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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%

Global manufacturer of inverters
Over 36GW SMA installed globally

1 in 3 inverters on the planet is SMA

More than 1,000 professionals in R&D

Founded in Germany 1981
Sales 2015 (exp)

€900 million

1 in 4 inverters in Australia is SMA
WHAT DOES SMA STAND FOR?

**System Mess Anlagentechnik**

Computer Control +

Measuring Technology +

Plant System Technology

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)

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: $V_{PV\text{set}}$, Cycle time: 1...10s

PV voltage ($V_{PV}$) -Controller:
Task: $V_{PV} = V_{MPP}$ and limit $V_{PV}$; Output: $i_{AC\text{set}}$, Cycle time: 10ms or 20ms (for 50Hz grid)

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

Line current ($I_{AC}$) -Controller:
Task: sinusoidal current, Output: PWM duty cycle $m$, Cycle time: $\sim 50\mu s$ @ $20kHz f_{switch}$
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 irradiation 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 $\mu$-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

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

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

> IGBTs are represented as switches for simplicity of explanation
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

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

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

<table>
<thead>
<tr>
<th>$i$</th>
<th>$P_{\text{euro},i}/P_{\text{nom}}$</th>
<th>$g_{\text{euro},i}$</th>
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<tr>
<td>1</td>
<td>5%</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>10%</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>20%</td>
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</tr>
<tr>
<td>4</td>
<td>30%</td>
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<tr>
<td>5</td>
<td>50%</td>
<td>0.48</td>
</tr>
<tr>
<td>6</td>
<td>100%</td>
<td>0.20</td>
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CEC-EFFICIENCY: $H_{\text{CEC}}$

**CEC-Efficiency** $\eta_{\text{CEC}}$

- Californian Energy Commission
- Weighted inverter efficiency at 18 (=6x3) points of operation
- $\eta_{\text{inv}}$ at $P = (10\%, 20\%, 30\%, 50\%, 75\%, 100\%) \ P_{\text{nom}}$. Higher weighting factor for $P > 50\% \ P_{\text{nom}}$
- $\eta_{\text{CEC}}$ includes impact of DC voltage on efficiency
  - $\eta_{\text{inv}}(V_{\text{DC}}) = \eta_{\text{inv}}(V_{\text{mpp.min}}), \eta_{\text{inv}}(V_{\text{mpp.nom}}), \eta_{\text{inv}}(V_{\text{mpp.max}})$

\[
\eta_{\text{CEC}} := \frac{1}{3} \sum_{k=1}^{3} \sum_{j=1}^{6} \pi_{\text{CEC},j} \cdot \eta_{\text{inv}}(P_{\text{CEC},j} V_k)
\]

<table>
<thead>
<tr>
<th>$\pi_{\text{CEC},j}$</th>
<th>$P_{\text{CEC},j}/P_{\text{nom}}$</th>
<th>$g_{\text{CEC},j}$</th>
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<tr>
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<td>0,04</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
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<tr>
<td>4</td>
<td>50%</td>
<td>0,21</td>
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<tr>
<td>5</td>
<td>75%</td>
<td>0,53</td>
</tr>
<tr>
<td>6</td>
<td>100%</td>
<td>0,05</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>$k$</th>
<th>$V_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$U_{\text{mpp.min}}$</td>
</tr>
<tr>
<td>2</td>
<td>$U_{\text{mpp.nom}}$</td>
</tr>
<tr>
<td>3</td>
<td>$U_{\text{mpp.max}}$</td>
</tr>
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</table>
MASS PRODUCTION OF PV INVERTERS
PROGRESS IN MANUFACTURING TECHNOLOGY
1991 / TODAY

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

I. SMD Assembly

1. Bare PCB
   → 1 screen print solder paste
      → 2 SMD Pick-and-Place
      → 3 SMD soldering
      → 4 Automatic optical inspection (I)

II. THT Assembly

   → 5 THT Placement
   → 6 THT wave soldering
   → 7 Automatic optical inspection (II)
   → 8 Electrical PCB Test
   → 9 PCB coating

III. Testing+Coating

   → Circuit Board completed

→ 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 inverter is functionally tested

• In particular: safety and protection functions

[Image: A factory floor with inverters being tested.]
D. FINISHING AND SHIPPING

• 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
SINGLE PHASE TECHNOLOGIES
1991 FIRST PV-INVERTER IN SERIES PRODUCTION FOR THE GERMAN 1000-ROOF-PROGRAM

- $\eta_{\text{max}}$: 90.5 %
- Topology:
  - HF transformer concept
- Power semiconductors:
  - Mosfet, IGBT and thyristors
1995 TRANSFORMER BASED STRING INVERTER

- $\eta_{\text{max}}$: 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

75 V ... 250 V
1999 TRANSFORMERLESS STRING INVERTER

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

125 V ... 600 V

PV

V_{PV}

V_{PV-PE}
2001 TRANSFORMERLESS STRING INVERTER WITH NEW CONTROL ALGORITHM

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

![Efficiency Graph](image)
2003 ADVANCES IN TOPOLOGIES FOR TRANSFORMERLESS STRING INVERTER

- $\eta_{\text{max}}$: 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 ($L_{\text{Choke}}$)
- for good EMC

350 V ... 650 V

![Diagram](image_url)
2005 TRANSFORMERLESS H5 TOPOLOGY

- $\eta_{\text{max}} > 98.0\%$, $\eta_{\text{eu}}: 97.7\%$
- New transformerless topology
- Without DC converter
- Higher inverter power
- OptiCool®
  power electronic packaging and cooling concept

![Diagram of transformerless topology]

![Graph showing efficiency vs. power ratio]
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
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 $\hat{e}_{grid.LL.max}$
- $\hat{e}_{grid.LL.max} = 400V \times 1.414 \times 110\% = 622 V$
- 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 $V_{PV.OC@-10C} = 2 \times V_{PV.MPP@70C}$
- $V_{dc.max}=2 \times 622 V=1244$, therefore 1200 V IGBT can not be used $\rightarrow$ 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
INVERTER IMPROVEMENTS
EXPERIENCE CURVE FOR PV INVERTER COST (1991-2012)

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

- PV inverter price (€/W<sub>AC</sub>):
  - 1991: 1.2
  - 1997: 0.8
  - 2005: 0.47
  - 2008: 0.33
  - 2012: 0.23

- Failure rate of PV inverters:
  - 1991: 80%
  - 1997: 47%
  - 2005: 33%
  - 2008: 23%
  - 2012: 23%

- PV inverter efficiency:
  - 1991: 80%
  - 1997: 91%
  - 2005: 93%
  - 2008: 96%
  - 2012: 98%

- Functionality:
  - 1991: 80%
  - 1997: 93%
  - 2005: 96%
  - 2008: 98%
  - 2012: 99%

String monitoring:
- 1991: 0.23
- 1997: 0.8
- 2005: 0.33
- 2008: 0.47
- 2012: 9.9

Graph showing progression from 1991 to 2012 in various aspects of PV inverters.
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

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)

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

There must be a source of energy down there.