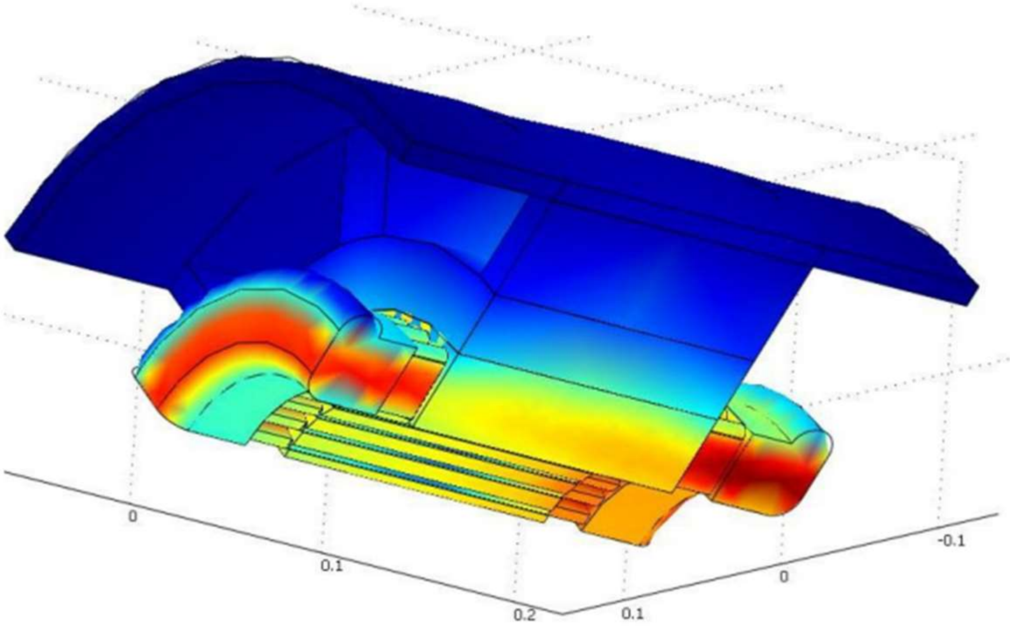
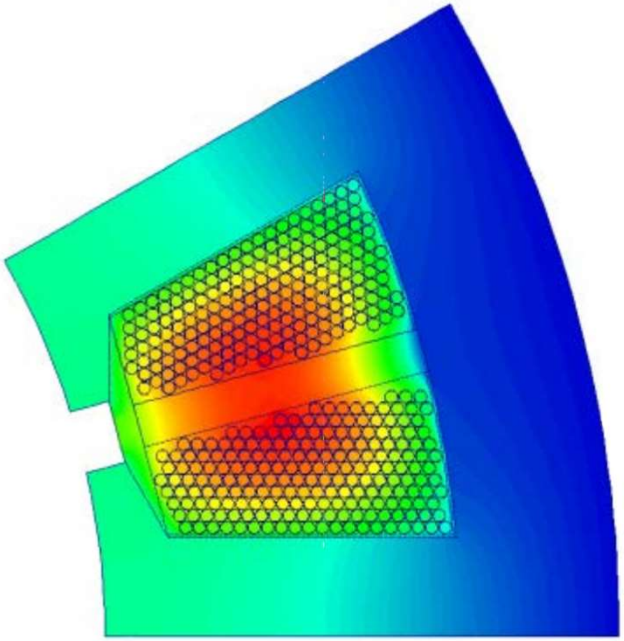
Losses



Losses in electrical machines



Loss spectrum

Proportional to current squared

Proportional to current squared and speed

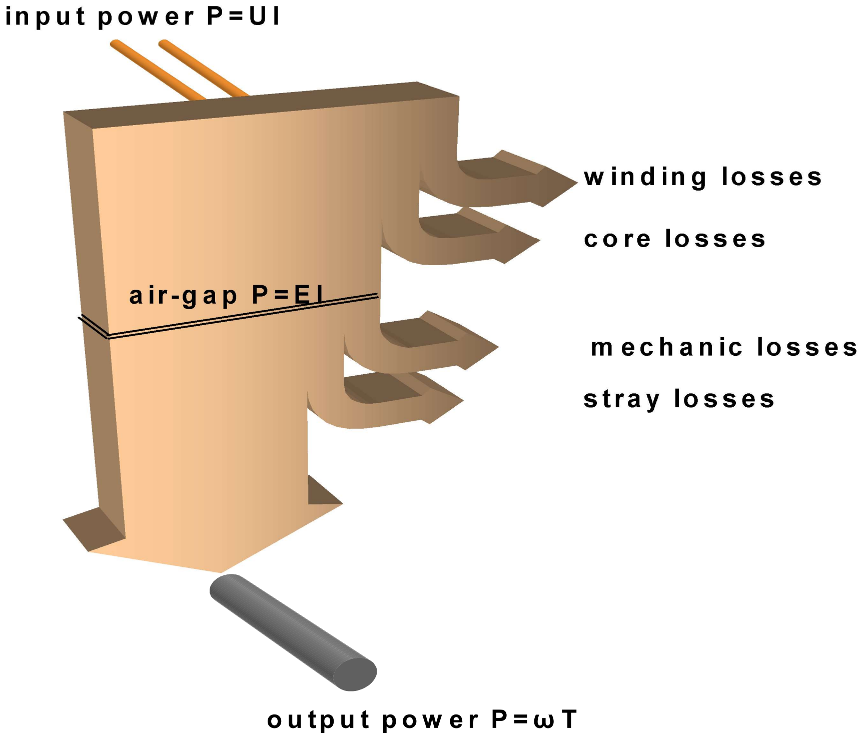
Proportional to speed

Proportional to square of speed

Proportional to cube of speed

$$P_{loss} = P_{dc} + P_{ac} + P_{hyst} + P_{eddy} + P_{frict}$$

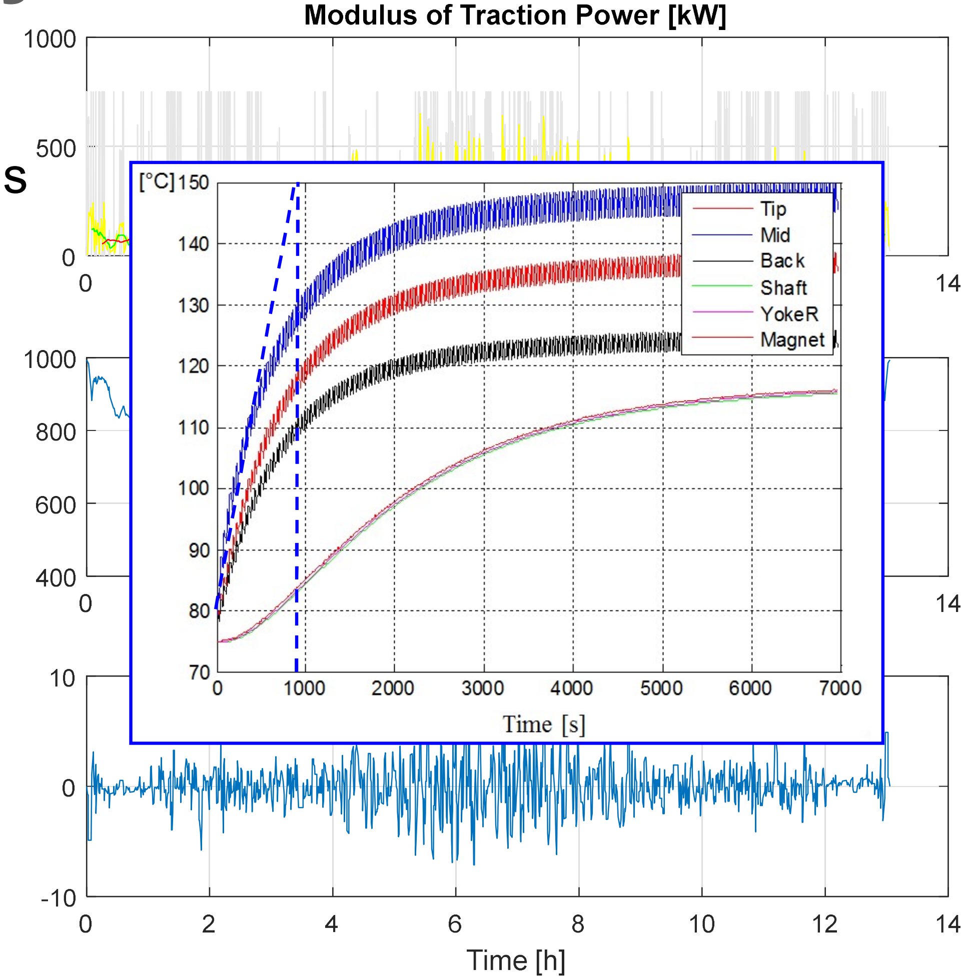
- P_{dc} – losses independent of the frequency
  - *dc winding loss, dependent on temperature and load*
- P_{ac} – *losses that depend on frequency*
  - *like resistive losses in skin depth*
- P_{hyst} – losses proportional to the frequency
  - *hysteresis loss, dependent on magnetization magnitude*
- P_{eddy} – losses proportional to the square of frequency
  - *eddy current losses*
- P_{frict} – losses proportional to the cube of frequency
  - *mechanic + air friction loss*



Heavy Duty Trucks

- Daily travel distance > 800 km
- 30..90 tons
- Full Electric now possible
  - On batteries, with ”Mega” Charging
  - On Electric Roads

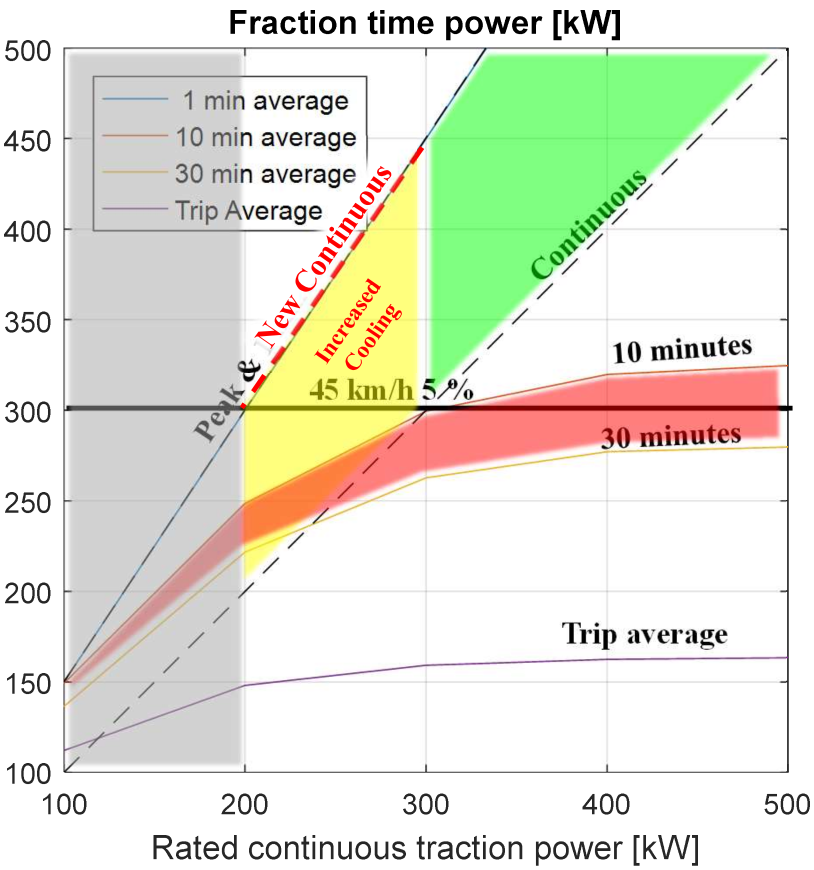
Full Electric Heavy Duty Trucks



- High power levels, during extended periods
  - Significant cooling requirements
- HDT in tough Long Haul cycle:
  - 44 ton
  - 500/750 kW traction power (cont/peak)
  - 13 h operation roundtrip
  - Max 60 [s] average Power = 651 [kW]
  - Max 600 [s] average Power = **325** [kW]
  - Max 1800 [s] average Power = **280** [kW]
  - Full trip average Power = 163 [kW]
- Is that reasonable?

Less power?

- Try 100...500 kW CONTINUOUS
- ... with 150...750 kW PEAK
  - *Assume thermal time constant 10...30 minutes*
  - *Assume >300 kW for performance*
  - *< 200 kW underperforms*
  - *200...300 kW enough, but overheating may occur ...*
  - *>> 300 kW overperforms?*
- Lower power with Increased Cooling may be interesting
  - *5...10 % less energy consumption*



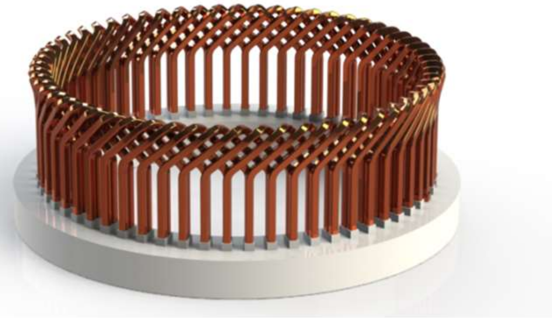
Increased Cooling ...?

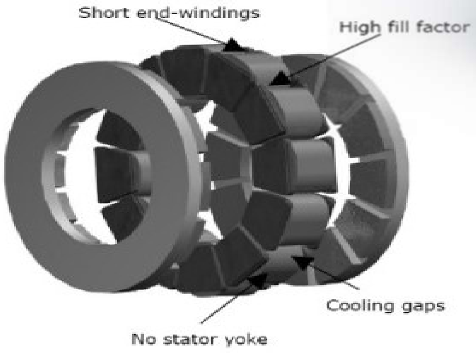
- Air cooling outside
- Water sleeve cooling
- Oil cooling, also on end winding and maybe inside rotor

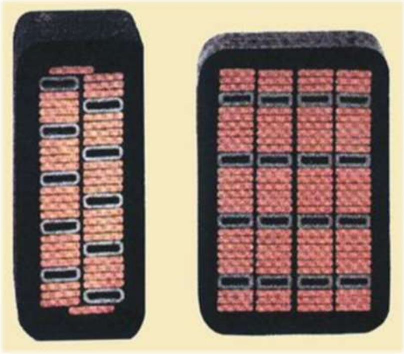
Peak Power determined by thermal capacitance

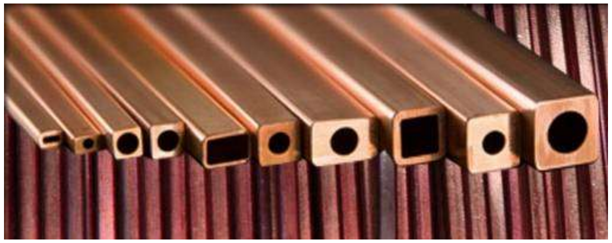
- Oil cooling directly on the windings
- Cooling inside the stator windings
- Cooling inside the stator conductors

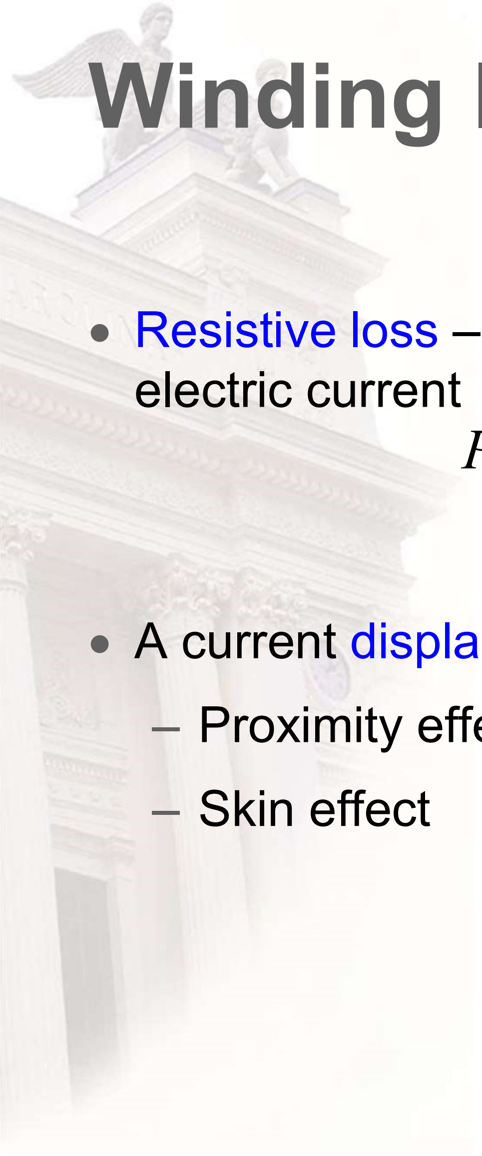
Peak Power determined by Direct winding cooling capability











Winding losses

- Resistive loss – energy wasted due to a material's opposition to the flow of electric current

$$P = \int \rho_{\vartheta} J^{2} dV \qquad \rho_{\vartheta} = \rho_{0} \cdot \left(1 + \alpha \left(\vartheta - \vartheta_{0}\right)\right)$$

- A current displacement effect – due to the opposing induced currents
  - Proximity effect
  - Skin effect

$$\nabla \times E = -\frac{\partial B}{\partial t} = -\frac{\partial}{\partial t}\left(\nabla \times A\right)$$

$$J = \frac{E}{\rho_{\vartheta}} - \frac{1}{\rho_{\vartheta}} \frac{\partial A}{\partial t}$$

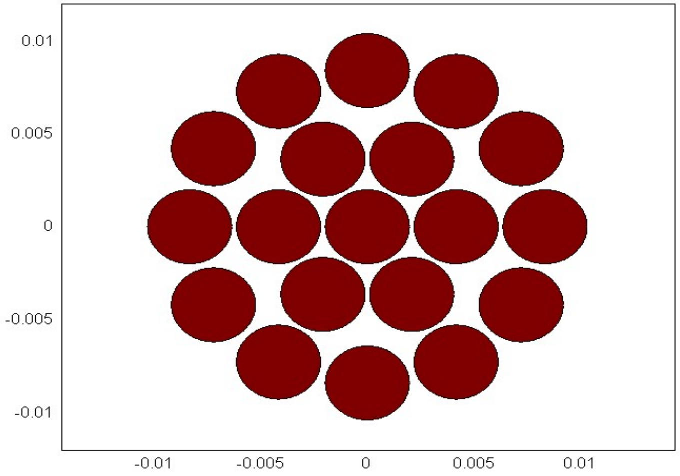
Static conductor loss – energy dissipated by resistance

Time independent current flow has uniform distribution, and the apparent conductor cross-section equals the actual one

$$P_{cu} = \rho_0\left(1 + \alpha(\vartheta - \vartheta_0)\right) \cdot J^2 \cdot \frac{\bar{L}_{cu}}{A_{cu}}$$

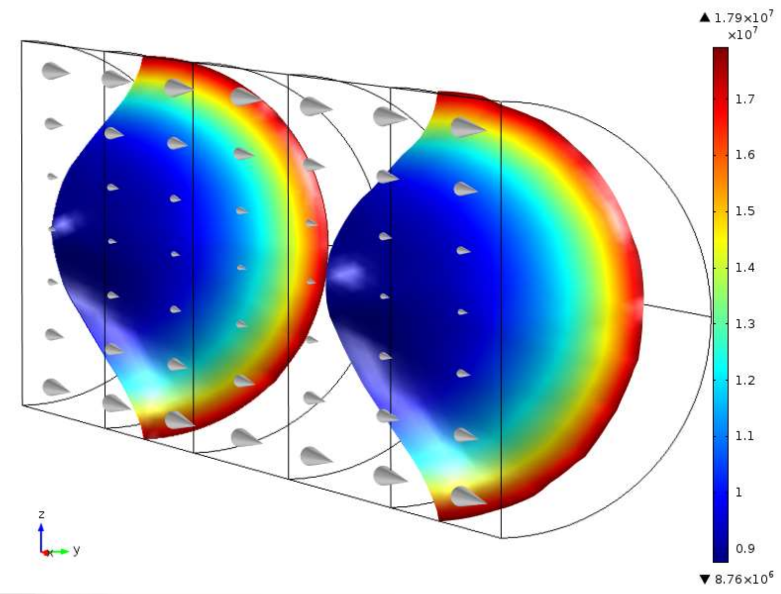
$$A_{cu} = N \cdot \pi \cdot r_c^2 = A_{slot} \cdot k_{fill}$$

- resistivity **ρ(ϑ)** [Ωm] at J
- temperature coefficient **α** [1/K]
- temperature ϑ [K]
- current density **J** [A/m^2]
- total cross-section area of N conductors **A_{cu}** [m^2]
- average length of N conductor turns **L_{cu}** [m]
- radius of the conductor **r_c** [m]
- filling factor **k_{fill}** [-]



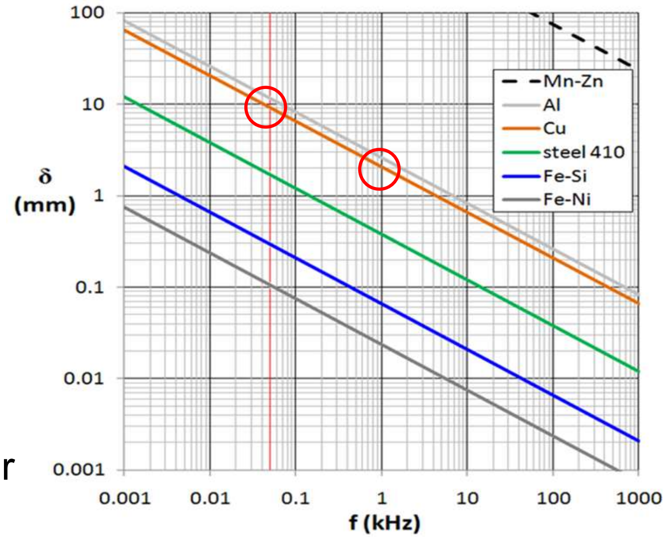
Skin effect – due to the current in the conductor itself

Induced currents oppose the applied current in the interior of the conductor and confine the current to flow on the surface layer of conductor



$$\delta = \sqrt{\frac{2\,\rho_{\vartheta}}{\omega\mu}}$$

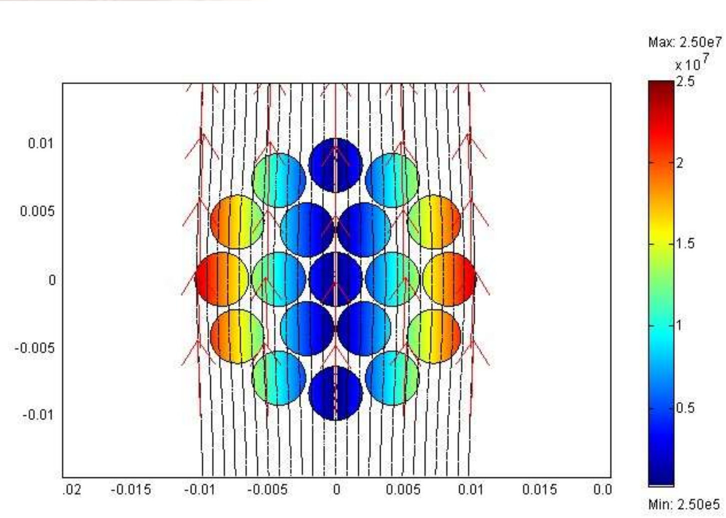
- skin penetration depth for a single conductor *δ(J)* [m] at *J*
- frequency *ω* [rad/s]
- magnetic permeability *μ* [Vs/Am]
- resistivity of electric conductor *ρ(J)* [Ωm] at *J*



Proximity effect – due to the external field variation

As a result of external field, the induced currents cause non-uniform current flow in the conductor

$$p_{ec}(t) = \frac{E^2}{\rho_\vartheta} \qquad E_z(x) = -x\frac{dB_y}{dt} \qquad P_{ec}(t) = \frac{r_c^2}{4\rho_\vartheta}\int_{Vcu}\left(\frac{dB}{dt}\right)^2 dV$$

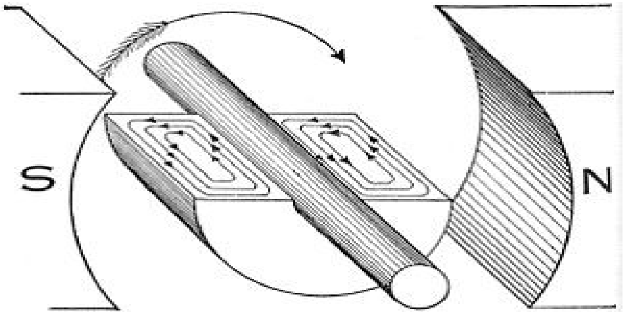


Induced currents @ Hy=100kA/m 50Hz

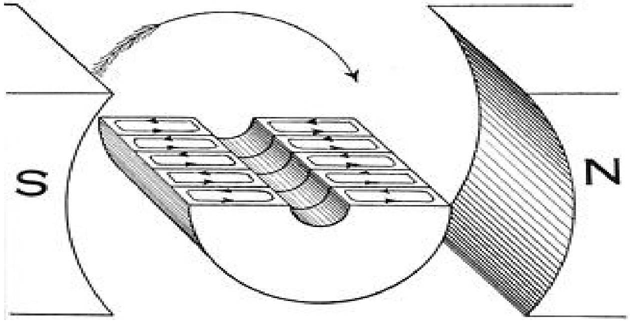
- electric field intensity E [V/m]
- magnetic induction B [Vs/m^2]
- resistivity of electric conductor ρ(J) [Ωm] at J

Reducing eddy current losses in the Core

SOLID

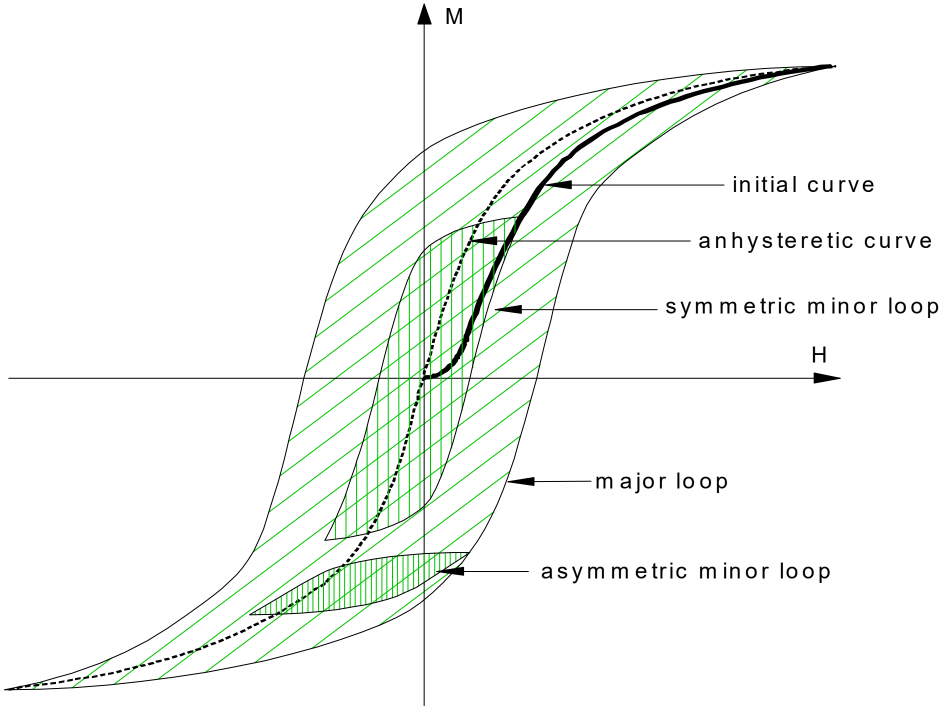


LAMINATED



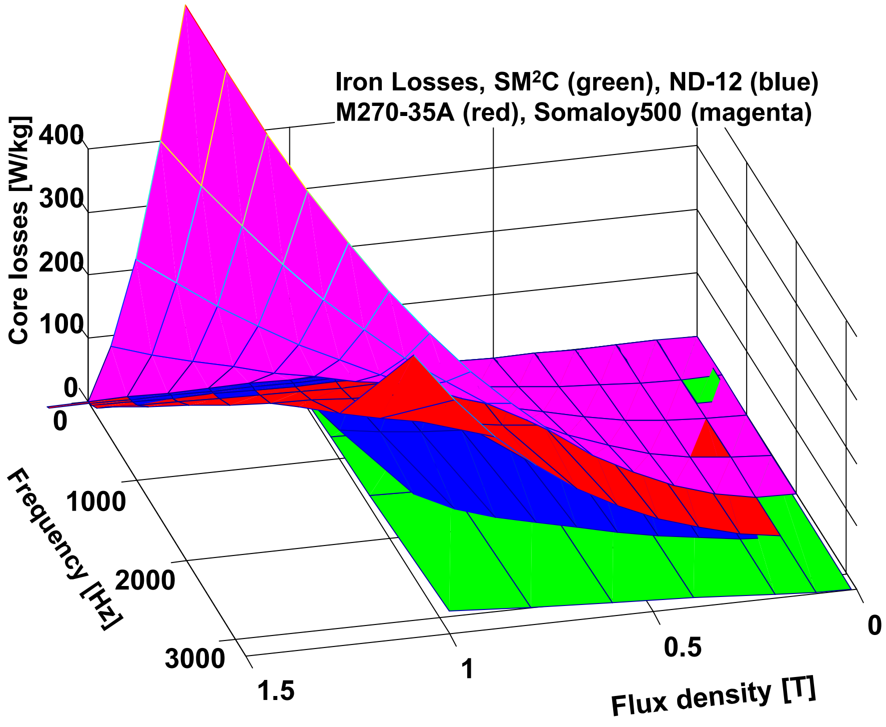
Hysteresis – magnetic friction

- Major loop
- Minor loops
- Irreversible magnetizations (with loss)
- Reversible magnetizations (no loss)
- Dynamic effects
- Dependence on shape and temperature



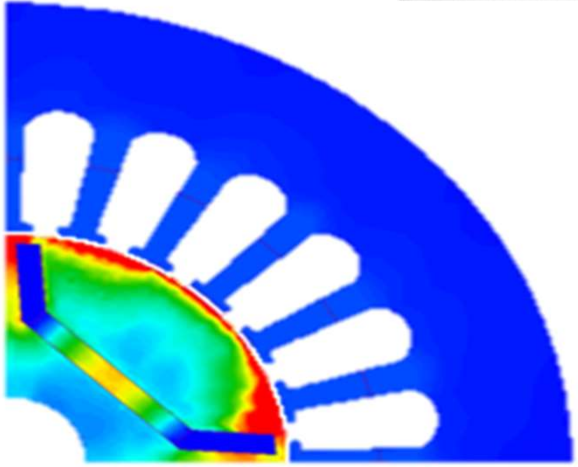
Material properties - losses

- Conductor losses due to resistivity
  - Copper
    0.017.09 Wmm^2/m
  - Aluminum
    0.027.89 Wmm^2/m
    = + 63% vs Cu
- Iron losses, due to eddy currents and hysteresis
- Increase non-linear with both flux density and frequency



Permanent magnet losses

- Due to variation of the magnetic flux through the magnets.
- Just like other eddy current losses.
- Can be reduced by splitting the magnets in smaller parts, isolated from each other.



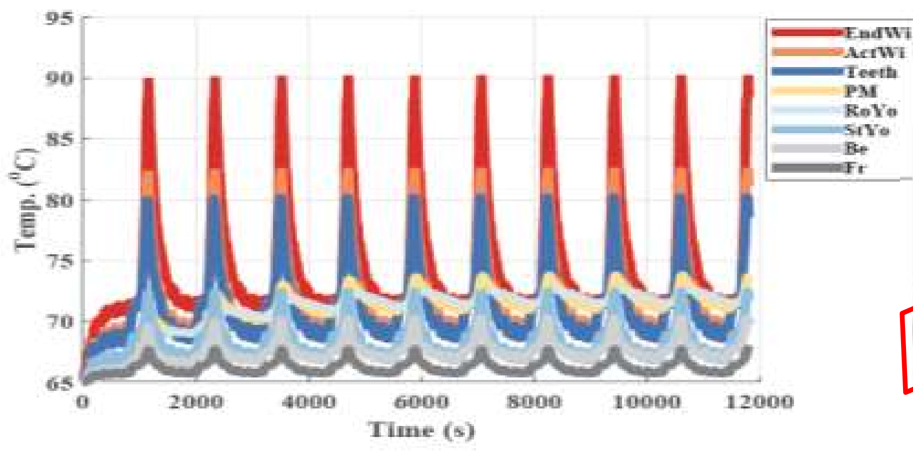
Thermally induced degradation

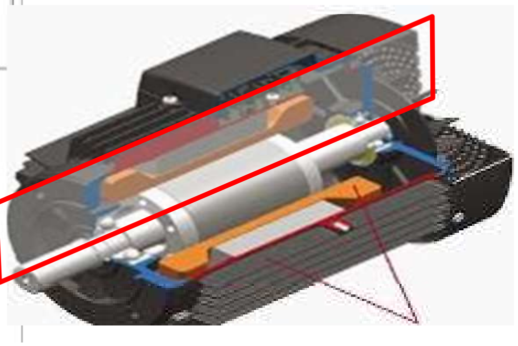
- Degradation of the Electric Insulation System
  - *Degradation and failure of **electrical machine***
  - *Degradation and failure of **electrified vehicle***

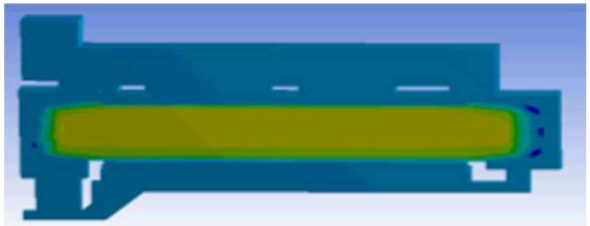
- TEAM stresses
  - ***T**hermal*
  - ***E**lectrical*
  - ***A**mbient*
  - ***M**echanical*

Dynamic temperatures

	Grid Fed **Industrial** Electrical Machine (EM)	**Industrial** EM on variable speed control	**Traction electrical machine**
Loading profile	Steady	Moderately variable	Variable from idle to peak power
Temperatures	Steady temperature	Steady temperature	Sudden changes in temperature
Life expectancy	~20,000 hrs	~20,000 hrs	~8,000 hrs (passenger vehicles) ~60,000 hrs (commercial vehicles)



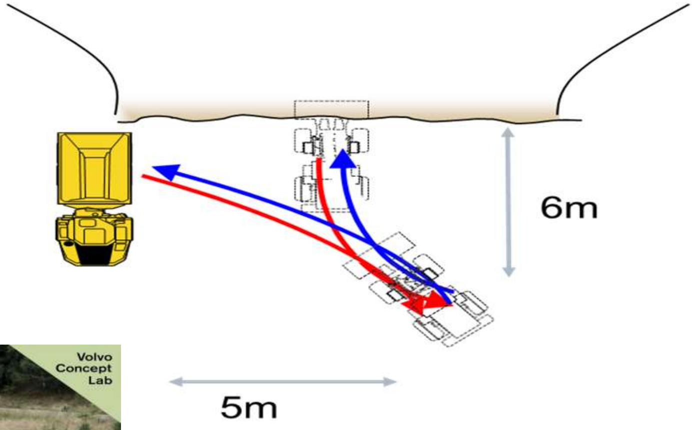




EMMA ARFA GRUNDITZ, "Design and Assessment of Battery Electric Vehicle Powertrain, with Respect to Performance, Energy Consumption and Electric Motor Thermal Capability", PhD Thesis, Chalmers University of technology, ISSN 0346-718X, Sweden, 2016

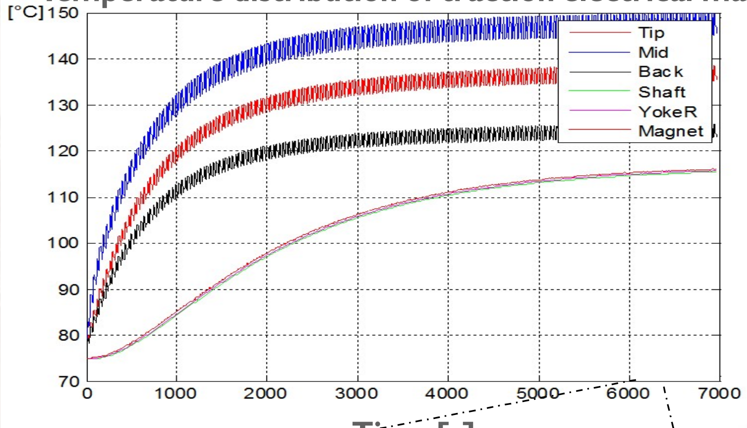
Application example – Wheel Loader

- Four wheel driven by electrical machines
- Short loading cycle (SLC)
  - Filling bucket
  - Leaving pile
  - Towards truck
  - Emptying bucket
  - Leaving truck
  - Toward pile

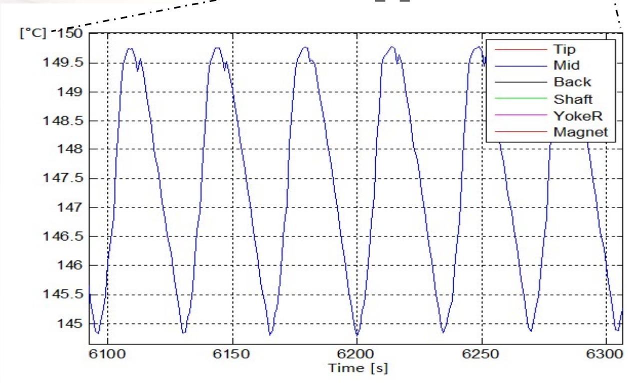


Traction Electrical machines temperatures after 200 Short Loading cycle (SLC)

Temperature distribution of traction electrical machine

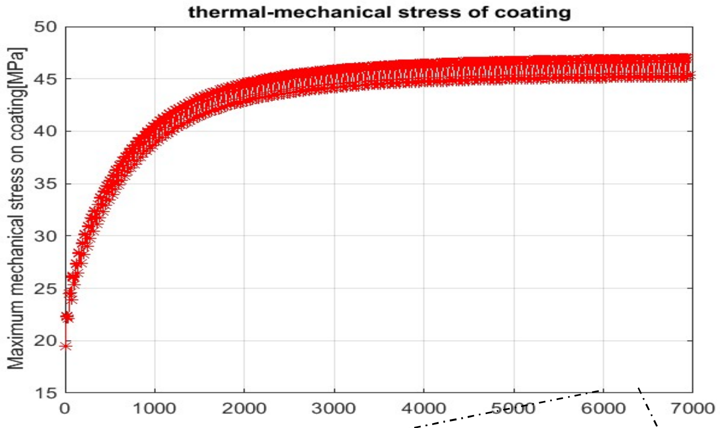


Time [s]

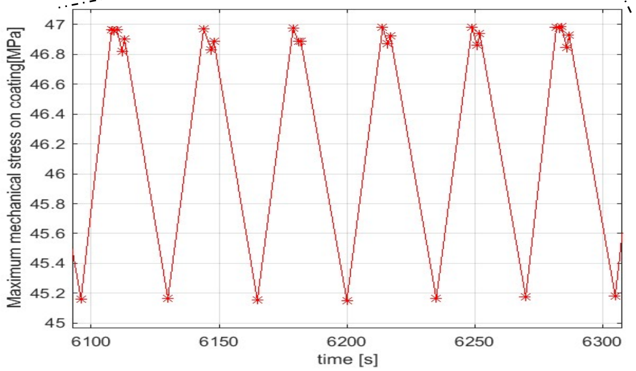


Traction Electrical machines thermal-mechanical stress after 200 Short Loading cycle (SLC)

Thermal-mechanical stress [MPa] in winding coating



Time [s]

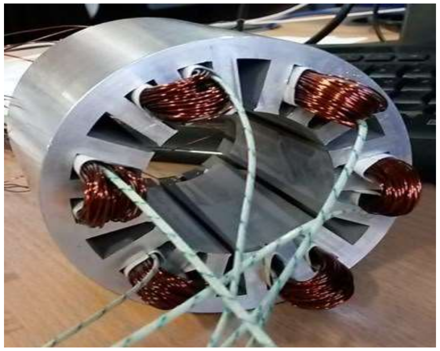


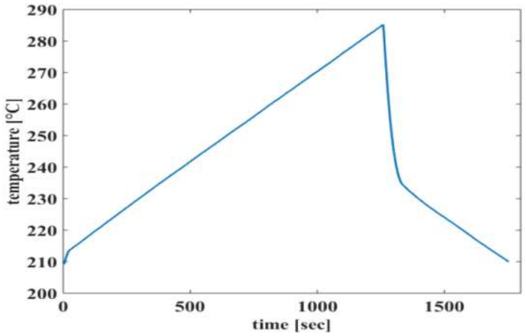
Other examples – thermal cycling

- Voitto Kokko, Fortum, ’Aging Due to Thermal Cycling by Power Regulation Cycles in Lifetime Estimation of Hydroelectric Generator Stator Windings’

Root cause	Distribution
Ageing by number of operation hours	15%
Ageing by thermal cycling	38%
Internal PD & defective corona protection	27%
Mechanical condition	8%
Vibration	8%
Contamination	4%

- C. Sciascera, University of Nottingham, ‘Lifetime Consumption and Degradation Analysis of the Winding Insulation of Electrical Machines’





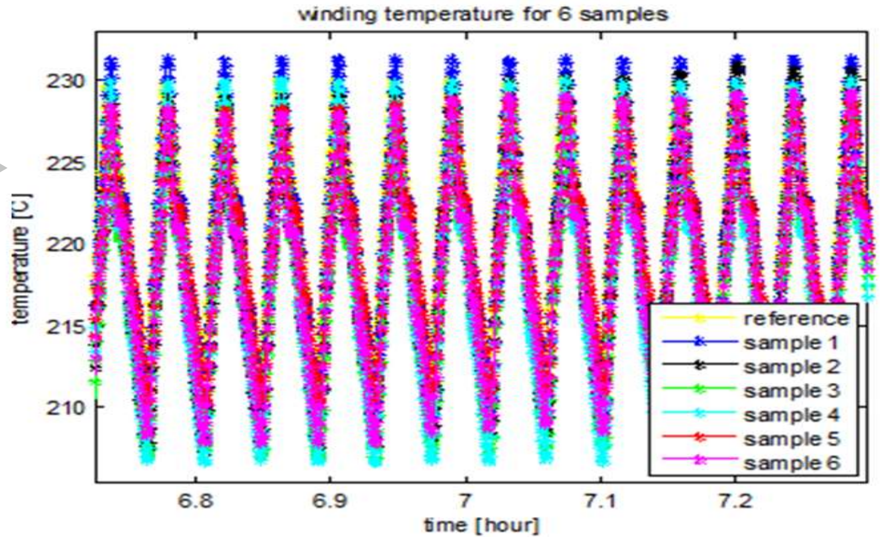
Expected lifetime: 713 hours,
Actual lifetime: 90 hours.

Thermal cycles – tested

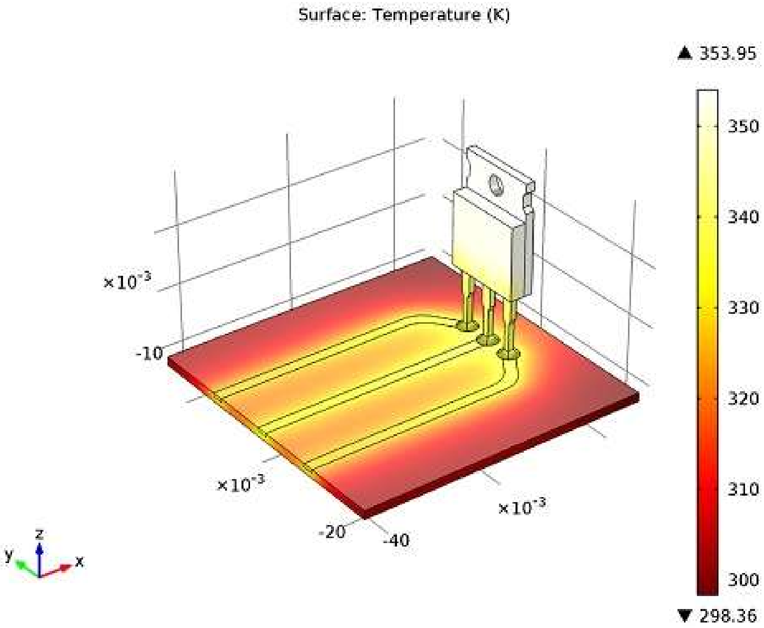
- Table shows three tested cycles with 20˚C depth

Cycle No.	θ_{min} [°C]	θ_{max} [°C]	τ [s]
# 1	210	230	150
# 2	190	210	250
# 3	180	200	250

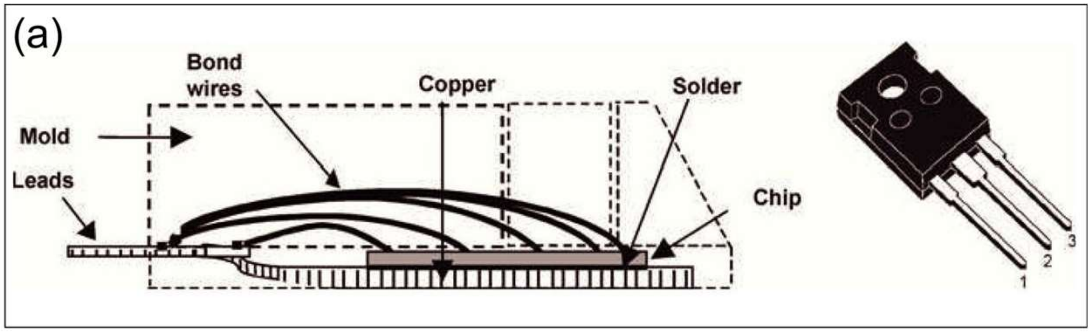
- Plot of measured hot spot temperatures (cycle #1)

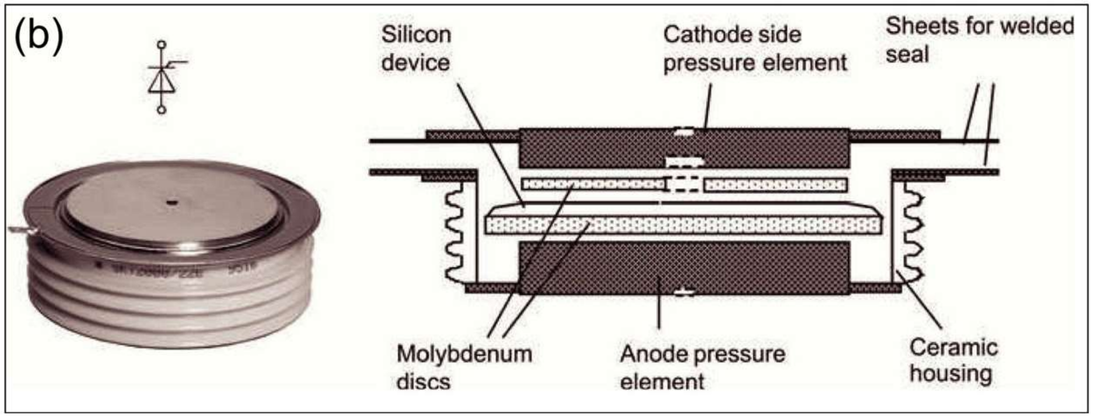


Losses in power electronic converters

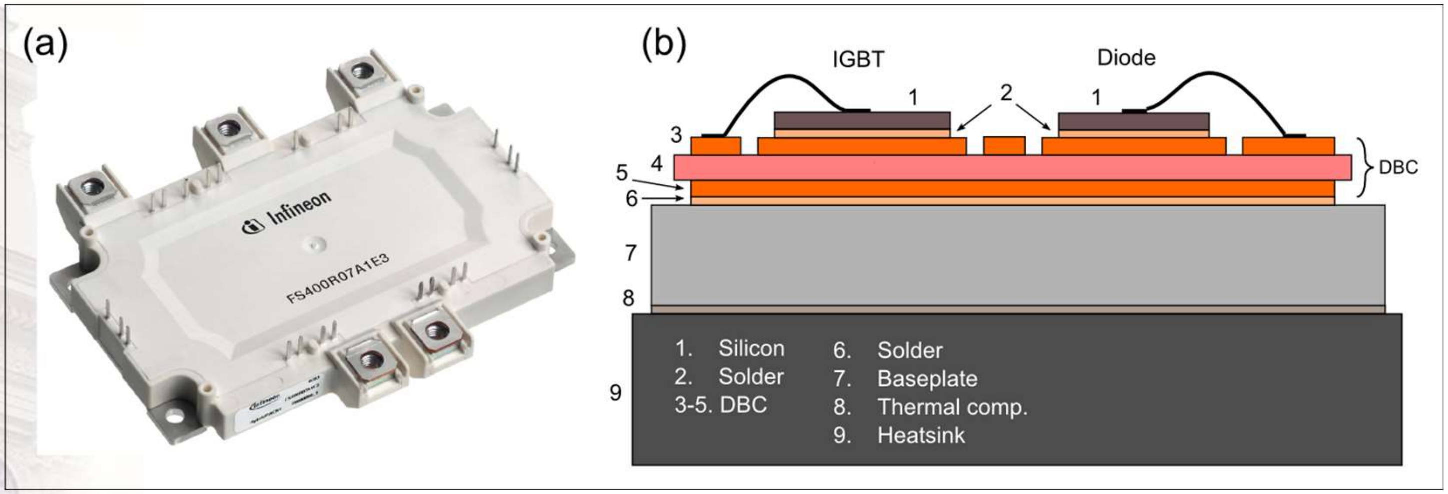


Power Semiconductor Layout 1

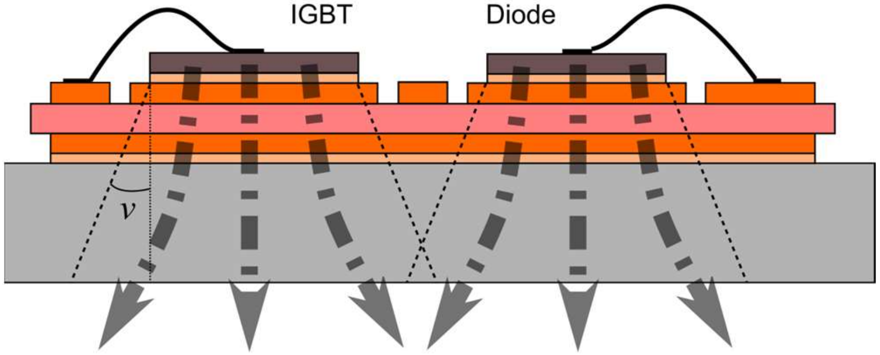




Power Semiconductor Layout 2



direct-bond-copper (DBC) structure



Thermal material properties

Material	Thermal conductivity [W/(m·°C)]	Heat capacity [J/(kg·°C)]	CTE [ppm/°C]	Standard thickness [µm]	Dielectric strength [kV/mm]
Si	150	712	2,6	70-250	-
SiC	340	830	2,8	400	-
Cu	498	385	17,8	300/400	-
Al	238	897	23,5	5000	-
Al_2SO_3	24	765	6,0	381	12
AlN	170	745	4,6	635	15
Si_3N_4	70	691	3,0	635	10
AlSiC	170-200	700-800	6,5-13,8	300/400	

Loss estimation I

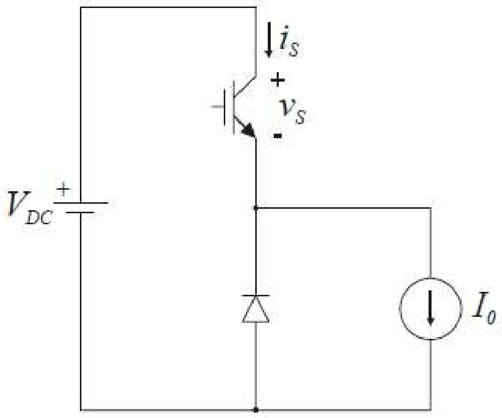


Figure 6.1: Step down converter used to illustrate loss estimation.

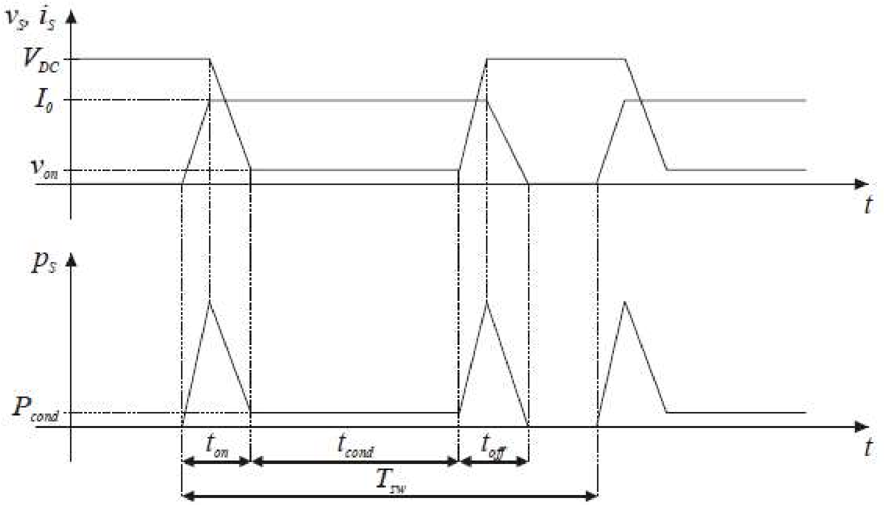


Figure 6.2: Approximate switching waveforms for the switch *S*.

$$p_s(t) = v_s(t) \cdot i_s(t)$$

Loss estimation II

Energy losses: $E_S(T_{sw}) = \int_{T_{sw}} p_S(\tau)\,d\tau = E_{S,on}(T_{sw}) + E_{S,cond}(T_{sw}) + E_{S,off}(T_{sw})$

$$E_{S,on}(T_{sw}) = \int_{t_{on}} p_S(\tau)\,d\tau = V_{DC}\cdot I_0 \cdot \frac{t_{on}}{2}$$

$$E_{S,cond}(T_{sw}) = \int_{t_{cond}} p_S(\tau)\,d\tau = V_{S(on)}\cdot I_0 \cdot t_{cond}$$

Note $V_{S(on)} = V_{S0} + R_S \cdot I_0$

$$E_{S,off}(T_{sw}) = \int_{t_{off}} p_S(\tau)\,d\tau = V_{DC}\cdot I_0 \cdot \frac{t_{off}}{2}$$

Power losses: $P_S(T_{sw}) = \dfrac{E_S(T_{sw})}{T_{sw}} = P_{S,on}(T_{sw}) + P_{S,cond}(T_{sw}) + P_{S,off}(T_{sw})$

$$P_{S,on}(T_{sw}) = \frac{E_{S,on}(T_{sw})}{T_{sw}} = E_{S,on}(T_{sw})\cdot f_{sw} = \frac{V_{DC}\cdot I_0 \cdot t_{on}}{2}\cdot f_{sw}$$

$$P_{S,cond}(T_{sw}) = \frac{E_{S,cond}(T_{sw})}{T_{sw}} = V_{S(on)}\cdot I_0 \cdot \frac{t_{cond}}{T_{sw}} = V_{S(on)}\cdot I_0 \cdot D_S$$

$$P_{S,off}(T_{sw}) = \frac{E_{S,off}(T_{sw})}{T_{sw}} = E_{S,off}(T_{sw})\cdot f_{sw} = \frac{V_{DC}\cdot I_0 \cdot t_{off}}{2}\cdot f_{sw}$$

$$P_{S,sw}(T_{sw}) = P_{S,on}(T_{sw}) + P_{S,off}(T_{sw})$$

Loss estimation III

If specified, use:

$$E_{S,on}(T_{sw})=\frac{E_{on,n}}{V_{DC,n}\cdot I_{0,n}}\cdot V_{DC}\cdot I_0$$

$$E_{S,off}(T_{sw})=\frac{E_{off,n}}{V_{DC,n}\cdot I_{0,n}}\cdot V_{DC}\cdot I_0$$

For the freewheeling diode:

$$P_{D,cond}(T_{sw})=V_{D(on)}\cdot I_0\cdot D_D \qquad V_{D(on)}=V_{D0}+R_D\cdot I_0$$

$$D_D\approx 1-D_S$$

$$P_{D,rr}=V_{DC}\cdot Q_f\cdot f_{sw} \qquad Q_f\approx\frac{1}{S+1}\cdot Q_{rr}\ \text{where}\ S=\frac{t_{rr1}}{t_{rr2}}$$

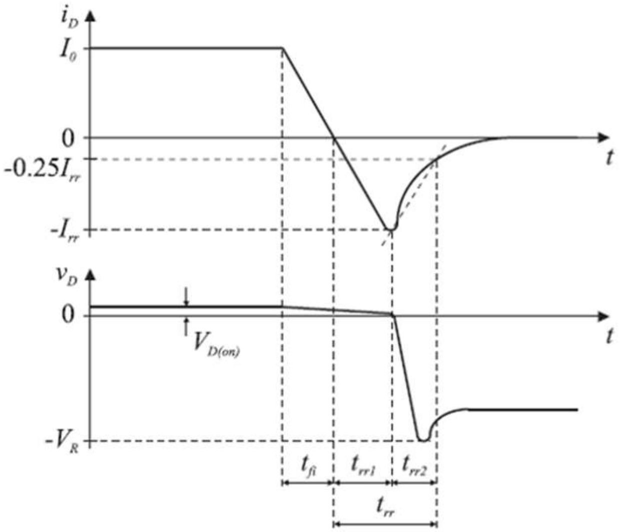


Figure 6.3: Diode turn-off.

If specified, use:

$$P_{D,off}=E_{D,off}(T_{sw})\cdot f_{sw}\ ,\ E_{D,off}(T_{sw})=\frac{E_{off,n}}{V_{DC,n}\cdot I_{0,n}}\cdot V_{DC}\cdot I_0 \qquad Q_f=\frac{Q_{f,n}}{I_{0,n}}\cdot I_0$$

Loss estimation IV

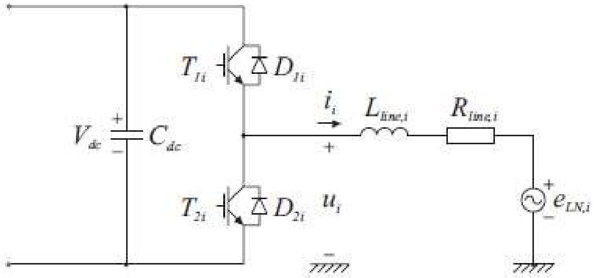


Figure 6.4: One half-bridge of a three-phase voltage source converter.

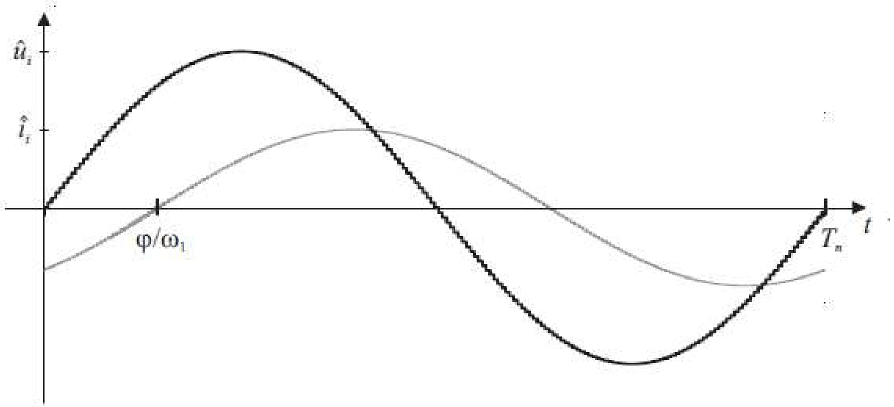
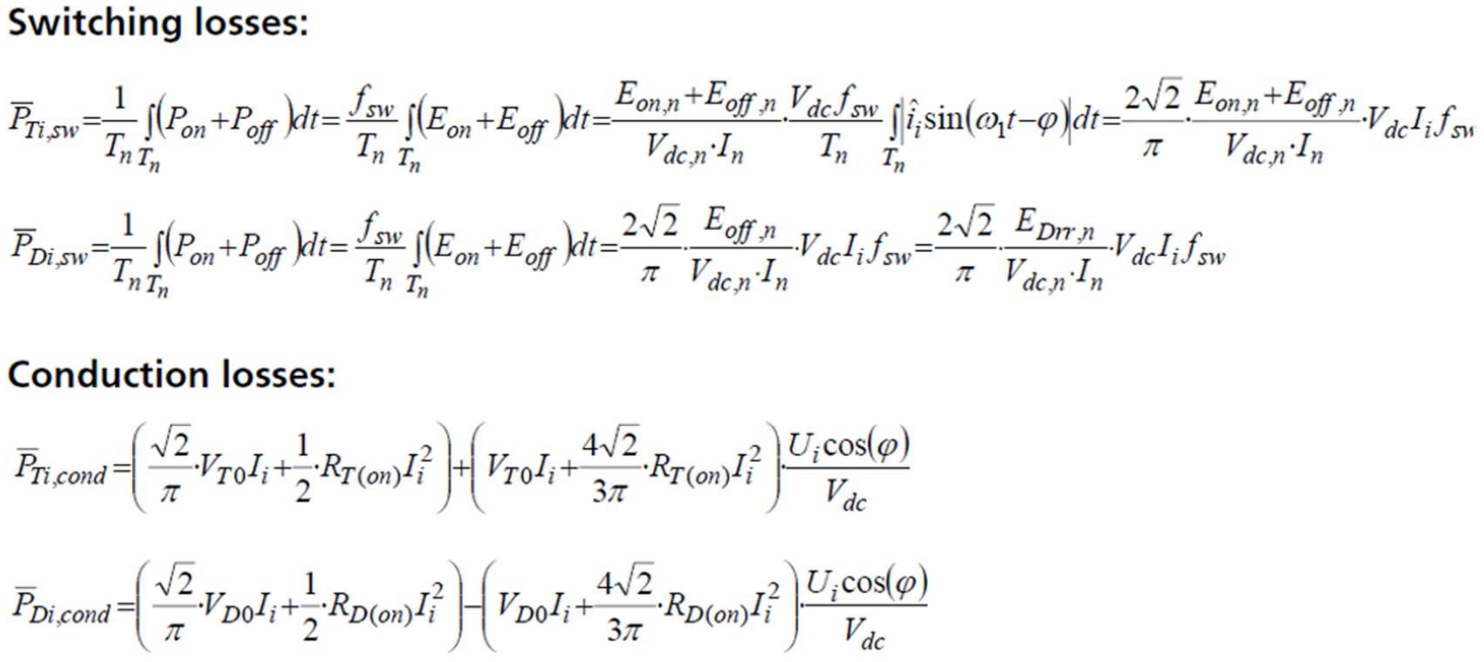


Figure 6.5: Converter output voltage and current. The current is displaced by an angle φ relative to the voltage.

Loss estimation V

- *For One Phase Leg of a Three Phase Converter*



Switching losses:

$$\overline{P}_{Ti,sw}=\frac{1}{T_n}\int_{T_n}(P_{on}+P_{off})dt=\frac{f_{sw}}{T_n}\int_{T_n}(E_{on}+E_{off})dt=\frac{E_{on,n}+E_{off,n}}{V_{dc,n}\cdot I_n}\cdot\frac{V_{dc}f_{sw}}{T_n}\int_{T_n}\left|\hat{i}_i\sin(\omega_1 t-\varphi)\right|dt=\frac{2\sqrt{2}}{\pi}\cdot\frac{E_{on,n}+E_{off,n}}{V_{dc,n}\cdot I_n}\cdot V_{dc}I_i f_{sw}$$

$$\overline{P}_{Di,sw}=\frac{1}{T_n}\int_{T_n}(P_{on}+P_{off})dt=\frac{f_{sw}}{T_n}\int_{T_n}(E_{on}+E_{off})dt=\frac{2\sqrt{2}}{\pi}\cdot\frac{E_{off,n}}{V_{dc,n}\cdot I_n}\cdot V_{dc}I_i f_{sw}=\frac{2\sqrt{2}}{\pi}\cdot\frac{E_{Drr,n}}{V_{dc,n}\cdot I_n}\cdot V_{dc}I_i f_{sw}$$

Conduction losses:

$$\overline{P}_{Ti,cond}=\left(\frac{\sqrt{2}}{\pi}\cdot V_{T0}I_i+\frac{1}{2}\cdot R_{T(on)}I_i^2\right)+\left(V_{T0}I_i+\frac{4\sqrt{2}}{3\pi}\cdot R_{T(on)}I_i^2\right)\cdot\frac{U_i\cos(\varphi)}{V_{dc}}$$

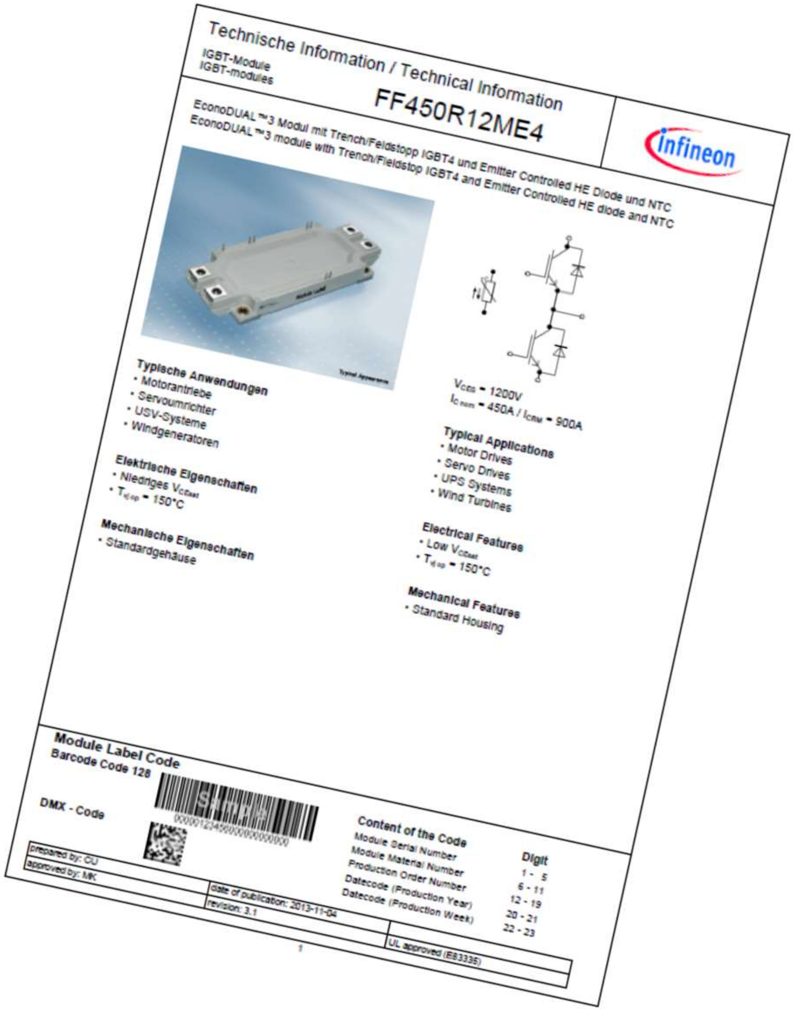
$$\overline{P}_{Di,cond}=\left(\frac{\sqrt{2}}{\pi}\cdot V_{D0}I_i+\frac{1}{2}\cdot R_{D(on)}I_i^2\right)-\left(V_{D0}I_i+\frac{4\sqrt{2}}{3\pi}\cdot R_{D(on)}I_i^2\right)\cdot\frac{U_i\cos(\varphi)}{V_{dc}}$$

Example :

V_to = 0.95; % [V]
V_do = 1.65; % [V]
R_t_on = 0.5/300;   % [Ohm]
R_d_on = 0; % [Ohm]
E_d_rr = 0.0485; % [J]
E_on = 26e-3; % [J]
E_off = 55.5e-3; % [J]

V_dc_n = 600; % [V]
I_n = 450; % [A]

Udc = 600; % [V]
P_max = 200000; % [W]



Technische Information / Technical Information

IGBT-Module
IGBT-modules

FF450R12ME4

EconoDUAL™3 Modul mit Trench/Feldstopp IGBT4 und Emitter Controlled HE Diode und NTC
EconoDUAL™3 module with Trench/Fieldstop IGBT4 and Emitter Controlled HE diode and NTC

Typical Appearance

V_{CES} = 1200V
$I_{C\,nom}$ = 450A / I_{CRM} = 900A

Typische Anwendungen
- Motorantriebe
- Servoumrichter
- USV-Systeme
- Windgeneratoren

Typical Applications
- Motor Drives
- Servo Drives
- UPS Systems
- Wind Turbines

Elektrische Eigenschaften
- Niedriges V_{CEsat}
- $T_{vj\,op}$ = 150°C

Electrical Features
- Low V_{CEsat}
- $T_{vj\,op}$ = 150°C

Mechanische Eigenschaften
- Standardgehäuse

Mechanical Features
- Standard Housing

Module Label Code
Barcode Code 128

DMX - Code

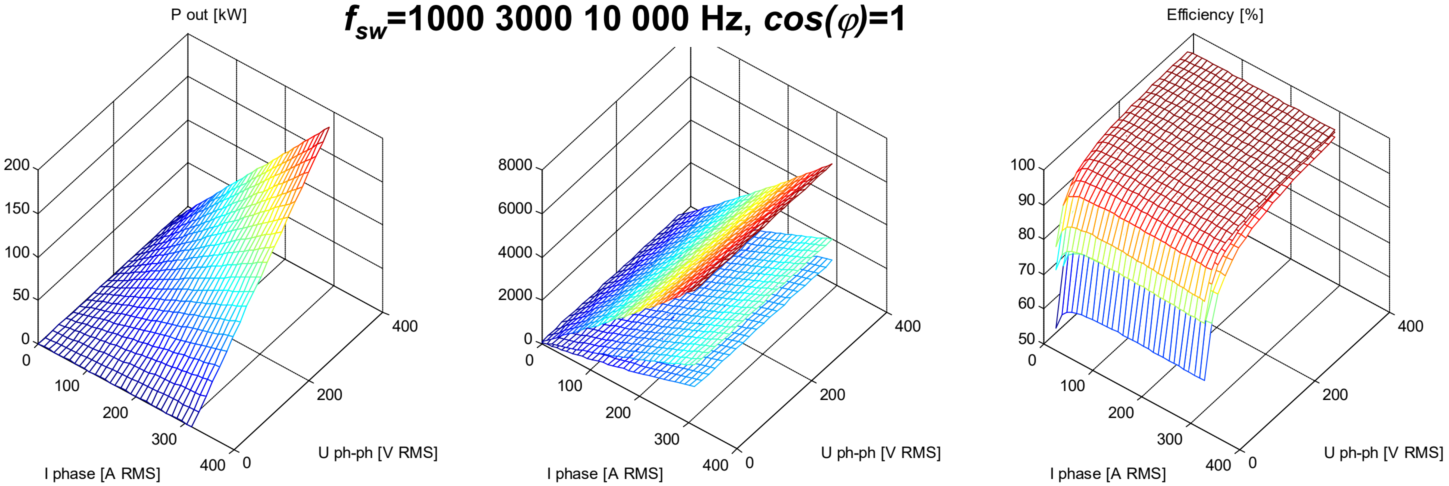
Content of the Code	Digit
Module Serial Number	1 - 5
Module Material Number	6 - 11
Production Order Number	12 - 19
Datecode (Production Year)	20 - 21
Datecode (Production Week)	22 - 23

prepared by: CU
approved by: MK
date of publication: 2013-11-04
revision: 3.1
UL approved (E83335)

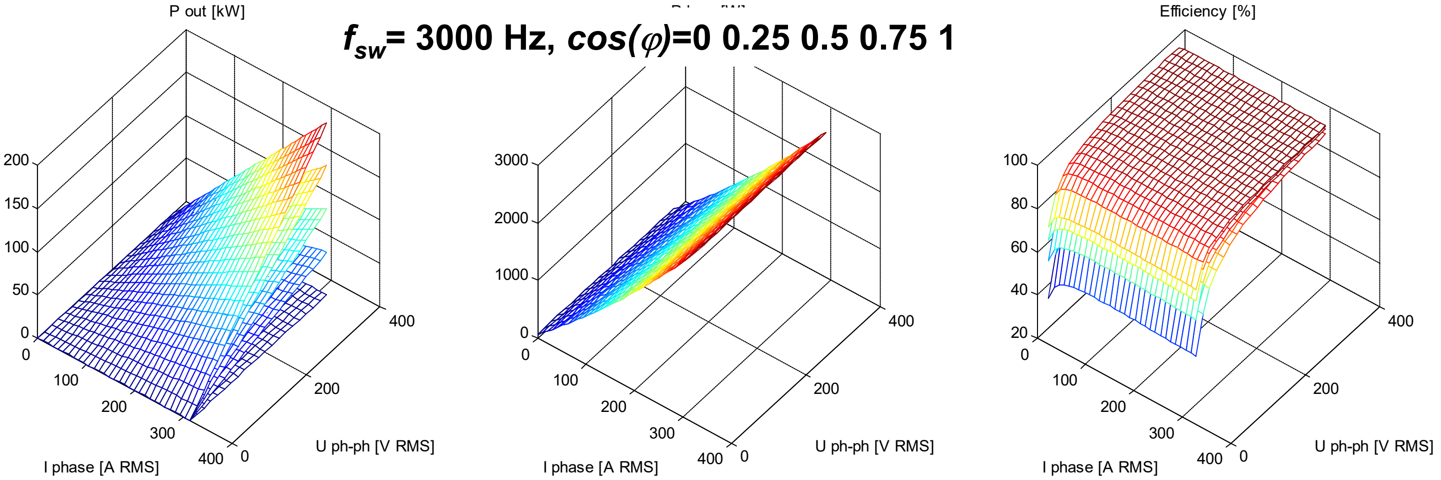
1

Converter Efficiency for different f_{sw} & $\cos(\varphi)$

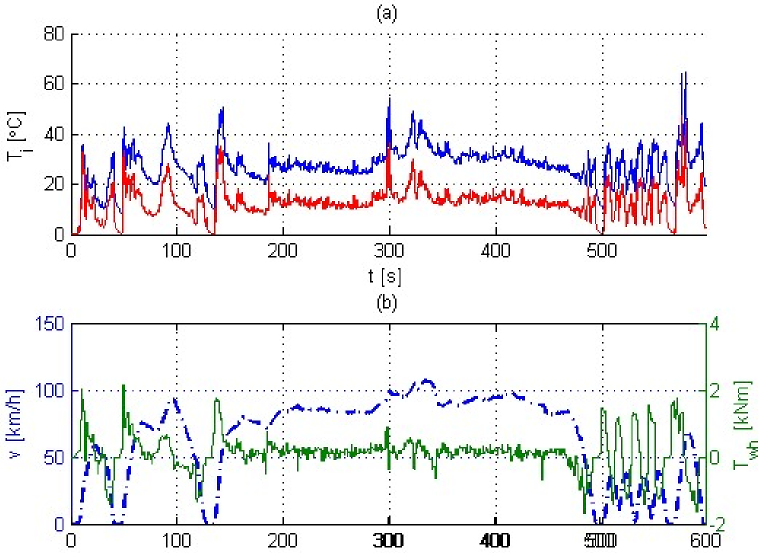
f_{sw}=1000 3000 10 000 Hz, $\cos(\varphi)$=1

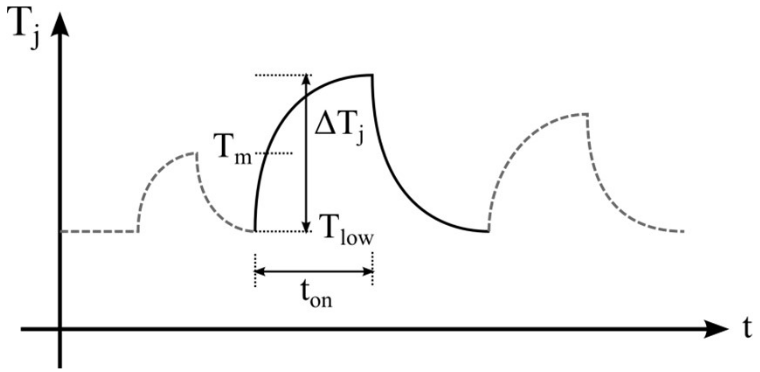


f_{sw}= 3000 Hz, $\cos(\varphi)$=0 0.25 0.5 0.75 1



Thermal Cycling





$$N_f = K \cdot \Delta T_j^{\beta_1} \cdot e^{\frac{\beta_2}{T_{low}}} \cdot t_{on}^{\beta_3} \cdot I^{\beta_4} \cdot V^{\beta_5} \cdot D^{\beta_6}$$

K and β_1- β_6 are fitting parameters.,
t_{on}, the heat-up time
I, the current per bond stitch
V, the voltage range of the device
D. the bond wire diameter