Wir schaffen Wissen – heute für morgen

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Thermal Design of Power Electronic Circuits

CERN Accelerator School 2014, Baden, Switzerland

12.5.2014

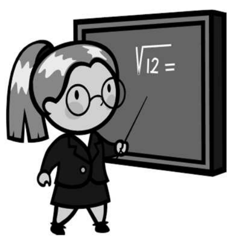
Motivation

Statement in a meeting:

“The converter works as specified, there are just a couple of tests missing to check its thermal behavior.”

Statement in the follow-up meeting 2 weeks later:

“We could only test up to 50% of the rated power, otherwise the converter would have been burnt away.”



Lesson learnt:

Take the losses and the heat dissipation issues into account from the very beginning!

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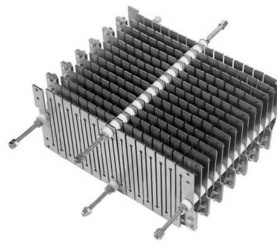
Heat Sources: Resistors

- Resistors
  - Continuous load
    - Sufficient heat transfer to ambient
    - Temperature ≈ stable
  - Pulsed load
    - Absorb energy during pulses
      → sufficient active material
    - Temperature ≠ stable
    - Limited repetition rate



- Cables
  - Use sufficient cross section → additional investment vs. loss costs
  - Skin effect
    - Skin depth in Cu @ 1kHz: 2.1mm
    - @ 10kHz: 0.7mm

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Heat sources: Magnetic Components

- Core losses
  - Eddy current losses
    - Iron sheet cores f < 1kHz
    - Powder cores f < 10kHz
    - Ferrite cores f > 10kHz
  - Hysteresis losses
    - Proportional to the area of the hysteresis curve and the frequency
  - Core losses in transformers
    - Designed to have a minimized hysteresis curve area
    - Losses increase with frequency
    - Losses are also present at zero load
  - DC-chokes
    - Are built to store a lot of energy → hysteresis curve spans a large area
    - Core losses depend on amplitude and frequency of the ripple current

Heat sources: Magnetic Components

- Winding losses
  - Arise from the ohmic resistance of the winding
  - Dissipated power is proportional to I^2
  - Winding resistance increases approx. 0.4% per K (for Cu)

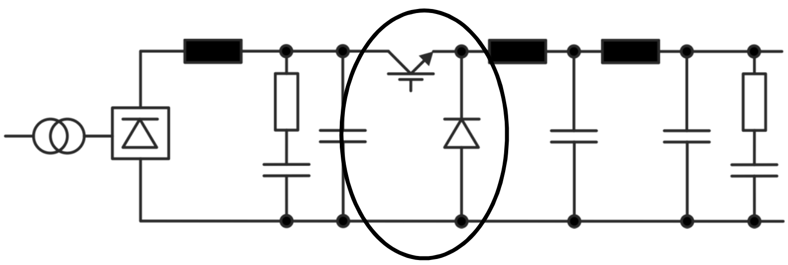
- Keep losses and temperatures low because
  - Higher tempeatures cause even higher losses
  - Wasted energy
  - Costs of the wasted energy
  - Costs for recooling
  - Lower temperatures increase the life time
  - The investments will be returned

Heat Sources: Semiconductors

- IGBT losses
  - Conduction losses
  - (Blocking losses)
  - Switching losses (ON and OFF)

- Diode losses
  - Conduction losses
  - (Blocking losses)
  - Switching losses (Recovery losses)

Example:



FF600R06ME3 [1]

V_{DC} = 250V
I_{Out} = 200A @ m = 0.8
f_s= 20kHz

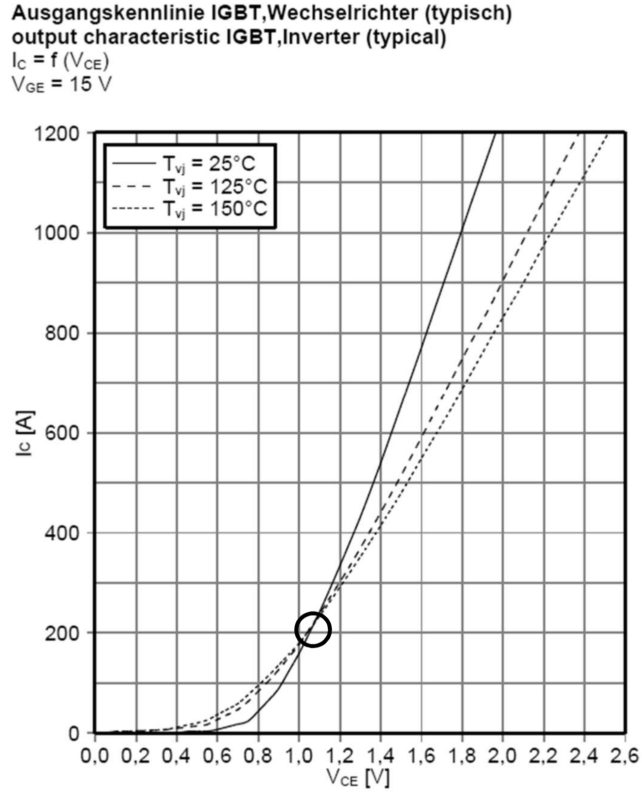
Heat Sources: IGBT losses

Conduction losses **I**GBT:

$$P_{CI} = m \cdot I_{Out} \cdot V_{CE}$$

Note: V_{CE} depends on the junction temperature

$$P_{CI} = 0.8 \cdot 200A \cdot 1.1V = 176W$$



Heat Sources: IGBT losses

Switching losses **I**GBT:

$$P_{SI} = fs \cdot (E_{on} + E_{off}) \cdot \left(\frac{V_{DC}}{V_{ref}}\right)^{K_v} \cdot K_T$$

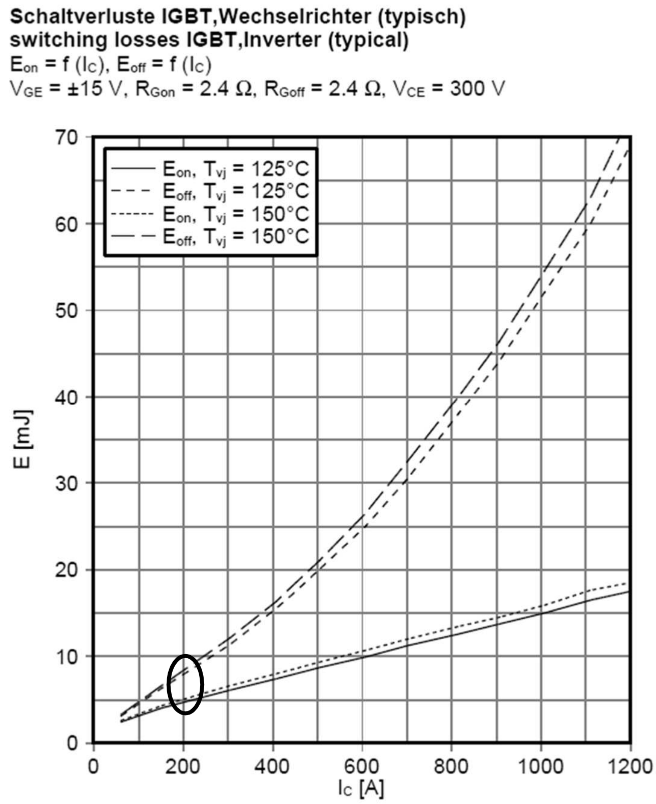
with $K_V = 1.3 \ldots\ldots 1.4$

and $K_T = 1 + 0.003K^{-1} \cdot (T_J - T_{Ref})$ [2]

In our example we assume $T_J \approx 90°C$

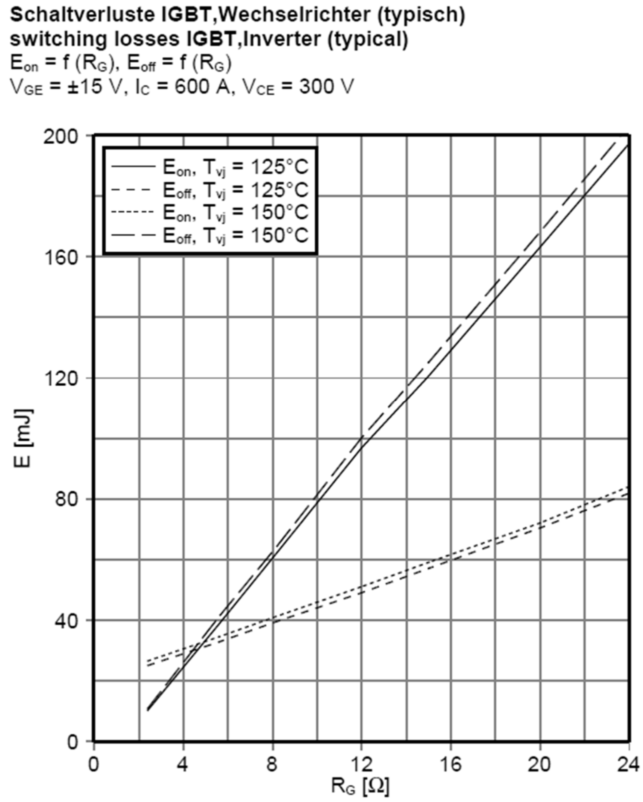
$$K_T = 1 + 0.003K^{-1} \cdot (90 - 125)$$
$$K_T = 0.895$$

$$P_{SI} = 20'000s^{-1} \cdot (5 + 8) \cdot 10^{-3}J \cdot \left(\frac{250V}{300V}\right)^{1.35} \cdot 0.895 = 182\ W$$



Heat Sources: IGBT losses

A softer switching (higher gate resistance) increases the switching losses dramatically



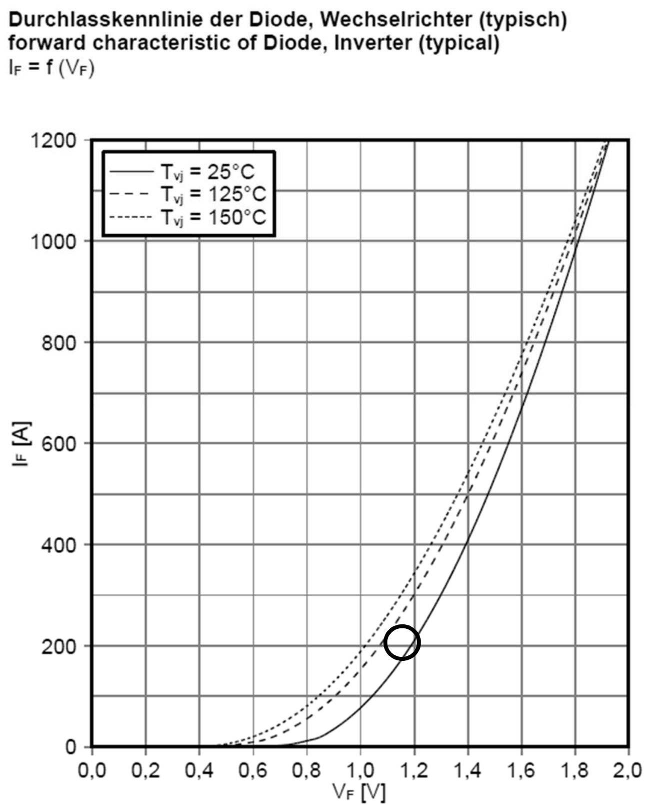
Heat Sources: Diode losses

Conduction losses **D**iode

$$P_{CD} = (1 - m) \cdot I_{Out} \cdot V_F$$

Note: Negative temperature coefficient!

$$P_{CD} = (1 - 0.8) \cdot 200A \cdot 1.15V = 46W$$



Heat Sources: Diode losses

Switching losses Diode

$$P_{SD} = f_s \cdot E_{Rec} \cdot \left(\frac{V_{DC}}{V_{ref}}\right)^{K_v} \cdot K_T$$

with $K_V = 0.6$

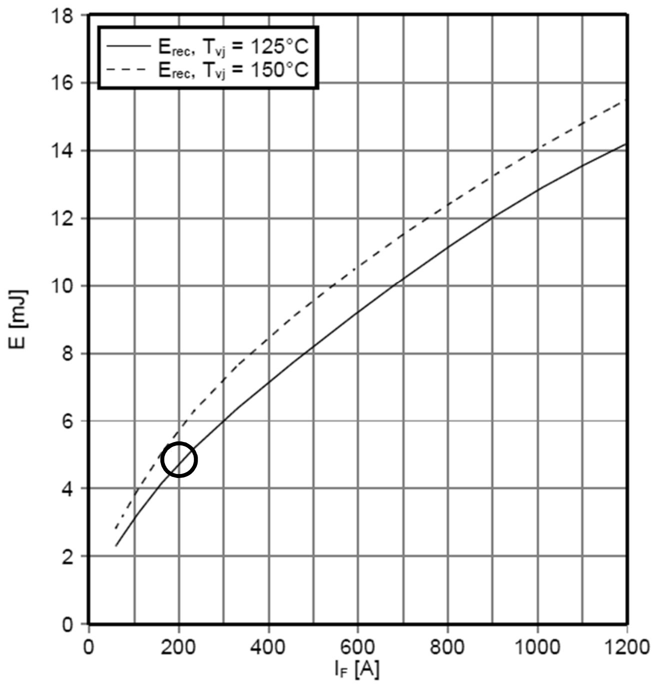
and $K_T = 1 + 0.006K^{-1} \cdot (T_J - T_{Ref})$ [2]

In our example we assume $T_J \approx 90°C$

$$K_T = 1 + 0.006K^{-1}(90 - 125)$$
$$K_T = 0.79$$

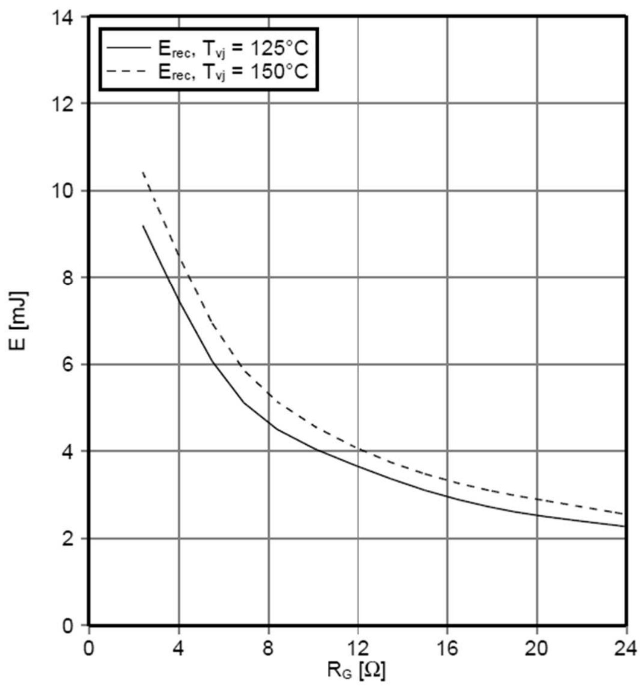
$$P_{SD} = 20'000s^{-1} \cdot 5 \cdot 10^{-3}J \cdot \left(\frac{250V}{300V}\right)^{0.6} \cdot 0.79$$
$$= 71\,W$$

Schaltverluste Diode, Wechselrichter (typisch)
switching losses Diode, Inverter (typical)
$E_{rec} = f(I_F)$
$R_{Gon} = 2.4\ \Omega$, $V_{CE} = 300$ V



Heat Sources: Diode losses

Schaltverluste Diode, Wechselrichter (typisch)
switching losses Diode, Inverter (typical)
$E_{rec} = f(R_G)$
$I_F = 600$ A, $V_{CE} = 300$ V



In contrary to the IGBT, a softer switching (higher gate resistance) reduces the switching losses of the freewheeling diode remarkably.

Summary losses

IGBT losses

$P_I = P_{CI} + P_{SI}$

$P_I = 176\text{W} + 182\text{W} = 358\text{W}$

Diode losses

$P_D = P_{CD} + P_{SD}$

$P_D = 46\text{W} + 71\text{W} = 117\text{W}$

Total losses per module

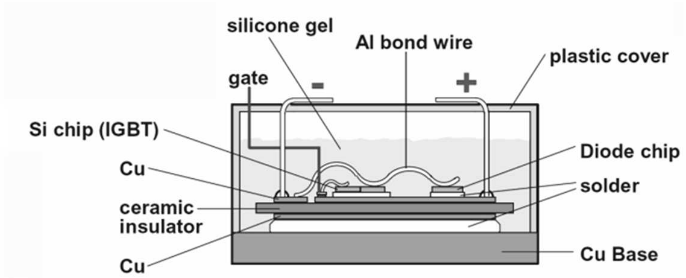
$P = P_I + P_D$

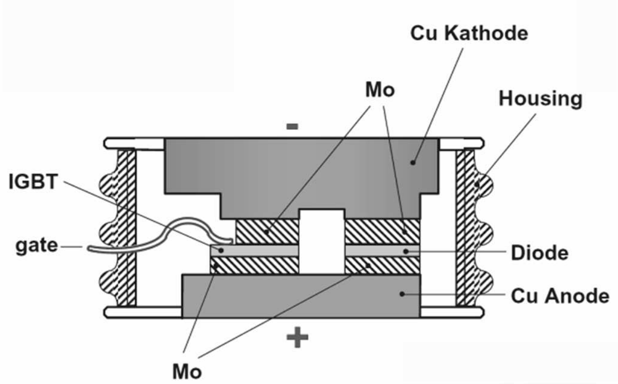
$P = 358\text{W} + 117\text{W} = 475\text{W}$

Heat transfer: Packages

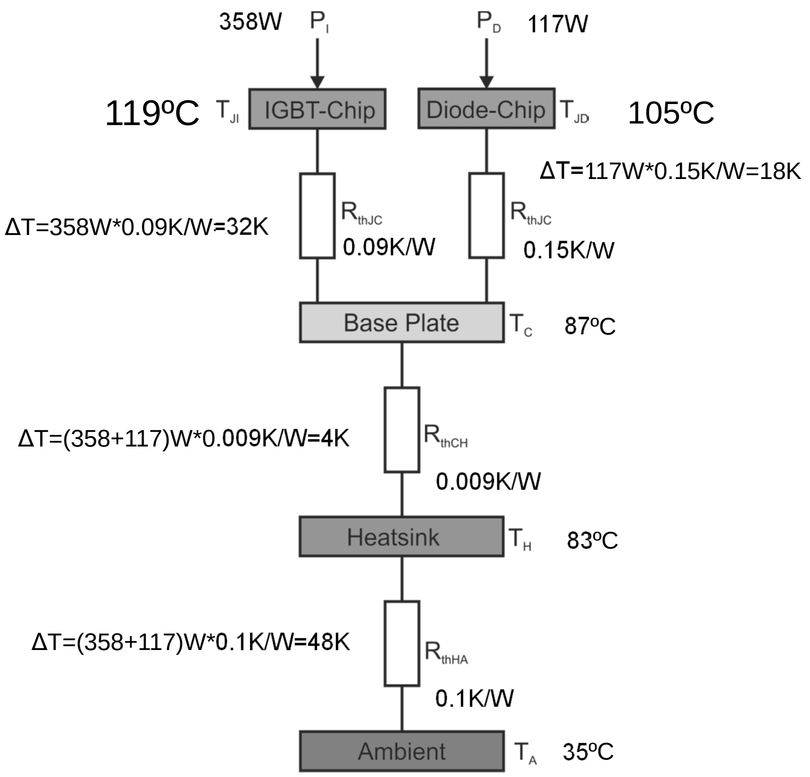
- Isolated module package
  - Isolated Cu Base
    - 1 heat sink for several devices
    - Heat sink on ground potential
  - Solder contacts
  - Cooling from one side only
  - Open circuit after failure
    - Parallel connection

- Press pack devices
  - Cooling via power terminals
    - Individual heat sinks for all devices
    - Heat sink on high voltage
  - Presspack contacts
  - Cooling from both sides
  - Short circuit after failure
    - Series connection



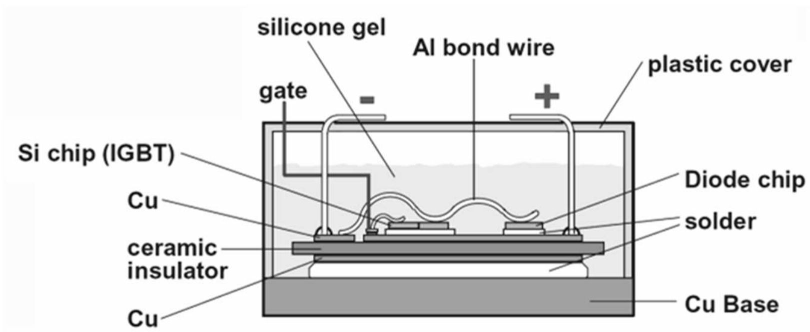


Heat transfer: Temperatures

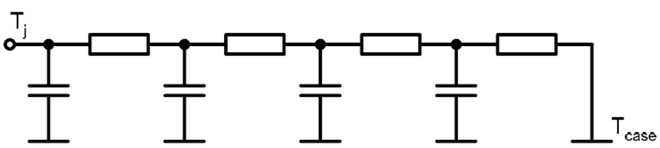


- Maximum ambient temperature
- Get thermal resistances from module data sheet
- Get thermal resistance from heat sink supplier
- IGBT- and diode-losses from calculation
- Calculate heatsink temperature
- Calculate base plate temperature
- Calculate diode and IGBT chip temperatures
- **There should be a safety margin of min. 25K!**

Transient thermal impedance

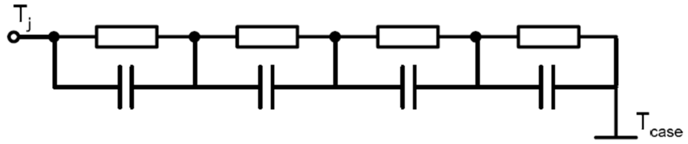


Continued fraction circuit (Cauer model)



Transient thermal impedance

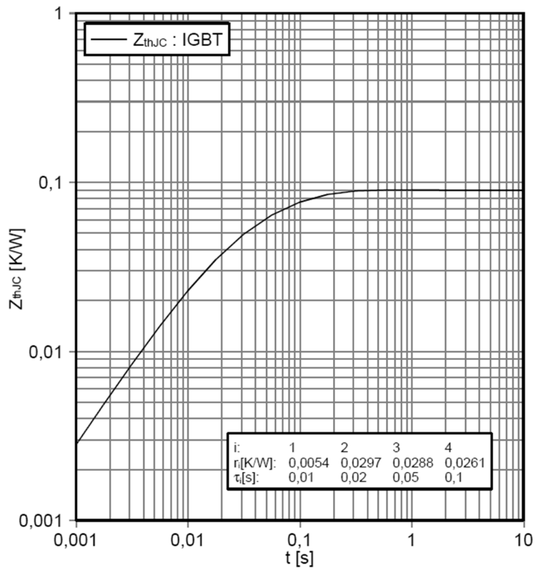
Partial fraction circuit (Foster model)



$$Z_{thjc}(t) = \sum_{i=1}^{n} r_i \cdot \left(1 - e^{-\frac{t}{\tau_i}}\right)$$

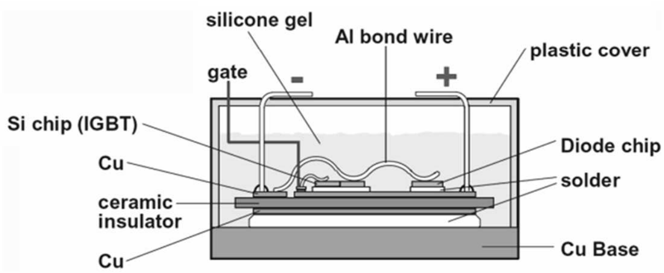
$$T_j(t) = P(t) \cdot Z_{thjc}(t) + T_{case}(t)$$

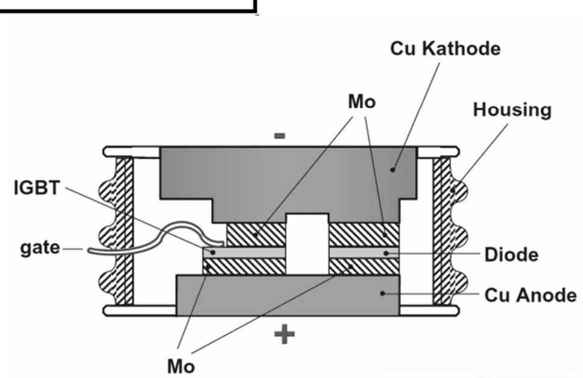
Transienter Wärmewiderstand IGBT,Wechselrichter
transient thermal impedance IGBT,Inverter
$Z_{thJC} = f(t)$



Stacking of different materials

Material	Expansion coefficient α [10^{-6}/K]
Silicon	4.1
Copper	17
Aluminum	24
Molybdenum	5
Solder	15 - 30
Ceramic	5 - 9



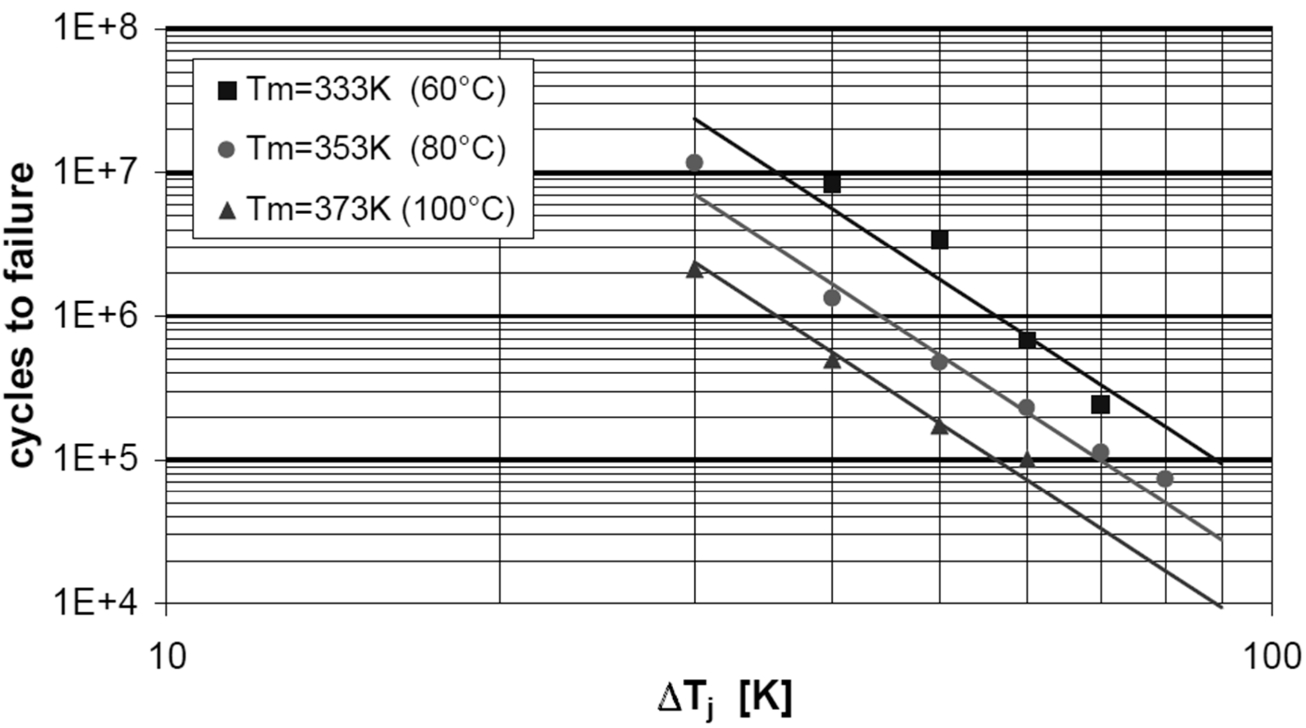


Temperature variations

- Power Cycling
  - Temperature variations of the silicon chips (fast)
  - Causes mechanical stress to bond wires
  - Bond wires lift off
  - V_{CE} increases
  - Losses increase
  - Larger temperature variations
  - Device fails
- Thermal Cycling
  - Temperature variations of the base plate (slow)
  - Causes mechanical stress to soldering joint
  - Aging of soldering joint
  - R_{th} increases
  - Larger temperature variations
  - Device fails

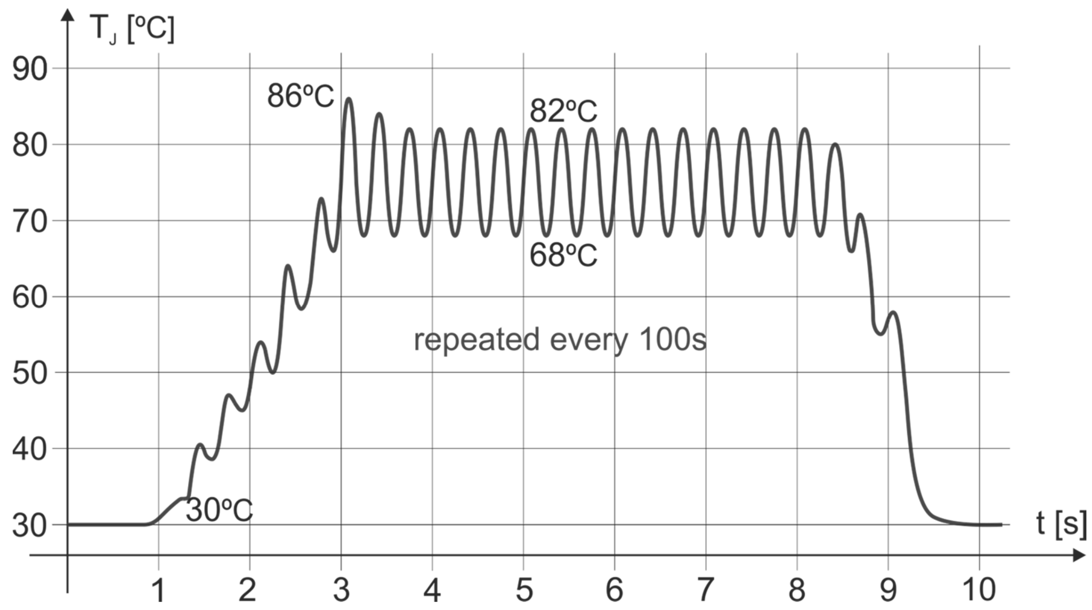
LESIT Project

Power Cycling of standard modules from various manufacturers (~1995)



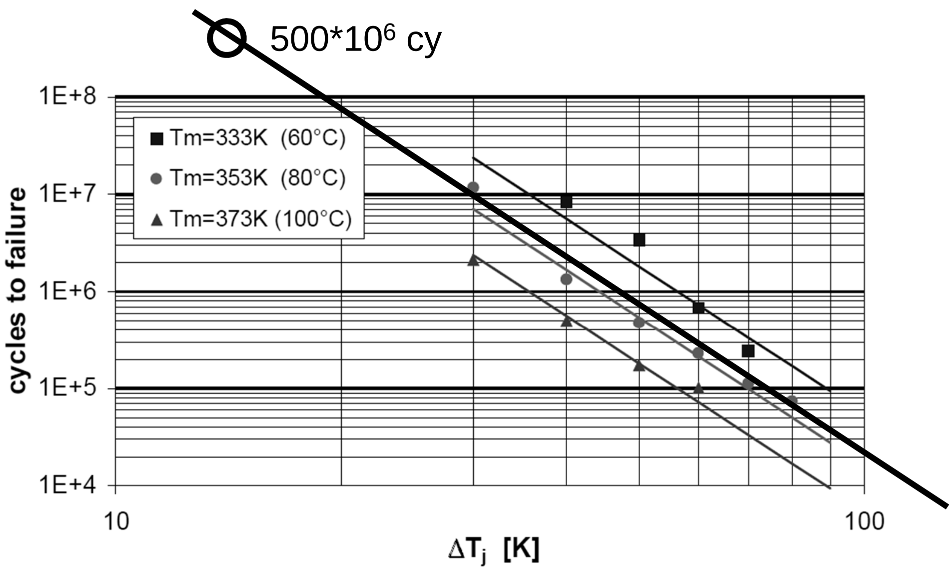
Practical Experience (1)

- SLS Booster Dipole Power Supply in Topup Mode
  - Junction temperature variations
  - IGBT failures after 3.5a of operation



Practical Experience (2)

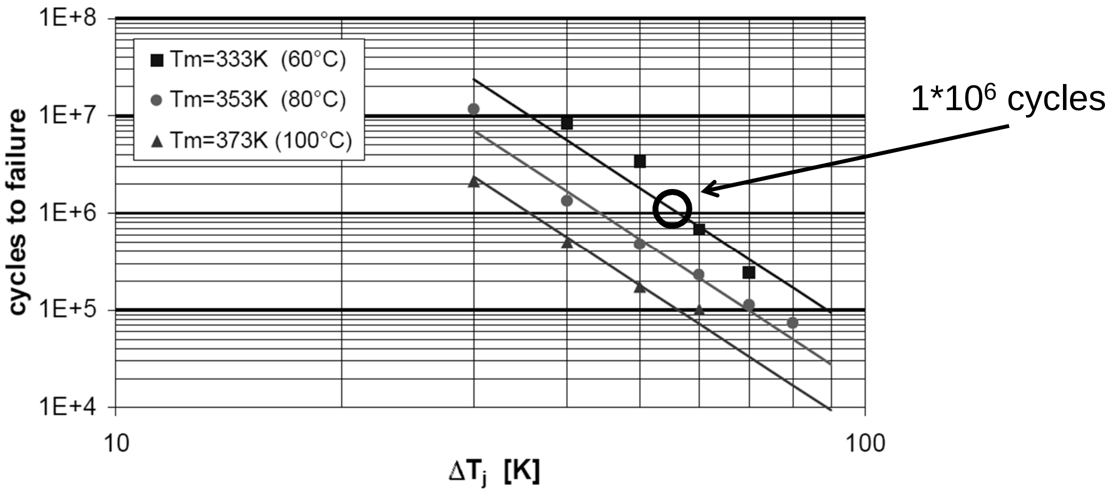
- 3Hz Oscillations: 68……82°C ΔT_j = 14K, Tm = 75°C
  - 40 weeks/a, continuous → $80*10^6$ cy/a → 6a to failure
  - 40 weeks/a, 16cy every 100s → $15*10^6$ cy/a → 33a to failure
  - Extreme extrapolation: Result valid ???



Practical Experience (3)

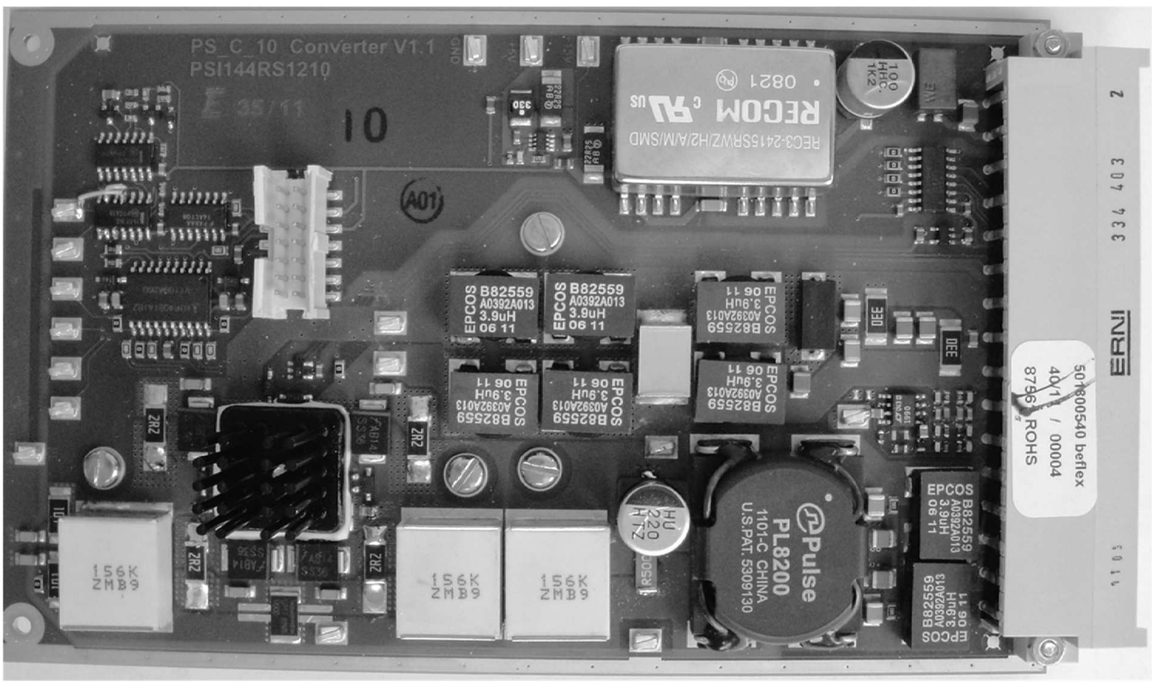
- 100s Oscillations: 30……86°C ΔT_j = 56K, Tm = 58°C
  - 40 weeks/a, 1cy every 100s   → $0.25 \cdot 10^6$ cy/a   → 4a to failure

that is, what we have experienced!



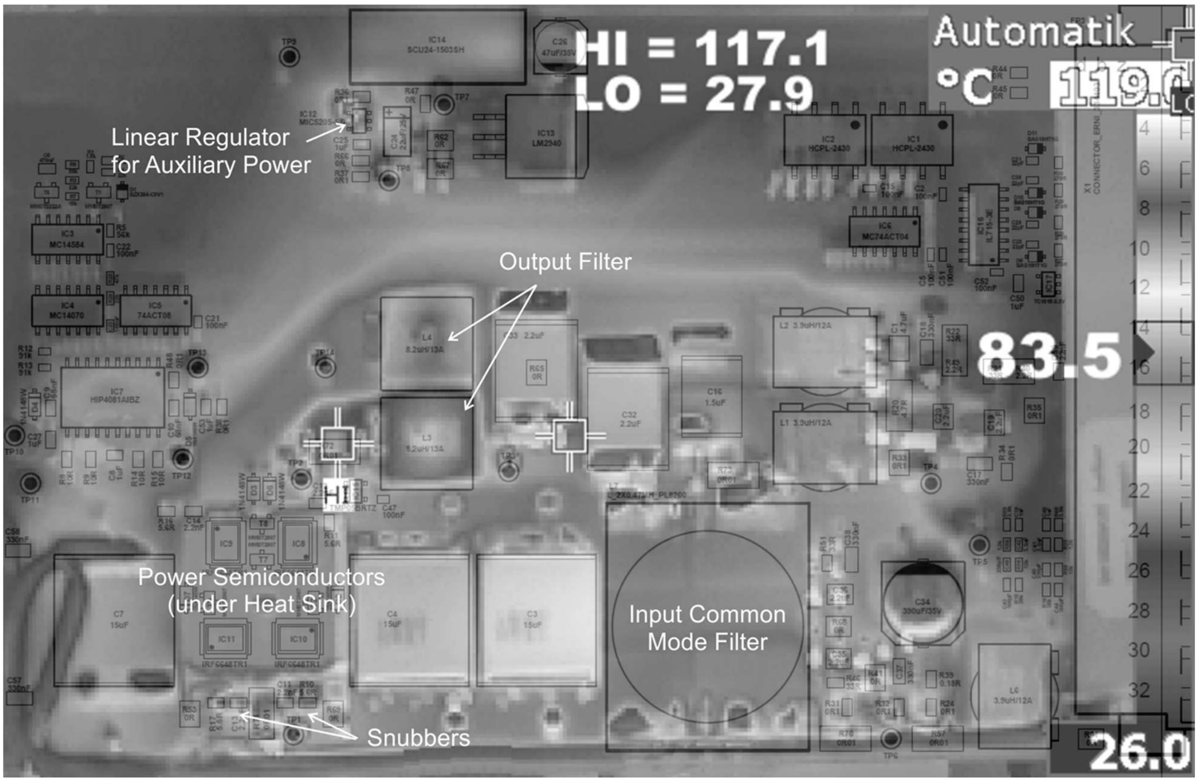
Thermal Design of a PCB

10A H-bridge on a PCB 100mm 160mm

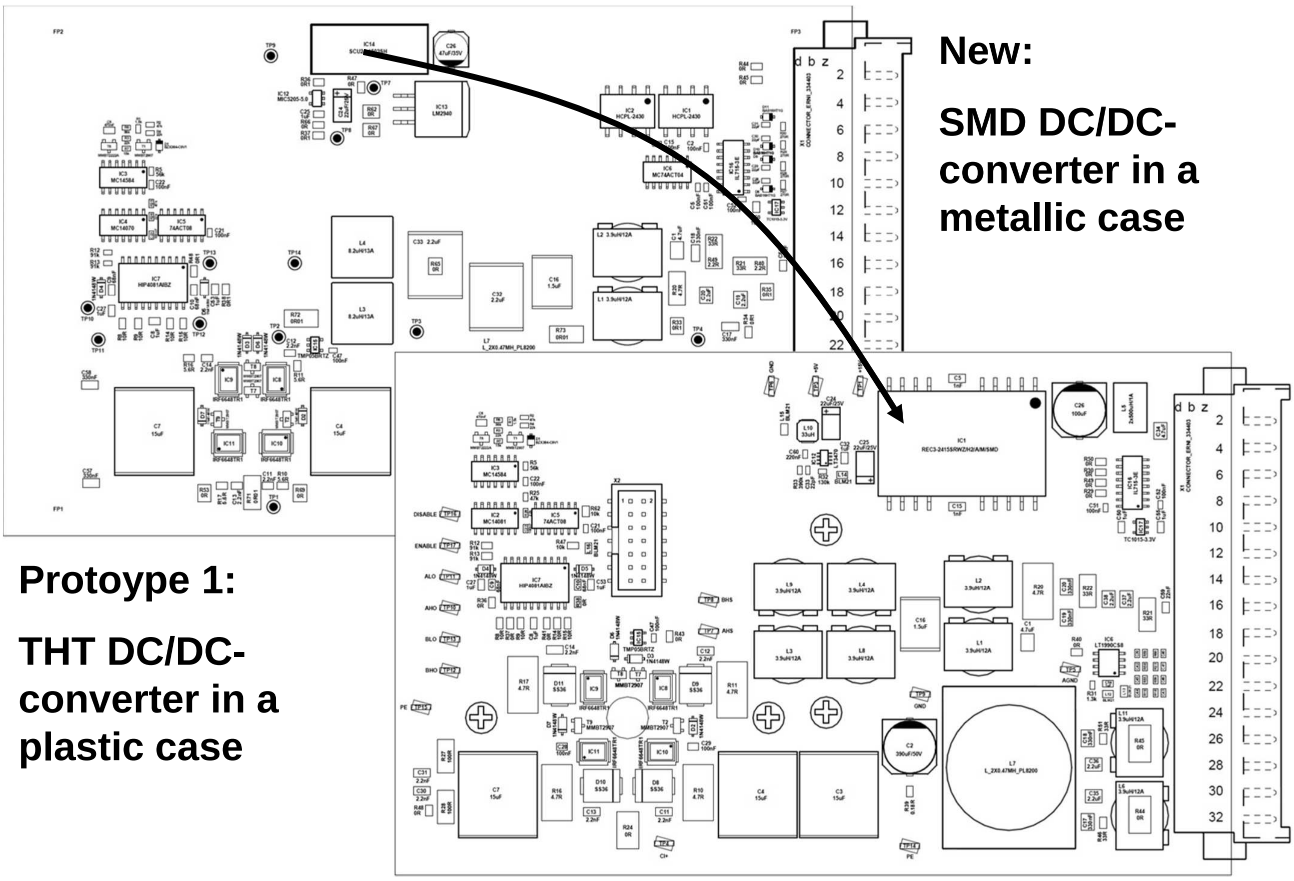


First prototype

Infrared image at full load



Replace DC/DC converter 24V/15V



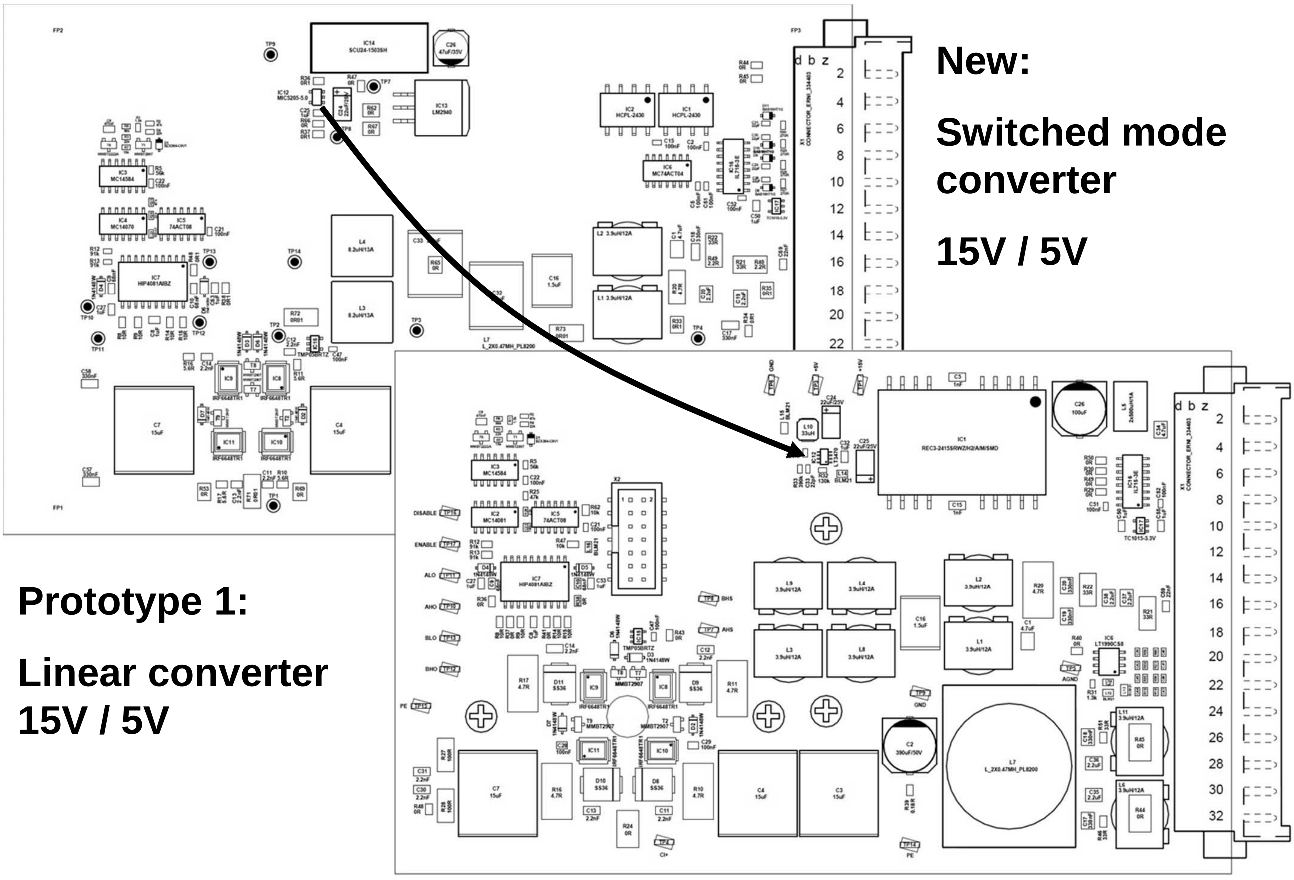
New:

SMD DC/DC-converter in a metallic case

Protoype 1:

THT DC/DC-converter in a plastic case

Replace DC/DC converters 15V/5V



New:

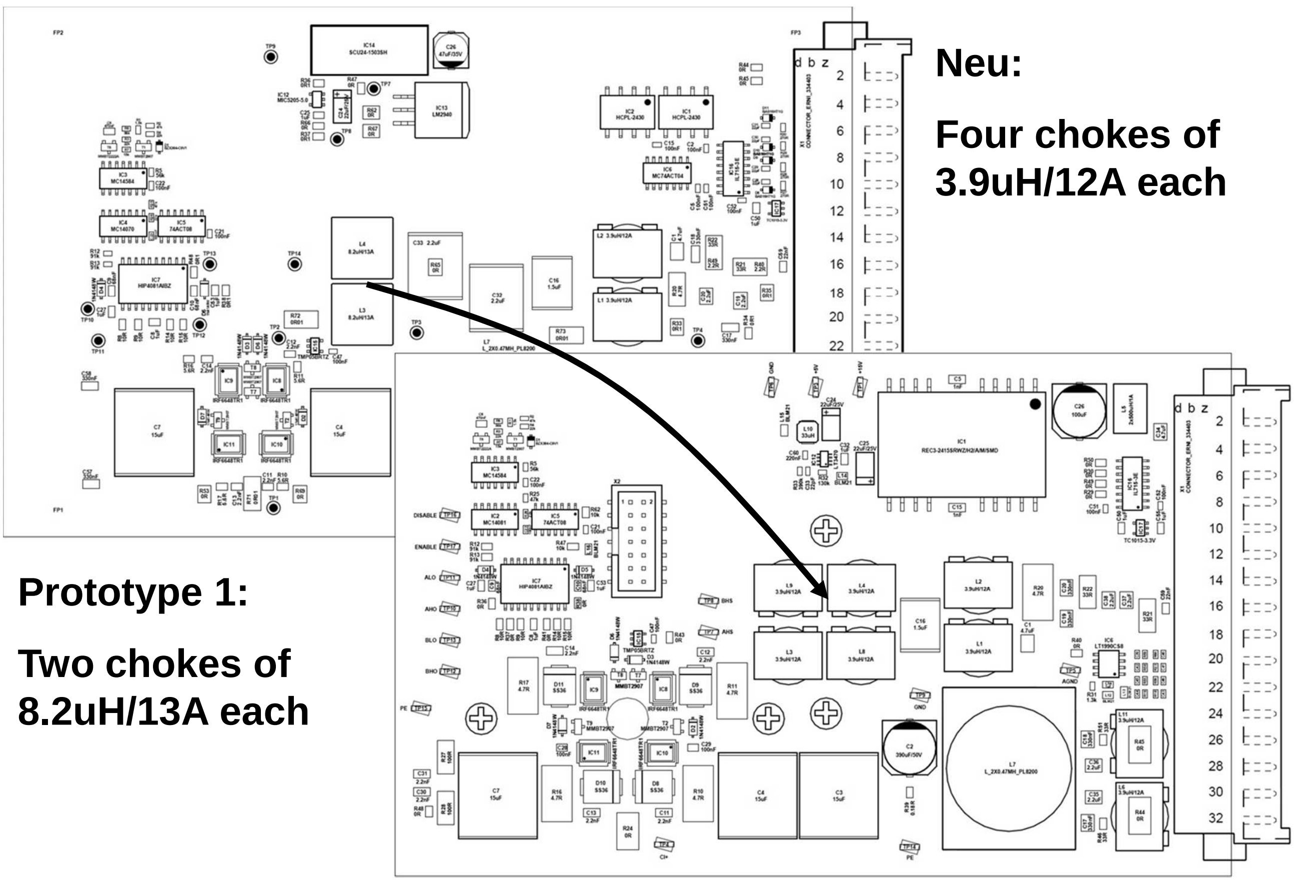
Switched mode converter

15V / 5V

Prototype 1:

Linear converter 15V / 5V

Replace filter chokes



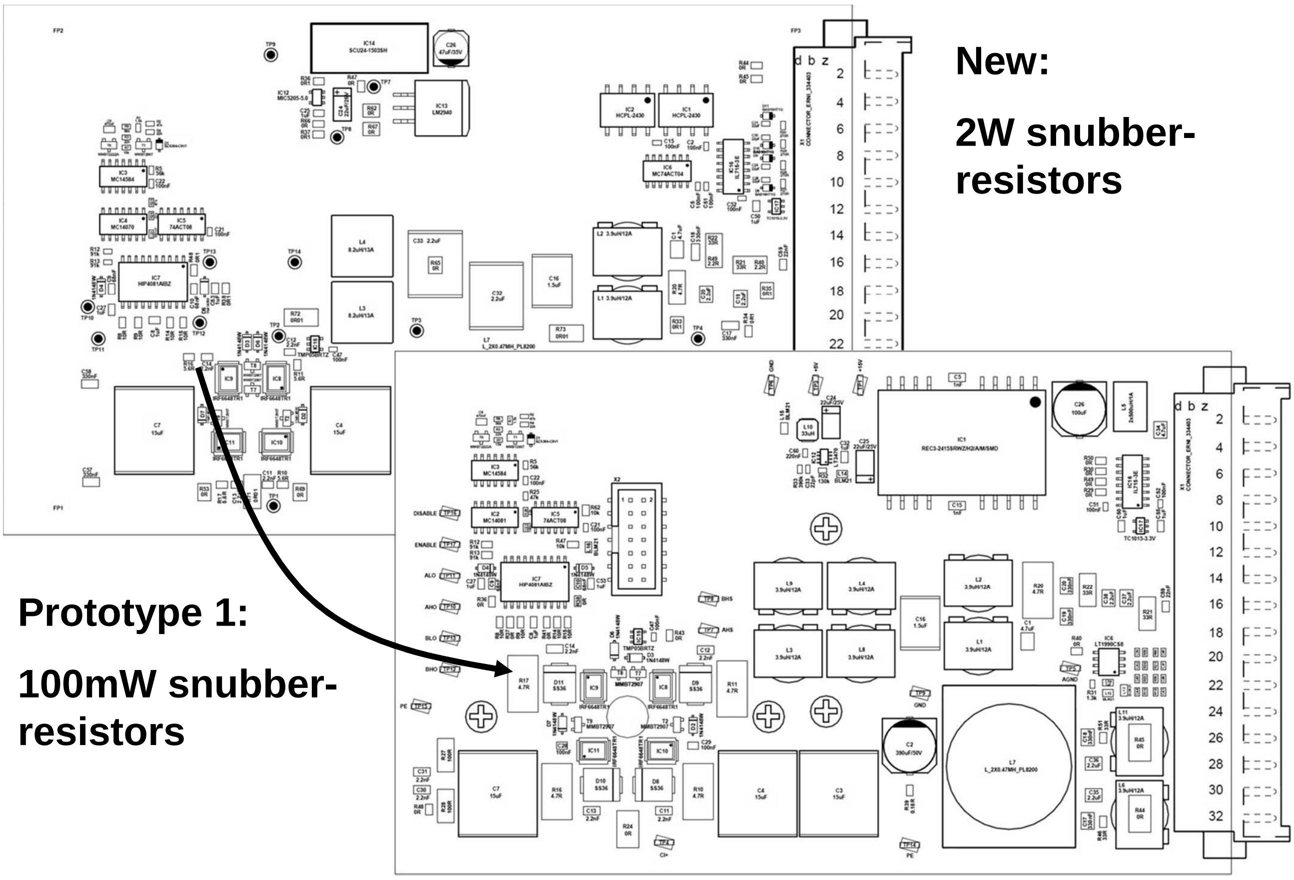
Neu:

Four chokes of 3.9uH/12A each

Prototype 1:

Two chokes of 8.2uH/13A each

Replace snubber resistors



New:

2W snubber-resistors

Prototype 1:

100mW snubber-resistors

Improve heat flow

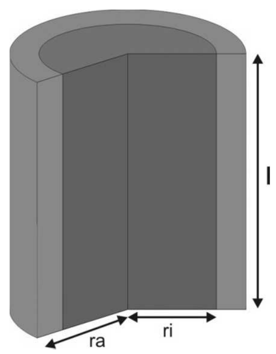
- Thermal conductivity of different materials λ [W/K m]
  - Gold 318
  - Silver 429
  - Copper 401
  - Aluminum 237
  - Steel 50
  - Heat transfer foil 2
  - PCB core material (FR-4) 0.3
  - Air 0.025

Improve heat flow

- Heat path through the PCB
  - Mounting area of semiconductors A = 2cm x 2cm = 4cm^2
  - Distance from top to bottom layer l = 1.6mm
  - Thermal conductivity PCB core (FR-4) λ = 0.3 W/K m
  - Total losses in the semiconductors P ≈ 10W
  - Thermal resistance: $$R_{th} = \frac{l}{\lambda \cdot A} = \frac{1.6mm \cdot m \cdot K}{0.3W \cdot 4cm^2} = 13.3\frac{K}{W}$$
  - Temp. difference Top - Bottom $$\Delta T = R_{th} \cdot P = 13.3\frac{K}{W} \cdot 10W = 133K$$

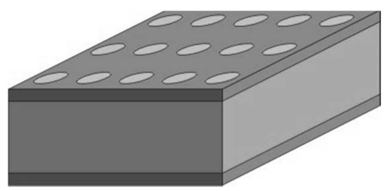
Improve heat flow

- Additional heat path through vias
  - Outside radius ra = 0.175mm
  - Inside radius ri = 0.15 mm
  - Via heigth l = 1.6 mm
  - Thermal conductivity of Cu λ = 400 W/K m



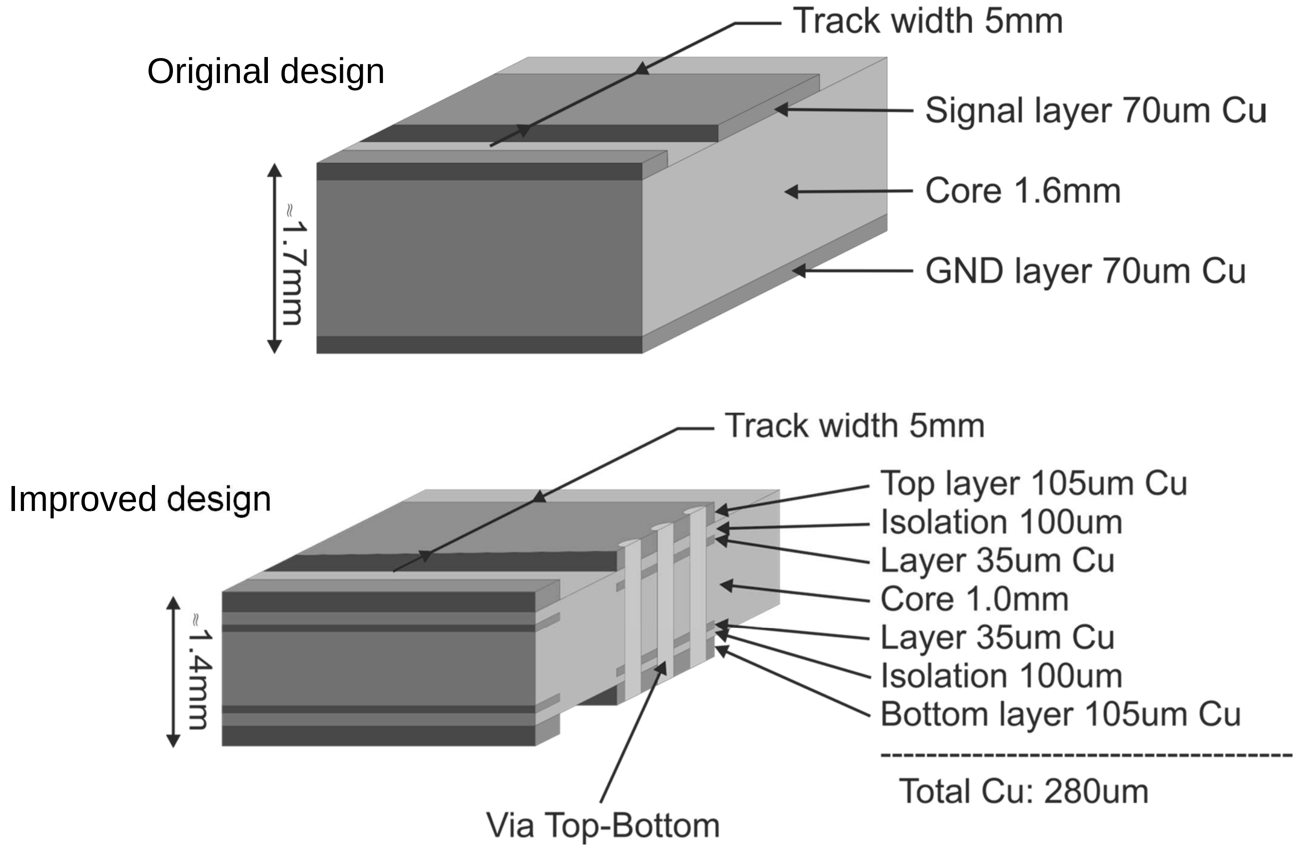
$$A = (ra^2 - ri^2) \cdot \pi = ((0.175mm)^2 - (0.15mm)^2) \cdot \pi = 0.0255mm^2$$

$$R_{th} = \frac{l}{\lambda \cdot A} = \frac{1.6mm \cdot m \cdot K}{400W \cdot 0.0255mm^2} = 156.8\frac{K}{W}$$

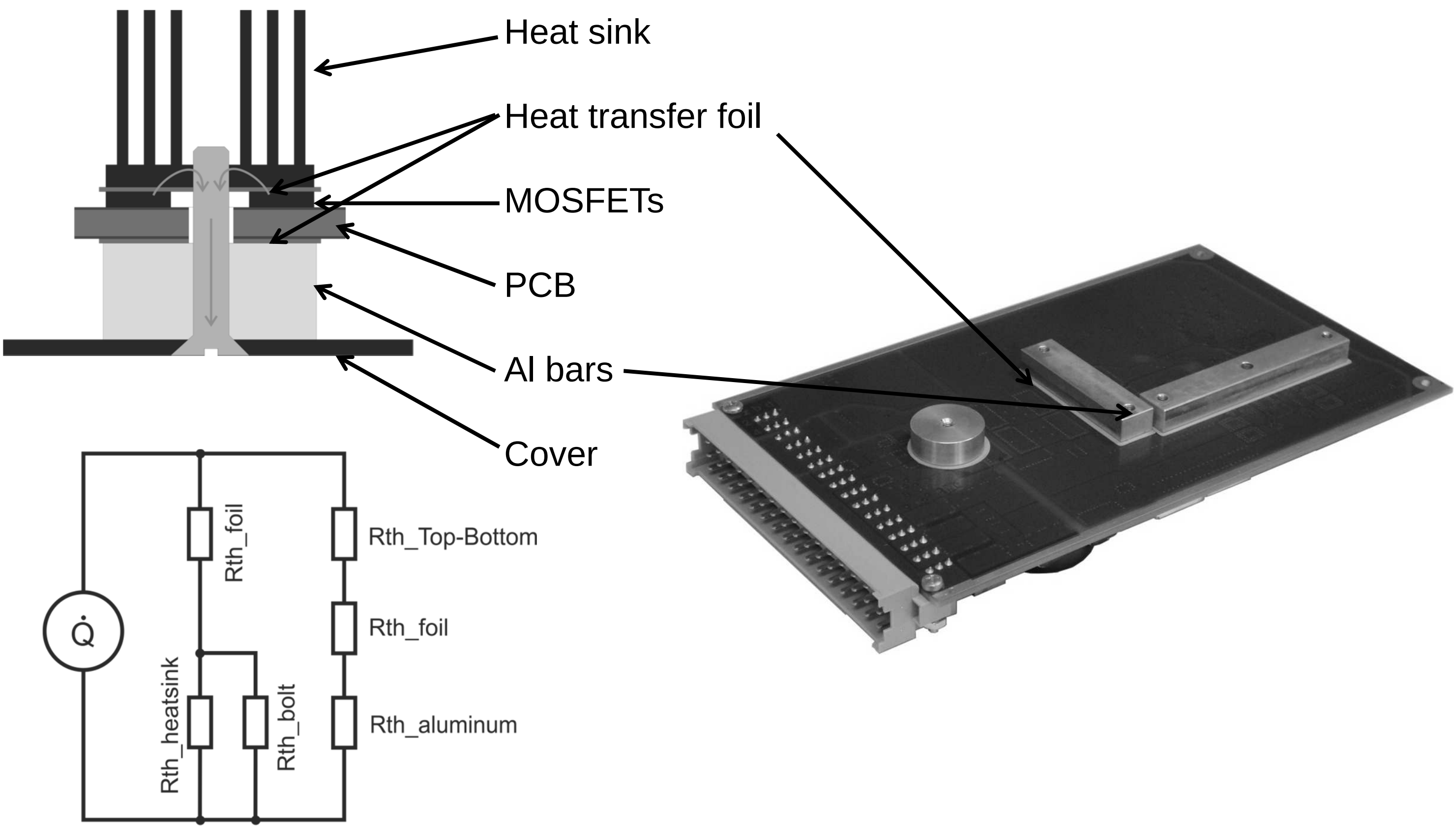


  - On 4 cm^2 there is space for 8 x 8 = 64 vias
  - Thermal resistance of 64 vias: $R_{th} = 2.45K/W$
  - Temperature difference Top - Bottom $$\Delta T = P \cdot \frac{1}{\frac{1}{R_{th-LP}} + \frac{1}{R_{th-Via}}} = 10W \cdot \frac{1}{\frac{1 \cdot W}{13.3K} + \frac{1 \cdot W}{2.45K}} = 20.7K$$

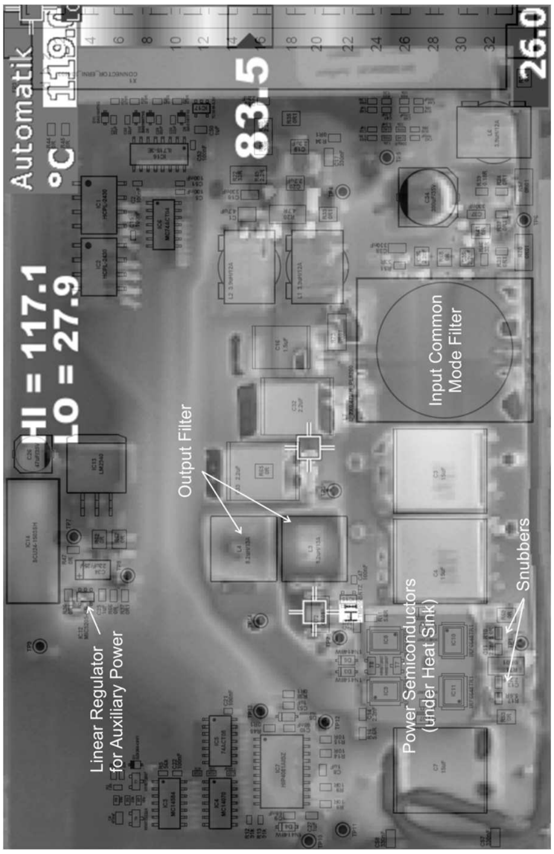
Improve heat flow

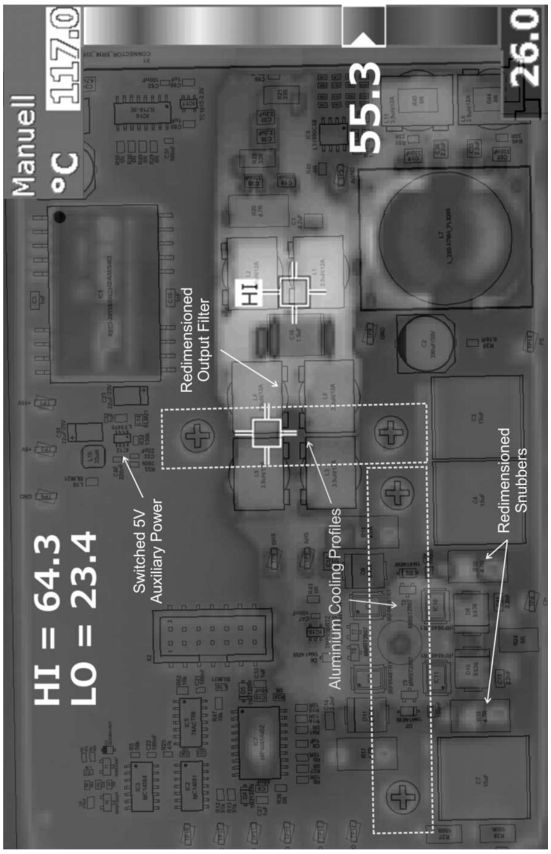


Heat transfer to ambient



Comparison Prototype 1 and 2





Better heat spreading

Lower temperatures

Good corre-lation with calcualtions

Thank you for your attention

Questions?

References

[1] Infineon, Datasheet FF600R06ME3 Rev. 3.1

[2] Semikron, Applikationshandbuch Leistungs-halbleiter, VSL Verlag 2010

[3] Infineon, Thermal equivalent circuit models, AN2008-03

[4] Infineon, Technical Information IGBT modules, Use of Power Cycling curves for IGBT4, AN2010-02