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ENM061 - Power Electronic Converters 7.5 ECTS, 2017

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Lecture outline

Active components

- On-state vs switching losses
- The diode
- The thyristor
- BJT (Bipolar Junction Transistor)
- The GTO (Gate Turn-Off Thyristor)
- The MOSFET (Metal-Oxide Semiconductor Field Effect Transistor)
- The IGBT (Insulated Gate Bipolar Transistor)
- Component selection
- Brief description of the Tutorial and PSpice exercises
- 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.
- Identify simple power electronic converter schematics. Recognizing the different parts in a physical circuit on which basic wave-shape and efficiency measurements is performed.
- Loss calculation in passive and active components. Evaluating the temperature rise in the active components and choosing an appropriate heat-sink. Gaining a basic understanding of component life time.
- 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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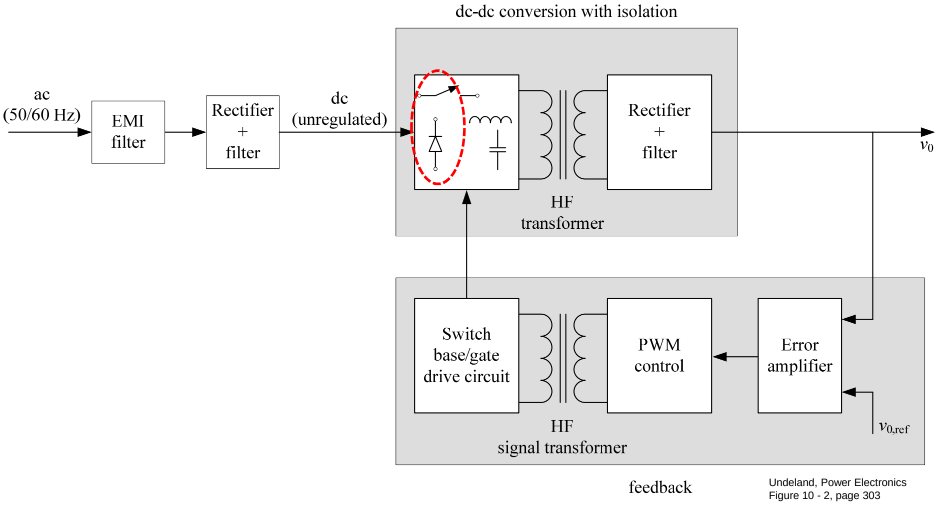
Switch-mode power supply



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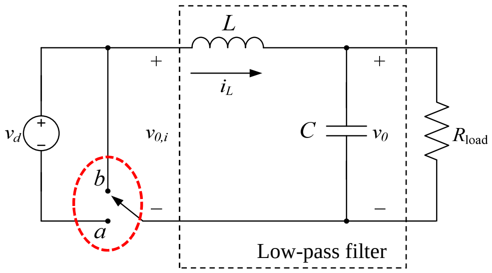
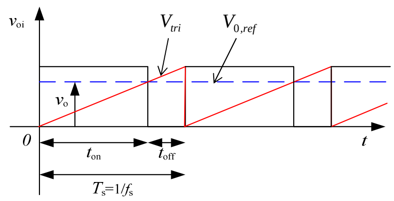
Switch-mode power supply

Equivalent circuit





Average load voltage

$$V_0 = \frac{1}{T_s}\int_0^{T_s} v_{0i}\,dt = \frac{t_{on}}{T_s}V_d = DV_d$$

Switching function

$$switch = \begin{cases} a, V_{0,ref} \geq V_{tri} \\ b, V_{0,ref} < V_{tri} \end{cases}$$

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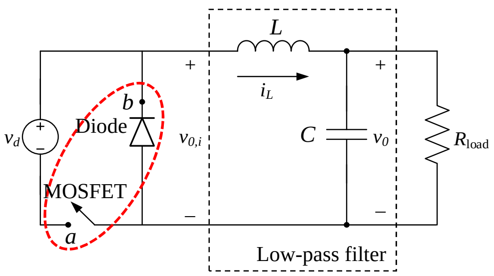
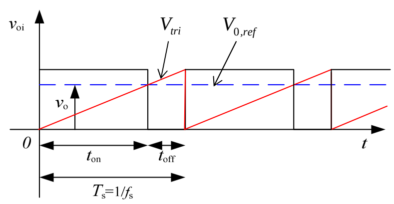
Switch-mode power supply

Equivalent circuit





Average load voltage

$$V_0 = \frac{1}{T_s}\int_0^{T_s} v_{0i}\,dt = \frac{t_{on}}{T_s}V_d = DV_d$$

Switching function

$$switch\ a = \begin{cases} on => Diode\ off, V_{0,ref} \geq V_{tri} \\ off\ => Diode\ on, V_{0,ref} < V_{tri} \end{cases}$$

On-state vs switching losses

Active components are characterized based on these parameters

Why are they important?

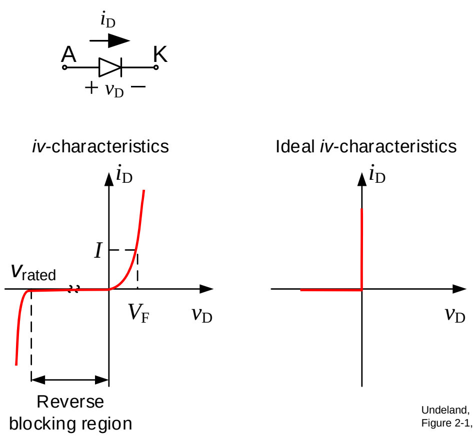
- System efficiency, temperature rise (heat sink selection=>size)
- Factors: switching frequency, load current and voltage
- What type of active components to choose
  - ❖ High vs low switching frequency => switching loss
  - ❖ High vs low load current => on-state loss

How are they calculated?

- On-state loss => steady-state current in the component
- Switching loss (turn-on and turn-off losses) => energy dissipation during a state change (on⇔off) of the component
- Factors: On-state resistance, on-state voltage drop, accumulated charge, switching energy function, transient current and voltage waveforms

The Diode

- On and off states controlled by the power circuit



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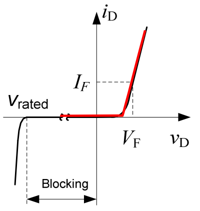
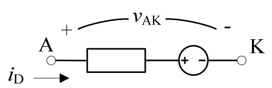
The Diode

High voltage diode

iv-characteristics

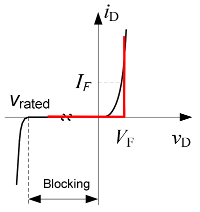


Equivalent circuit when conducting

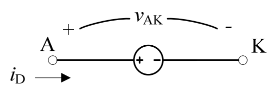


Low voltage diode

iv-characteristics

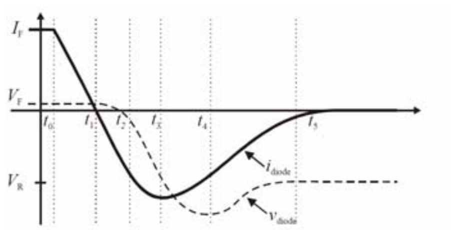


Equivalent circuit when conducting



The Diode – Dynamic Characteristics

- Reverse recovery – when the diode goes from conducting state to blocking state a negative current can flow through the diode for a short time.



- Long reverse recovery – higher switching loss

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The Diode - Different Types

- Schottky diode
  - ✓ Low voltage drop
  - ✓ No recovery and hence low reverse blocking voltage
- Line frequency (rectifying) diodes
  - ✓ Lower voltage drop
  - ✓ Large recovery and hence high reverse blocking voltage
- Fast-recovery (switching) diodes
  - ✓ Higher voltage drop
  - ✓ Low recovery

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Diode data sheet

Shottky diode

Electrical Specifications

	Parameters	19TQ	Units	Conditions	
V_{FM}	Max. Forward Voltage Drop (1) * See Fig. 1	0.36	V	@ 19A	T_J = 25 °C
		0.46	V	@ 38A	
		0.32	V	@ 19A	T_J = 75 °C
		0.43	V	@ 38A	
I_{RM}	Max. Reverse Leakage Current (1) * See Fig. 2	10.5	mA	T_J = 25 °C	V_R = rated V_R
		522	mA	T_J = 100 °C	
		465	mA	T_J = 100 °C	V_R = 12V
		285	mA	T_J = 100 °C	V_R = 5V
C_T	Max. Junction Capacitance	2000	pF	V_R = 5V_{DC}, (test signal range 100Khz to 1Mhz) 25 °C	
L_S	Typical Series Inductance	8.0	nH	Measured lead to lead 5mm from package body	
dv/dt	Max. Voltage Rate of Change (Rated V_R)	10,000	V/ µs		

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Diode data sheet

Switch diode TO-220

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	

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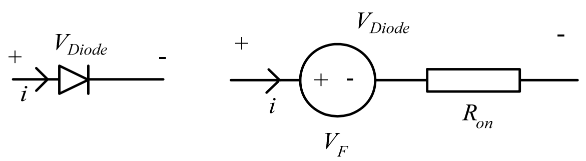
The diode - On-state/switching loss



$$V_{Diode} = V_F + R_{on} i(t)$$

Ex.: P_{on} = ?

$$P_{on} = \frac{1}{T}\int_0^T p(t)\,dt = \frac{1}{T}\int_0^T V_{Diode}(t)i(t)\,dt = \frac{1}{T}\int_0^T \left(V_F i(t) + R_{on} i(t)^2\right)dt$$

$$=> P_{on} = V_F I_{AVG} + R_{on} I_{RMS}^2$$

- The switching loss which mainly is the turn-off loss depends on the type of diode (reverse recovery time and current, blocking voltage)

$$P_{switching} = \frac{1}{T}\int_{t_{on,0}}^{t_{on,0}+t_{on}} V_{Diode}(t)i(t)\,dt + \frac{1}{T}\int_{t_{off,0}}^{t_{off,0}+t_{off}} V_{Diode}(t)i(t)\,dt \approx \frac{1}{T}\int_0^{t_{rr}} V_{Diode}(t)i(t)\,dt$$

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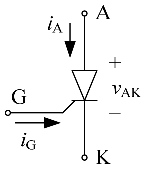
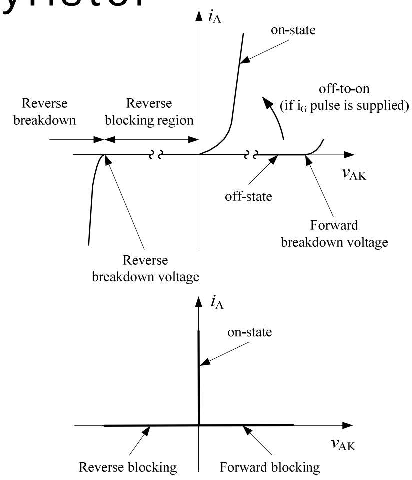
The Thyristor





- Basically a diode that can be turned on.
- Does not conduct when forward biased unless a current is applied on the gate terminal

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Figure 2-3, page 18

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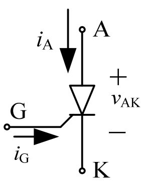
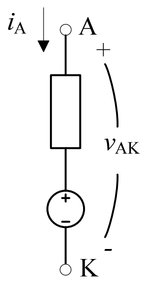
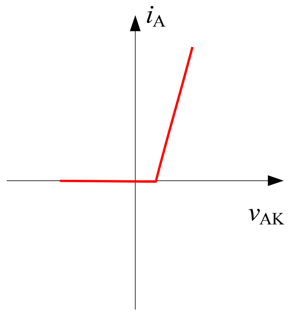
The Thyristor

Equivalent circuit when conducting

simplified *iv*-characteristics

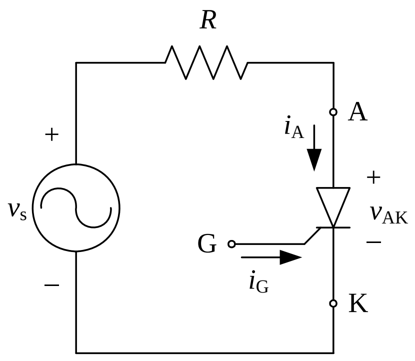


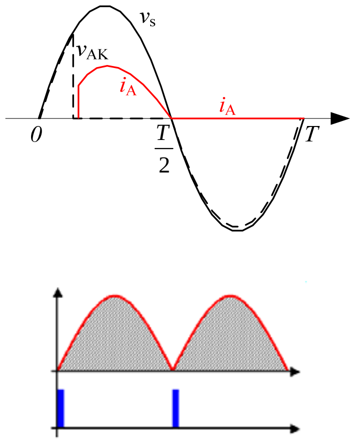




- Semi-controlled device
- Latches ON by a gate-current pulse if forward biased
- Turns-off if current tries to reverse

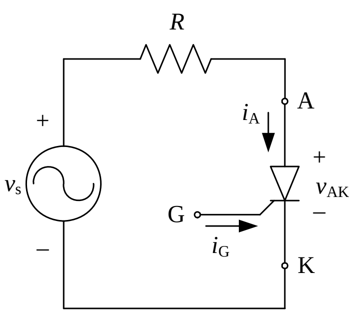
The Thyristor

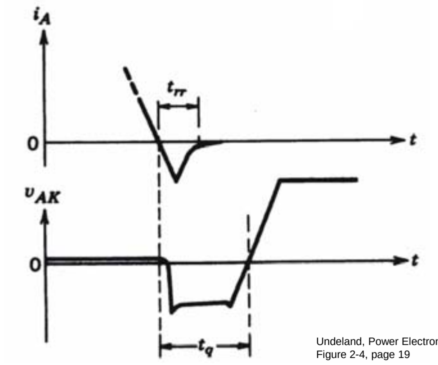




The Thyristor

- After a thyristor has been switched off by forced commutation, a time delay (t_q) must elapsed before it can be positively biased again.
- If the time interval is too short, the thyristor can self-trigger by the remaining charge carriers that have not yet recombined.





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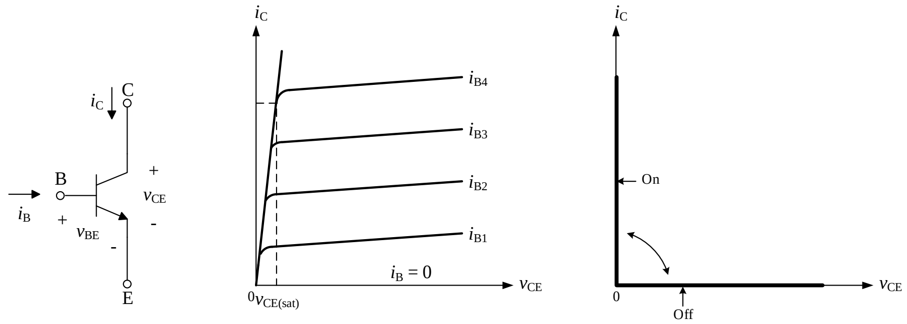
The BJT



symbol — *i-v* characteristic — idealized characteristic

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Figure 2-7, page 24

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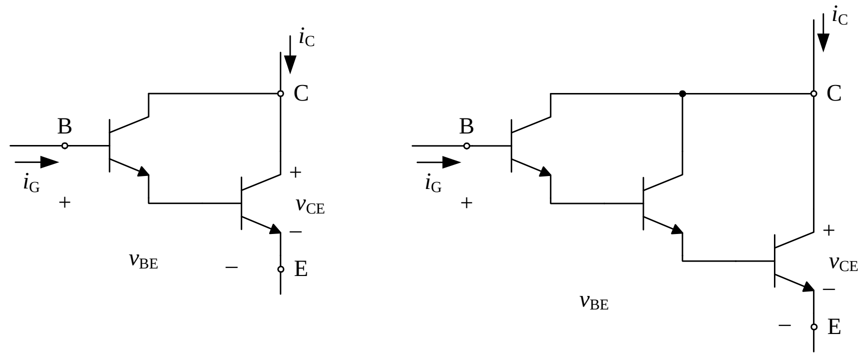
The BJT - Darlington connection



- Used commonly in the past
- Now used in specific applications
- Replaced by MOSFETs and IGBTs

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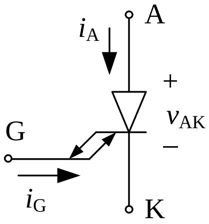
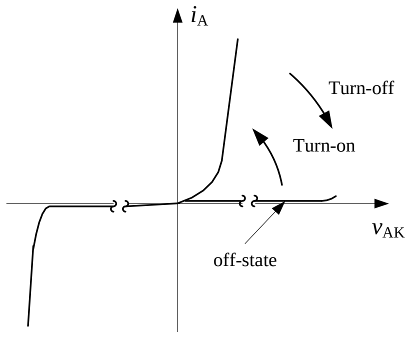
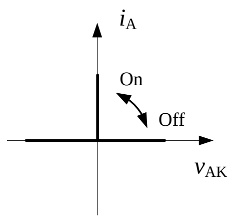
Figure 2-8, page 25

The GTO

- A thyristor that can be turned off by applying a current to the gate in the reverse direction to that required to turn it on.







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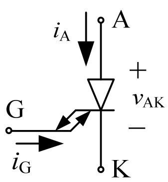
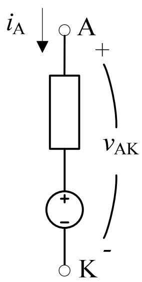
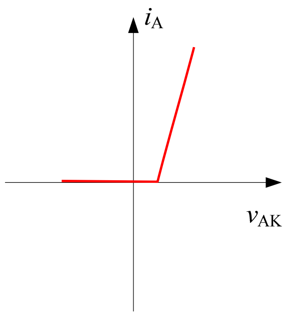
The GTO



Equivalent circuit when conducting



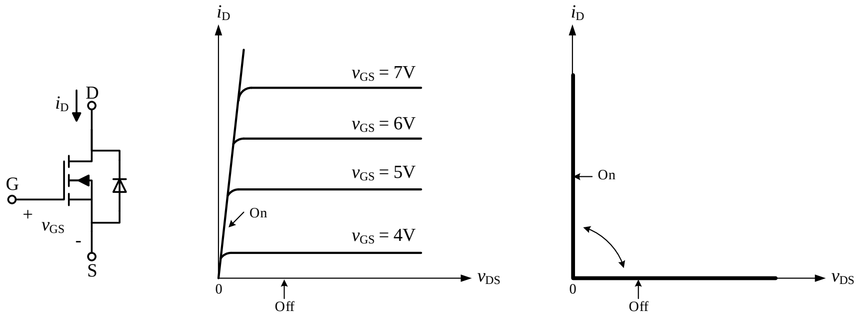
simplified *iv*-characteristics



- Slow switching speeds
- Used at very high power levels
- Require elaborate gate control circuitry and a turn-off snubber

The MOSFET

- The power MOSFET behaves as a voltage controlled switch



symbol | *i-v* characteristic | idealized characteristic

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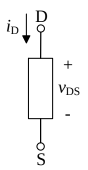
Figure 2-9, page 25

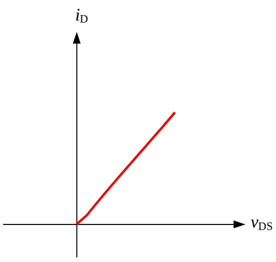
- Easy to control by the gate-source voltage
- Optimal for low-voltage (low power)/high switching frequency applications
- On-state resistance a concern at higher voltages

The MOSFET

- When conducting, the power MOSFET can be represented with a resistance ($R_{DS(on)}$)
- Fast switching and relatively simple gate drive circuitry



Equivalent circuit when conducting



Simplified *i-v* characteristics

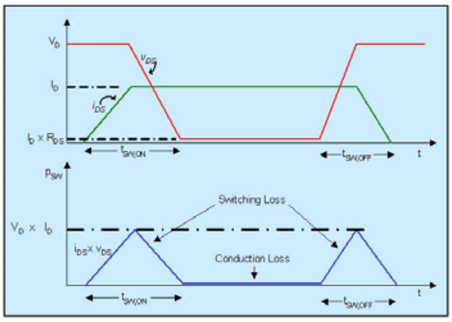


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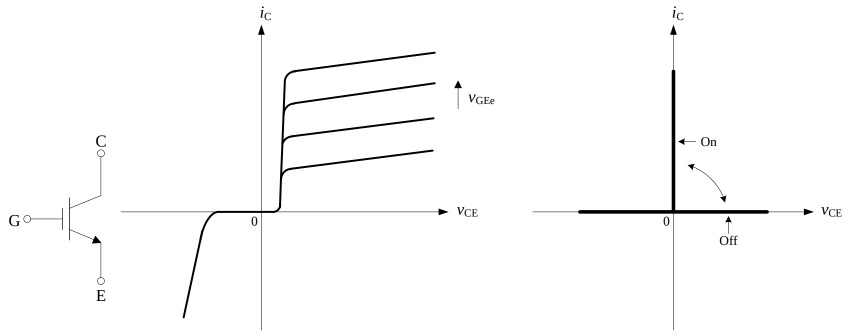
Figure 2-6, page 21

The IGBT

- A bipolar junction transistor with an insulated gate that facilitates the control of the component



symbol | *iv* characteristics | idealized characteristics

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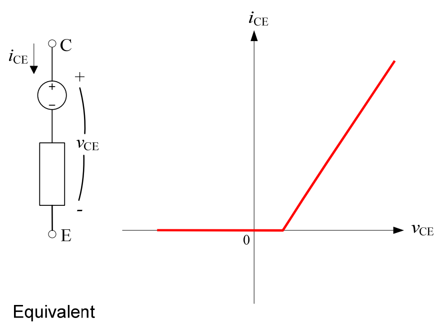
The IGBT

- A bipolar junction transistor with an insulated gate that facilitates the control of the component



Equivalent circuit when conducting

Simplified *i-v* characteristics

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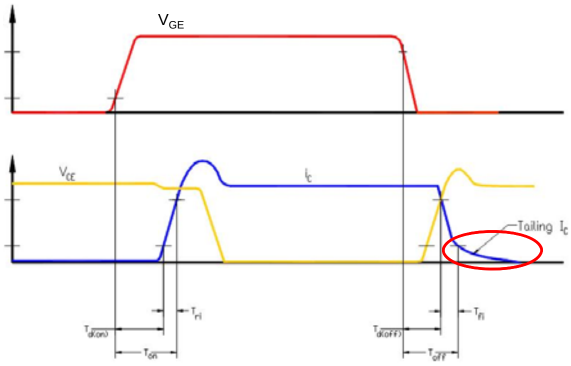
The IGBT

- Simple switching behavior but with a tail current that increases the turn-off losses



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Component Selection – application

Device	*Power level*	*Swiching speed*	*control*
Diode	variable	variable	None
Thyristor	High	Slow	Semi (current)
BJT	Medium	Medium	Full (current)
GTO	High	Slow	Full (current)
MOSFET	Low	Fast	Full (voltage)
IGBT	Medium	Medium	Full (voltage)

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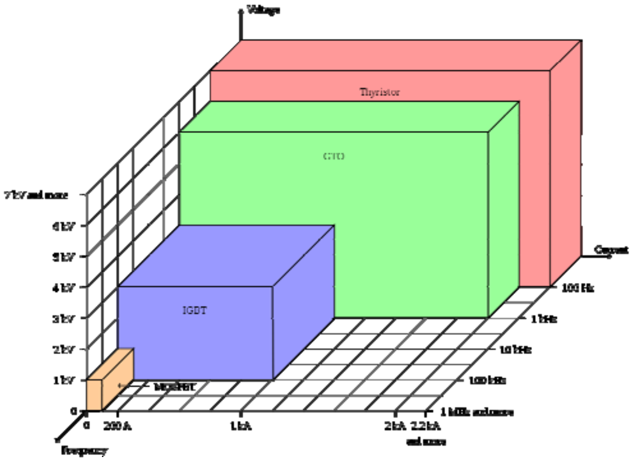
Component Selection – Power Handling



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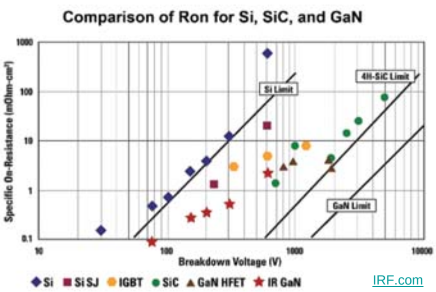
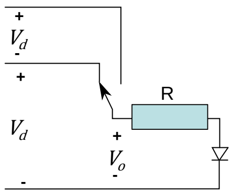
Component Selection – Upcoming Technologies



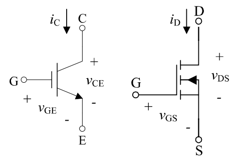
- GaN – in telecom and computer applications
- SiC - in industrial applications that require higher voltages and current.
- Manufacturing costs of GaN and SiC are expected to come down

- Si (Silicon)
- SiC (Silicon Carbide)
- GaN (Gallium Nitride)

Tutorial 2



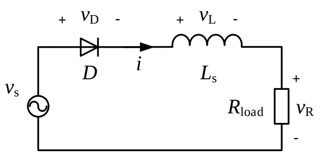
V_d = 15V
f_{sw}=20kHz
D= 0.6 (duty cycle)
v_f= 0.82V (diode forward voltage drop)
R = 5 ohms (load)

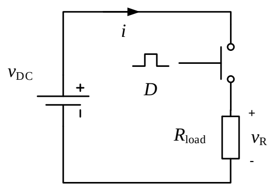


- Average diode current, average output voltage, power dissipation over the resistor and the diode
- V_{CE} and V_{Ds} waveforms in terms of i_C and i_D as well as expressions to calculate conduction losses

PSpice 1

Power electronc circuits and Fourier analysis in Cadence PSpice





- Waveforms
- Phasor methods
- AVG vs RMS values

- Fourier calculation
- AVG vs RMS values
- Harmonic components

Summary

- What does the on-state and Switching losses represent?
- Can you differentiate between a diode and a thyristor?
- Can you differentiate between a BJT and a GTO?
- Can you differentiate between a MOSFET and an IGBT?
- Can you differentiate in the applications of the active components?
- Can you sketch and differentiate the steady-state current-voltage characteristics of the active components?
- Learning outcome:
  - Operating principles of the most common active components (e.g. diode, thyristor, BJT, GTO, MOSFET, and IGBT)