Converter Loss Analysis

ECE 482 Lecture 4
January 17, 2014

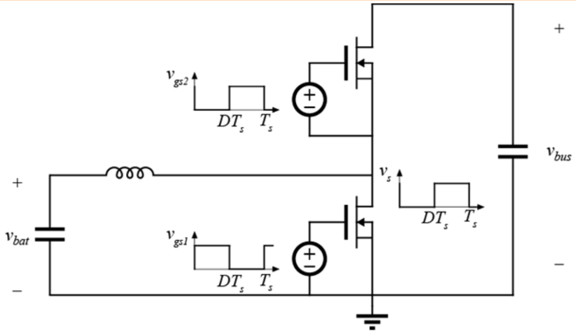
Announcements

- Finish Experiment 1: report due Monday, 1/27
- This week: Experiment 2
  - Boost open-loop construction and modeling
  - Prelab: Inductor design and switch selection
- Component kits available in circuits store
  - $80 *per group* for components for Labs 2 and 3
  - Plan to spend additional <$5.00 on resistors

Analytical Loss Modeling

- High efficiency approximation is acceptable for hand calculations, as long as it is justified
  - Solve waveforms of lossless converter, then calculate losses
- Alternate approach: average circuit
  - Uses average, rather than RMS currents
  - Difficult to include losses other than conduction
- Argue which losses need to be included, and which may be neglected

Boost Converter Loss Analysis



- Begin by solving important waveforms throughout converter assuming lossless operation

Power Stage Losses

	MOSFETS	IGBTs	Diodes	Inductor	Capacitors
Conduction Losses	• R_{on}	• r_{ce} • V_{ce}	• V_F • R_d	• R_{dc}	• ESR
Frequency-Dependent Losses	• C_{oss}	• Current tailing	• C_d • Reverse-Recovery	• Skin Effect • Core Loss • Fringing • Proximity	• Dielectric Losses

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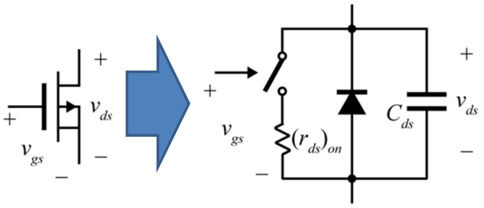
Conduction Loss Modeling

MOSFET Equivalent Circuit



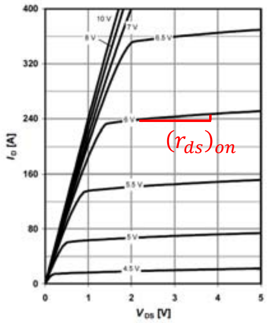
- Considering only power stage losses (gate drive neglected)
- MOSFET operated as power switch
- Intrinsic body diode behaviors considered using normal diode analysis

MOSFET On Resistance

5 Typ. output characteristics

I_D=f(V_{DS}); T_j=25 °C

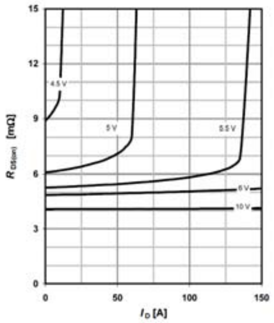
parameter: V_{GS}



6 Typ. drain-source on resistance

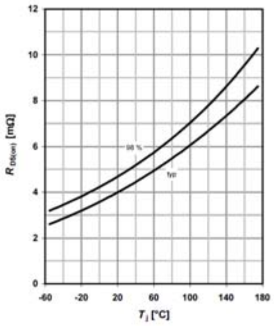
$R_{DS(on)}$=f(I_D); T_j=25 °C

parameter: V_{GS}



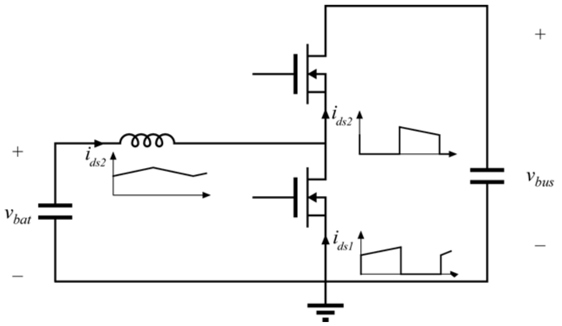
9 Drain-source on-state resistance

$R_{DS(on)}$=f(T_j); I_D=100 A; V_{GS}=10 V



- On resistance extracted from datasheet waveforms
- Significantly dependent on V_{gs} amplitude, temperature

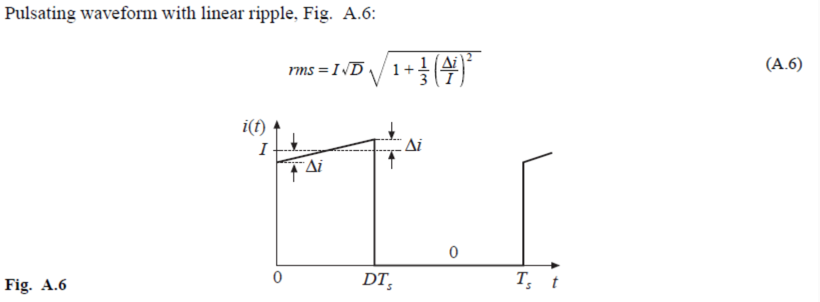
Boost Converter RMS Currents



- MOSFET conduction losses due to $(r_{ds})_{on}$ depend given as

$$P_{cond,FET} = I_{d,rms}{}^2 (r_{ds})_{on}$$

MOSFET Conduction Losses



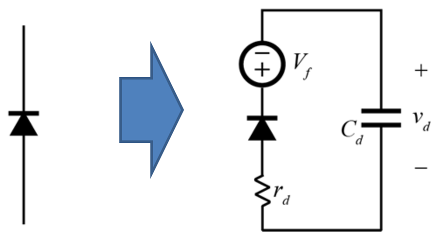
Pulsating waveform with linear ripple, Fig. A.6:

$$rms = I\sqrt{D}\sqrt{1+\frac{1}{3}\left(\frac{\Delta i}{I}\right)^2} \qquad \text{(A.6)}$$

Fig. A.6

- RMS values of commonly observed waveforms appendix from Power Book

Diode Loss Model



- Example loss model includes resistance and forward voltage drop extracted from datasheet

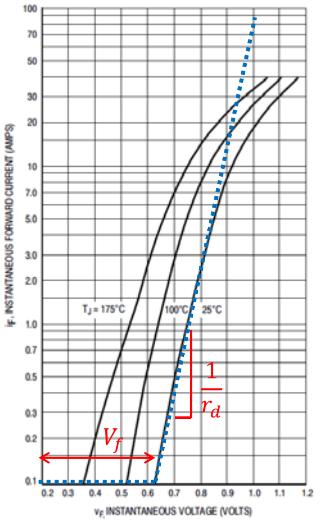
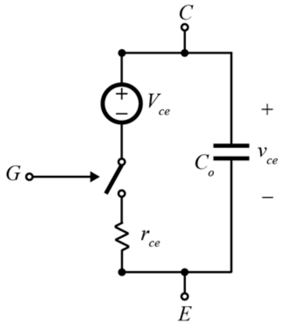


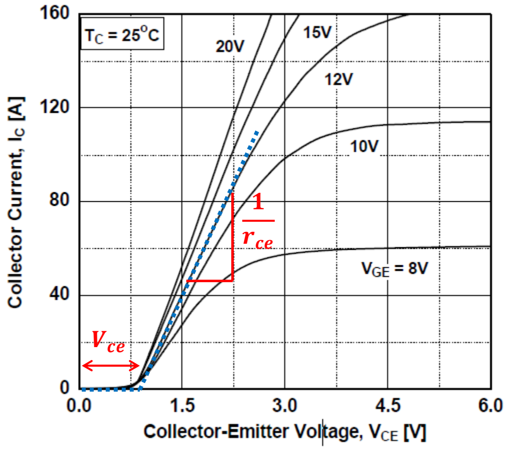
Figure 1. Typical Forward Voltage

IGBT Loss Model

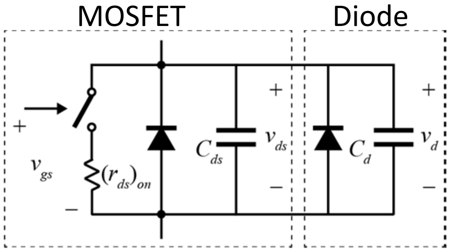


$$P_{cond} = I_{c,rms}{}^2 r_{ce} + V_{ce} I_{c,avg}$$

Figure 1. Typical Output Characteristics

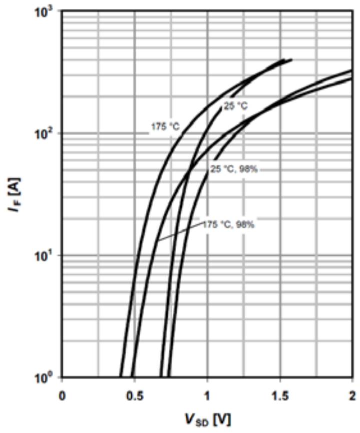


Semiconductor Switch Conduction Loss



- Equivalent circuit of MOSFET with external antiparallel diode has two, non-ideal diodes
- Diodes, even when matched, will not share current equally, but $v_d = v_{ds}$ must remain true
- Silicon rectifier diodes are minority carrier devices
  - Concentration of minority carriers depends heavily on temperature

Diode Paralleling



12 Forward characteristics of reverse diode

$I_F=f(V_{SD})$

parameter: T_j

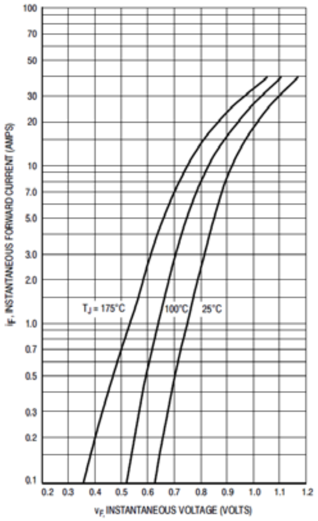
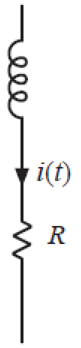


Figure 1. Typical Forward Voltage

DC Inductor Resistance



- DC Resistance given by

$$R_{DC} = \rho \frac{l_b}{A_w}$$

- At room temp, $\rho = 1.724 \cdot 10^{-6}$ Ω-cm
- At 100°C, $\rho = 2.3 \cdot 10^{-6}$ Ω-cm

- Losses due to DC current:

$$P_{cu,DC} = {I_{L,rms}}^2 R_{DC}$$

Inductor Conduction Losses

DC plus linear ripple, Fig. A.2:

$$rms = I\sqrt{1+\frac{1}{3}\left(\frac{\Delta i}{I}\right)^2} \qquad \text{(A.2)}$$

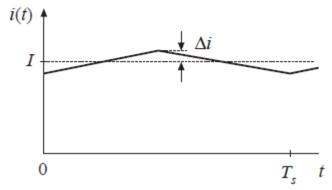
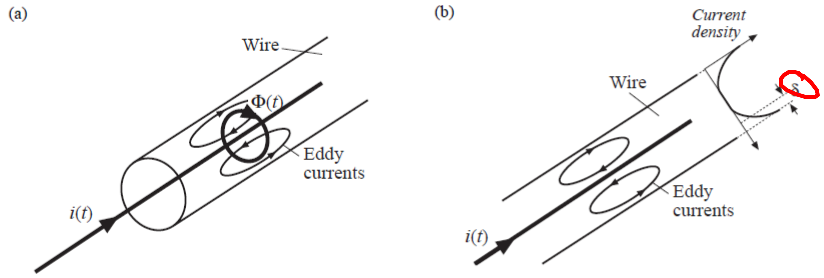


Fig. A.2

- Conduction losses dependent on RMS current through inductor

Skin Effect in Copper Wire



- Current profile at high frequency is exponential function of distance from center with characteristic length δ

Skin Depth

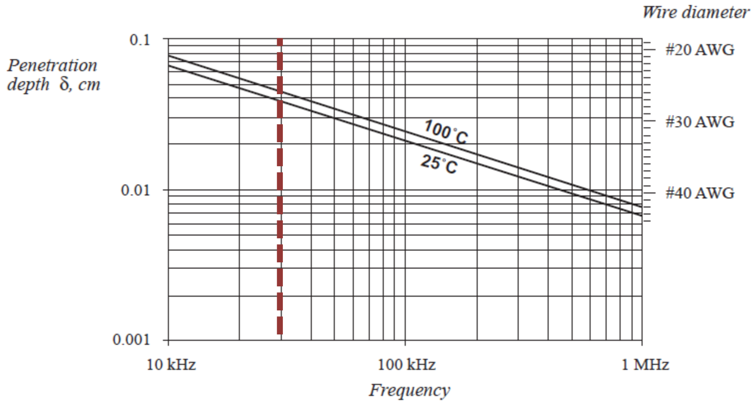
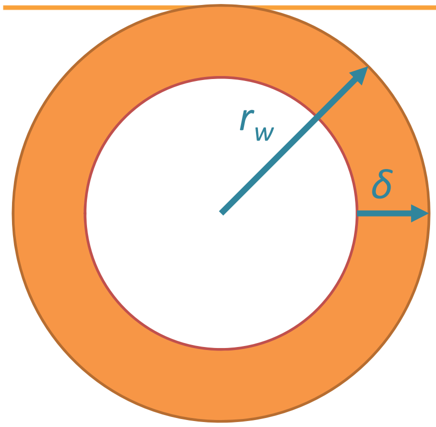


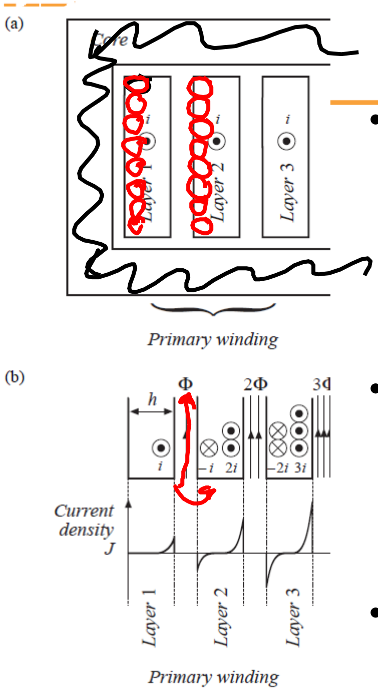
Fig. 13.23 Penetration depth δ, as a function of frequency *f*, for copper wire.

AC Resistance



$$A_{w,eff} = \pi {r_w}^2 - \pi(r_w - \delta)^2$$

$$R_{ac} = \rho \frac{l_b}{A_{w,eff}}$$



Proximity Effect

- In *foil* conductor closely spaced with ~~h~~ d >> δ, flux between layers generates additional current according to Lentz's law.

$$P_1 = {I_{L,rms}}^2 R_{ac}$$

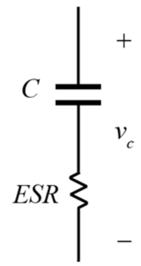
- Power loss in layer 2:

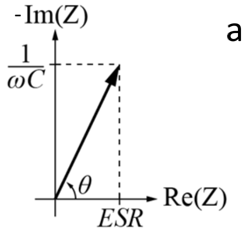
$$P_2 = {I_{L,rms}}^2 R_{ac} + \left(2I_{L,rms}\right)^2 R_{ac}$$

$$P_2 = 5P_1$$

- Needs modification for non-foil conductors

Capacitor Loss Model



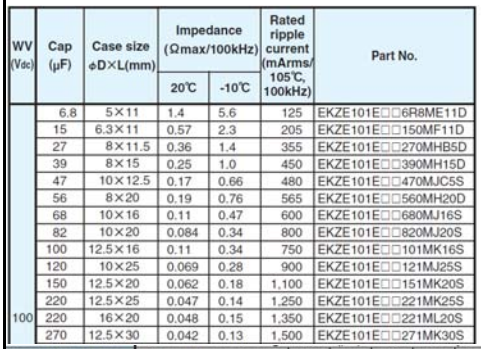


- Operation well below resonance
- All loss mechanisms in a capacitor are generally lumped into an empirical loss model
- Equivalent Series Resistance (ESR) is *highly* frequency dependent
- Datasheets may give effective impedance at a frequency, or loss factor:

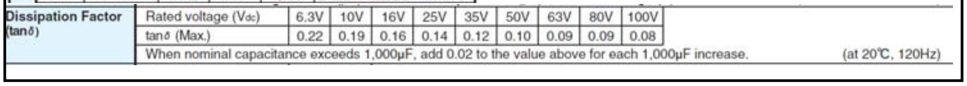
$$\delta = \frac{\pi}{2} - \theta$$

$$D = \tan(\delta)$$

Capacitor ESR Extraction



WV (Vdc)	Cap (μF)	Case size ϕD×L(mm)	Impedance (Ωmax/100kHz)		Rated ripple current (mArms/105℃, 100kHz)	Part No.
			20℃	-10℃		
100	6.8	5×11	1.4	5.6	125	EKZE101E□□6R8ME11D
	15	6.3×11	0.57	2.3	205	EKZE101E□□150MF11D
	27	8×11.5	0.36	1.4	355	EKZE101E□□270MHB5D
	39	8×15	0.25	1.0	450	EKZE101E□□390MH15D
	47	10×12.5	0.17	0.66	480	EKZE101E□□470MJC5S
	56	8×20	0.19	0.76	565	EKZE101E□□560MH20D
	68	10×16	0.11	0.47	600	EKZE101E□□680MJ16S
	82	10×20	0.084	0.34	800	EKZE101E□□820MJ20S
	100	12.5×16	0.11	0.34	750	EKZE101E□□101MK16S
	120	10×25	0.069	0.28	900	EKZE101E□□121MJ25S
	150	12.5×20	0.062	0.18	1,100	EKZE101E□□151MK20S
	220	12.5×25	0.047	0.14	1,250	EKZE101E□□221MK25S
	220	16×20	0.048	0.15	1,350	EKZE101E□□221ML20S
	270	12.5×30	0.042	0.13	1,500	EKZE101E□□271MK30S

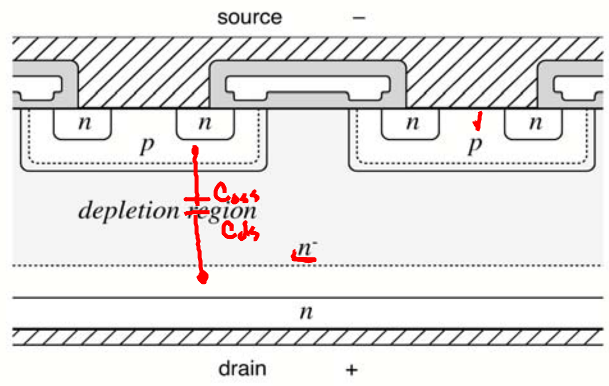


Dissipation Factor (tanδ)	Rated voltage (Vdc)	6.3V	10V	16V	25V	35V	50V	63V	80V	100V
	tanδ (Max.)	0.22	0.19	0.16	0.14	0.12	0.10	0.09	0.09	0.08
	When nominal capacitance exceeds 1,000μF, add 0.02 to the value above for each 1,000μF increase. (at 20℃, 120Hz)									

Dissipation Factor: 1% Max. (25 °C, 1kHz)

Switching Loss Modeling

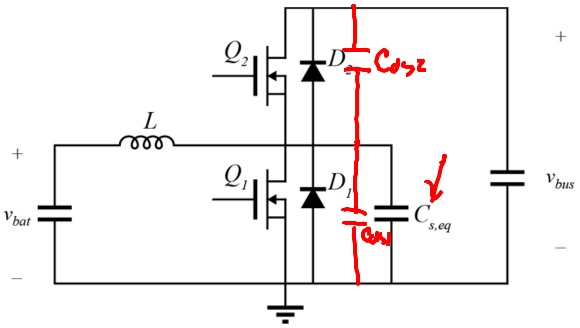
MOSFET Parasitic Capacitances



- p-n^- junction is reverse-biased
- off-state voltage appears across n^- region

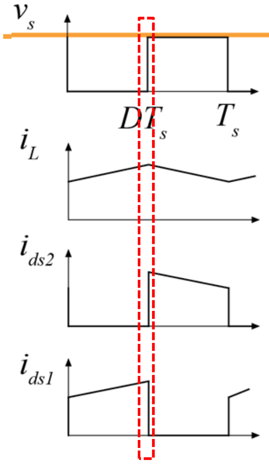
$V_{ds} > 6$

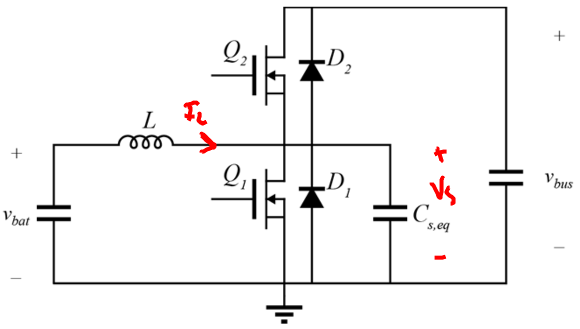
Lump Switched Node Capacitance



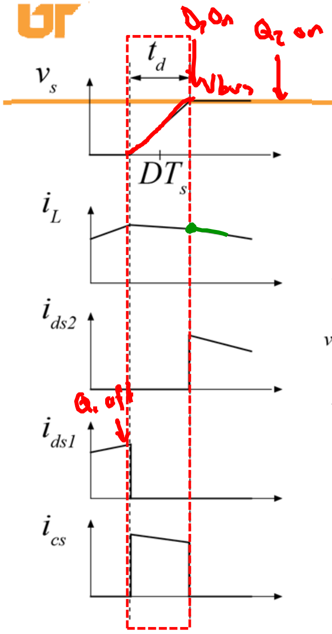
- Consider a single equivalent capacitor at switched node which combines energy storage due to all four semiconductor devices

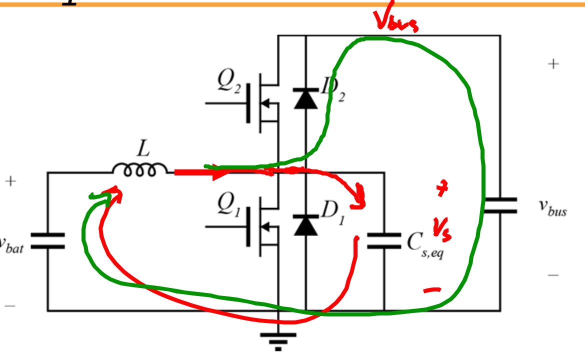
Q_1 Turn off





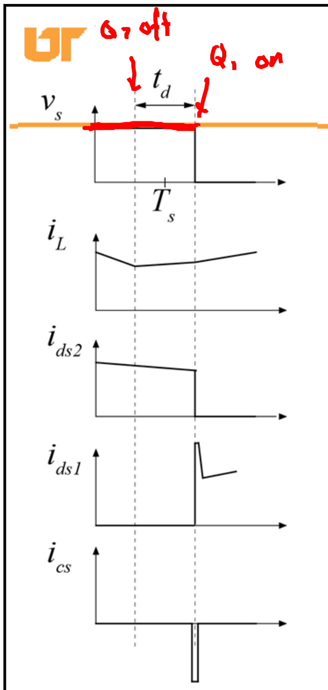
Q_1 Turn off

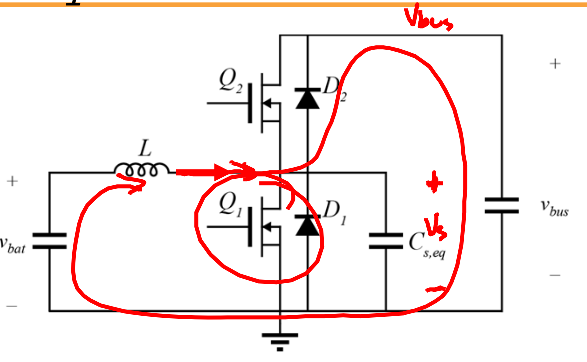




$E_{loss} = 0$

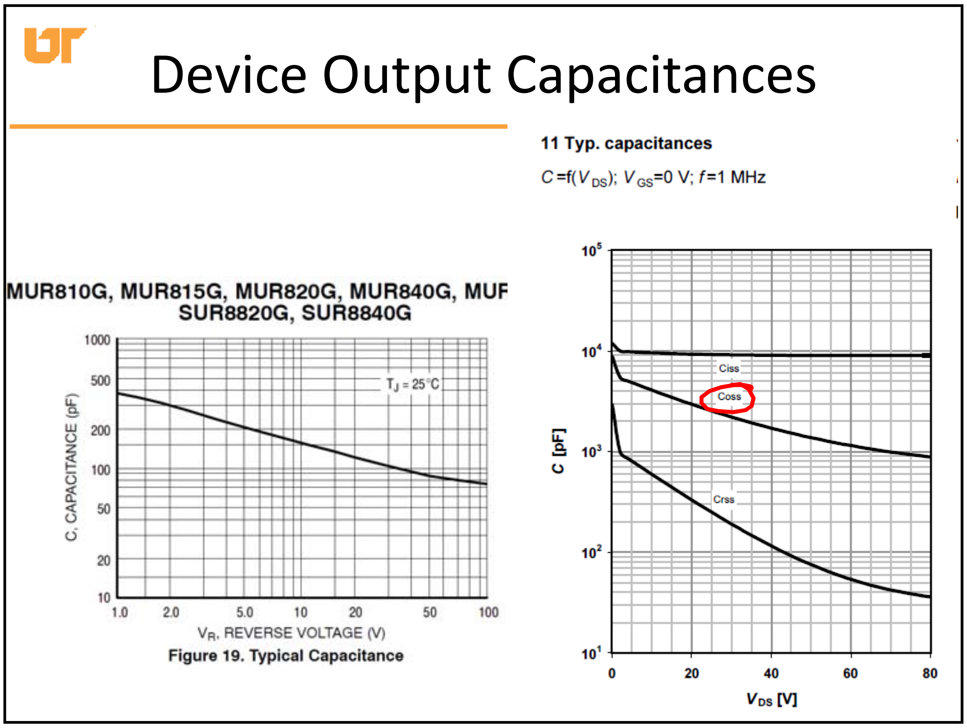
Q_1 Turn on





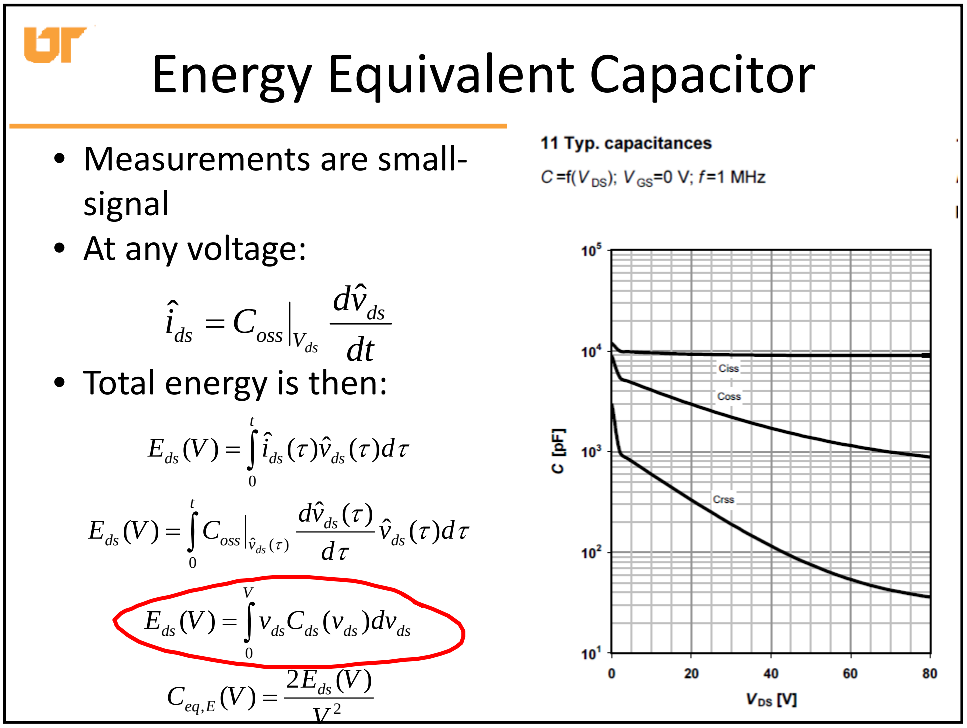
$E_{Q_1,on} = \frac{1}{2} C_s V_{bus}^2 \leftarrow$

$P_{sw} = E_{Q_1,on} f_s$



Device Output Capacitances

Figure 19. Typical Capacitance



Energy Equivalent Capacitor

- Measurements are small-signal
- At any voltage:

$$\hat{i}_{ds} = C_{oss}\big|_{V_{ds}} \frac{d\hat{v}_{ds}}{dt}$$

- Total energy is then:

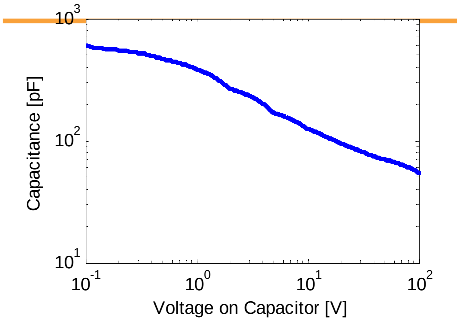
$$E_{ds}(V) = \int_0^t \hat{i}_{ds}(\tau)\hat{v}_{ds}(\tau)d\tau$$

$$E_{ds}(V) = \int_0^t C_{oss}\big|_{\hat{v}_{ds}(\tau)} \frac{d\hat{v}_{ds}(\tau)}{d\tau}\hat{v}_{ds}(\tau)d\tau$$

$$E_{ds}(V) = \int_0^V v_{ds}C_{ds}(v_{ds})dv_{ds}$$

$$C_{eq,E}(V) = \frac{2E_{ds}(V)}{V^2}$$

Energy Storage Example



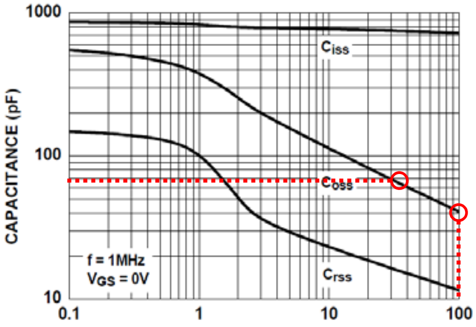


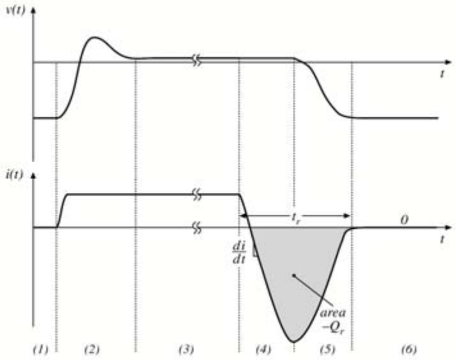
Figure 8. Capacitance vs Drain to Source Voltage

- Different device (FDMC2610)
- Charged to 100 V, capacitance stores same energy as 67pF linear capacitor

```
E = trapz(vx(range), Cx(range).*abs((vx(range))));
Cper = 2*(E)/Vg^2;
```

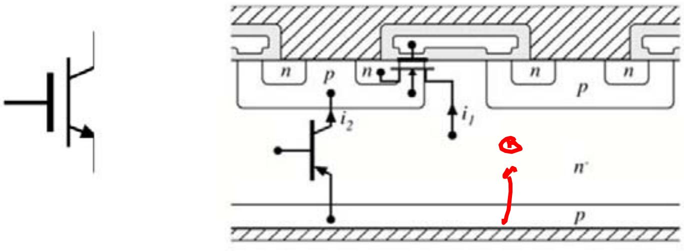
Diode Reverse Recovery

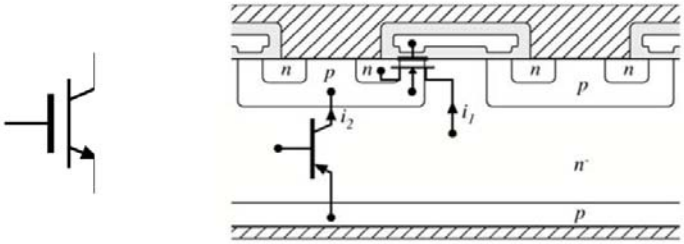
- Diodes will turn on during dead time intervals
- Significant reverse recovery possible on both body diode and external diode



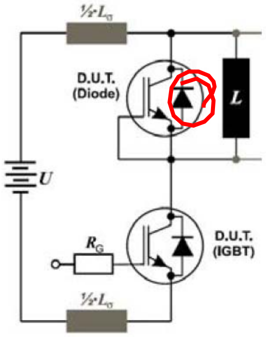
$$E_{on,rr} = \left(\left(I_L - \Delta i_L\right)t_{rr} + Q_{rr}\right)V_{bus}$$

IGBT Switching

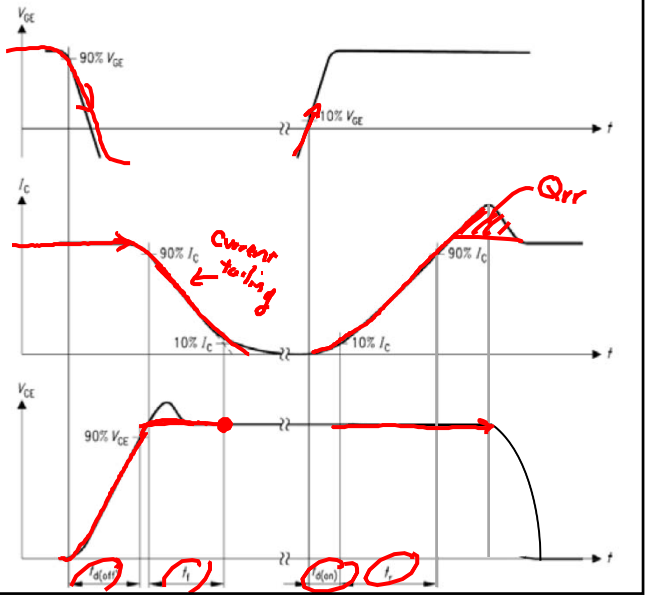




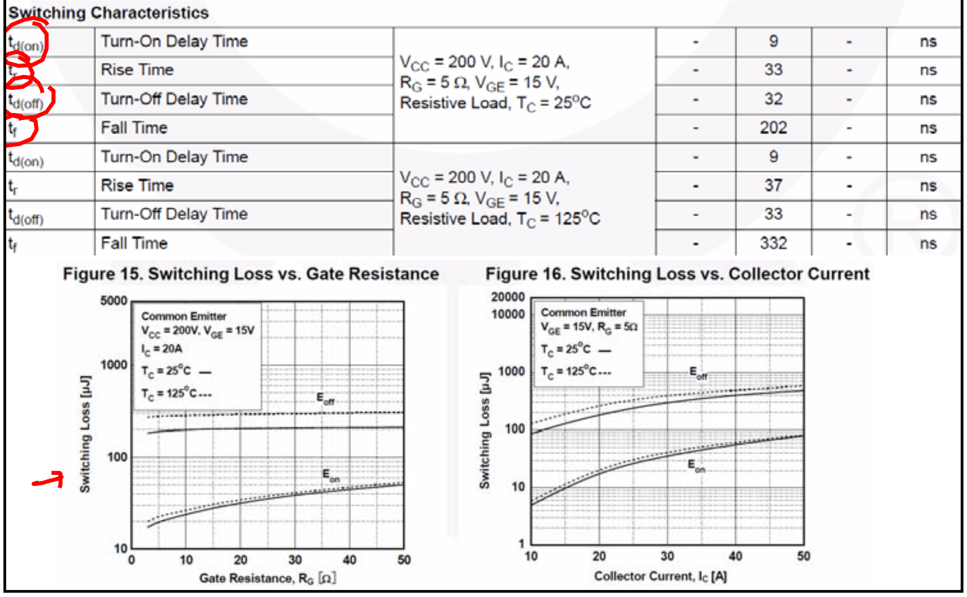
IGBT Switching Waveforms



Test circuit
(inductive switching)



Datasheet Reporting of IGBT Switching Loss



Switching Characteristics

$t_{d(on)}$	Turn-On Delay Time	V_{CC} = 200 V, I_C = 20 A, R_G = 5 Ω, V_{GE} = 15 V, Resistive Load, T_C = 25°C	-	9	-	ns
t_r	Rise Time		-	33	-	ns
$t_{d(off)}$	Turn-Off Delay Time		-	32	-	ns
t_f	Fall Time		-	202	-	ns
$t_{d(on)}$	Turn-On Delay Time	V_{CC} = 200 V, I_C = 20 A, R_G = 5 Ω, V_{GE} = 15 V, Resistive Load, T_C = 125°C	-	9	-	ns
t_r	Rise Time		-	37	-	ns
$t_{d(off)}$	Turn-Off Delay Time		-	33	-	ns
t_f	Fall Time		-	332	-	ns

Figure 15. Switching Loss vs. Gate Resistance

Figure 16. Switching Loss vs. Collector Current