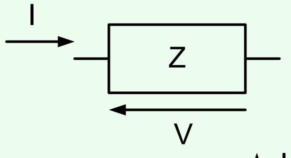
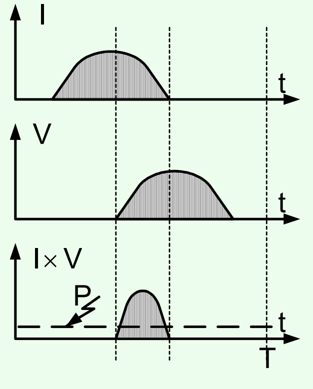
Power elements

Conduction Losses

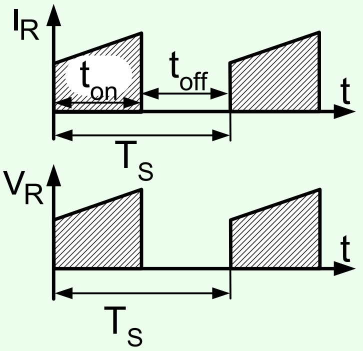


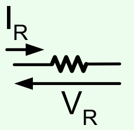
$$P = \frac{1}{T}\int_0^T V \cdot I \, dt \quad \text{(time domain)}$$



Resistor

- Periodic waveform





$$V_R = I_R \cdot R$$

$$P_R = \frac{1}{T_s}\int_0^{T_s} V_R \cdot I_R\, dt$$

$$P_R = R\{\frac{1}{T_s}\int_0^{T_s} (I_R)^2\, dt\}$$

$$\sqrt{\{\frac{1}{T_s}\int_0^{T_s} (I_R)^2\, dt\}} \equiv I_{rms}$$

$$P_R = I_{R(rms)}{}^2\, R$$

Average power

$$I = I_{av} + \sum_i I_i \cos(\omega_i t)$$

$$V = V_{av} + \sum_i V_i \cos(\omega_i t)$$

$$P = \frac{1}{T}\int_0^T V \cdot I\, dt \quad \text{(time domain)}$$

$$\int_0^T \mathrm{Cos}(\omega_n t)\,\mathrm{Cos}(\omega_m t)dt = 0 \qquad \text{if } n \neq m$$

Conclusion:

- Only V,I components of same frequency produce real power.
- DC $\rightarrow \omega=0$

Average power

$$I_{rms} = \sqrt{\{\frac{1}{T_s}\int_0^{T_s}(I_R)^2\,dt\}}$$

$$I_{rms} = \sqrt{\sum_i (I_i)^2}$$

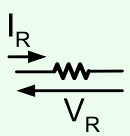
$$V_{rms} = \sqrt{\sum_i (V_i)^2}$$

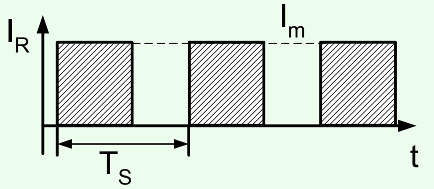
$I_1, I_2, I_3 \ldots$

of different frequencies

$V_1, V_2, \ldots.$

Example 1

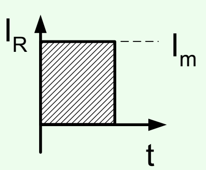




Consider only t_{on}

$P_{on} = (I_m)^2 R$

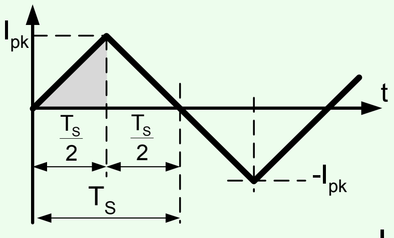
$P_{av} = P_{on}\, t_{on}/T_s = P_{on} D_{on}$



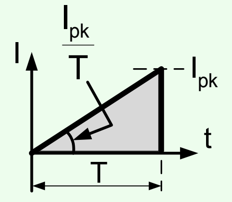
$$P_{av} = I_m^2 \cdot R \cdot D_{on} = R \cdot I_{rms}^2$$

$$I_{rms} = I_m \sqrt{D_{on}}$$

Example 2



This is an AC signal $I_{av} = 0$!



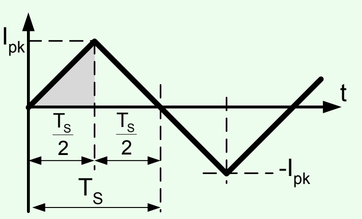
$$I = \frac{I_{pk}}{T} \cdot t$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T \left(\frac{I_{pk}}{T}\right)^2 t\,dt} = \sqrt{\frac{I_{pk}^2}{T^3} \frac{t^3}{3}\bigg|_0^T} = \sqrt{\frac{I_{pk}^2}{3}} = \frac{I_{pk}}{\sqrt{3}}$$

$$I_{rms} = \frac{I_{pk}}{\sqrt{3}}$$

$$P_R = \frac{I_{pk}^2}{3} R$$

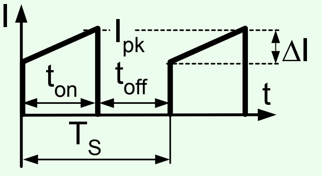
Example 2 (Cont.)



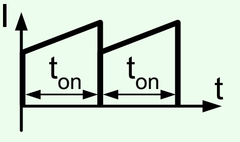
For each of the sub- triangle: $I_{rms} = \frac{I_{pk}}{\sqrt{3}}$

- Therefore for complete waveform: $I_{rms} = \frac{I_{pk}}{\sqrt{3}}$

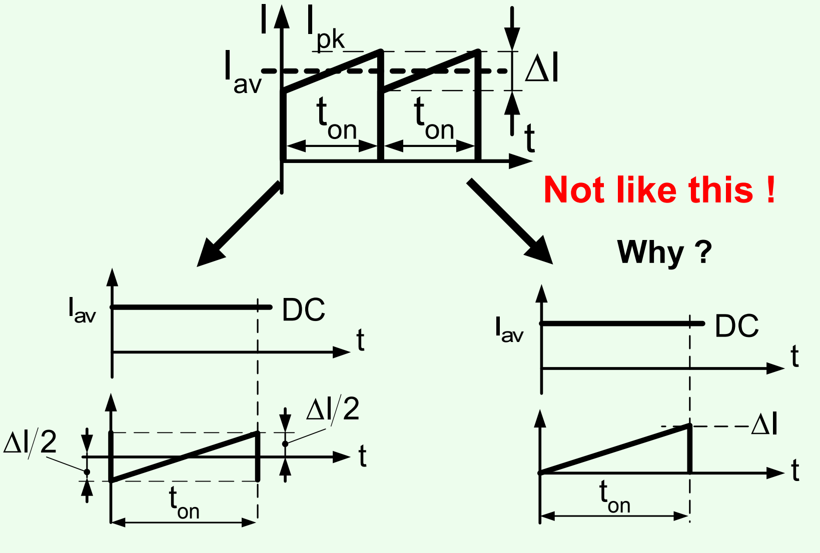
Example 3



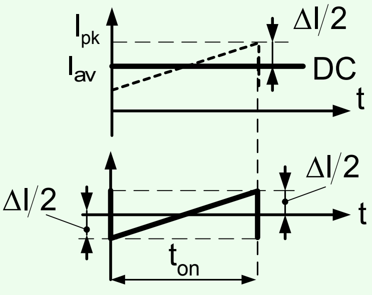
Separate into waveforms
of different frequencies
assuming a repeating wave:



Waveform decomposition



Waveform decomposition

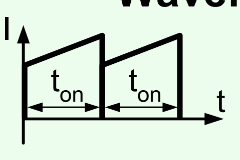


$$I_{av} = (I_{pk} - \frac{\Delta I}{2}) = I(av)_{rms}$$

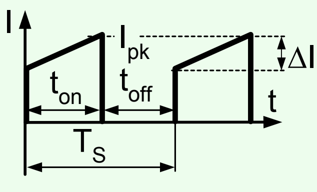
$$I_{\frac{\Delta I}{2}}(rms) = \frac{\Delta I}{2}\frac{1}{\sqrt{3}}$$

$$I^2{}_{rms}(t_{on}) = I_{av}^2 + (\frac{\Delta I}{2}\frac{1}{\sqrt{3}})^2$$

Waveform decomposition



$$I^2{}_{rms}(t_{on}) = I_{av}^2 + (\frac{\Delta I}{2}\frac{1}{\sqrt{3}})^2$$



Averaging the power over T_s:

$$I^2{}_{rms} = \left(I_{av}^2 + (\frac{\Delta I}{2}\frac{1}{\sqrt{3}})^2\right) \cdot D_{on}$$

$$I_{rms} = \sqrt{D_{on}}\sqrt{I_{av}^2 + (\frac{\Delta I}{2}\frac{1}{\sqrt{3}})^2}$$

$$I_{rms} = \sqrt{D_{on}}\sqrt{I_{av}^2 + \frac{\Delta I^2}{12}} \qquad I_{rms} = \sqrt{D_{on}}\sqrt{(I_{pk} - \frac{\Delta I}{2})^2 + (\frac{\Delta I}{2}\frac{1}{\sqrt{3}})^2}$$

$$P_R = I_{rms}^2 \cdot R$$

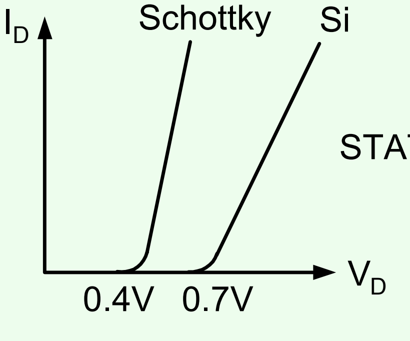
Switching Elements

1.Diode
- 1.1 Types of diodes
- 1.2 Diode conduction losses
- 1.3 Diode recovery

2. Power switches
- 2.1 BJT
- 2.2 MOSFETs
- 2.3 IGBT
- 2.3 Other switches

3. Capacitor
- 3.1 Capacitor types
- 3.2 Specifications, model, ESR
- 3.3 Assignments (ΔV_{ESR})
- 3.4 Losses

Diodes

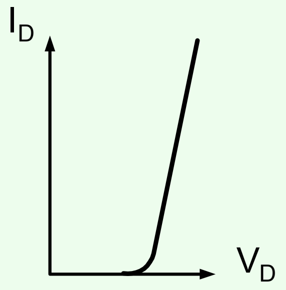


STATIC

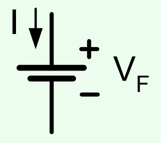
Silicone - Slow →Fast

Schottky - Fast

Diode conduction losses



$V_D = V_F \approx$ constant



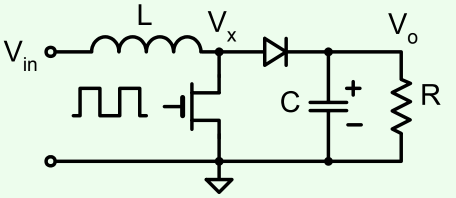
P ?

V_F=DC frequency=0

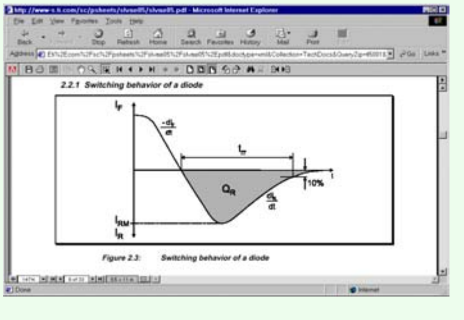
Only DC components of I are important:

$$\mathbf{P = I_{av} V_F}$$

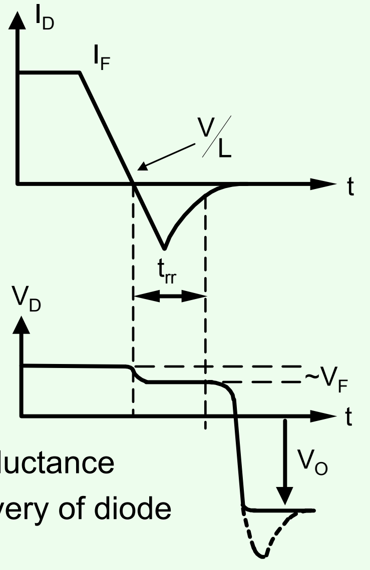
Diodes recovery



Reverse current at switch turn on



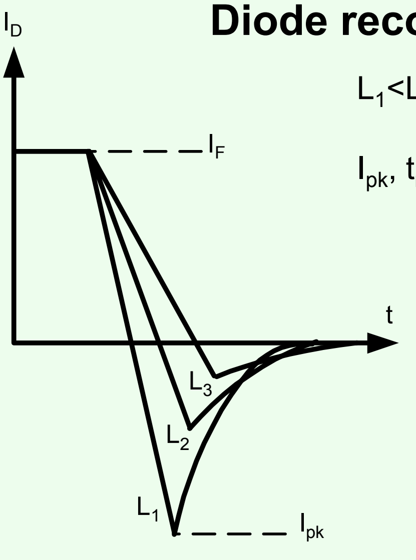
Diode recovery



L - parasitic inductance

Reverse Recovery of diode

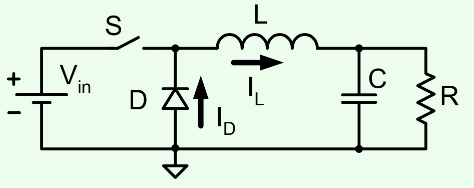
Diode recovery

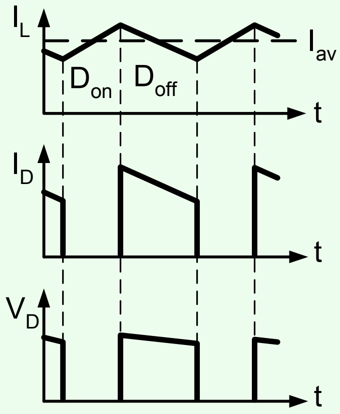


$L_1<L_2<L_3$

I_{pk}, t_{rr} are function of I_F, L, T

Diode conduction losses

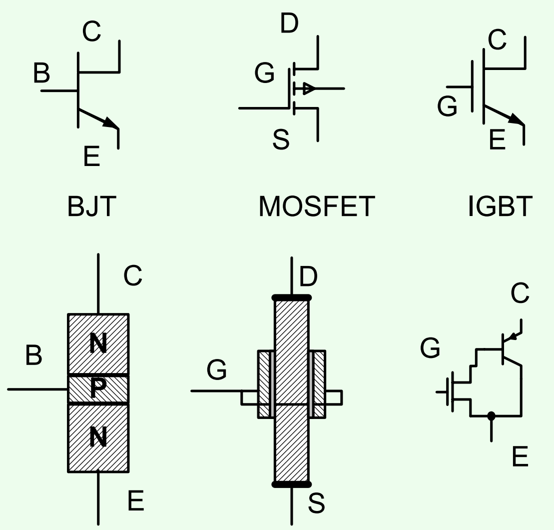




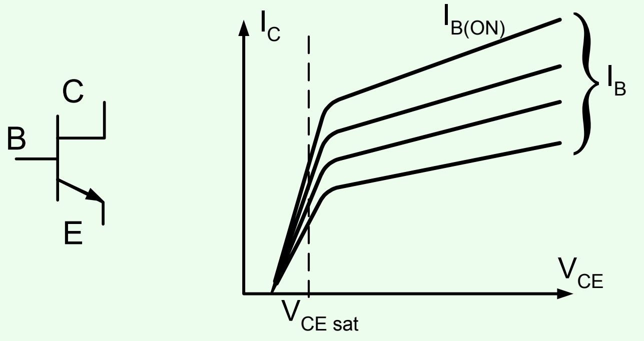
$I_{Dav} = I_{av} \bullet D_{off}$

$P = I_{Dav} \bullet V_F$

Power Switches



BJT STATIC CHARACTERSTICS



In linear region $I_C = h_{fe} I_B \rightarrow I_B = \frac{I_C}{h_{fe}}$

At saturation $I_B >> \frac{I_C}{h_{fe}}$

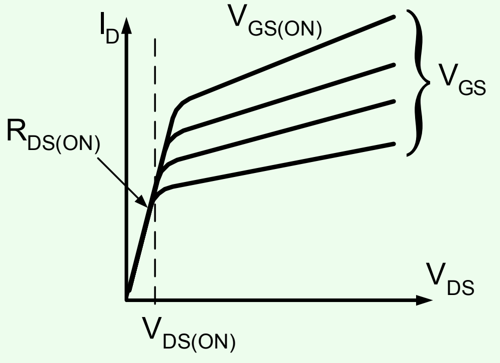
BJT Drive problems

- Relatively slow (storage time)
- Replaced by MOSFET or IGBT
- Still is use in lamp ballasts and in very high power applications (motor drive)

MOSFET STATIC CHARACTERSTICS

$V_{DS} = I_D \cdot R_{DS(ON)}$

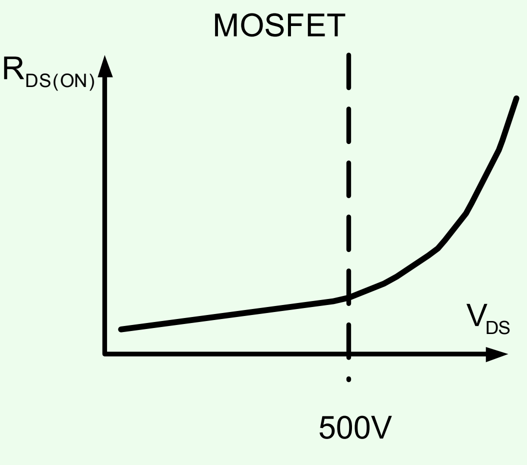
$R_{DS(ON)} \rightarrow 10\Omega - 10m\Omega$



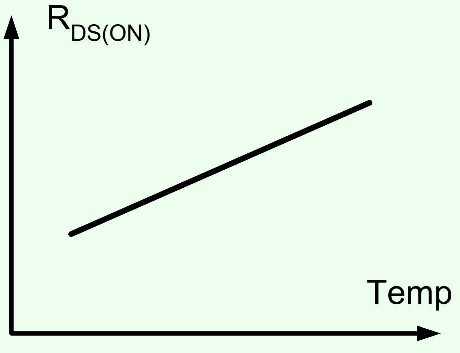
Power MOSFETS

- Parallel connections of many basic MOSFET cells

RDSon as a Function of Breakdown Voltage



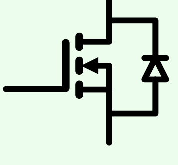
RDS(ON) as a Function of Temperature



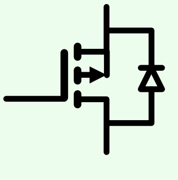
● **Permits parallel connection of MOSFETs**

MOSFET

n channel



p channel



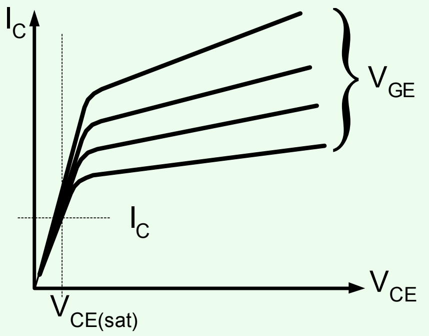
- Internal diodes
- Gate voltage

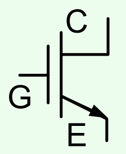
Normal :	15V	-15V
Logic level:	5V	-5V

<u>n channel</u>

- more popular
- less expensive

IGBT





- Similar to BJT but faster
- Same gate voltage as MOSFET

$V_{CE(sat)}$
- Slow IGBT - 1V
- Fast IGBT - 3V

Other Switches

- SCR - low frequency no forced turn off
- MCT - SCR+FET input
- GTO - turn on and off; slow, high current

Conduction Losses of Active Switches

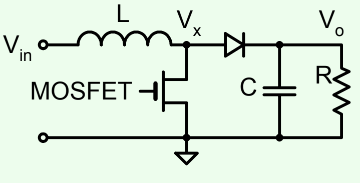
MOSFET $\rightarrow$ Rds(on)

BJT, IGBT $\rightarrow V_{CE}$ (sat)

Pd(MOSFET) $\rightarrow (I_{rms})^2$ Rds(on)

Pd(BJT, IGBT) $\rightarrow I_{av} V_{CE}$ (sat)

Example:



L=10uH; f_s= 100kHz;

R_{ds}(on)= 1 Ω

V_{in}=25V; V_o=100V;

P_{out}=100W

$$I_o V_o = P_o$$

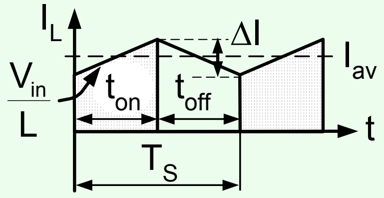
$$I_o = \frac{P_o}{V_o} = \frac{100}{100} = 1\text{Amp}$$

$$\frac{V_o}{V_{in}} = \frac{1}{D_{off}} \qquad \frac{100}{25} = \frac{1}{D_{off}}$$

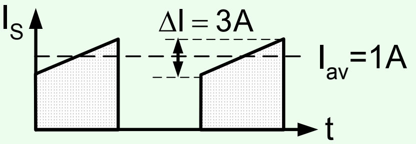
$$D_{off} = 0.25 \quad D_{on} = 0.75$$

$$t_{off} = \frac{D_{off}}{f_s} = 2.5\text{uS} \quad t_{on} = \frac{D_{on}}{f_s} = 7.5\text{uS}$$

Example:



$$\Delta I = \frac{V_{in}}{L} t_{on} = \frac{10}{25u} 7.5u = 3Amp$$

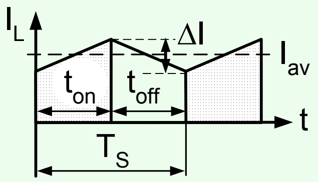


$$I_{av} = \frac{P_o}{V_o} = 1Amp$$

Example:

I_{av}=4A ΔI=1A

$R_{DS(on)}$=1ohm D_{on}=0.75



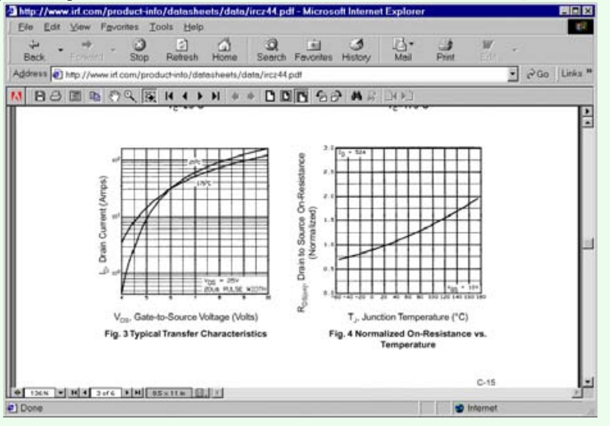
$$I_{rms} = \sqrt{I_{av}^2 + \left(\frac{\Delta I}{2} \frac{1}{\sqrt{3}}\right)^2} \sqrt{D_{on}} = \sqrt{4^2 + \left(\frac{0.5}{\sqrt{3}}\right)^2} \sqrt{0.75} = 3.47A$$

$$P_d = I_{rms}^2 R_{ds(on)}$$

$$I_{rms} = 3.47\,A$$

$$P_d = 12.063\,W$$

RDS(ON) as a Function of Temperature



Over useful temp: Rds(on) =1.5 x Rds(on)[25^{0}C]

- The limitation:

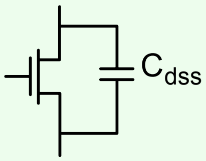
Junction Temp. T_j: 120^{0}C- 175^{0}C

Parallel connection

- IMPORTANT

Parallel connections of a number of MOSFETs is possible because of the positive temp coefficient of R_{ds}(on)

$\frac{CV^2}{2}$ Losses

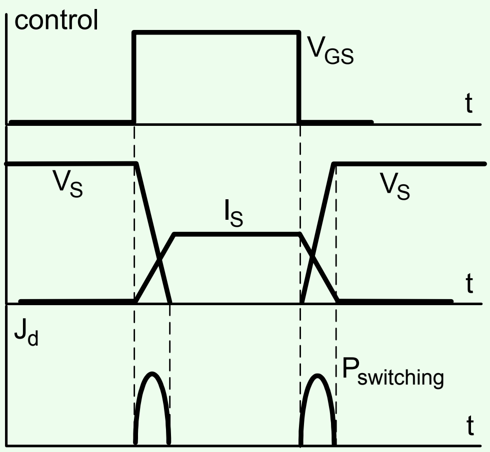


$$\left[\frac{C_{dss} V_{max}^2}{2}\right] f_s \rightarrow \text{lost to heat}$$

Linear with f_s!

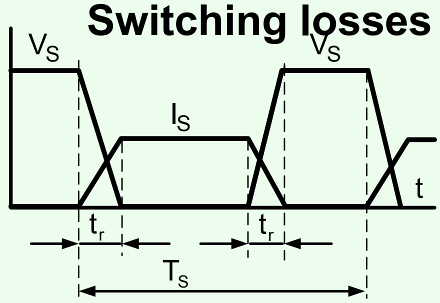
Switching losses (overlap) also linear with f_s!

Switching losses



Switching losses due to overlap P_d linear with f_S !

Switching losses

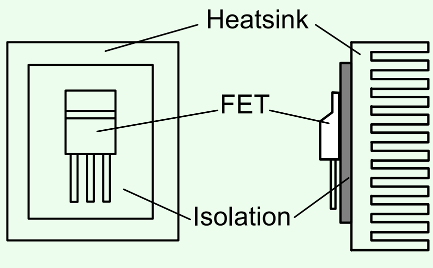


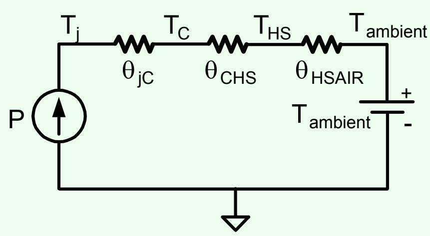
$$E_{don} \approx E_{doff} \approx \int_0^{t_r} \left(\frac{I_S}{t_r} t \right) \cdot V_S \left(1 - \frac{1}{t_r} t \right) dt = \frac{I_S V_S}{6} t_r$$

$$P_d = \frac{E_d}{T_S} = \frac{E_{don} + E_{doff}}{T_S} \approx \frac{2E_{don}}{T_S} \approx \frac{I_S V_S}{3T_S} t_r = \frac{I_S V_S}{3} t_r f_S$$

Switching losses due to overlap P_d linear with f_S !

Heat conduction





Equivalent circuit
$P \rightarrow I \quad T \rightarrow V \quad \theta_{°C/W} \rightarrow R$

Transistors' Data

θ_{jC}

Very small transistors	$20\,°c/w$
Large Modern MOSFET T247	$0.5\,°c/w$
Isolator	$\sim 0.5 \div 1°c/w$
HS Surface-Airspeed $\theta_{HS\text{-}AIR}$	$10 \div 0.5\,°c/w$

Example

$P_d = 15\ w$, $T_{jmax} = 110\,°c$

$\theta_{jC} = 1\ °c/w$, $T_{amb(max)} = 50°c$

$\theta_{CHS} = 1\ °c/w$,

Find $\theta_{HS\text{-}AIR}$

$$15(\theta_{jC}+\theta_{CHS}+\theta_{HSAIR})+25=110\ °C$$

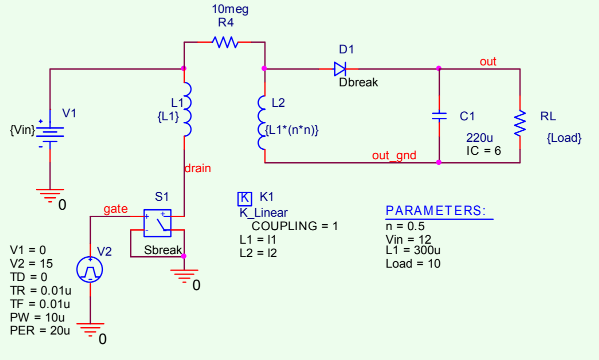
$$15(1+1+x)=85$$

$$\theta_{HSAIR} = \frac{85}{15} - 2 = 3.6\ °C/W$$

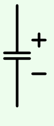
Assignment

Modify circuit to include R_S=500mΩ.

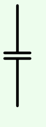
Find by simulation losses on switch and overall efficiency.



Capacitors



Polarized (electrolytic)



Non Polarized
C < 10μF

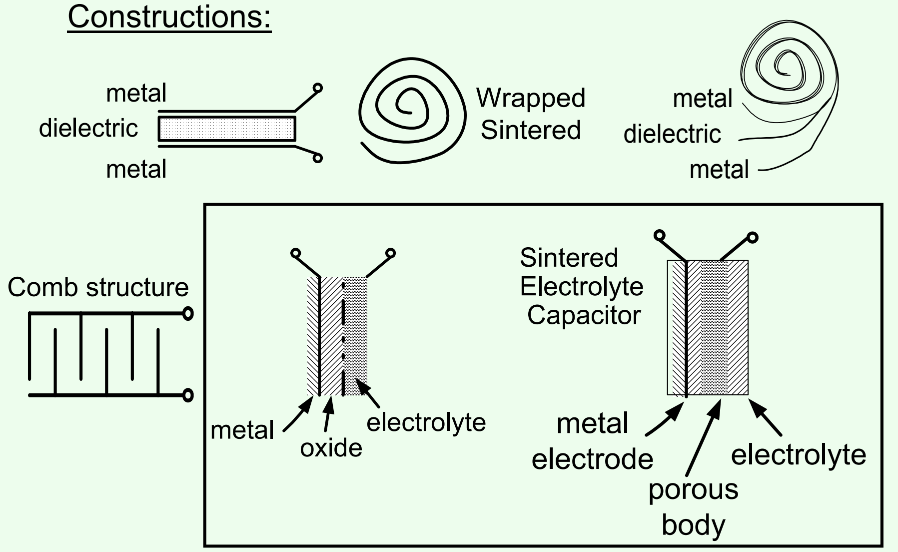
Materials:

Tantalum
Aluminum

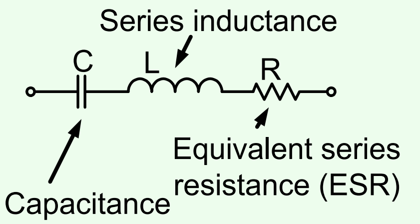
Paper
Plastic
Teflon
Polypropylene
Minerals
Mica

Capacitors

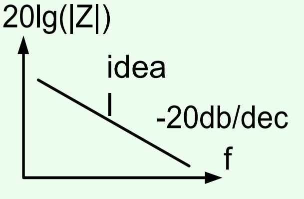
Constructions:



Capacitors

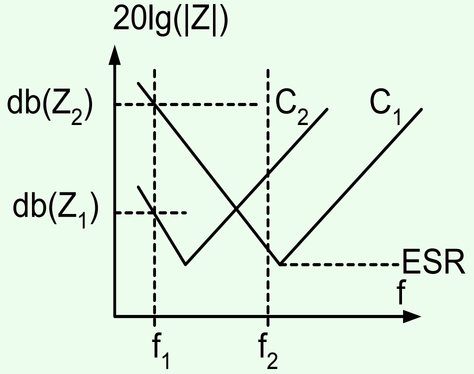


- Wrapped capacitors will tend to have higher inductance



$$|Z| = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

Practical C

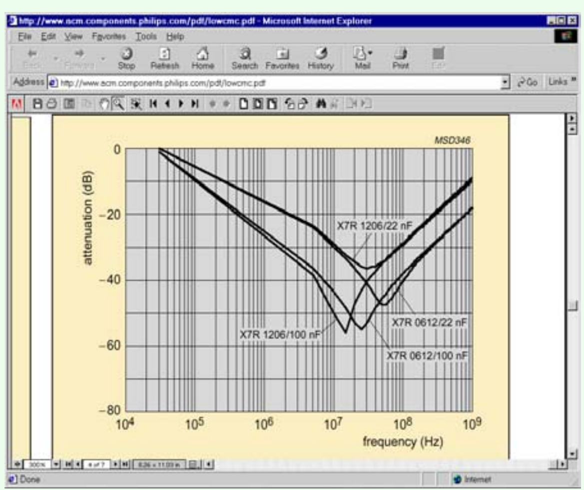


$C_2 > C_1$

$$\frac{1}{2\pi f_1 C_2} < \frac{1}{2\pi f_1 C_1}$$

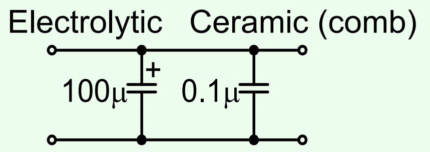
$$\frac{1}{2\pi f_2 C_2} > \frac{1}{2\pi f_2 C_1}$$

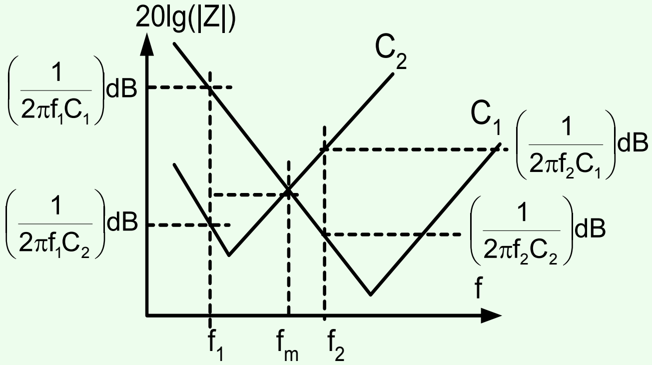
Philips ceramic capacitors



Parallel connection of Capacitors

Why?





At f_1:

$$Z_1 \approx \left(\frac{1}{2\pi f_1 C_2}\right) dB$$

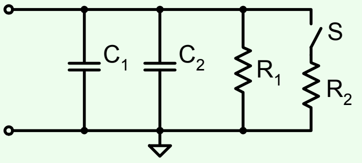
At f_2:

$$Z_2 \approx \left(\frac{1}{2\pi f_2 C_2}\right) dB$$

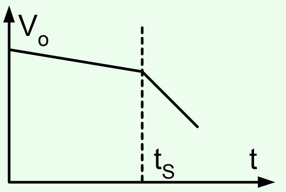
Specifications of capacitor

- Capacitance
- Maximum voltage
- Maximum current
- Inductance or plot
- ESR, Sometime: $tg\delta = \omega C R_{ESR}$ (ω = test frequency)

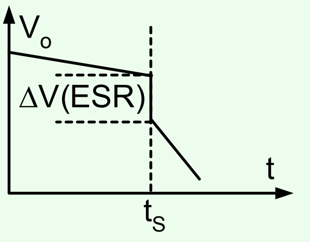
Implication- Load Step



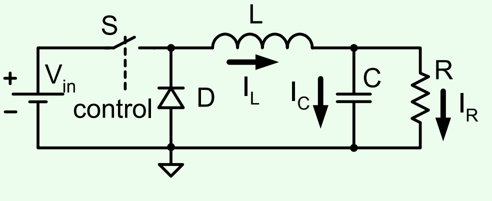
Ideal response

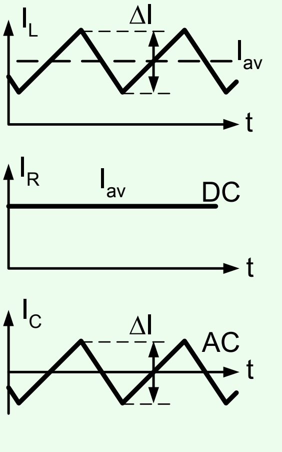


Practical response



Capacitor losses





$$I_{Crms} = \frac{\Delta I}{2} \frac{1}{\sqrt{3}}$$

$$P = I_{Crms}{}^{2} \cdot ESR$$