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ENM061 - Power Electronic Converters 7.5 ECTS, 2017

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Lecture outline

Temperature control and component lifetime

- Component lifetime
- The mechanisms of heat transfer
- The origin of losses
- Thermal resistance - steady-state processes
- Heat sinks and how to select a proper size
- Thermal Impedance – dynamic processes
- Summary

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Learning outcomes

- Fourier components and total harmonic distortion (THD) for basic waveforms.
- Operating principles of the most common active components (e.g. diode, thyristor, IGBT, and MOSFET) and passive components (e.g. capacitors, transformers and inductors).
- Operation of a pulse width modulation (PWM), the purpose of controlling the desired quantity and the need for a controller circuit within the power electronic converter.
- Analysis of ideal DC/DC converters (e.g. buck, boost, buck-boost, flyback, the forward, the push-pull, half-bridge and full-bridge converters) in CCM and DCM operation.
- Operating principles of single-phase and three-phase AC/DC inverters with different modulation strategies (e.g. PWM and square wave operation).
- Operation of multilevel converters (e.g. NPC, flying capacitor and MMC topologies) using current and voltage waveform analysis. Pros and Cons of the converter in terms of harmonics and losses.
- Operation of single- and three-phase diode rectifiers operating with voltage-stiff and current-stiff DC-side. Investigating the impact of line impedance within the converter circuit for current commutation.
- Operation of single- and three-phase thyristor rectifiers operating with a current-stiff DC-side and the impact of line impedance for current commutation. Investigating the use of 6/12-pulse configurations.
- Loss calculation in passive and active components. Evaluating the temperature rise in the active components and choosing an appropriate heat-sink.
- Identify simple power electronic converter schematics. Recognizing the different parts in a physical circuit on which basic wave-shape and efficiency measurements is performed.
- Utilizing the software Cadence PSpice to simulate basic power electronic circuits and the practical labs to have a firsthand experience of how real DC/DC converters operate.

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Why Control Component Temperature?

- All components (capacitors, inductors, transformers, semiconductor devices and circuits have maximum operating temperatures specified by manufacturers.
  - Component reliability decreases with increasing temperature. Semiconductor failure rate doubles for every 10 - 15 °C increase in temperature above 50 °C
- High operating temperature has undesirable effects on components.

<u>Capacitors</u>

- Significant increase in electrolyte evaporation rate with an increase in temperature and this shortens lifetime.

<u>Magnetic Components</u>

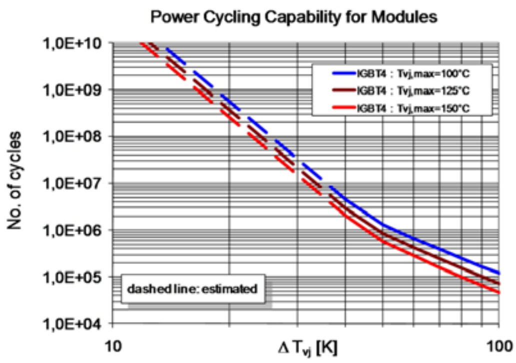
- Losses (at constant power input) increase above 100°C
- Winding insulation (lacquer or varnish) degrades above 100°C

<u>Semconductors</u>

- Unequal power sharing in parallel/series devices.
- Reduction in breakdown voltage in some devices.
- Increase in leakage currents

Lifetime of Active Components

- Due to mechanical stress, the maximum allowed number of thermal cycles are often specified for an IGBT power module
- The cycling capability depends on the temperature swing (ΔT_{vj}) and the maximum component temperature ($T_{vj,\,max}$)



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Lifetime of Passive Components

- Capacitors:
  - Dielectric breakdown due to overvoltage or aging of the dielectric (when the breakdown voltage falls below operating voltage)
  - Electrode materials migrating across the dielectric, forming conductive paths
  - Increase of dissipation factor due to contamination of capacitor materials
  - Electrolyte contamination from moisture corroding the electrodes, leading to capacitance loss and shorts
- Inductors:
  - Mainly mechanical stress due to thermal cycling
  - Also, insulation breakdown in the windings due to thermal hot-spots may occur

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Temperature Control Methods

- Control voltages and current through components
  - Snubbers may be required for semiconductor devices
- Maximize heat transfer via convection and radiation from components
  - Short heat flow paths and large component surface area
- Use of heat sinks for temperature-critical components
  - Proper design for adequate air flow so that heat sinks dissipate heat to the ambient.

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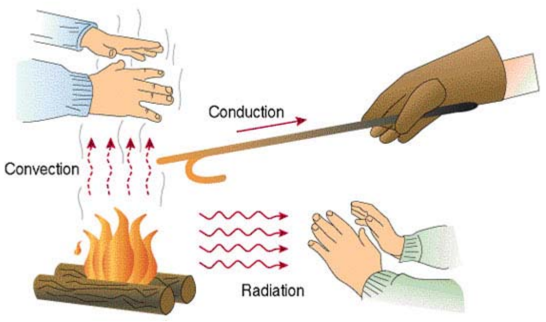
Mechanisms of Heat Transfer Three Fundamental Principles

- Radiation
- Convection
- Conduction



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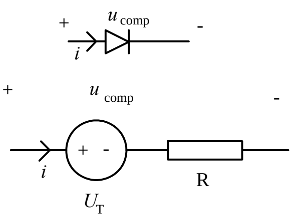
The Origin of Losses - Conduction

Steady-state is assumed for all calculations!



$$u_{comp}(t) = U_T + Ri(t)$$

$$P_{on} = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T u_{comp}(t)i(t)dt = \frac{1}{T}\int_0^T \left(U_T i(t) \ + Ri(t)^2\right)dt = U_T I_{AVG} + RI_{rms}^2$$

$$I_{AVG} = \frac{1}{T}\int_0^T i(t)dt \qquad I_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T i^2 dt}$$

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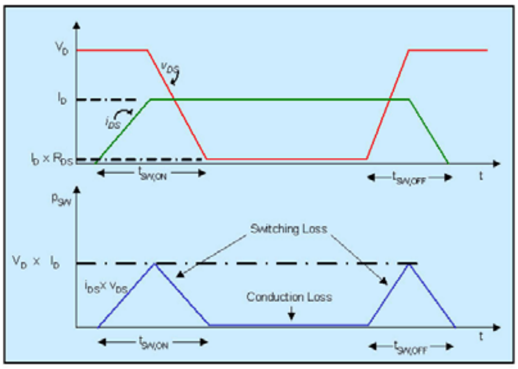
The Origin of Losses – Switching

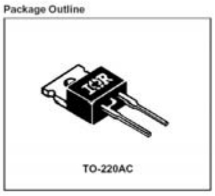
- A high voltage and current at the same time gives rise to switching losses (see simplified MOSFET switching event below)



Practical Applications
A Switch Diode in TO-220 Package

- Depending on the type and application, both the forward voltage drop (V_F) and the forward resistance can be specified in the diode datasheet

Package Outline



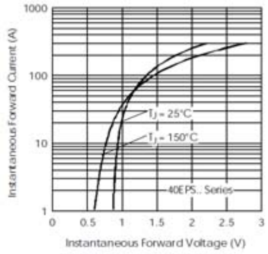


Fig. 5 - Forward Voltage Drop Characteristics

Electrical Specifications

	Parameters	20ETF..	Units	Conditions	
V_{FM}	Max. Forward Voltage Drop	1.3	V	@ 20A, T_J = 25°C	
r_t	Forward slope resistance	12.5	mΩ	T_J = 150°C	
$V_{F(TO)}$	Threshold voltage	0.9	V		
I_{RM}	Max. Reverse Leakage Current	0.1	mA	T_J = 25 °C	V_R = rated V_{RRM}
		5.0		T_J = 150 °C	

Practical Applications
A MOSFET in TO-220 Package

- For a MOSFET, the most important parameter $R_{DS(on)}$ is specified.
- The switching losses are determined by the switching times and depend on the operating conditions.

BUZ10

N - CHANNEL 50V - 0.06Ω - 23A TO-220
STripFET™ MOSFET

ON (*)

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
$V_{GS(th)}$	Gate Threshold Voltage	$V_{DS} = V_{GS}$ I_D = 1 mA	2.1	3	4	V
$R_{DS(on)}$	Static Drain-source On Resistance	V_{GS} = 10V I_D = 14 A		0.06	0.07	Ω

SWITCHING

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
$t_{d(on)}$ t_r $t_{d(off)}$ t_f	Turn-on Time Rise Time Turn-off Delay Time Fall Time	V_{DD} = 30 V I_D = 10 A R_{GS} = 4.7 Ω V_{GS} = 10 V		20 45 48 10		ns ns ns ns

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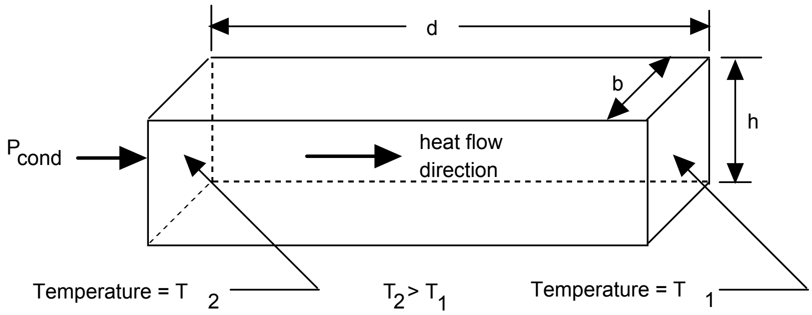
Thermal Model of a Semiconductor in Steady-State

- The most important form of heat flow for cooling of electronic components is conduction



$$P_{cond} = \frac{\lambda bh}{d}(T_2 - T_1) => \Delta T = P_{cond}\frac{d}{\lambda bh} = P_{cond}R_{th}$$

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Thermal Model of a Semiconductor in Steady-State

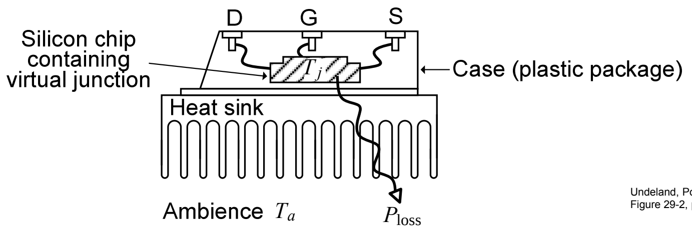

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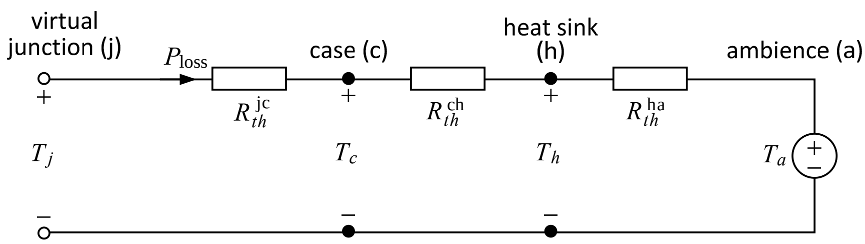
Figure 29-2, page 733



Practical Applications
A MOSFET in TO-220 Package

- The thermal performance is determined by the thermal resistance of the components which in turn depends on the mounting conditions

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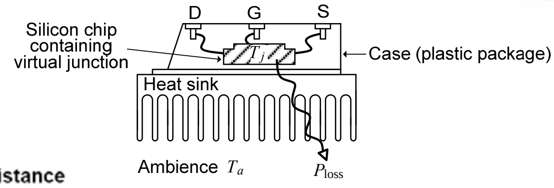
N - CHANNEL 50V - 0.06Ω - 23A TO-220
STripFET™ MOSFET



Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	1.0	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface ④	0.50	—	
$R_{\theta JA}$	Junction-to-Ambient④	—	62	
$R_{\theta JA}$	Junction-to-Ambient (PCB mount)⑤	—	40	

Heat Sinks – Selection Criteria

- Choice of heat sink depends on required thermal resistance, $R_{\theta sa}$, which is determined by several factors.
  - Maximum power, P_{diss}, dissipated in the component on the heat sink.
  - Component's maximum internal temperature, $T_{j,max}$
  - Component's junction-to-case thermal resistance, $R_{\theta jc}$.
  - Maximum ambient temperature, $T_{a,max}$.
- $R_{\theta sa} = \{T_{j,max} - T_{a,max}\}/P_{diss} - R_{\theta jc}$
  - P_{diss} and $T_{a,max}$ determined by particular application.
  - $T_{j,max}$ and $R_{\theta jc}$ set by component manufacturer.

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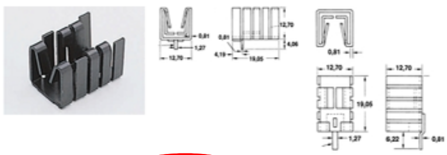
Heat Sinks – Datasheet Values

- In the datasheet for the heat sink, the thermal resistance at a specific power dissipation is specified
- The given figure also assume no forced convection and correct mounting/direction.

TO220 heatsink



Thermal resistance: 16 °C/W at 5 W

Mfr. Aavid
Heatsink with spring-loaded (no screws), four point clamp to package.
Black matt anodised aluminium

TO220, TOP3 heatsink

Mfr. Aavid
Heatsink with spring-loaded damp to package for easier installation.
Indudes solder pin to attach the heatsink.

		Type	Thermal resistance °C/W	Height mm	Stock number		Price / items 1-	25-	100-
1	Buy!	53328-220	9.0 at 6 W	50.8	75-612-93	i	4.87	3.60	2.77

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Heat Sinks – The Effect of Forced Convection on a Heat Sink

- As the speed of the surrounding air increases, the thermal resistance of the heat sink decreases

0m³/h gives:
$R_{th} = 9K/W$

2m³/h gives:
$R_{th} = 0.4 \cdot 9\,K/W = 3.6K/W$

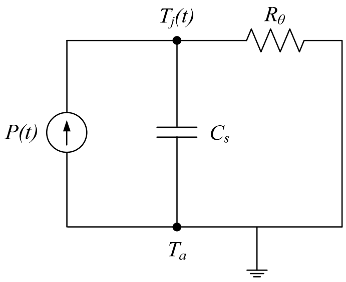
TO220, TOP3 heatsink

Mfr. Aavid
Heatsink with spring-loaded damp to package for easier installation.
Indudes solder pin to attach the heatsink.

		Type	Thermal resistance °C/W	Height mm	Stock number		Price / items 1-	25-	100-
1	Buy!	53328-220	9.0 at 6 W	50.8	75-612-93	i	4.87	3.60	2.77

Transient Thermal Impedance

- For transient events, the heat capacity per volume (C_v) of the material also needs to be considered.
- An approximate solution of the time-dependent heat diffusion equations can be obtained from the electric circuit analogy below.
- For a step input power,



$$C_v = \frac{dQ}{dT} \Rightarrow C_s = C_v A d$$

$$T_j = P_o R_\theta \left[t / \tau_\theta\right]^{1/2} + T_a$$

$$\tau_\theta = \pi R_\theta C_s / 4$$

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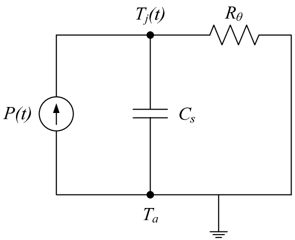
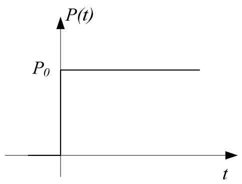
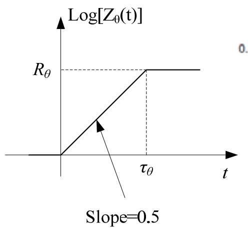
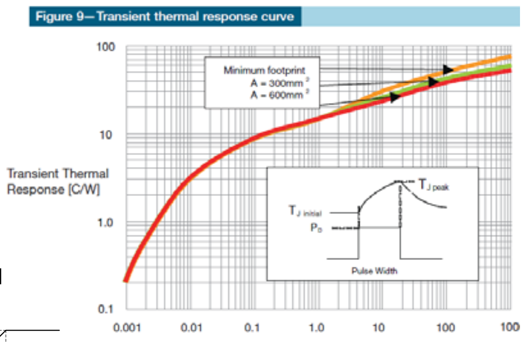
Figure 29-3, page 734

Transient Thermal Impedance
Thermal Time-Dependent Impedance









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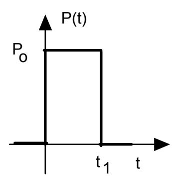
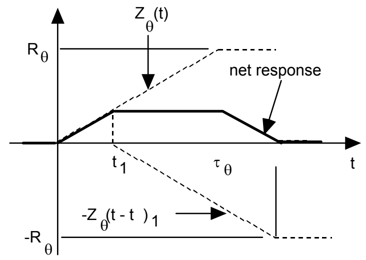
Transient Thermal Impedance
Thermal Time-Dependent Impedance

- Symbolic response for a rectangular power dissipation pulse

$P(t) = Po \{u(t) - u(t - t_1)\}$.





- $T_j(t) = P_o \{ Z_\theta(t) - Z_\theta(t - t_1) \}$

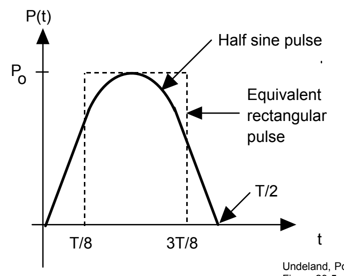


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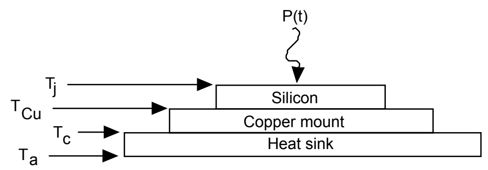
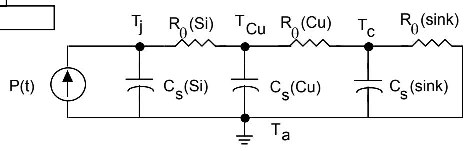
Figure 29-5, page 736

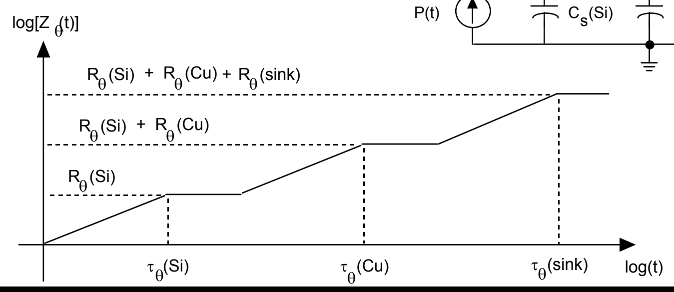
- Symbolic solution for half sine power dissipation pulse.
  - $P(t) = P_o \{u(t - T/8) - u(t - 3T/8)\}$
    area under the two curves identical
  - $T_j(t) = Po \{ Z_\theta(t - T/8) - Z_\theta(t - 3T/8) \}$

Transient Thermal Impedance
Multiple Layers



- Assume separated time-scales





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Transient Thermal Impedance GTO-Example

Characteristic values

Parameter	Symbol	Conditions	min	typ	max	Unit
Thermal resistance junction to case	$R_{th(jc)}$	Double side cooled			12	K/kW
	$R_{th(jc)A}$	Anode side cooled			22	K/kW
	$R_{th(jc)C}$	Cathode side cooled			27	K/kW
Thermal resistance case to heatsink (Double side cooled)	$R_{th(ch)}$	Single side cooled			6	K/kW
	$R_{th(ch)}$	Double side cooled			3	K/kW

Analytical function for transient thermal impedance:

$$Z_{thJC}(t) = \sum_{i=1}^{n} R_i(1 - e^{-t/\tau_i})$$

i	1	2	3	4
R_i(K/kW)	5.400	4.500	1.700	0.400
τ_i(s)	1.2000	0.1700	0.0100	0.0010

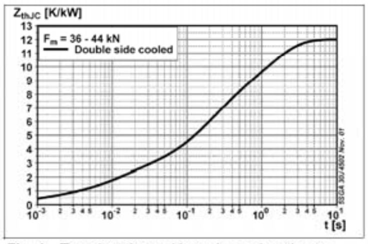

Fig. 1 Transient thermal impedance, junction to case.

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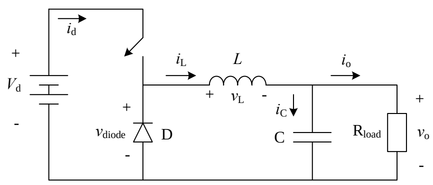
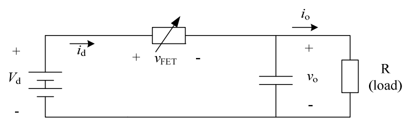
Tutorial 12

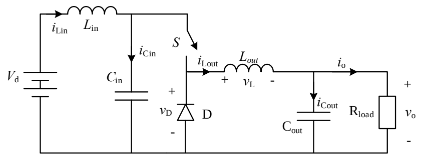




Realistic active and passive components

- Efficiency calculation
- MOSFET temperature with and without heat sink
- Efficiency comparison with linear power supply where $V_{FET} = V_d - V_o$. How does the loss impact on the cooling of the transistor?

PSpice 7



Nominal values	
Source voltage (V_d)	15V
Output Inductance (L)	2.2µH
Output Capacitance (C)	150µF
Load Resistance (R_{load})	2Ω
Switching frequency (f_{sw})	300kHz
Duty ratio steady state (D)	0.667

- Current waveforms through the input and output filters
- Origins of losses in the passive and active components
- What is the impact of switching frequency and diode type on efficiency
- Junction temperature, impact of heat sink thermal resistance/impedance

Summary

- Component lifetime
- Mechanism of heat transfer
- Origin of heat - switching and conduction losses
- Thermal resistance and the concept of thermal impedance
- Heat sinks and cooling mechanisms
- Learning outcome:
  - ❖ Loss calculation in passive and active components. Evaluating the temperature rise in the active components and choosing an appropriate heat-sink.