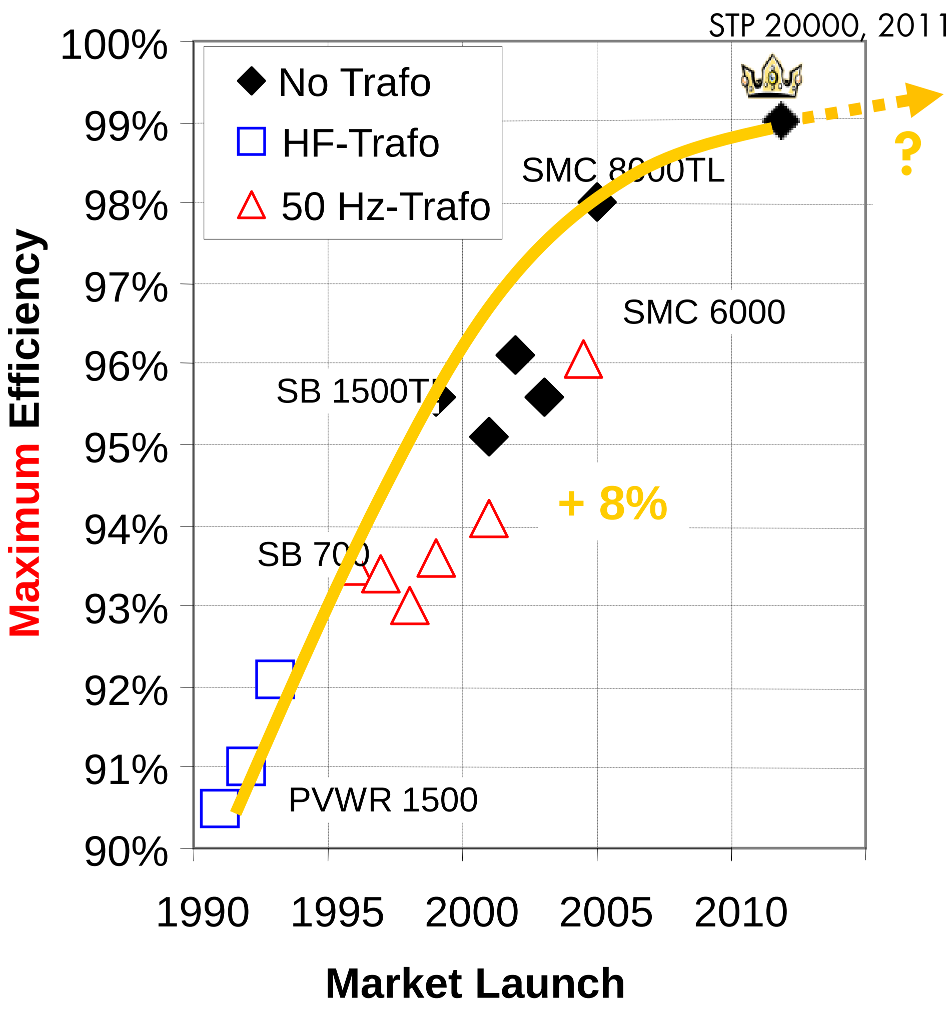
INVERTER IMPROVEMENTS

EXPERIENCE CURVE FOR PV INVERTER COST (1991-2012)



- Cost reduction targets can be reached
- future market growth is needed

IMPROVEMENT OF PV INVERTER EFFICIENCY IN THE PAST



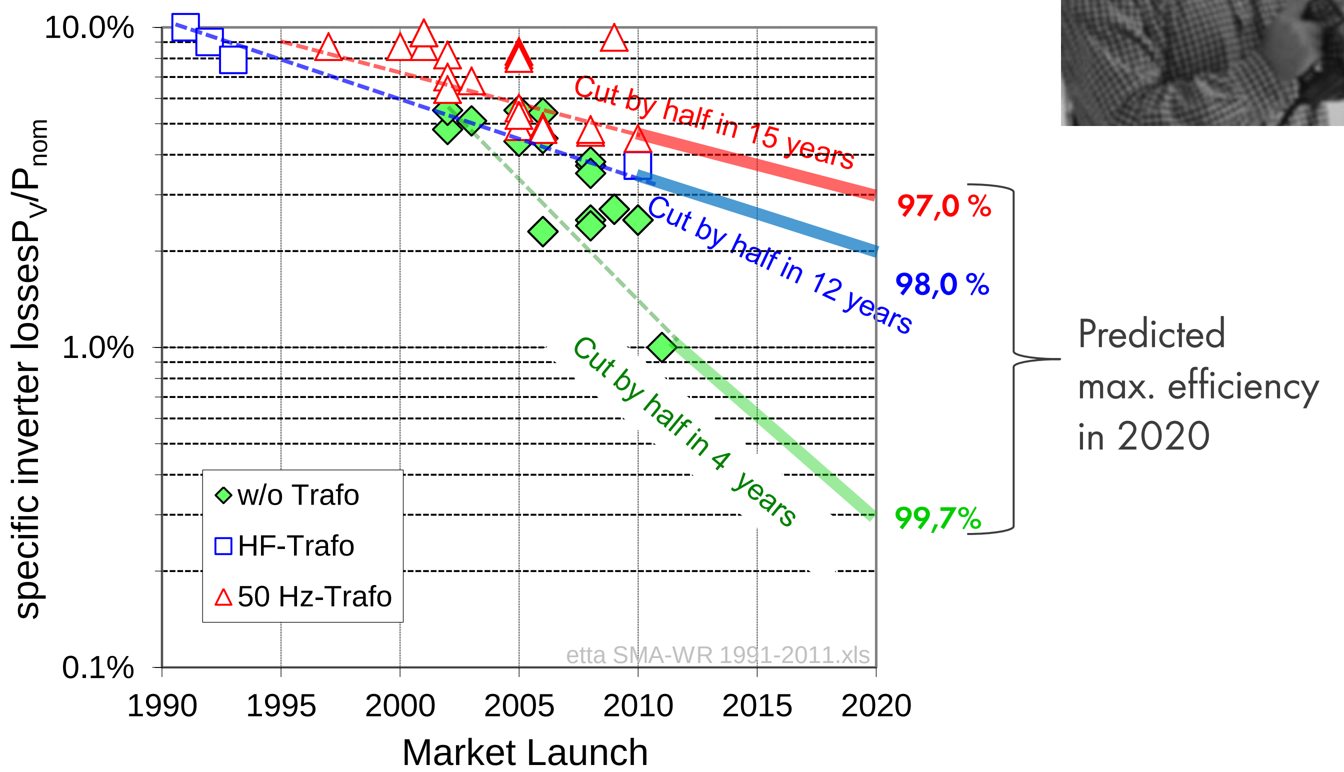
→ What will happen in the future?

Further Increase in efficiency?

FUTURE DEVELOPMENT – "MEINHARDT'S LAW"

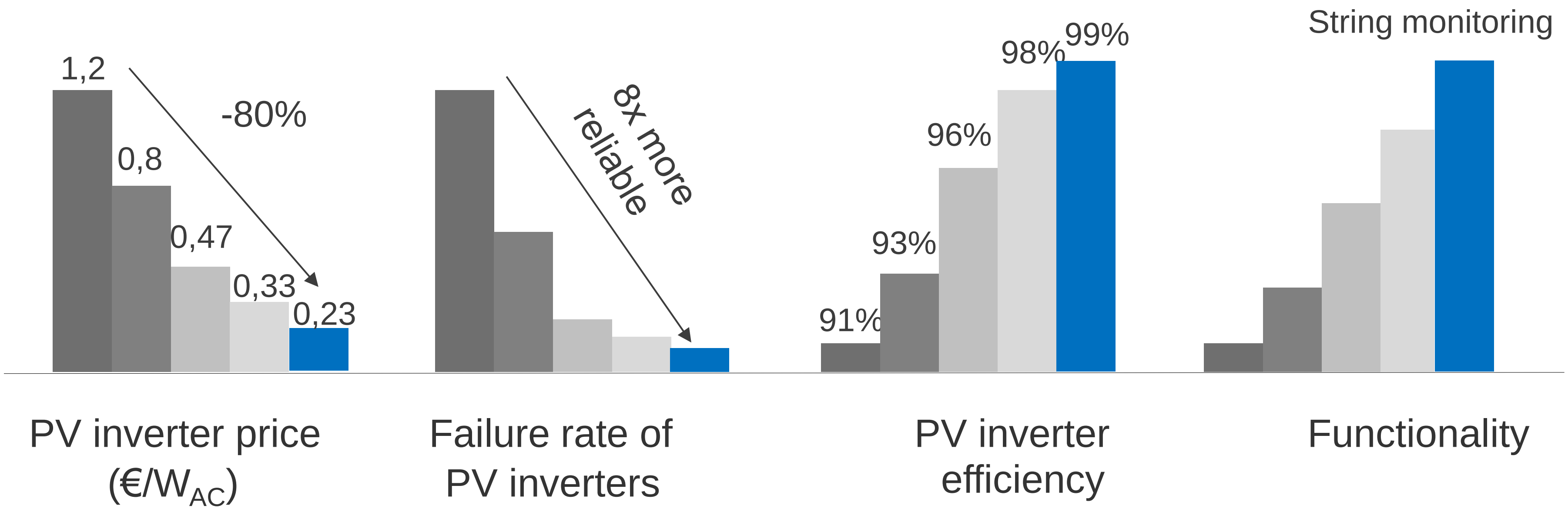
Mike Meinhardt, 2005:

- „Losses of PV inverters are cut by half every 5 years!"*



* Based on analysis of max. efficiency of SMA inverters (< 20 kW) from 1991

PV INVERTERS: ACHIEVEMENTS 1991-2012



GENERAL REMARKS ON FUTURE TRENDS OF PV-INVERTERS

- Cost reduction (design for manufacturing)
- Reduction of material intensity (packaging)
- 30 years lifetime

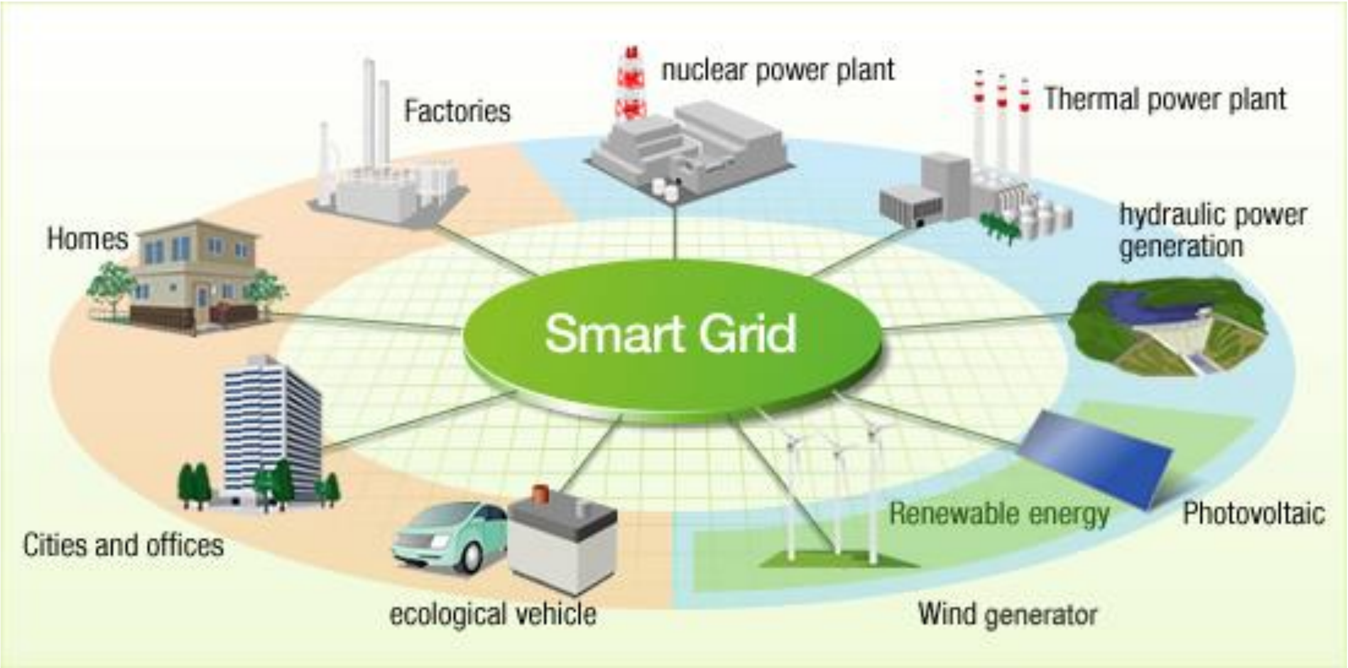
- Global market – standardisation of inverter requirements
- New markets – new requirements

- New inverter components/materials (semiconductors, magnetics)
- New topologies for these new components
- New topologies for (thin-film) solar modules (grounding)

- New control strategies (controller power is “unlimited”)
- New functionality (“auxiliary utility services”, storage, ...)

HOW ARE INVERTERS LEADING TO A SMARTER GRID?

WHAT IS A SMART GRID

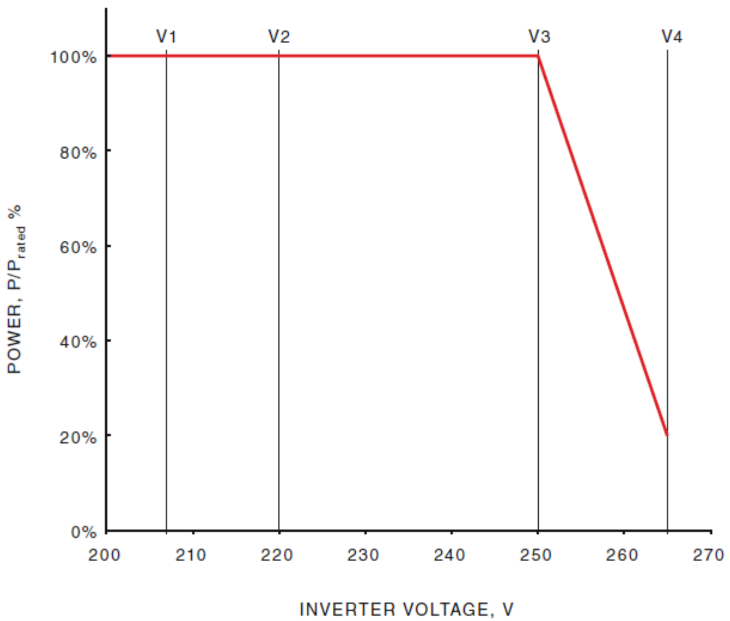


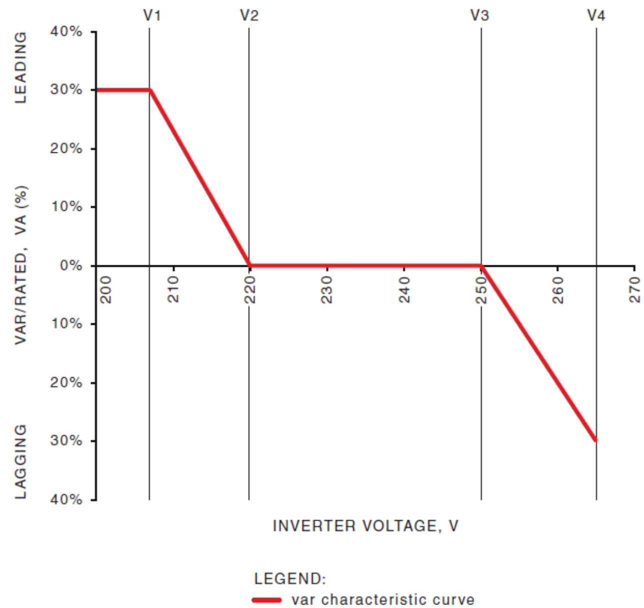
- Source: https://www.csiac.org/sites/default/files/images/SCADASmartGridEfficacy_Page_2_Image_0004.jpg

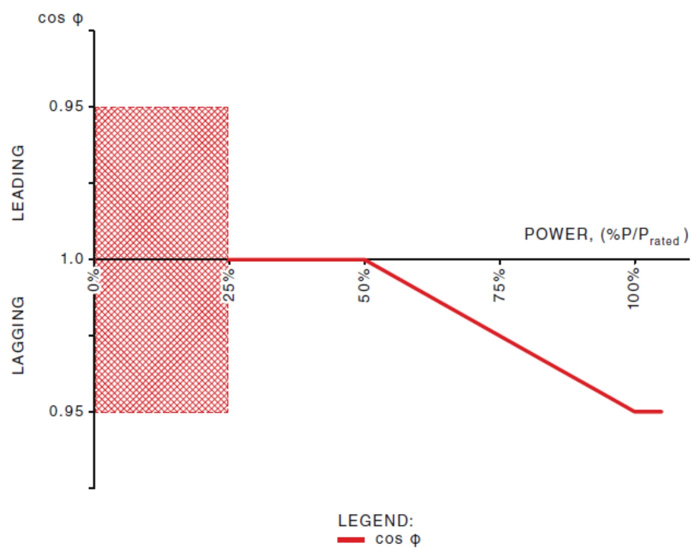
- Smart grid is not a final state but an aspirational target for electric power grids. Smart grid allows the secure 2-way communication between both utilities and devices connected to the grid, and between grid connected devices. This is true for both grid connected devices which consume and generate electricity. Consumption of electricity is managed through a mixture of technology (Demand Response, Smart Meters, etc) and market mechanisms (variable pricing, peak charges, financial incentives for offsetting consumption) such that peak demand is minimised and the integrity of the grid is protected. Smart grid means not only managing large amounts of data, but having the ability to verify the integrity of data, and mechanisms in place to secure the transfer, storage and actions invoked upon certain data. Smart grid should make it possible to increase the prevalence of EV's and other yet to be invented electric devices, without the need for massive upgrade of network assets. Smart grid needs to be based upon standards so the different systems connected are able to operate together

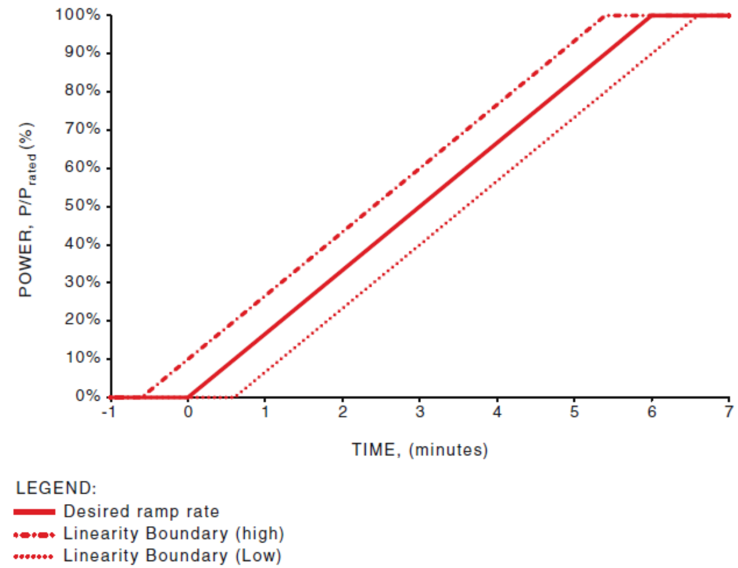
INVERTERS ARE HELPING REALISE THE SMART GRID

GRID SUPPORT FUNCTIONS

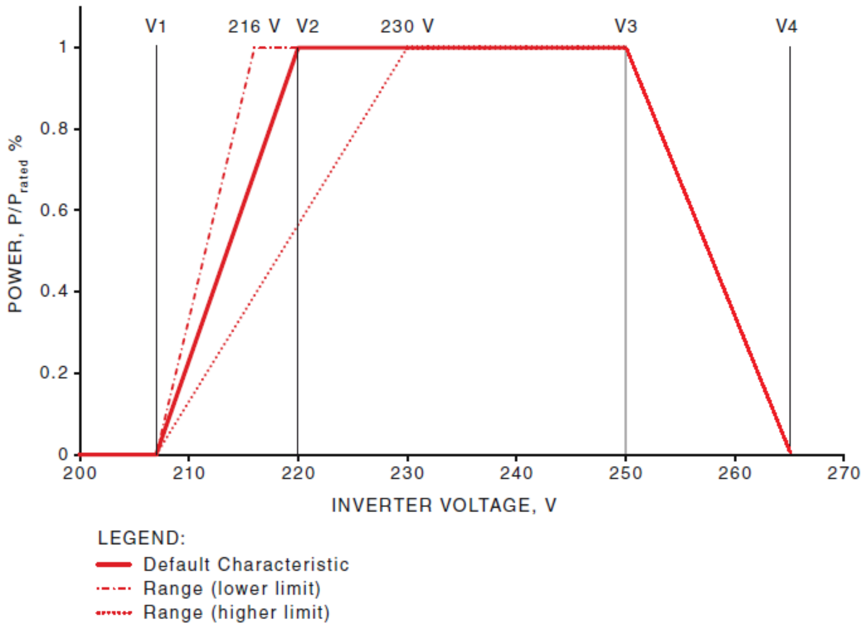


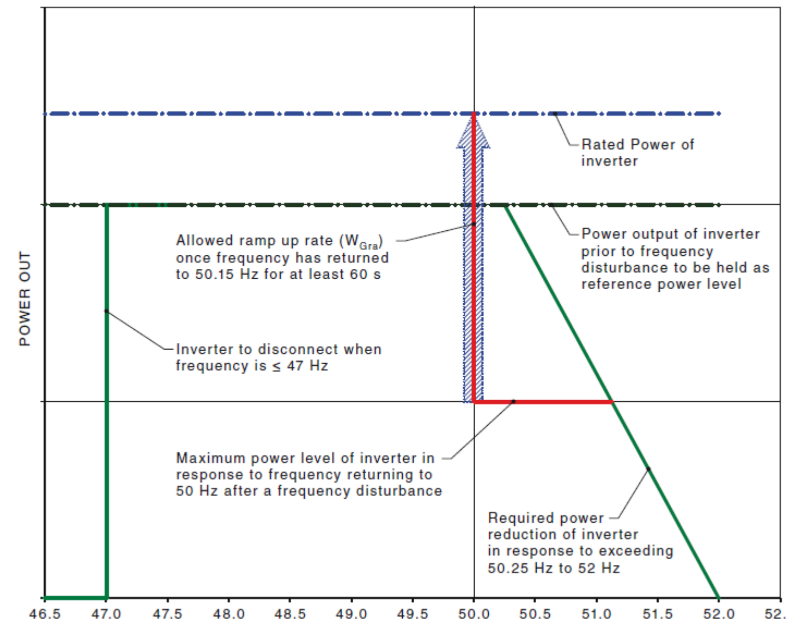






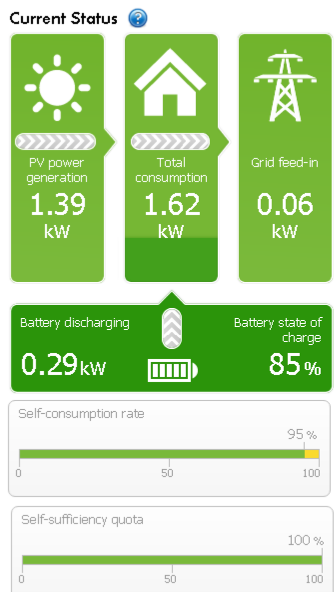
GRID SUPPORT FUNCTIONS

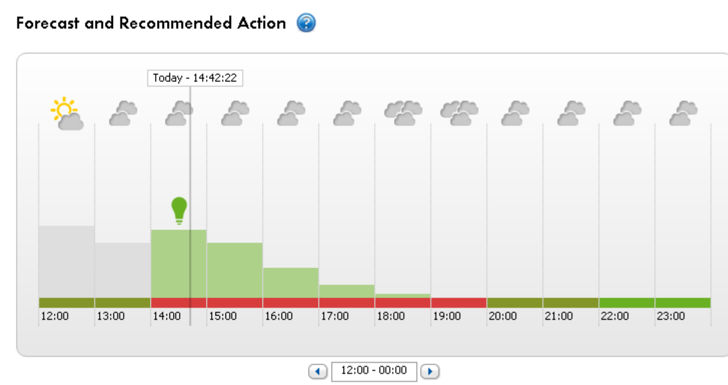




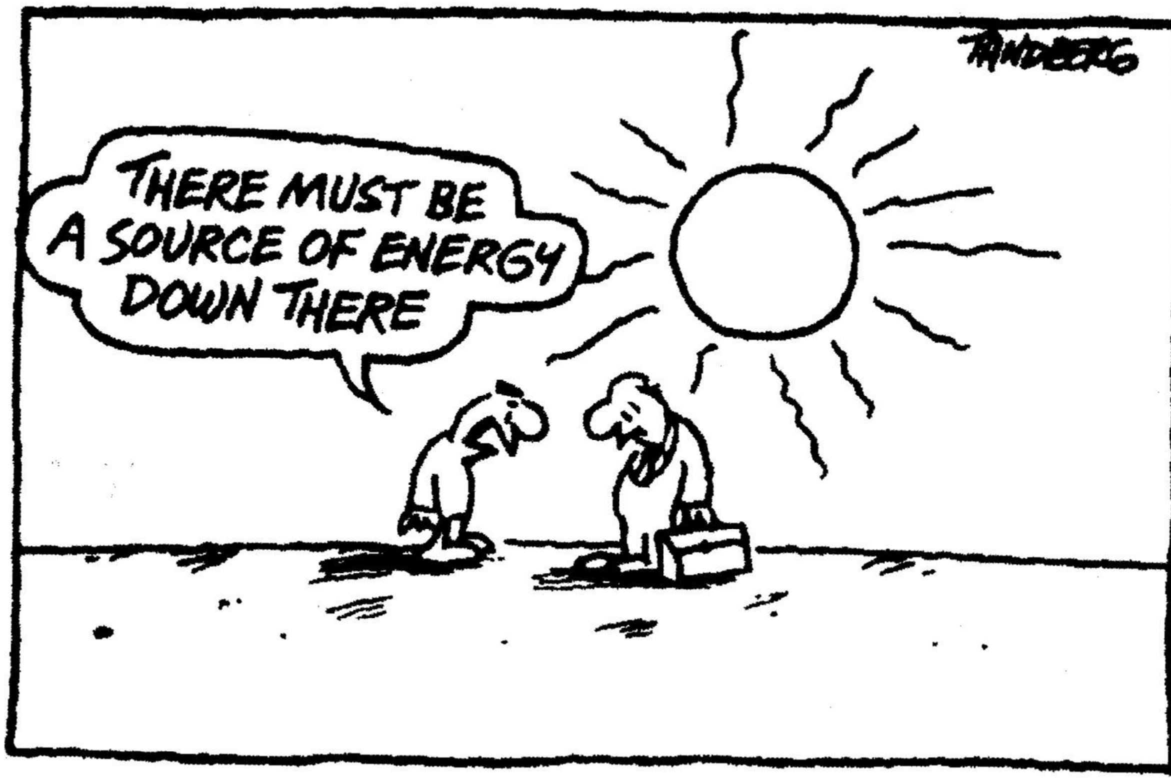
DEMAND RESPONSE MODES (DRMs)

Mode	Requirement
DRM 0	Operate the disconnection device
DRM 1	Do not consume power
DRM 2	Do not consume at more than 50% of rated power
DRM 3	Do not consume at more than 75% of rated power AND Source reactive power if capable
DRM 4	Increase power consumption (subject to constraints from other active DRMs)
DRM 5	Do not generate power
DRM 6	Do not generate at more than 50% of rated power
DRM 7	Do not generate at more than 75% of rated power AND Sink reactive power if capable
DRM 8	Increase power generation (subject to constraints from other active DRMs)





QUESTIONS AND ANSWERS



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