Conditions for Continuous Current Operation

$$\cancel{V_{cout}} \quad I_{cout} = C_{out} \frac{dV_{cout}}{dt}$$

$$\frac{dV_{cout}}{dt} = \frac{I_{cout}}{C_{out}}$$

$$V_{cout}(t_2) = V_{cout}(t_1) + \frac{1}{C_{out}} \int_{t_1}^{t_2} I_{cout}\, dt$$

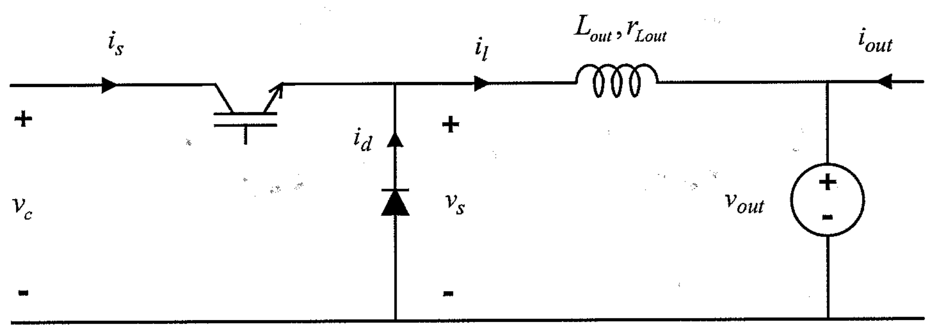
$$\Delta V_{cout} = \frac{1}{C_{out}} \frac{1}{2} \frac{1}{2} T_{sw} \frac{1}{2} \Delta I_L$$

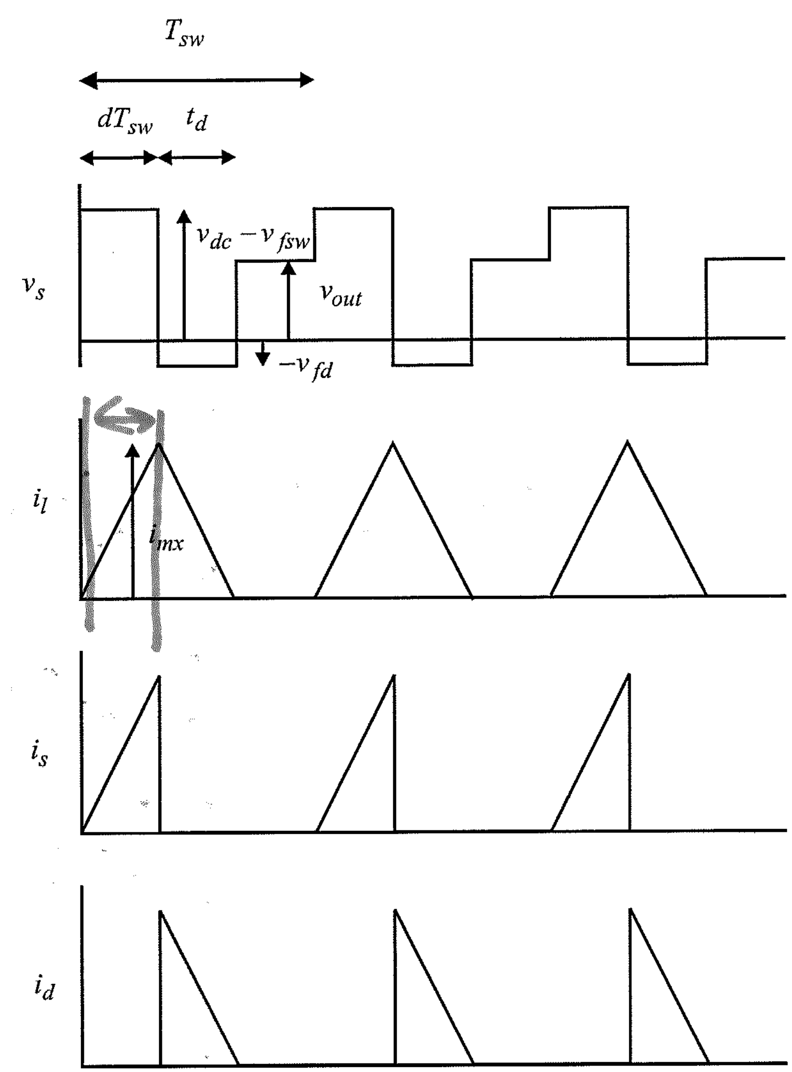
$$\boxed{\Delta V_{cout} = \frac{1}{8 C_{out} f_{sw}} \Delta I_L}$$

$$I_{min} > 0 \qquad I_{min} = \bar{I}_L - \frac{\Delta I_L}{2} > 0$$

$$\boxed{\Delta I_L < 2\bar{I}_L}$$

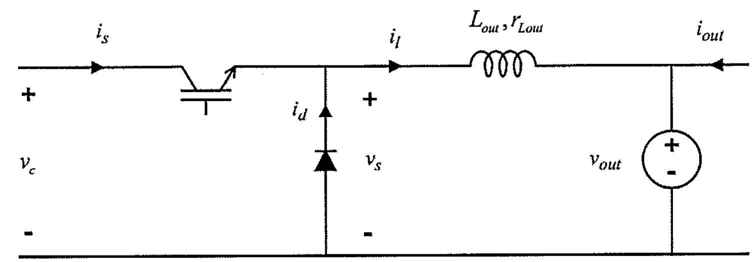
Discontinuous Current (DC) Buck Operation





Discontinuous Current (DC) Buck Operation

- Consider the on period.



$$-V_c + V_{fsw} + L_{out}\cancel{\frac{di_l}{dt}} \rightarrow \frac{i_{mx}}{dT_{sw}}$$

$$+ r_{Lout}\cancel{i_l} + V_{out} = 0$$

$$\rightarrow \frac{i_{mx}}{2} \qquad + r_{Lout}\frac{i_{mx}}{2}$$

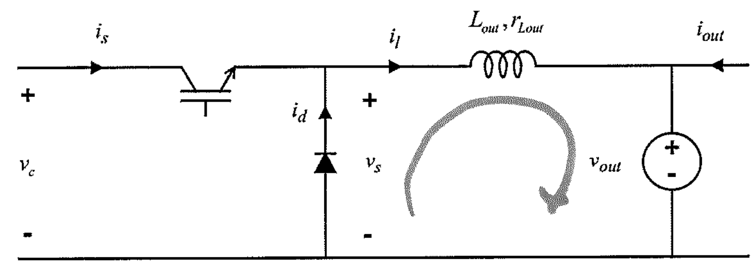
$$L_{out}\frac{i_{mx}}{dT_{sw}} = V_c - V_{fsw} - V_{out}$$

- Thus

$$\boxed{i_{mx} = \frac{2\left(v_c - v_{fsw} - v_{out}\right)dT_{sw}}{2L_{out} + r_{Lout}dT_{sw}}}$$

Discontinuous Current (DC) Buck Operation

- Consider the off period



$$-v_{fd} + L_{out}\frac{di_l}{dt} + r_{Lout} i_l + v_{out} = 0$$

$$\frac{di_l}{dt} \rightarrow -\frac{i_{mx}}{t_d} \qquad i_l \sim \frac{i_{mx}}{2}$$

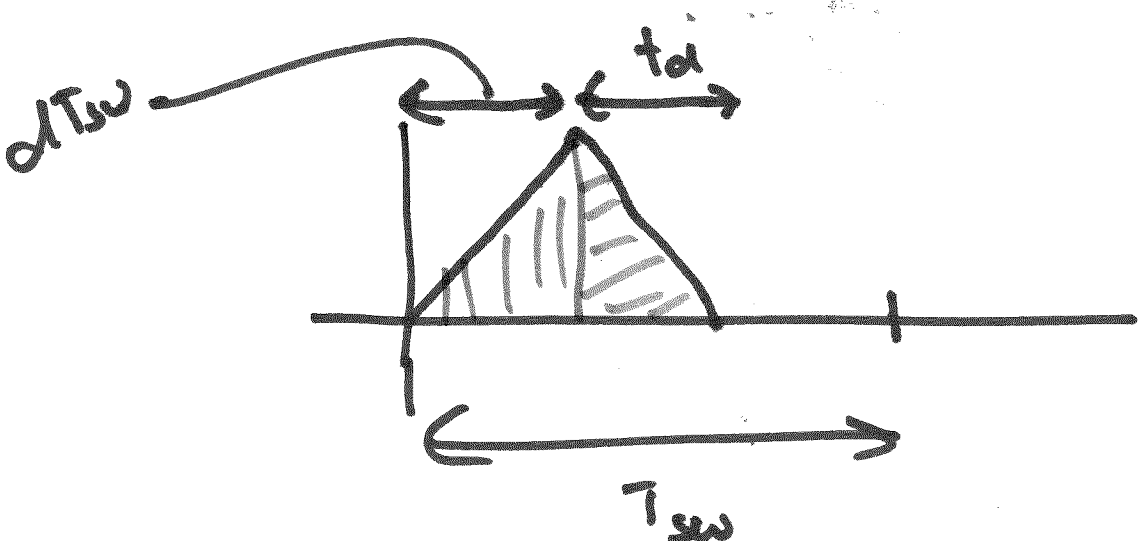
- Thus

$$t_d = \frac{L_{out} i_{mx}}{v_{out} + v_{fd} + \frac{1}{2} r_{Lout} i_{mx}}$$

Discontinuous Current (DC) Buck Operation

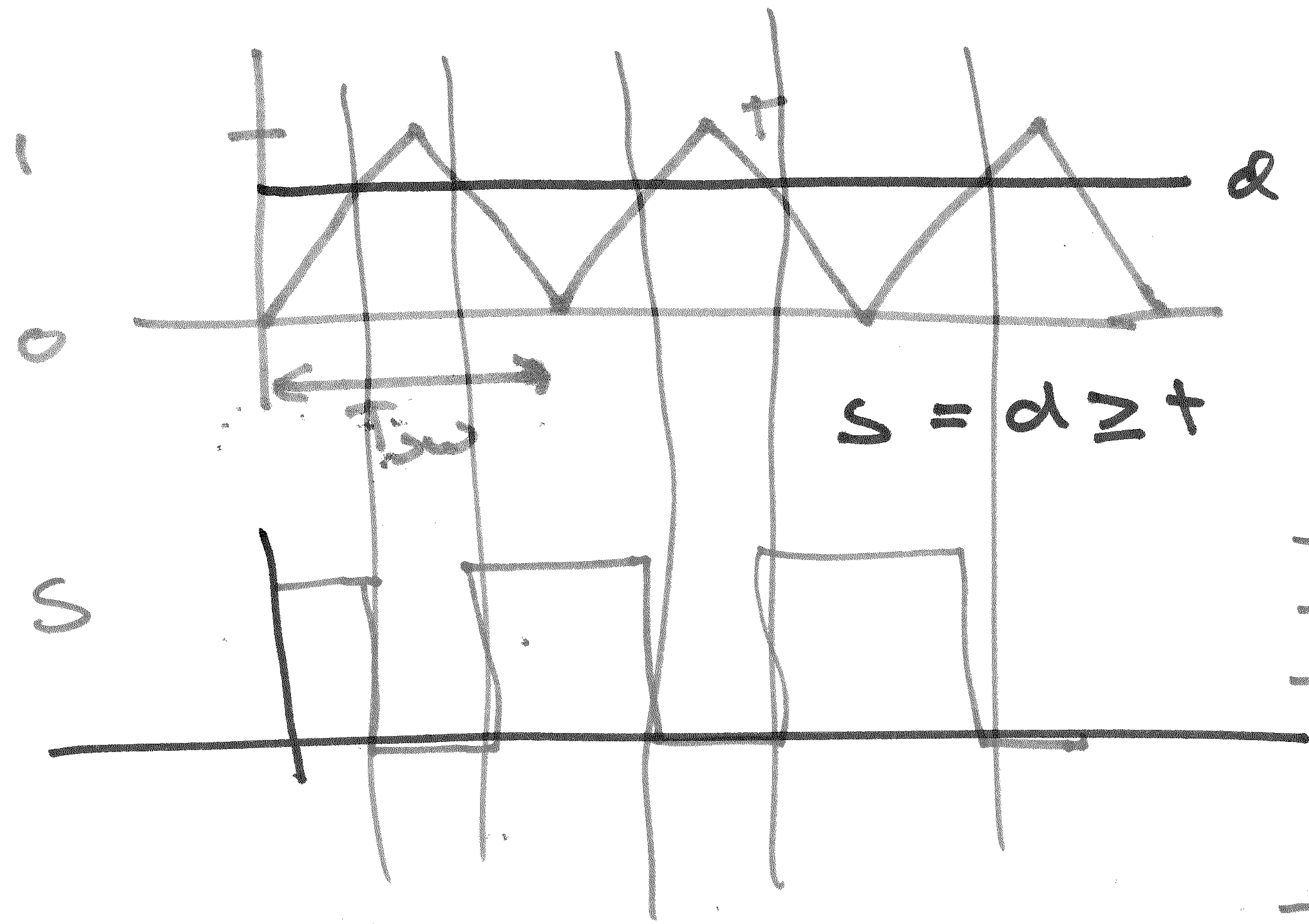
- Now, the average current may be given by

$$\bar{i}_l = \frac{1}{T_{sw}}\left(\frac{1}{2}dT_{sw}i_{mx} + \frac{1}{2}t_d i_{mx}\right)$$



$$\bar{I}_l = \frac{1}{T_{sw}}\int_0^{T_{sw}} i_l\,dt = \frac{1}{T_{sw}}\left[\frac{1}{2}dT_{sw}\,i_{mx} + \frac{1}{2}t_d\,i_{mx}\right]$$

Duty Cycle Modulation



→ simple

→ periodic

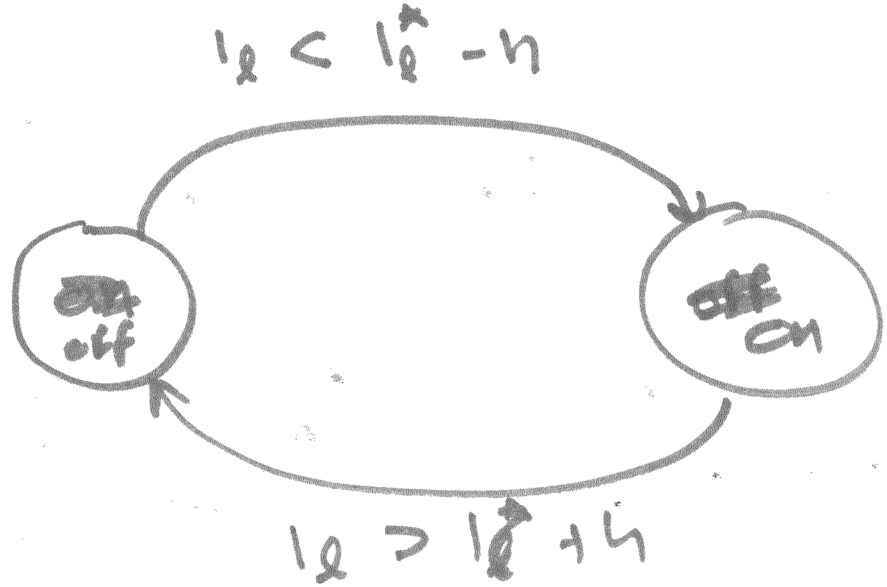
→ switching freq is fixed

→ transients are not well controlled

→ voltage source control

$$V_s \approx \alpha V_c$$

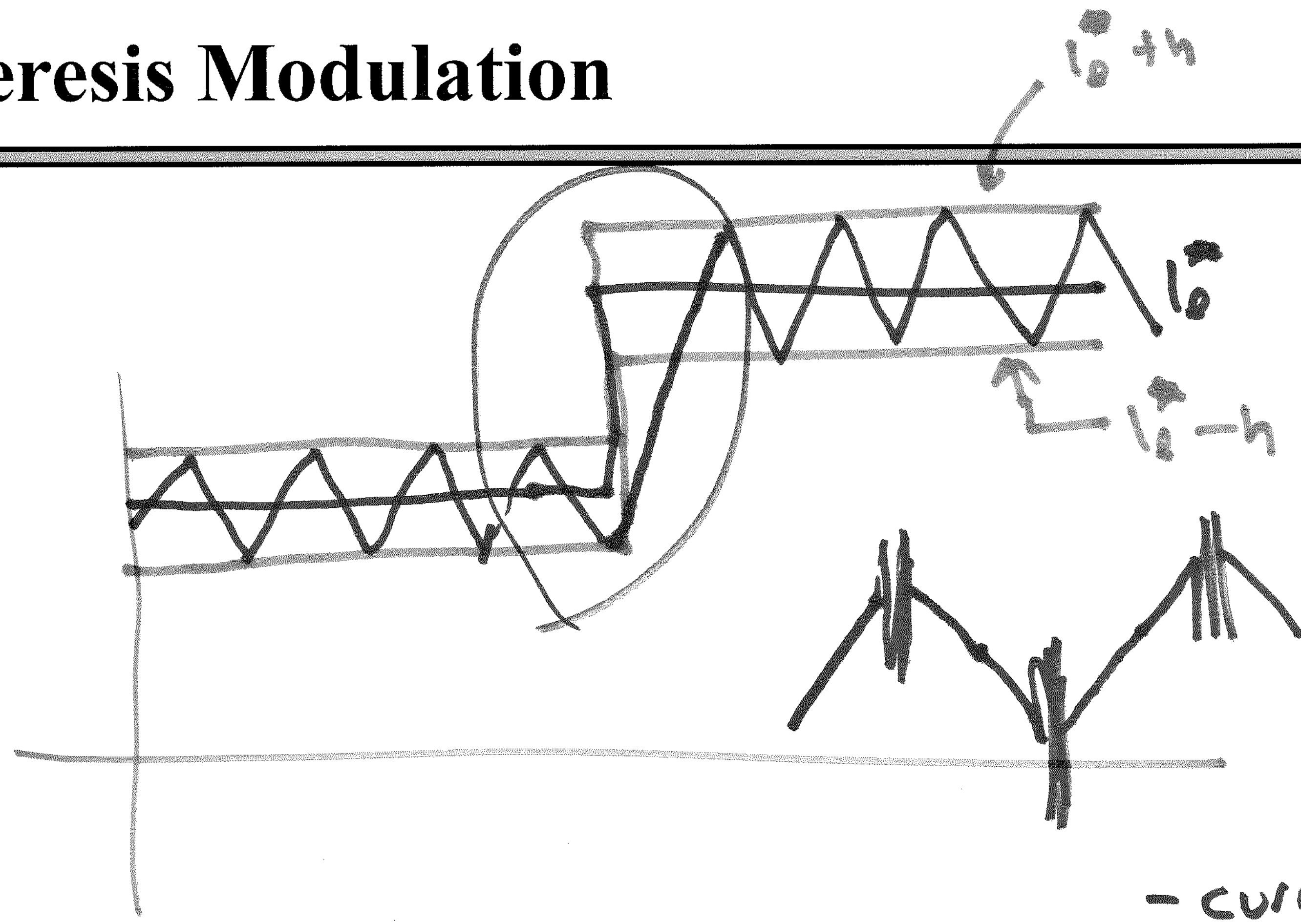
Hysteresis Modulation



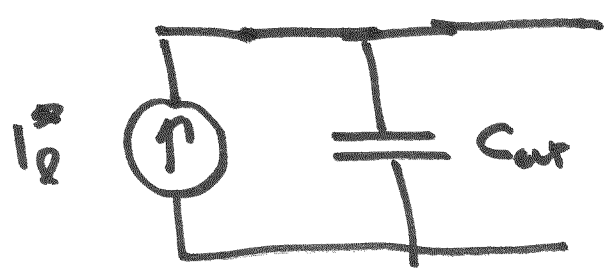
→ current control

$i_\ell \approx i_\ell^*$

Hysteresis Modulation



t →



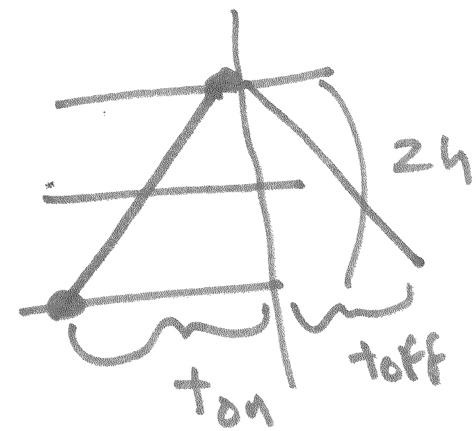
- current source
- robust to faults
- need a <u>good</u> current sensor
- variable switching frequency

Hysteresis Modulation

- On time

$$-v_c + v_{fsw} + L_{out}\frac{di_l}{dt} + r_{Lout} i_l + v_{out} = 0$$

$$\frac{di_l}{dt} \rightarrow \frac{2h}{t_{on}}, \qquad i_l \rightarrow i_l^*$$



$$\Downarrow$$

- Thus

$$t_{on} = \frac{2hL_{out}}{v_{in} - v_{fsw} - r_{Lout} i_l^* - v_{out}}$$

Hysteresis Modulation

- Off time

$$-V_{fd} + L_{out}\underbrace{\cancel{\frac{di_l}{dt}}}_{-\frac{2h}{t_{off}}} + r_{Lout}\overbrace{\cancel{i_l}}^{i_l^*} + V_{out} = 0$$

$$\Downarrow$$

- Thus

$$t_{off} = \frac{2hL_{out}}{v_{fd} + r_{Lout}\,i_l^* + v_{out}}$$

Hysteresis Modulation

- On time: $t_{on} = \dfrac{2hL_{out}}{v_{in} - v_{fsw} - r_{Lout} i_l^* - v_{out}}$
- Off time: $t_{off} = \dfrac{2hL_{out}}{v_{fd} + r_{Lout} i_l^* + v_{out}}$
- Now $f_{sw} = \dfrac{1}{T_{sw}} = \dfrac{1}{t_{on} + t_{off}}$

$$\Downarrow$$

- So

$$f_{sw} = \frac{1}{2hL_{out}} \frac{\left(v_{fd} + r_{Lout} i_l^* + v_{out}\right)\left(v_{in} - v_{fsw} - r_{Lout} i_l^* - v_{out}\right)}{v_{in} + v_{fd} - v_{fsw}}$$

ECE61016 Power Electronic Converters and Systems

Lecture Set 3B: Buck Converter Design

S.D. Sudhoff

Fall 2016

Overview

- Inductor sizing
- Capacitor sizing
- Conduction losses
- Switching losses
- Design constraints
- Design metrics
- Design fitness

Ferrite Core DC Inductor Size & Loss

- Sizing model for ferrite core dc inductor

$$K_J = 1$$

$$E_{mi} = \frac{1}{2} L_{inc} i_{pk}^2$$

peak <u>dc</u> current over operating points of interest

$$M = c_M E_{mi} \prod_{k=1}^{K_M} \left(J_{pk} E_{mi}^{1/3} + b_{M,k} \right)^{n_{M,k}}$$

current density corresponding to i_{pk}

$$P_{dc} = c_P K_J^2 E_{mi}^{1/3} \prod_{k=1}^{K_P} \left(J_{pk} E_{mi}^{1/3} + b_{P,k} \right)^{n_{P,k}}$$

dc loss corresponding to i_{pk}

Sudhoff, S.D.; Shane, G.M.; Suryanarayana, H., "Magnetic-Equivalent-Circuit-Based Scaling Laws for Low-Frequency Magnetic Devices," *Energy Conversion, IEEE Transactions on* , vol.28, no.3, pp.746,755, Sept. 2013

Ferrite Core DC Inductor Size & Loss

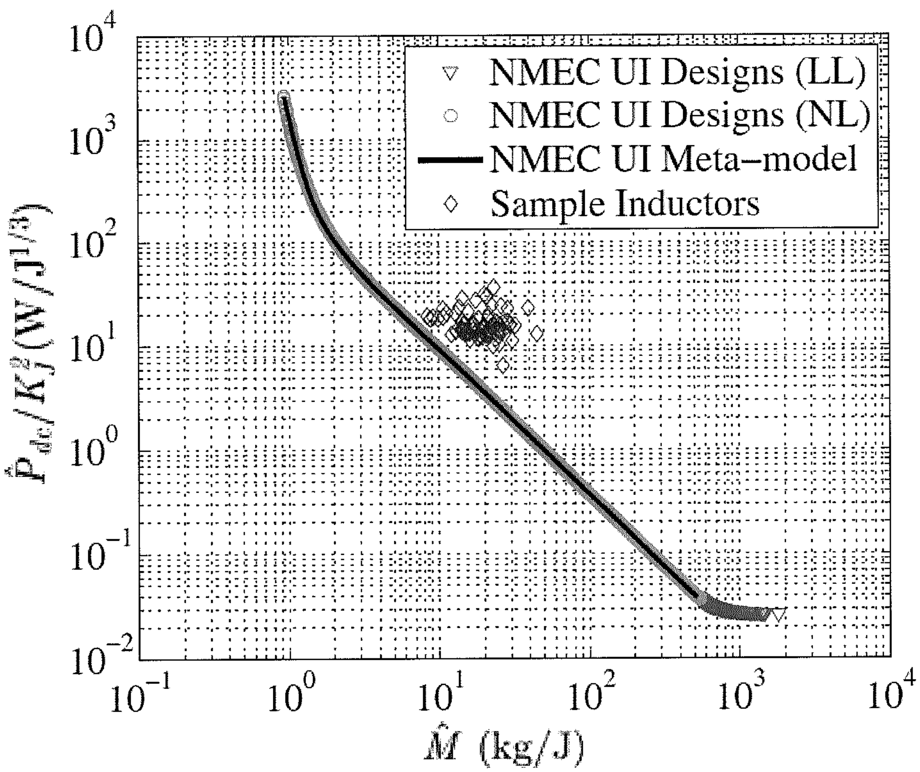
TABLE I
METAMODEL PARAMETERS

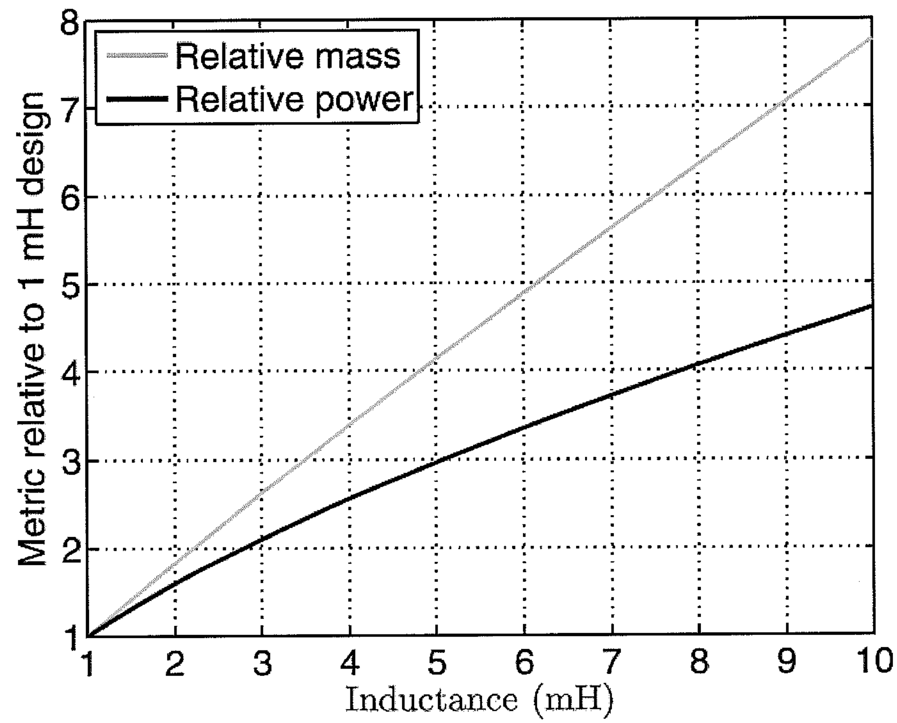
k	$b_{M,k}$	$n_{M,k}$	$b_{P,k}$	$n_{P,k}$
1	0	0.24700	0	0.54482
2	100.05	0.24673	$1.1658 \cdot 10^3$	0.25254
3	100.05	-1.3215	$1.1658 \cdot 10^3$	0.17114
4	$3.4677 \cdot 10^6$	-1.2423	$1.1659 \cdot 10^3$	0.24906
5	$8.2537 \cdot 10^6$	2.4809	$5.1412 \cdot 10^4$	-0.15241
6	$7.3079 \cdot 10^7$	-2.0633	$4.4344 \cdot 10^5$	0.52755
7	$1.0430 \cdot 10^8$	1.5530	$1.2330 \cdot 10^6$	-0.59614

$c_M = 5.9851$; $c_P = 1.1021 \cdot 10^{-5}$

Sudhoff, S.D.; Shane, G.M.; Suryanarayana, H., "Magnetic-Equivalent-Circuit-Based Scaling Laws for Low-Frequency Magnetic Devices," *Energy Conversion, IEEE Transactions on* , vol.28, no.3, pp.746,755, Sept. 2013

Ferrite Core DC Inductor Size & Loss





Sudhoff, S.D.; Shane, G.M.; Suryanarayana, H., "Magnetic-Equivalent-Circuit-Based Scaling Laws for Low-Frequency Magnetic Devices," *Energy Conversion, IEEE Transactions on* , vol.28, no.3, pp.746,755, Sept. 2013

Electrolytic Capacitor Size & Loss

- Behavioral Sizing Model

$$C = C_0\left(\alpha_C + \frac{1-\alpha_C}{1+(f_{sw}/f_C)^{\eta_C}}\right)$$

$$M_C = \beta_C C_0 v_{C,b}^{3/2}$$

$$r_C = \frac{\gamma_C}{C_0 v_{C,b}}$$

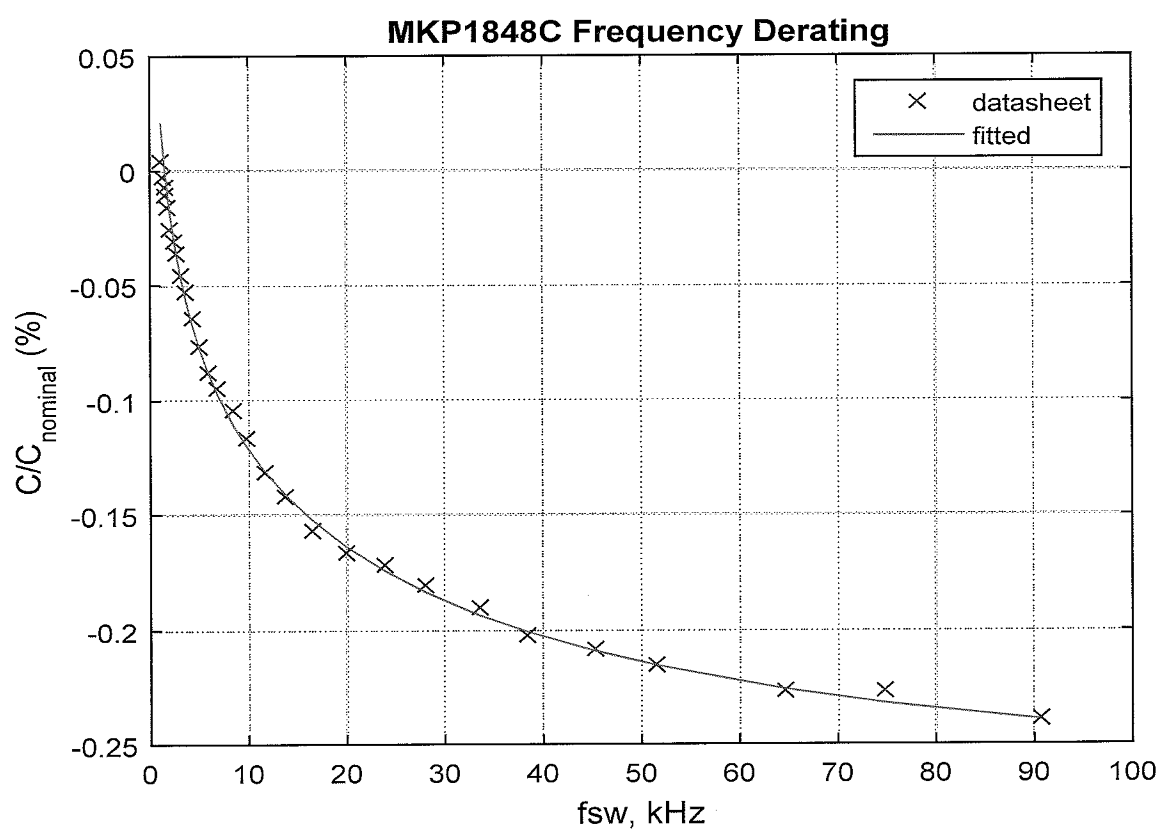
<u>Evox Rifa PEH200 Output Capacitor</u>

α_C	$1.436\cdot10^{-19}$	Effective capacitance model parameter
f_C	8746.2 Hz	Effective capacitance model parameter
n_C	1.9255	Effective capacitance model parameter
β_C	$3.3578\cdot10^{-2}$ kg/(F·V$^{3/2}$)	Effective mass model parameter
γ_C	$2.694\cdot10^{-2}$ Ω·F·V	Effective ESR model parameter

S.Wang, "Automated design approaches for power electronics converters," Ph.D. dissertation, School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA, Aug. 2010.

Polypropylene Capacitor Size & Loss

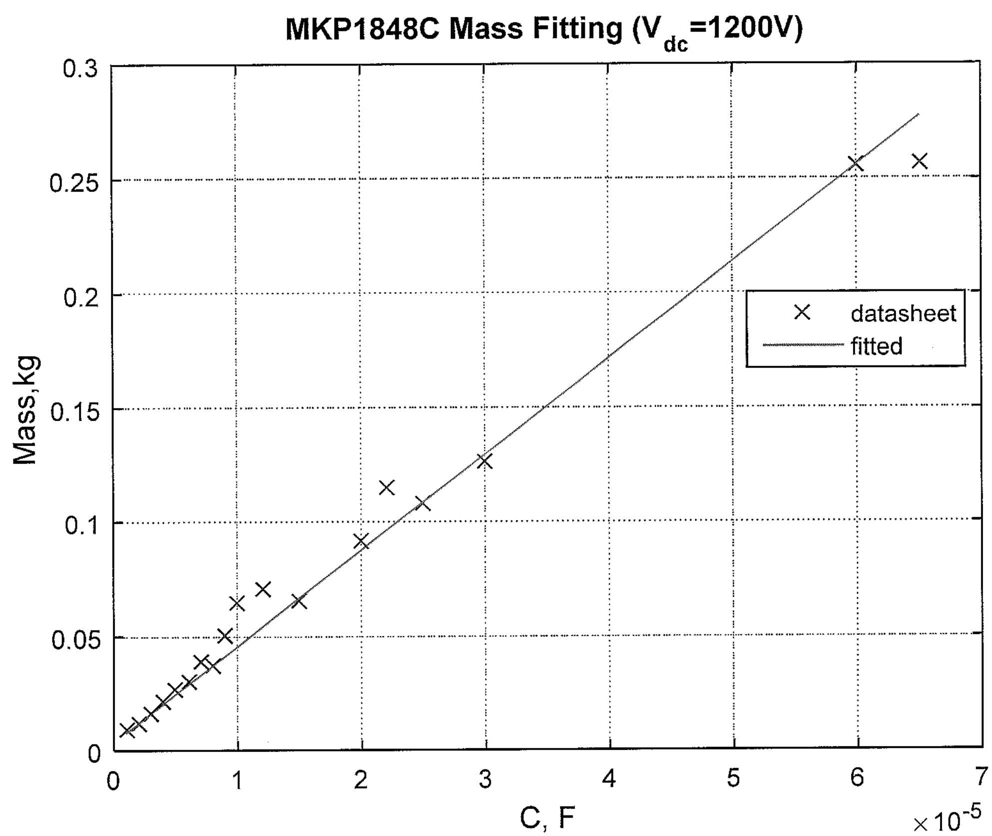
- Consider VISHA MKP1848C (500-1200 V)



Vishay Intertechnology, Inc, “MKP1848C DC-Link Datasheet.” Available: vishay.com

Polypropylene Capacitor Size & Loss

- Mass



$$M_C = \alpha_m C + \beta_m$$

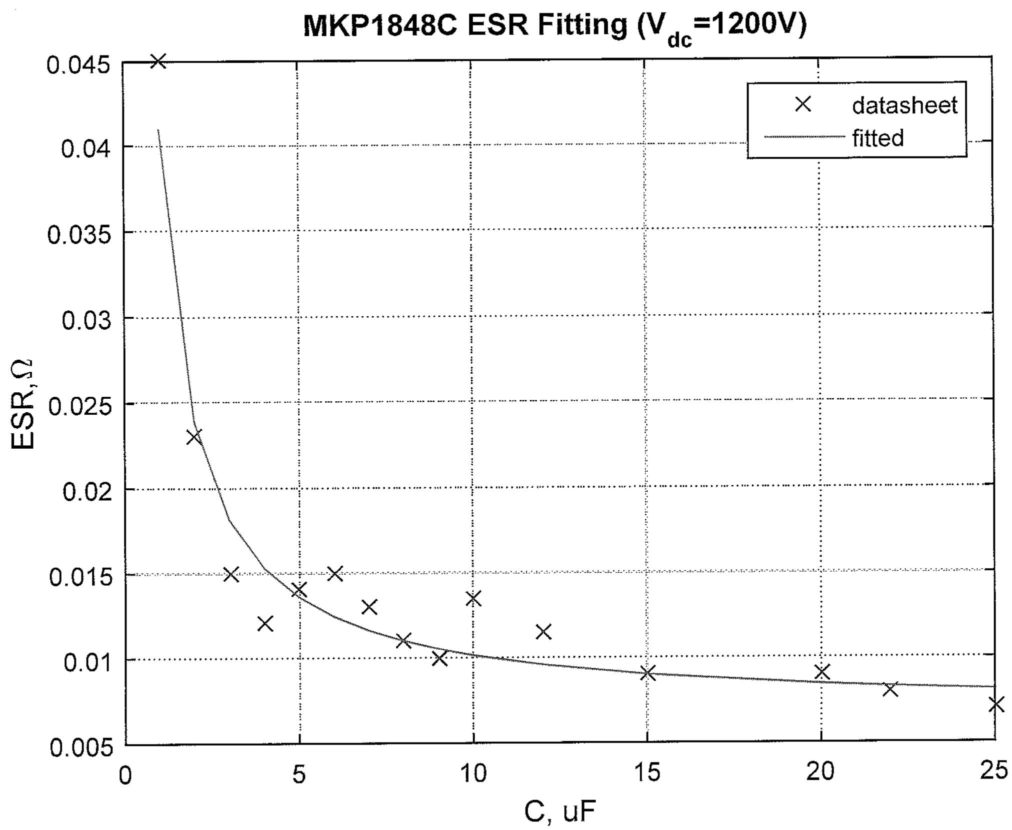
$$\alpha_m = 4.21 \cdot 10^3 \text{ kg/F}$$

$$\beta_m = 3.3 \cdot 10^{-3} \text{ kg}$$

Vishay Intertechnology, Inc, "MKP1848C DC-Link Datasheet." Available: vishay.com

Polypropylene Capacitor Size & Loss

- Loss



$$P_{esr} = R_{esr} I_{c,rms}^2$$

$$R_{esr} = \frac{\alpha_{esr}}{C} + \beta_{esr}$$

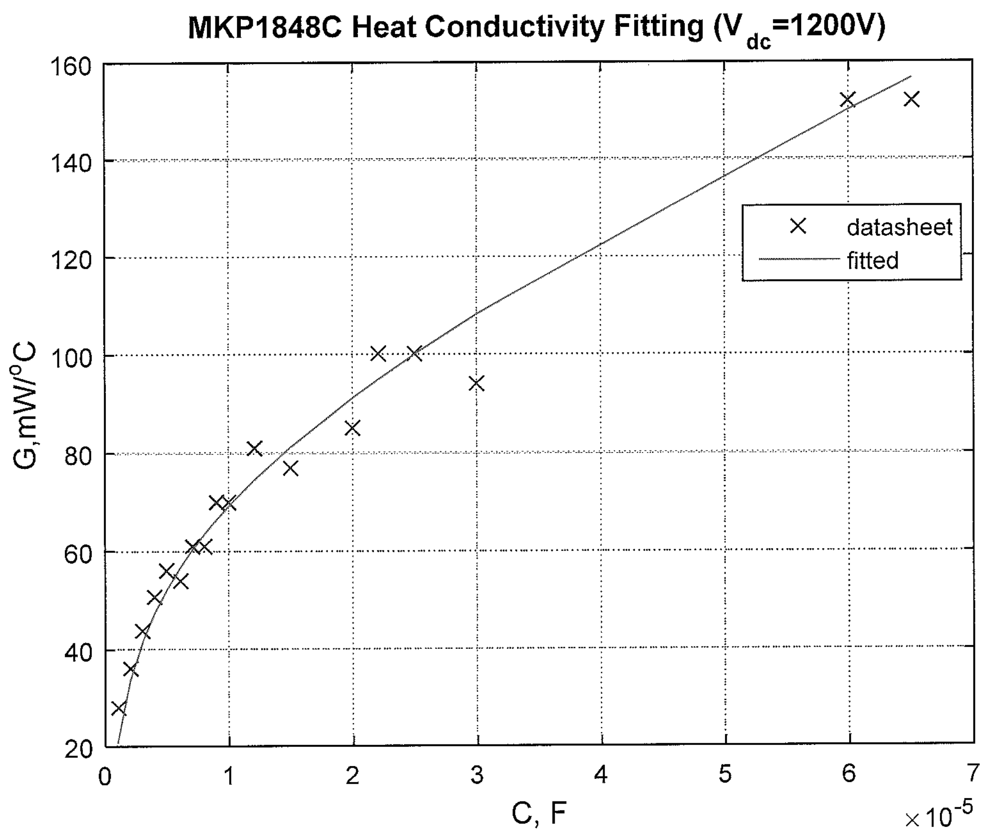
$$\alpha_{esr} = 3.43 \cdot 10^{-8}\ \Omega\mathrm{F}$$

$$\beta_m = 6.7 \cdot 10^{-3}\ \Omega$$

Vishay Intertechnology, Inc, "MKP1848C DC-Link Datasheet." Available: vishay.com

Polypropylene Capacitor Size & Loss

- Thermal Conductivity



$$T_{Ccase} = T_A + \frac{P_{esr}}{G_{Ccase}}$$

$$G_{Ccase} = \alpha_G \ln\left(\frac{C}{1\mathrm{F}}\right) + \beta_G C + \gamma_G$$

$$\alpha_G = 1.73 \cdot 10^{-2} \frac{W}{{}^oC}$$

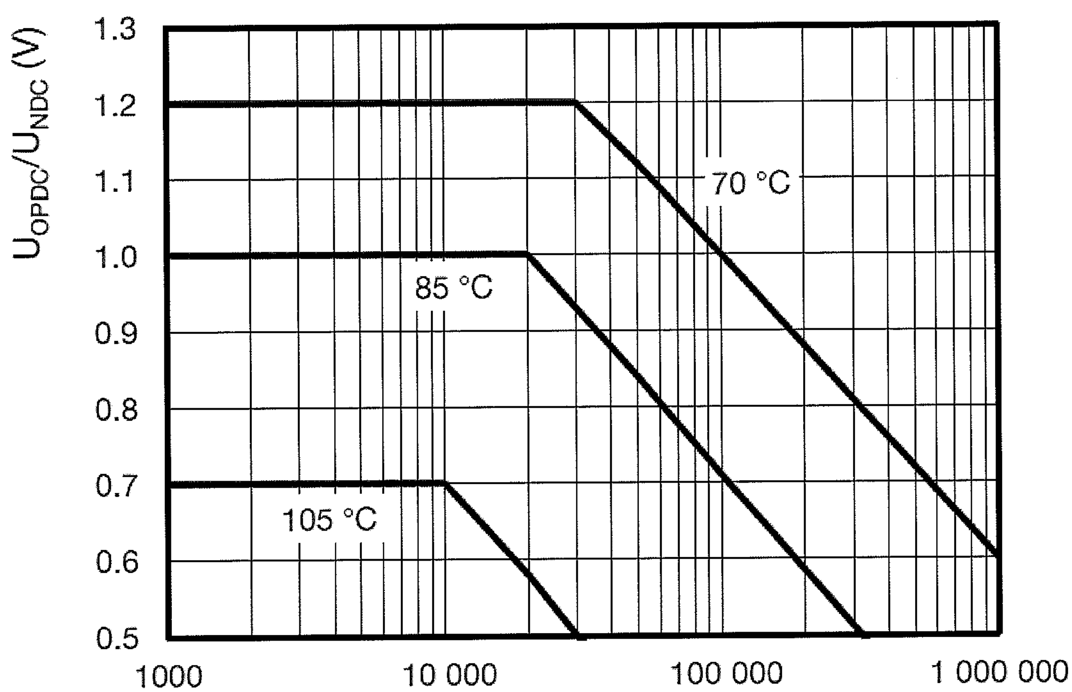
$$\beta_G = 1.00 \cdot 10^{3} \frac{W}{{}^oC\ F}$$

$$\gamma_G = 2.58 \cdot 10^{-1} \frac{W}{{}^oC}$$

Vishay Intertechnology, Inc, “MKP1848C DC-Link Datasheet.” Available: vishay.com

Polypropylene Capacitor Size & Loss

- Lifetime



Lifetime expectancy
(typical)

Vishay Intertechnology, Inc, "MKP1848C DC-Link Datasheet." Available: vishay.com

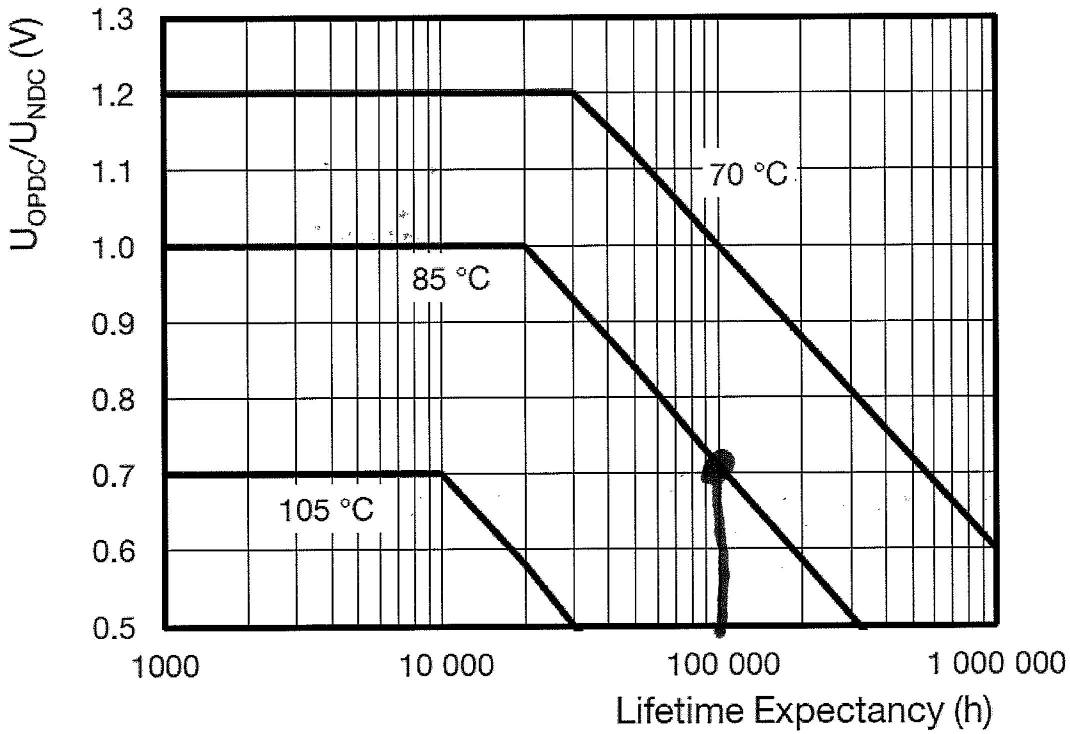
Polypropylene Capacitor Size & Loss

- Example. Suppose we are design a buck converter and selecting an input capacitor. The rms current into the capacitor so 10 A rms, and the nominal voltage is ~~600~~ 340 V. What is the voltage and minimum capacitance we can use assuming we want to operate on the 85°C curve and achieve a 100,000 h expected lifetime. Ambient temperature $T_A = 40°C$.

Polypropylene Capacitor Size & Loss

- Voltage

$$U_{NDC} = \frac{840V}{0.7} = 1200V$$

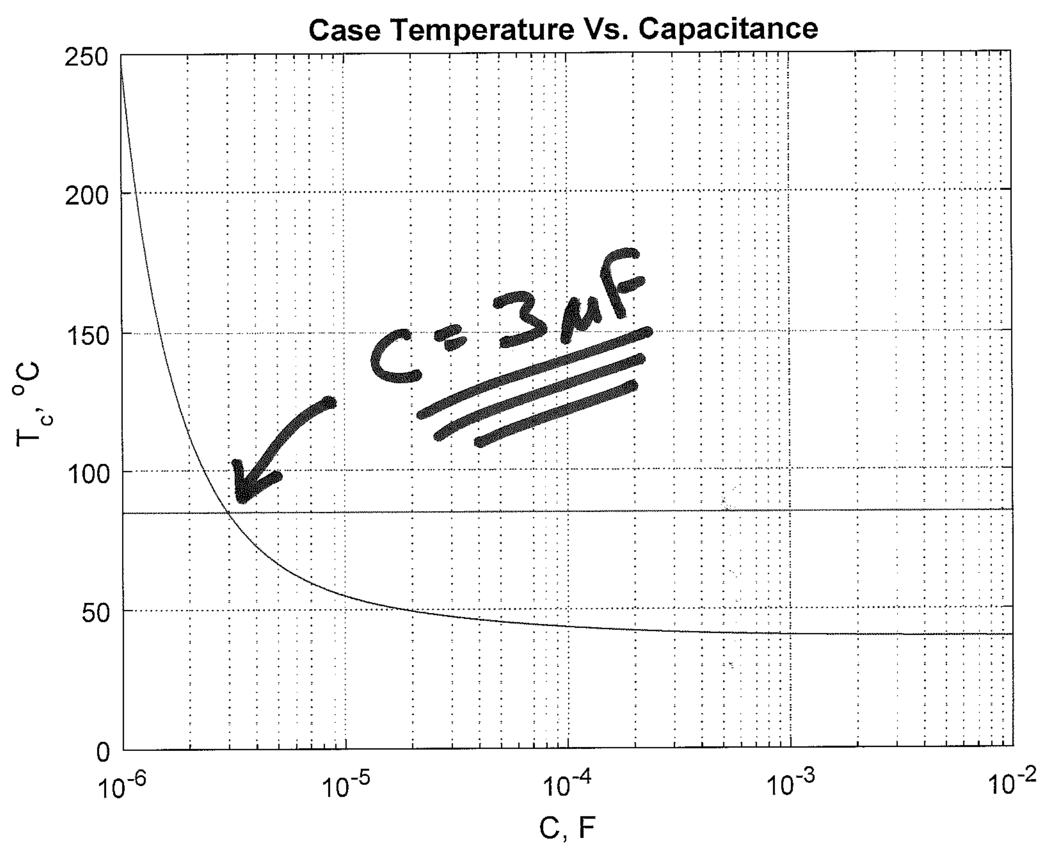


Lifetime expectancy
(typical)

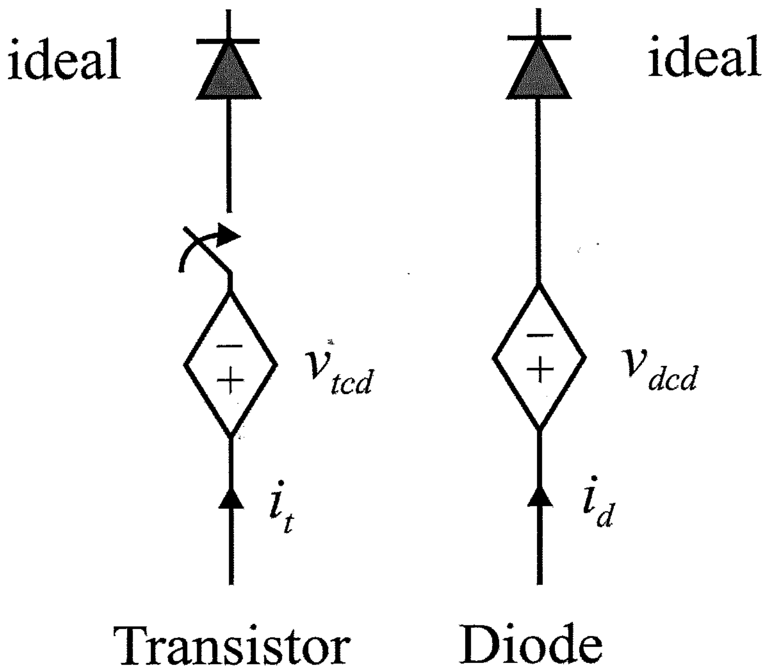
Polypropylene Capacitor Size & Loss

- Capacitance

$$C \rightarrow G \rightarrow T$$
$$C \rightarrow R \rightarrow P \rightarrow T$$



Representation of Conduction Losses



$$v_{xcd} = f_{xcd}(i_x, T_{xj})$$

$x = \{ 't', 'd' \}$

~~v_{fsw}~~ v_{fsw}

v_{fd}

B.T. Cassimere, *Computationally Efficient Modeling and Characterization of Power Semiconductor Losses*, PhD dissertation, Purdue University, May 2008

IGBT Conduction Drop

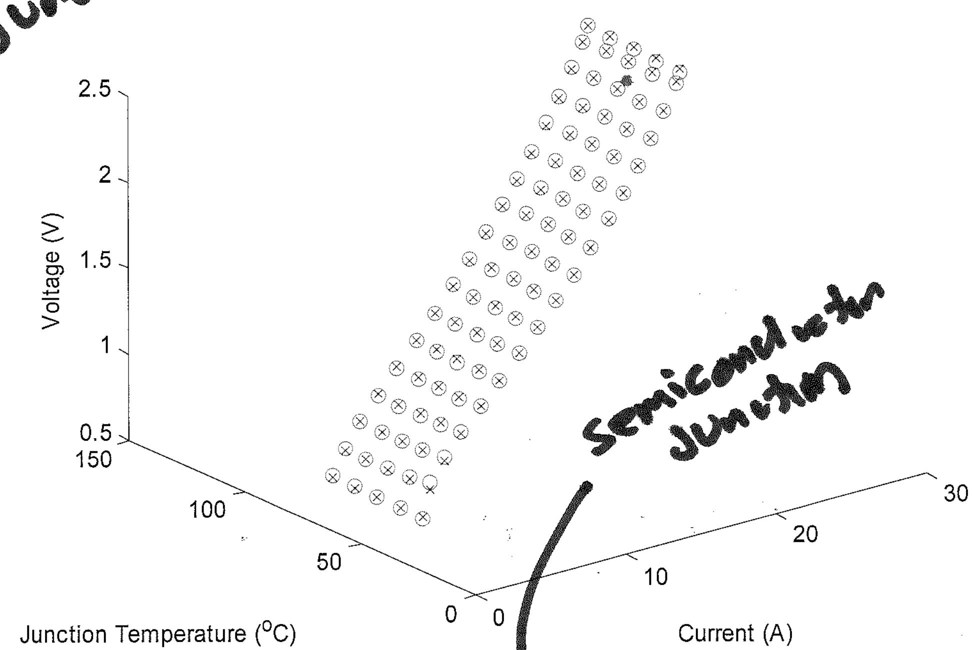
Fuji 7MBR30SA060 (30 A, 600 V)

$$v_{tcd} = \sum_{j=1}^{3} a_{t,j} T_{jt}^{b_{t,j}} i_t^{c_{t,j}}$$

Junction temp

Table 4.4 – IGBT Parameters

Parameter	Value	Unit
$a_{t,1}$	2.420	$\frac{\Omega}{A^{c-1} \circ C^{b}}$
$b_{t,1}$	-2.151×10^{-1}	
$c_{t,1}$	-8.605×10^{-2}	
$a_{t,2}$	-1.060	$\frac{\Omega}{A^{c-1} \circ C^{b}}$
$b_{t,2}$	-3.343×10^{-1}	
$c_{t,2}$	-4.552×10^{-1}	
$a_{t,3}$	9.634×10^{-2}	$\frac{\Omega}{A^{c-1} \circ C^{b}}$
$b_{t,3}$	9.764×10^{-2}	
$c_{t,3}$	7.266×10^{-1}	



Semiconductor junction

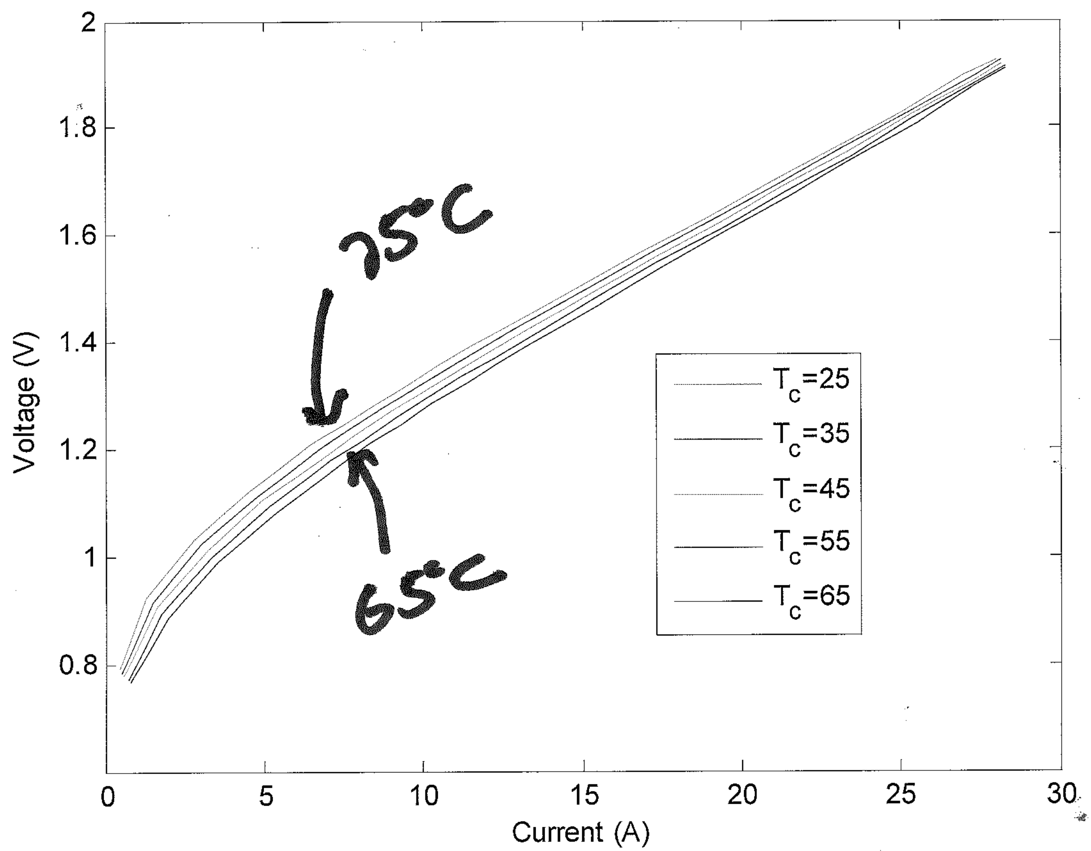
Case

$$T_j = R_{jc} P_j + T_c$$

B.T. Cassimere, *Computationally Efficient Modeling and Characterization of Power Semiconductor Losses*, PhD dissertation, Purdue University, May 2008

Diode Conduction Losses

Fuji 7MBR30SA060 (30 A, 600 V)



B.T. Cassimere, *Computationally Efficient Modeling and Characterization of Power Semiconductor Losses*, PhD dissertation, Purdue University, May 2008

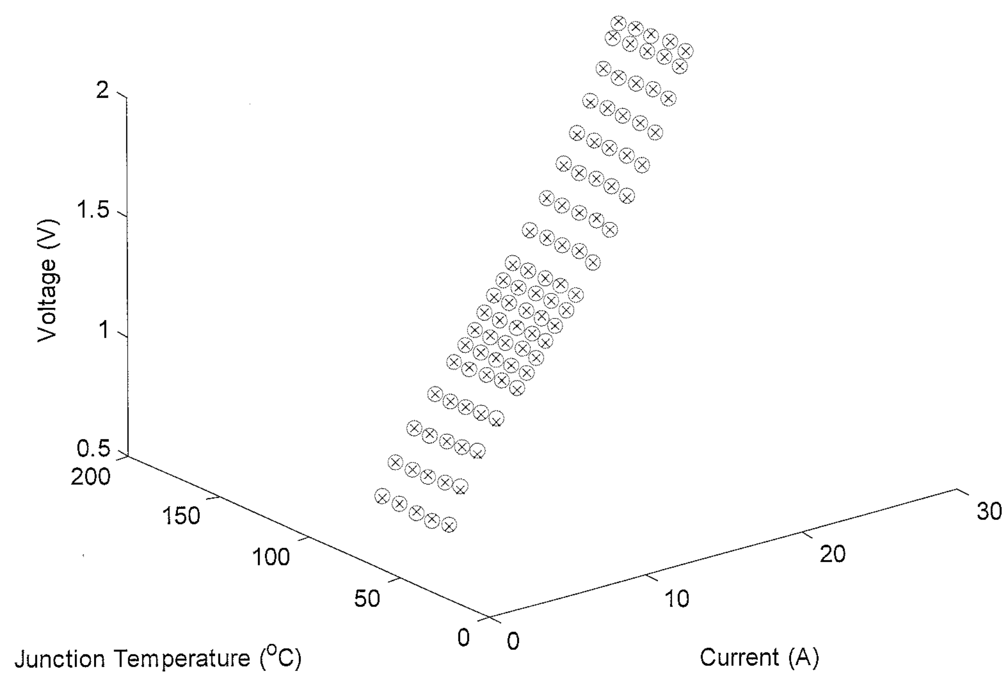
Diode Conduction Drop

Fuji 7MBR30SA060 (30 A, 600 V)

$$v_{dcd} = \sum_{j=1}^{3} a_{d,j} T_{jd}^{b_{d,j}} i_d^{c_{d,j}}$$

Table 4.5 - Diode Parameters

Parameter	Value	Unit
$a_{d,1}$	2.932×10^{-2}	$\frac{\Omega}{A^{c-1} \circ C^{b}}$
$b_{d,1}$	-2.472×10^{-2}	
$c_{d,1}$	1.058	
$a_{d,2}$	-2.482	$\frac{\Omega}{A^{c-1} \circ C^{b}}$
$b_{d,2}$	-2.155	
$c_{d,2}$	1.777	
$a_{d,3}$	1.382	$\frac{\Omega}{A^{c-1} \circ C^{b}}$
$b_{d,3}$	-1.398×10^{-1}	
$c_{d,3}$	1.261×10^{-1}	



B.T. Cassimere, *Computationally Efficient Modeling and Characterization of Power Semiconductor Losses*, PhD dissertation, Purdue University, May 2008

Semiconductor Conduction Losses

- Let's consider a simpler form

instantaneous loss

$$p_{x,cd} = \alpha_{x,cd} i + \beta_{x,cd} i^{\gamma_{x,cd}}$$

average loss

$$P_{x,cd} = \frac{1}{T_{sw}} \int_0^{T_{sw}} p_{x,cd} \, dt$$

suppose $i = mt + b$

<u>aside</u>

$$T = \int \alpha_{x,cd}(mt+b) + \beta_{x,cd}(mt+b)^{\gamma_{x,cd}} \, dt$$

$$= \frac{1}{2}\frac{\alpha_{x,cd}}{m}(mt+b)^2 + \frac{\beta_{x,cd}}{m(\gamma_{x,cd}+1)}(mt+b)^{\gamma_{x,cd}+1}$$

$$T = \frac{1}{2}\frac{\alpha_{x,cd}}{m} i^2 + \frac{\beta_{x,cd}}{m(\gamma_{x,cd}+1)} i^{\gamma_{x,cd}+1}$$

Semiconductor Conduction Losses

- For diode

$$P_{d,cd} = \frac{1}{T_{sw}} \int_0^{T_{sw}} p_{t,cd} \, dt$$

$$i = mt + b \longrightarrow m = \left(\frac{I_{mn} - I_{mx}}{(1-d)T_{sw}} \right)$$

$$P_{d,cd} = \frac{1}{T_{sw}} \int_0^{(1-d)T_{sw}} p_{d,cd} \, dt$$

$$= \frac{1}{\cancel{T_{sw}} \left(\frac{I_{mn} - I_{mx}}{(1-d)\cancel{T_{sw}}} \right)} \left[\frac{1}{2} \alpha_{d,cd} \left(I_{mn}^2 - I_{mx}^2 \right) + \frac{1}{\gamma_{d,cd}+1} \beta_{d,cd} \left(I_{mn}^{\gamma_{cd}+1} - I_{mx}^{\gamma_{cd}+1} \right) \right]$$

$$= \frac{1-d}{I_{mx} - I_{mn}} \left[\frac{1}{2} \alpha_{d,cd} \left(I_{mx}^2 - I_{mn}^2 \right) + \frac{1}{\gamma_{d,cd}+1} \beta_{d,cd} \left(I_{mx}^{\gamma_{cd}+1} - I_{mn}^{\gamma_{cd}+1} \right) \right]$$

IGBT Switching Losses

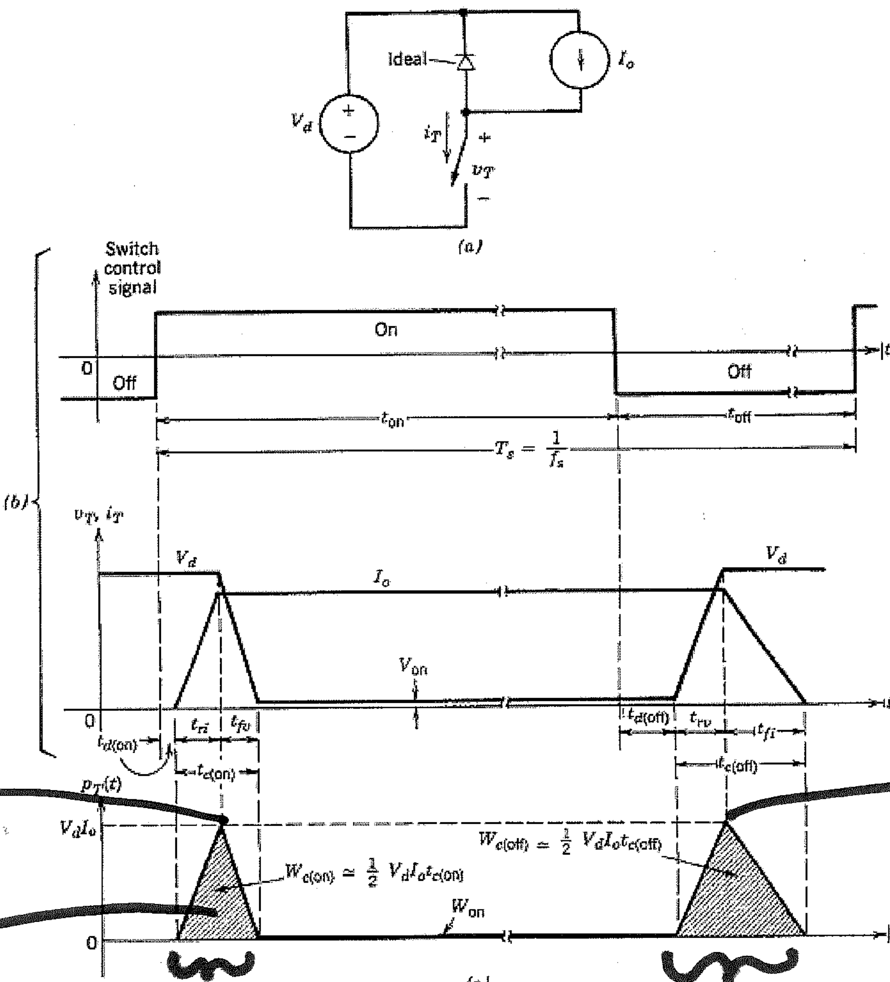


Figure 2-6 Generic-switch switching characteristics (linearized): (*a*) simplified clamped-inductive-switching circuit, (*b*) switch waveforms, (*c*) instantaneous switch power loss.

$V_d I_o$

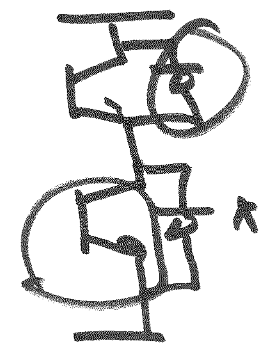
ton

$\boxed{E_{on} = \frac{1}{2} t_{on} V_d I_o}$

$V_d I_o$

toff

$E_{off} = \frac{1}{2} t_{off} V_d I_o$



*Mohan, Undeland, Robbins, *Power Electronics, Converters, Applications, and Design*, 2nd Edition

IGBT Switching Losses

- One approach

$$\mathrm{E}_{t,y}(i, v_{CE}) = \frac{v_{CE}}{v_{t,b}}\left(\alpha_{t,y} i_t^2 + \beta_{t,y} i_t + \gamma_{t,y}\right)$$

$$P_{t,on} = f_{sw}\,\mathrm{E}_{t,on}(i_{mn}, v_c)$$

$$P_{t,off} = f_{sw}\,\mathrm{E}_{t,off}(i_{mx}, v_c)$$

Shane, G.M.; Sudhoff, S.D., "Design Paradigm for Permanent-Magnet-Inductor-Based Power Converters," *Energy Conversion, IEEE Transactions on* , vol.28, no.4, pp.880,893, Dec. 2013

Power Diode Turn Off Losses

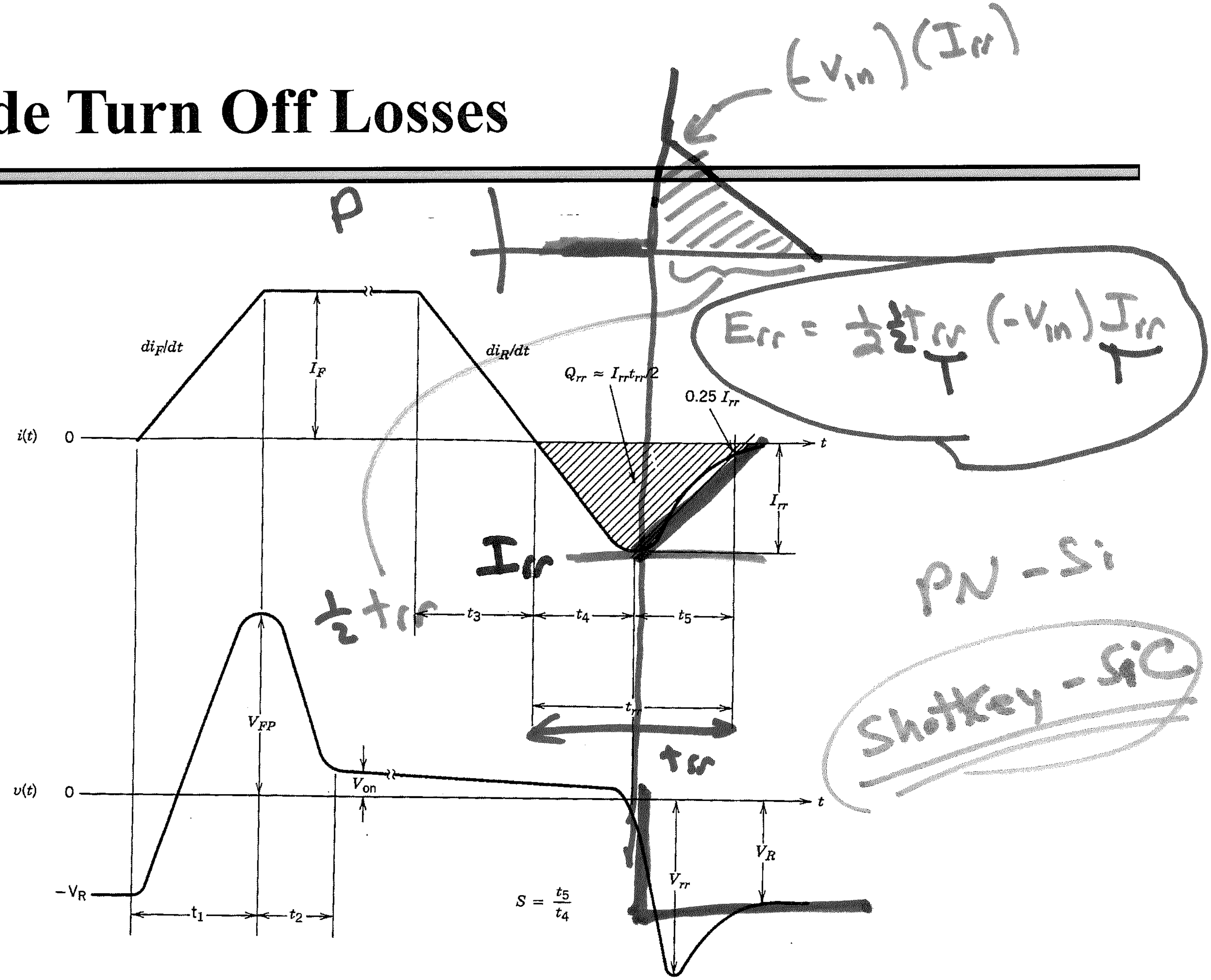


Figure 20-9 Voltage and current waveforms for a power diode driven by currents with a specified rate of rise during turn-on and a specified rate of fall during turn-off.

*Mohan, Undeland, Robbins, *Power Electronics, Converters, Applications, and Design, 2nd Edition*

Power Diode Turn Off Losses

- One approach

$$I_{rr0}(i_d) = \alpha_{d,I_{rr}} i_d + \beta_{d,I_{rr}} (i_d)^{\gamma_{d,I_{rr}}}$$

nominal I_{rr} at a base value of voltage $V_{d,b}$

$$t_{rr}(i_d) = \alpha_{d,t_{rr}} i_d + \beta_{d,t_{rr}} (i_d)^{\gamma_{d,t_{rr}}}$$

reverse recovery time

$$I_{rr}(i_d) = \frac{\cancel{v_{d,off}} \; -v_{in}}{v_{d,b}} I_{rr0}(i_d)$$

actual reverse recovery current scaled for voltage

$$P_{d,rr} = \frac{v_{in}^2 I_{rr0}(i_{mn}) t_{rr}(i_{mn})}{4 v_{d,b} T_{sw}}$$

$$E_{rr} = \frac{1}{4} t_{rr} (-V_{in}) I_{rr}$$

$$P_{d,rr} = f_{sw} E_{rr} = \frac{E_{rr}}{T_{sw}}$$

Shane, G.M.; Sudhoff, S.D., "Design Paradigm for Permanent-Magnet-Inductor-Based Power Converters," *Energy Conversion, IEEE Transactions on* , vol.28, no.4, pp.880,893, Dec. 2013

Power Diode Turn Off Losses

- Explanation

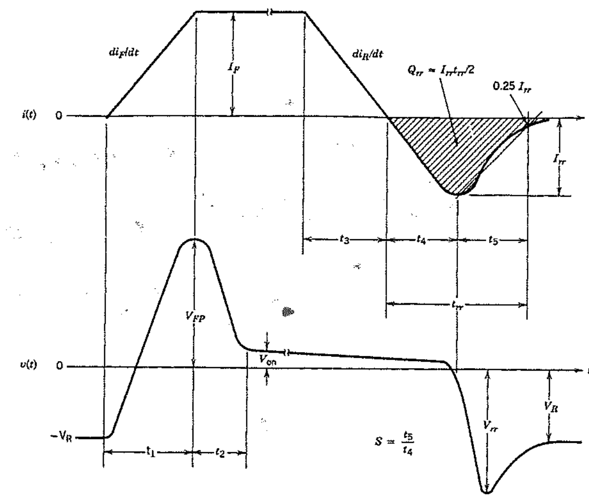
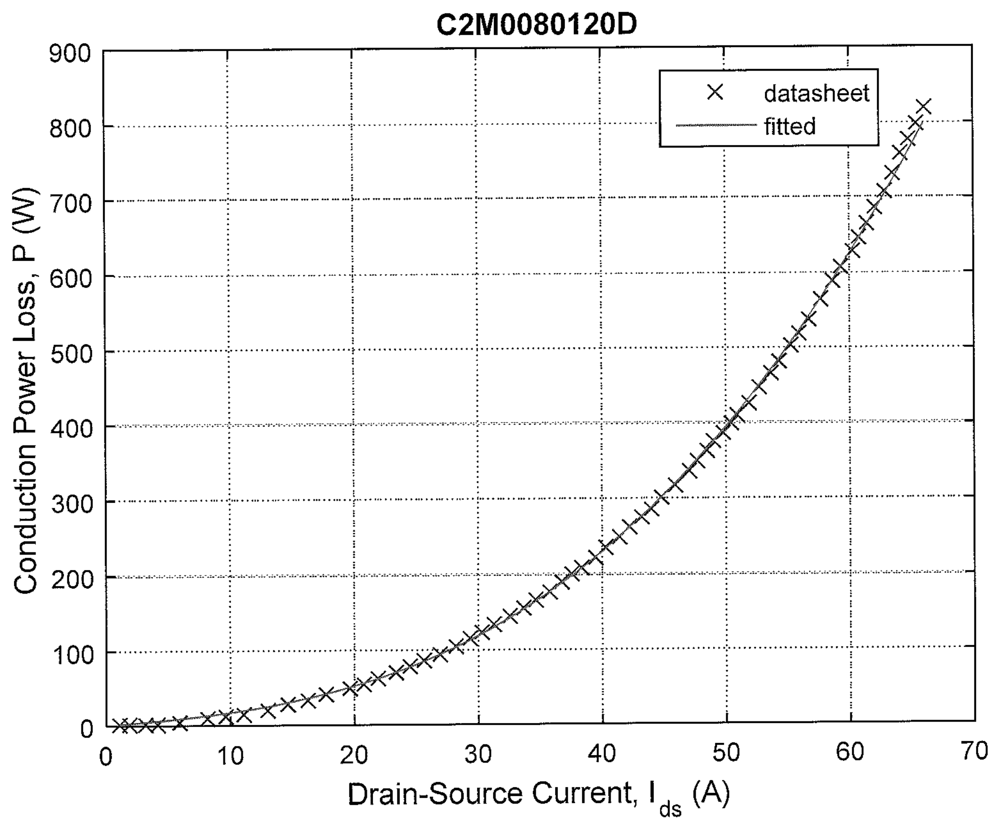


Figure 20-9 Voltage and current waveforms for a power diode driven by currents with a specified rate of rise during turn-on and a specified rate of fall during turn-off.

SiC MOSFETS

- Conduction loss (C2M0080120D – 1.2 kV, 36 A)



$$P_{t,cd} = \alpha_{t,cd} i_{ds} + \beta_{t,cd} i_{ds}^{\gamma_{t,cd}}$$

$$\alpha_{t,cd} = 1.30\ \mathrm{V}$$

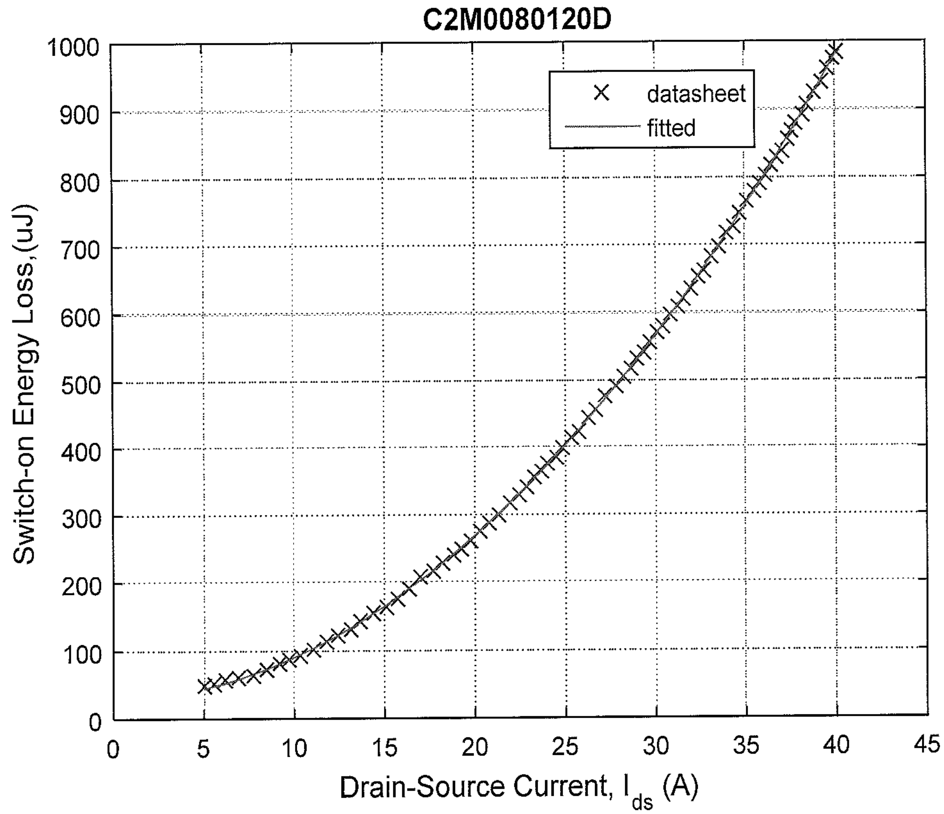
$$\beta_{t,cd} = 6.4 \cdot 10^{-3} V$$

$$\gamma_{t,cd} = 2.77$$

Junction at 150°C

SiC MOSFETS

- Turn on Loss (C2M0080120D – 1.2 kV, 36 A)



$$E_{t,on} = \left(\alpha_{t,on} i_{ds}^2 + \beta_{t,on} i_{ds} + \gamma_{t,on}\right) \frac{v_{CE}}{v_{t,b}}$$

$$\alpha_{t,on} = 0.585\ \mathrm{J/A^2}$$

$$\beta_{t,on} = 0.375\ \mathrm{Vs}$$

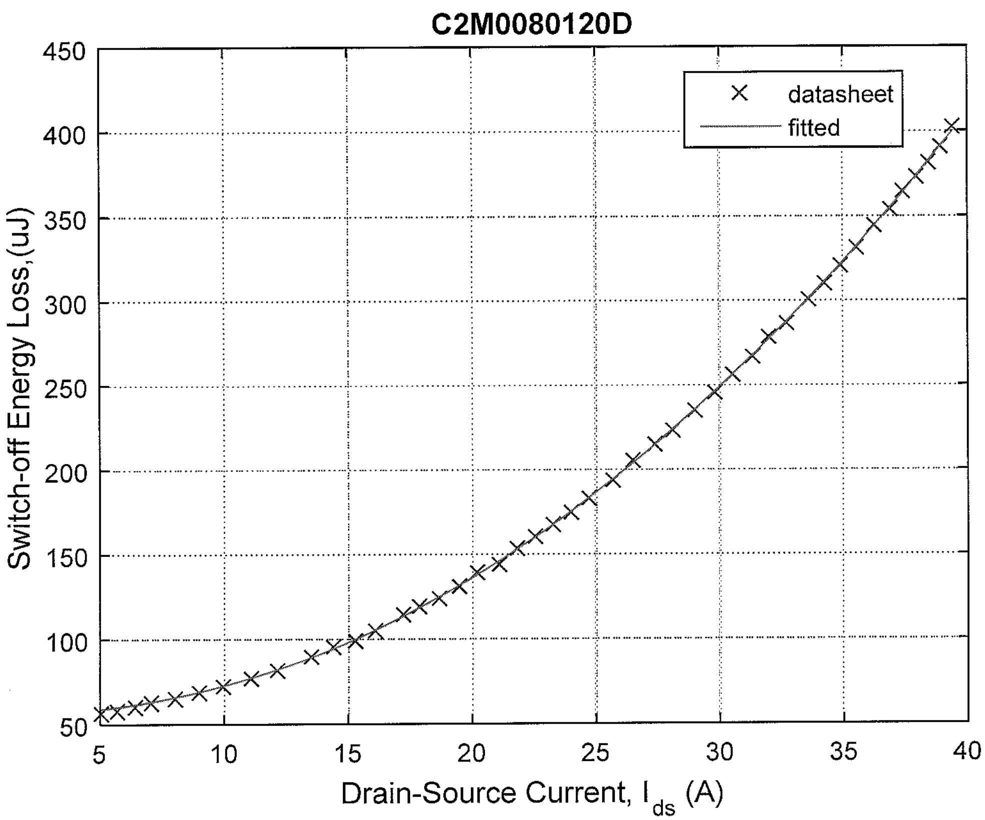
$$\gamma_{t,on} = 2.74 \cdot 10^{-5}\ \mathrm{J}$$

$$v_{t,b} = 800\ \mathrm{V}$$

Junction at 150°C

SiC MOSFETS

- Turn off Loss (C2M0080120D – 1.2 kV, 36 A)



$$E_{t,off} = \left(\alpha_{t,off} i_{ds}^2 + \beta_{t,off} i_{ds} + \gamma_{t,off}\right) \frac{v_C}{v_{t,}}$$

$$\alpha_{t,off} = 0.245 \text{ J/A}^2$$

$$\beta_{t,off} = -0.994 \text{ Vs}$$

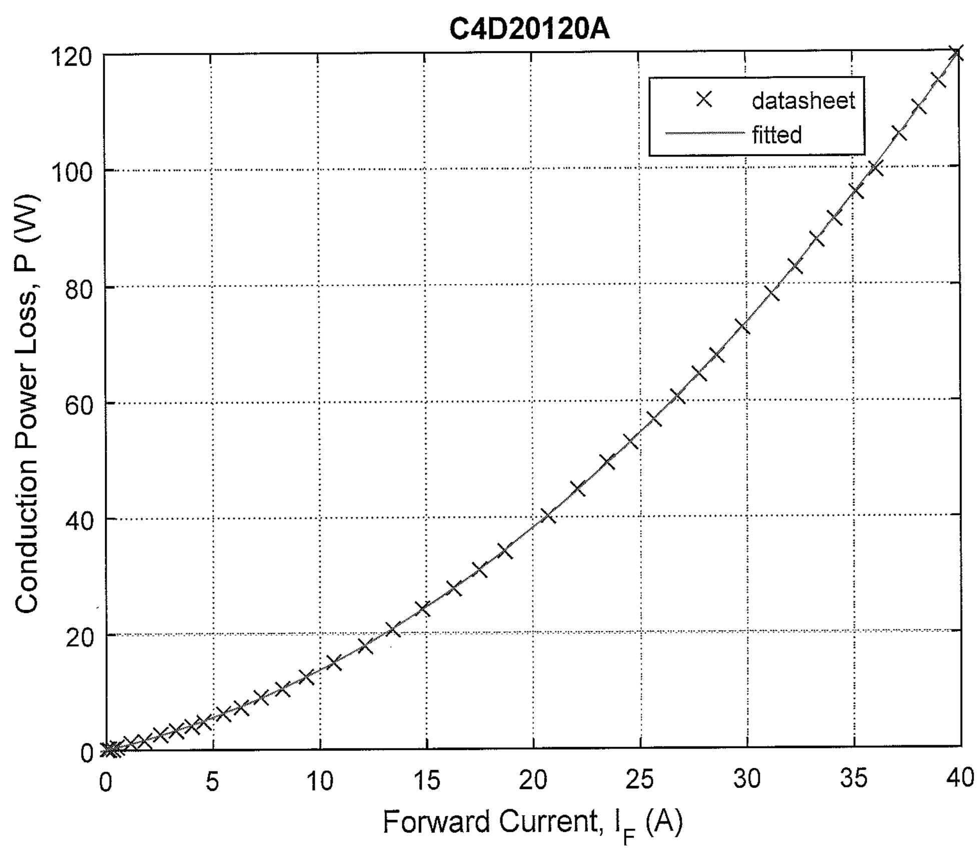
$$\gamma_{t,off} = 5.75 \cdot 10^{-5} \text{ J}$$

$$v_{t,b} = 800 \text{ V}$$

Junction at 150°C

SiC DIODES

- Conduction loss (C4D2012A – 1.2 kV, ~25 A)



$$P_{d,cd} = \alpha_{d,cd} i_{ds} + \beta_{d,cd} i_{ds}^{\gamma_{d,cd}}$$

$$\alpha_{d,cd} = 0.845 \text{ V}$$

$$\beta_{d,cd} = 5.04 \cdot 10^{-2} V$$

$$\gamma_{d,cd} = 2.01$$

Junction at 125°C

Steady-State Analysis

- Given v_{fsw}, and v_{fd} what is d?
- Recall

Know V_{in} V_{out} P_{out}

$$\overline{i}_l = -\overline{i}_{out}$$

$$\overline{i}_s = d\overline{i}_l$$

$$\overline{v}_{out} = \overline{v}_s - r_{Lout}\overline{i}_l$$

$$\overline{I}_l = \frac{P_{out}}{V_{out}}$$

$$\overline{v}_s = d(\overline{v}_c - v_{fsw}) - (1-d)v_{fd}$$

$$\overline{v}_c = \overline{v}_{in} - r_{Lin}\overline{i}_s$$

$$\begin{aligned}
\overline{V}_{out} &= d(\overline{V}_c - V_{fsw}) - (1-d)V_{fd} - r_{Lout}\overline{I}_l \\
&= d(\overline{V}_{in} - r_{Lin} d\overline{I}_l - V_{fsw}) - (1-d)V_{fd} - r_{Lout}\overline{I}_l \\
&= d\left(\overline{V}_{in} - r_{Lin} d\frac{P_{out}}{V_{out}} - V_{fsw}\right) - (1-d)V_{fd} - r_{Lout}\frac{P_{out}}{V_{out}}
\end{aligned}$$

Steady-State Analysis

$$0 = \underbrace{\left[-r_{Lin}\frac{P_{out}}{V_{out}}\right]}_{a} d^2 + \overbrace{\left[\bar{V}_{in} - V_{Fsw} + V_{Fd}\right]}^{b} d + \underbrace{\left[-V_{out} - V_{Fd} - r_{Lout}\frac{P_{out}}{V_{out}}\right]}_{c}$$

$$d = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad d \approx -\frac{c}{b}$$

why

$$\sqrt{1-x} \approx 1 - \tfrac{1}{2}x$$

$$d = \frac{-b \pm b\sqrt{1 - \frac{4ac}{b^2}}}{2a}$$

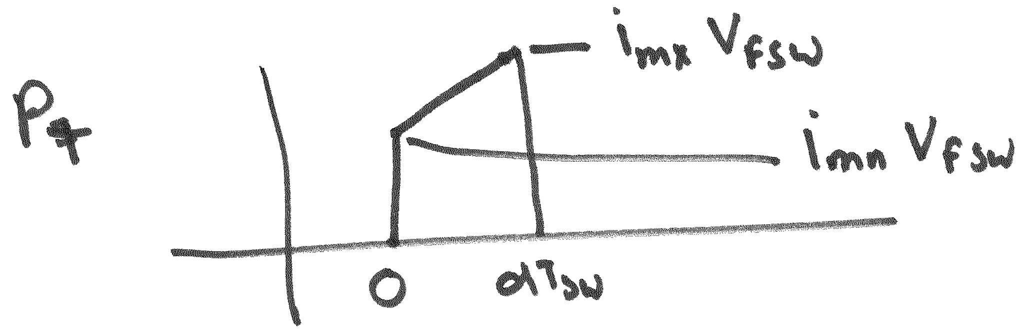
$$= \frac{\cancel{-b} + b\left(\cancel{1} - \frac{1}{2}\frac{4ac}{b^2}\right)}{2a} = \frac{-\cancel{\tfrac{1}{2}}\cancel{4}a c}{\cancel{2}b\cancel{a}}$$

Steady-State Analysis

- Thus

Steady-State Analysis

- Given d, what is v_{fsw} ?



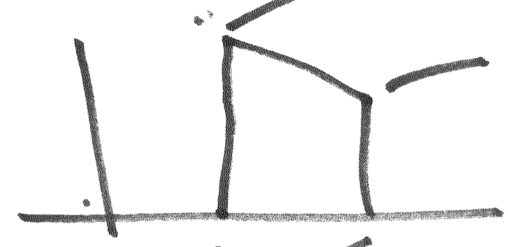
$$\overline{p}_+ = \frac{1}{\cancel{T_{sw}}}(d\cancel{T_{sw}})\frac{1}{2}\left(i_{mx} v_{fsw} + i_{mn} v_{fsw}\right)$$

$$= d\, v_{fsw}\, \overline{i}_l$$

$$\boxed{v_{fsw} = \frac{\overline{p}_+}{d\, \overline{i}_l}}$$

Steady-State Analysis

- Given d, what is v_{fd}?



$\bar{I}_\ell$

$$\bar{p}_d = \frac{1}{\cancel{T_{sw}}}(1-d)\cancel{T_{sw}}\,\cancel{\tfrac{1}{2}(i_{mx}+i_{mn})}\,v_{fd}$$

$$= (1-d)\,\bar{I}_\ell\, v_{fd}$$

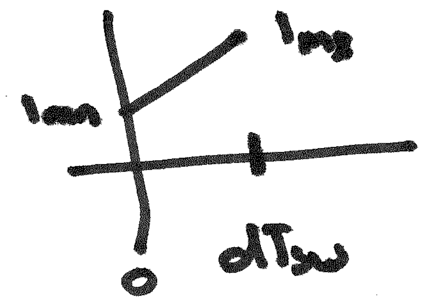
$$v_{fd} = \frac{\bar{p}_d}{(1-d)I_\ell}$$

total power loss in the diode

Semiconductor Conduction Losses

- For transistor

$$P_{t,cd} = \frac{1}{T_{sw}} \int_0^{dT_{sw}} P_{t,cd}\, dt$$



$$P_{t,cd} = \frac{1}{\cancel{T_{sw}}\left(\frac{I_{mx}-I_{mn}}{d\cancel{T_{sw}}}\right)} \left[\frac{1}{2} \alpha_{t,cd} \left(I_{mx}^2 - I_{mn}^2\right) + \frac{\beta_{t,cd}}{\gamma_{t,cd}+1}\left(I_{mx}^{\gamma_{t,cd}+1} - I_{mn}^{\gamma_{t,cd}+1}\right)\right]$$

$$m = \left(\frac{I_{mx}-I_{mn}}{dT_{sw}}\right)$$

$$P_{t,cd} = \frac{d}{I_{mx}-I_{mn}} \left[\frac{1}{2} \alpha_{t,cd} \left(I_{mx}^2 - I_{mn}^2\right) + \frac{1}{\gamma_{t,cd}+1} \beta_{t,cd} \left(I_{mx}^{\gamma_{t,cd}+1} - I_{mn}^{\gamma_{t,cd}+1}\right)\right]$$

Steady-State Analysis

- Iterative algorithm for computing d, v_{fsw}, and v_{fd}

Initialization

$K = 1$ (iteration count)

$e = 0$ (error)

$v_{fsw} = 0$

$v_{fd} = 0$

$\bar{i}_l = \frac{P_{out}}{V_{out}}$

$i_{in} = \frac{P_{out}}{V_{in}}$

$c_1 = 1$ analysis is OK (flag)

Based on i_l, J_{out}, L_{out} $\longrightarrow r_{Lout}$

Steady-State Analysis

while $(k=1)$ OR $[\,(e > e_{max})$ and
$(k \leq k_{max})$ and
$(c_1 = 1)\,]$

Based on $\dot{i}_{in}$, J_{in}, L_{in} $\longrightarrow$ r_{Lin}

$$c_1 = \begin{cases} 1 & \text{if } b^2 - 4ac \geq 0 \\ 0 & \text{if not} \end{cases} \Bigg\} \text{ slide 32}$$

if c_1

Find d, $\dot{i}_{mn}$, $\dot{i}_{mx}$

Find $V_{fsw,new}$
$V_{fd,new}$

$$e = \sqrt{(V_{fsw,new} - V_{fsw})^2 + (V_{fd,new} - V_{fd})^2}$$

Steady-State Analysis

$V_{fsw} = V_{fsw,new}$

$V_{fd} = V_{fd,new}$

$\overline{I_{in}} = d\,\overline{I_L}$

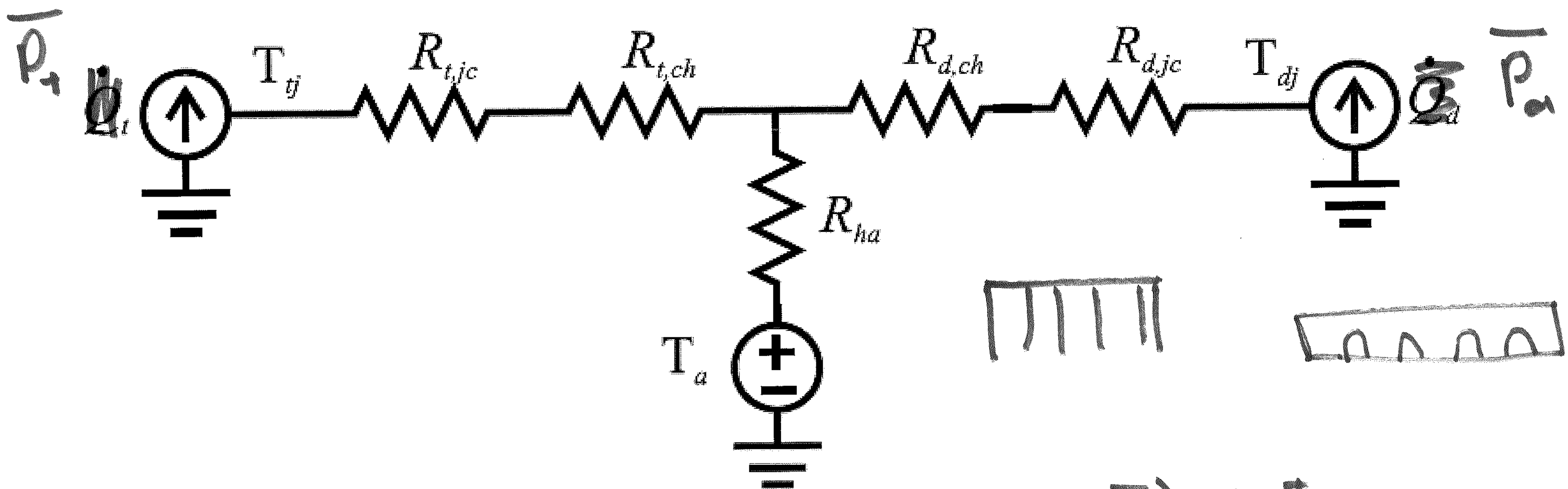
$k = k + 1$

end % if

end % while

Heat Sink

- Simple thermal model



$$T_{tj} = (R_{t,jc} + R_{t,ch})\overline{P}_t + R_{ha}(\overline{P}_t + \overline{P}_d) + T_a$$

$$T_{dj} = (R_{d,jc} + R_{d,ch})\overline{P}_d + R_{ha}(\overline{P}_t + \overline{P}_d) + T_a$$