Announcements

Reading assignments (by lecture 3), no need to turn in anything:

Section 19.1, *Sinusoidal analysis of resonant converters*

Section 19.2, *Examples*

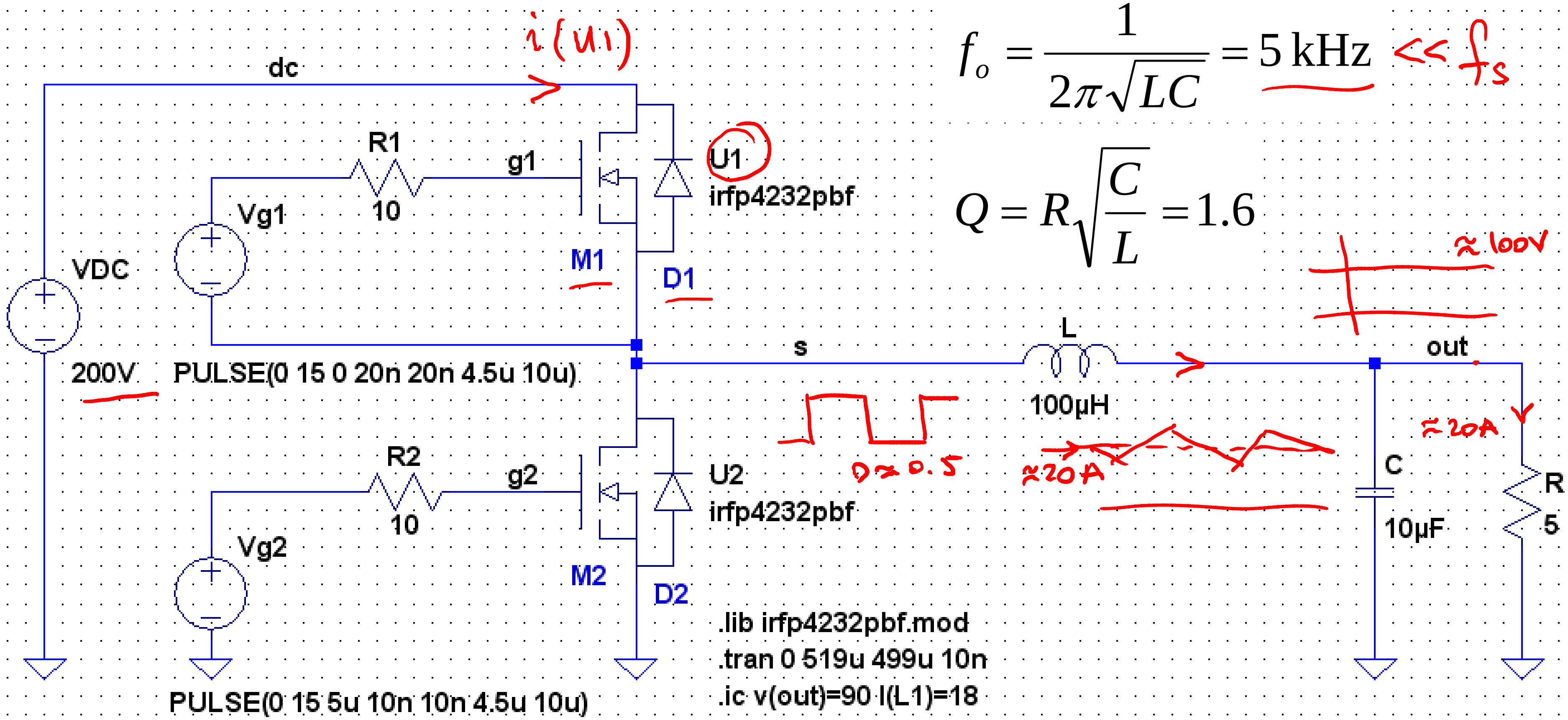
HW1 (review problems) has been posted, due Friday, Jan.22

Circuit Example: Standard "Hard-Switched" PWM Operation

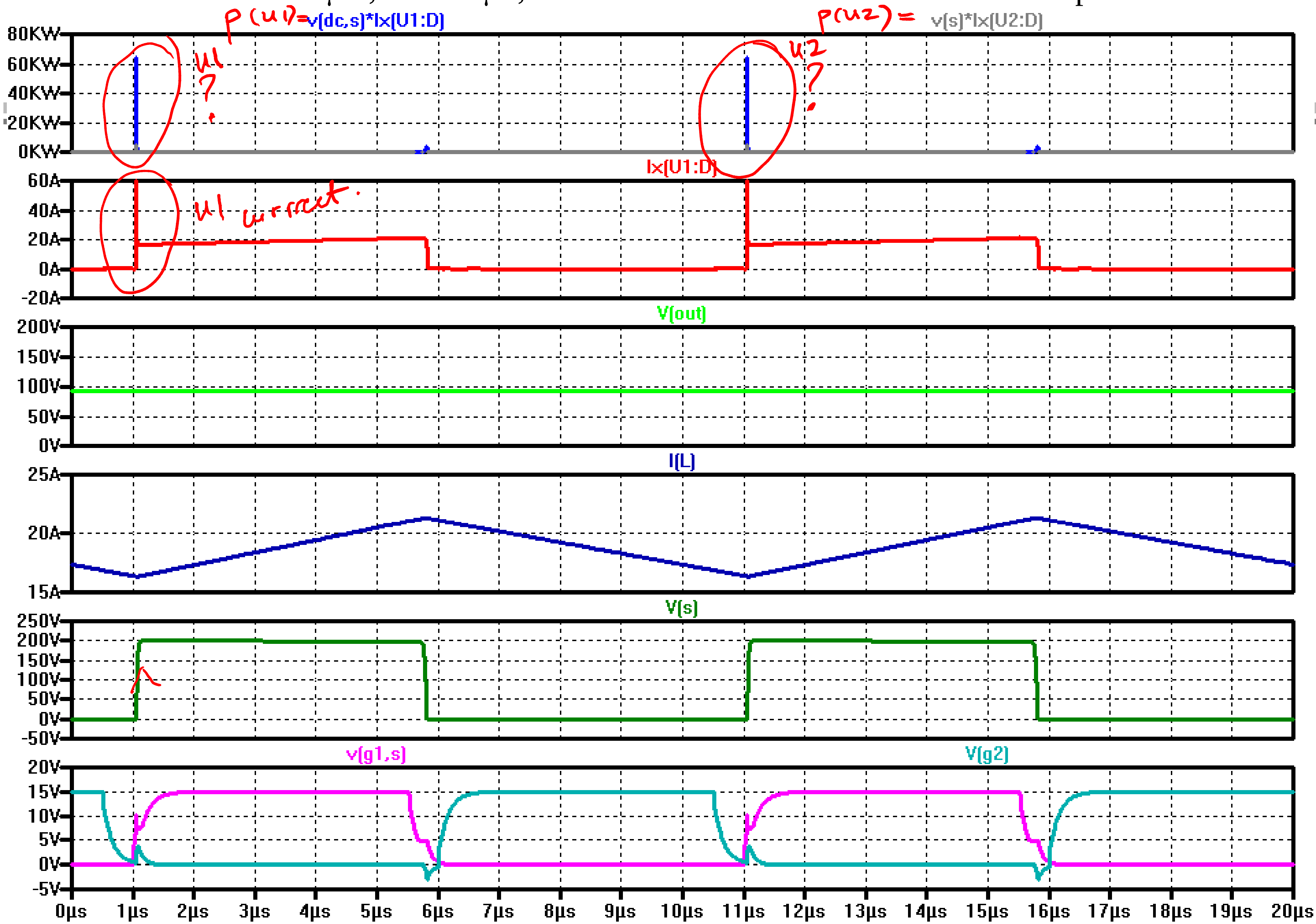
$$f_s = 100\ \text{kHz},\ D \approx 0.5$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 5\ \text{kHz} \ll f_s$$

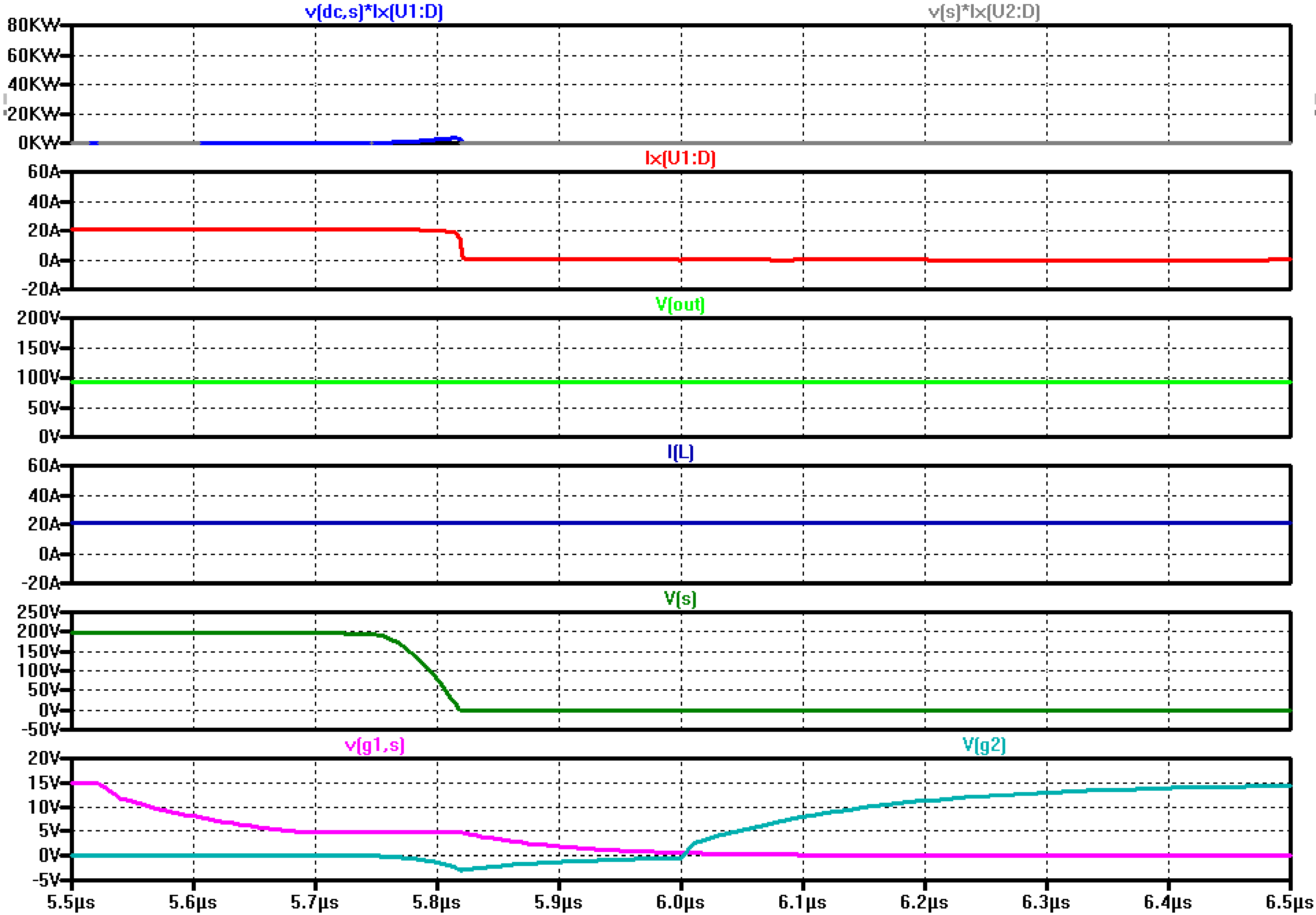
$$Q = R\sqrt{\frac{C}{L}} = 1.6$$



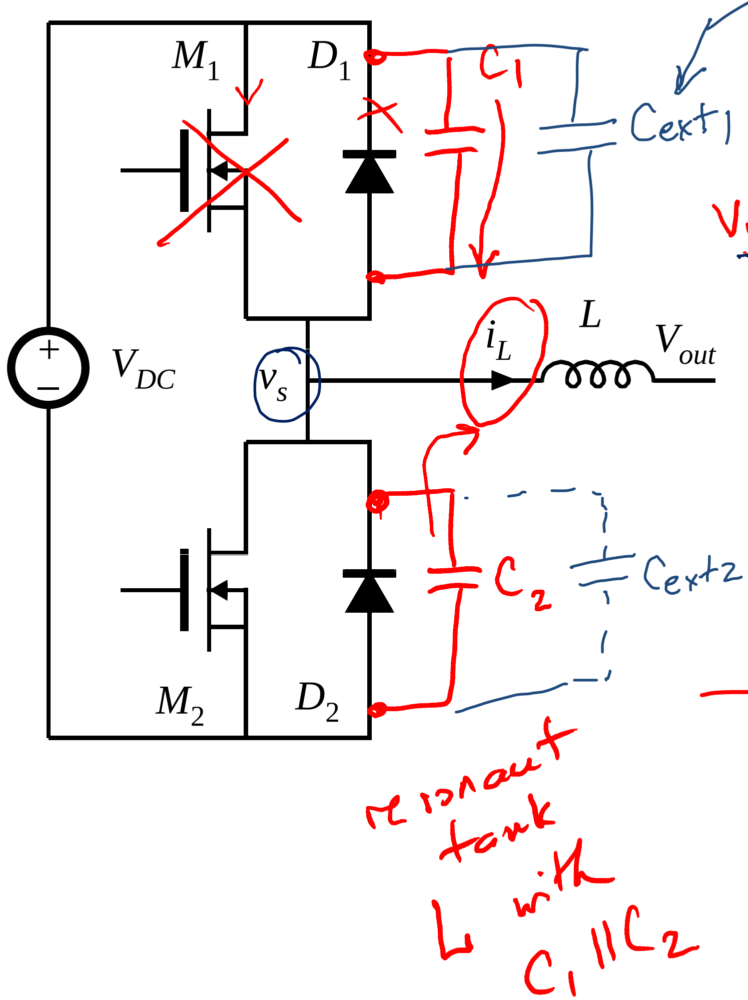
L = 100 μH, C = 10 μF, R = 5 Ω: standard hard-switched PWM operation

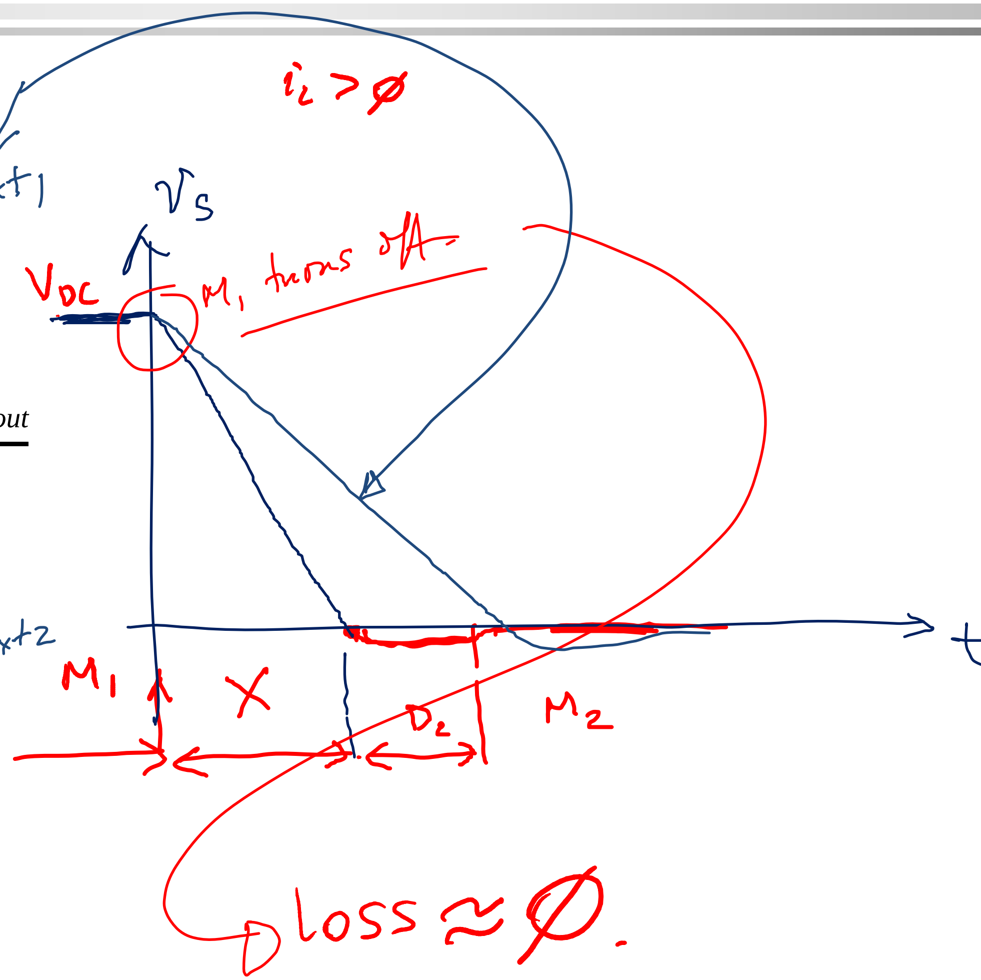


L = 100 μH, C = 10 μF, R = 5 Ω: M1 turn-off, M2 turn on transition



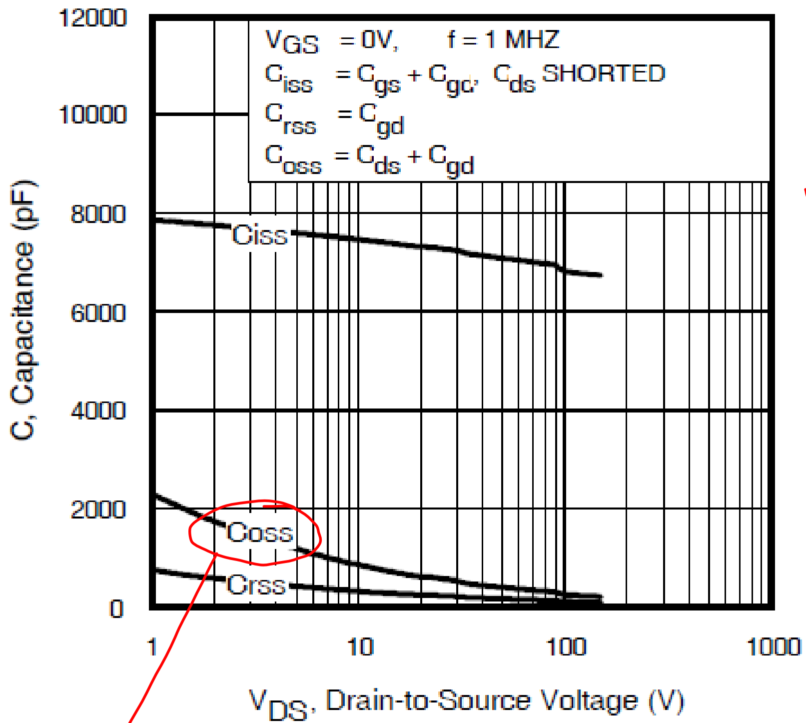
M1 turn-off, M2 turn-on transition



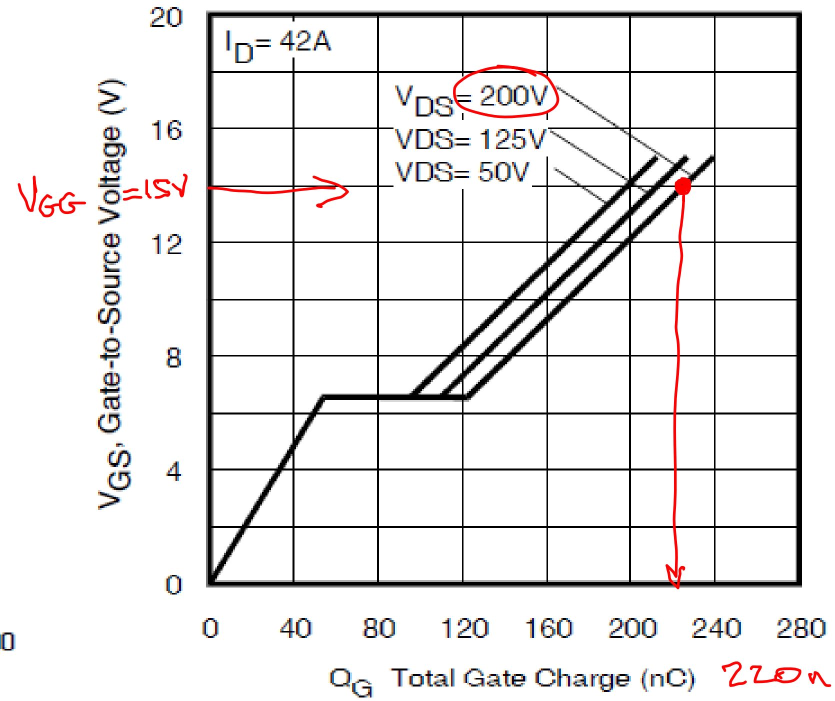


Device capacitances

irfp4232 example



C_1, C_2



220 nC = Q_G

$\boxed{\text{gate-drive loss}}$

$Q_G \cdot V_{GG} \cdot f_s$ = sw. loss

220 nC · 15V · 100kHz ≈ 0.4 W

Transistor switching times

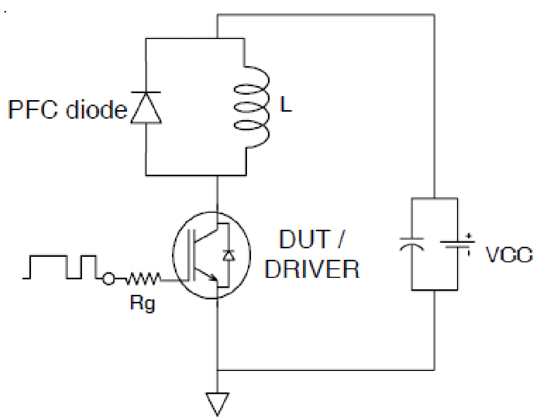
MOSFET

- Majority carrier device
- Turn-on and turn-off delays as well as current rise/fall times are in the order of several tens of nanoseconds
- At turn off, device output capacitance slows down v_{ds} voltage increase
- No significant energy loss during MOSFET turn-off transition, even if current prior to turn-off is not zero; device capacitance is charged up

IGBT

- Conduction through built in bipolar transistor, a minority-carrier device; base charge must be removed at turn-off ("current tail" observed at turn-off)
- Turn-on/turn-off times in the hundreds of nanoseconds
- If current prior to turn-off is not zero, energy loss during turn off can be significant

Transistor switching speed and turn-off transition: IGBT example



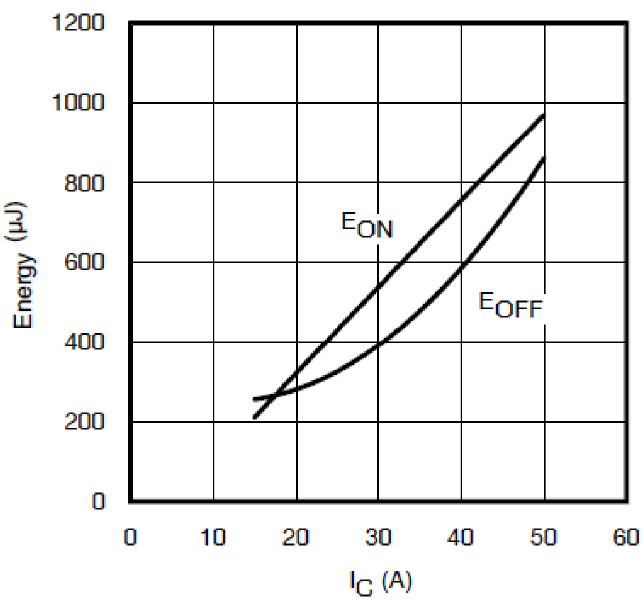
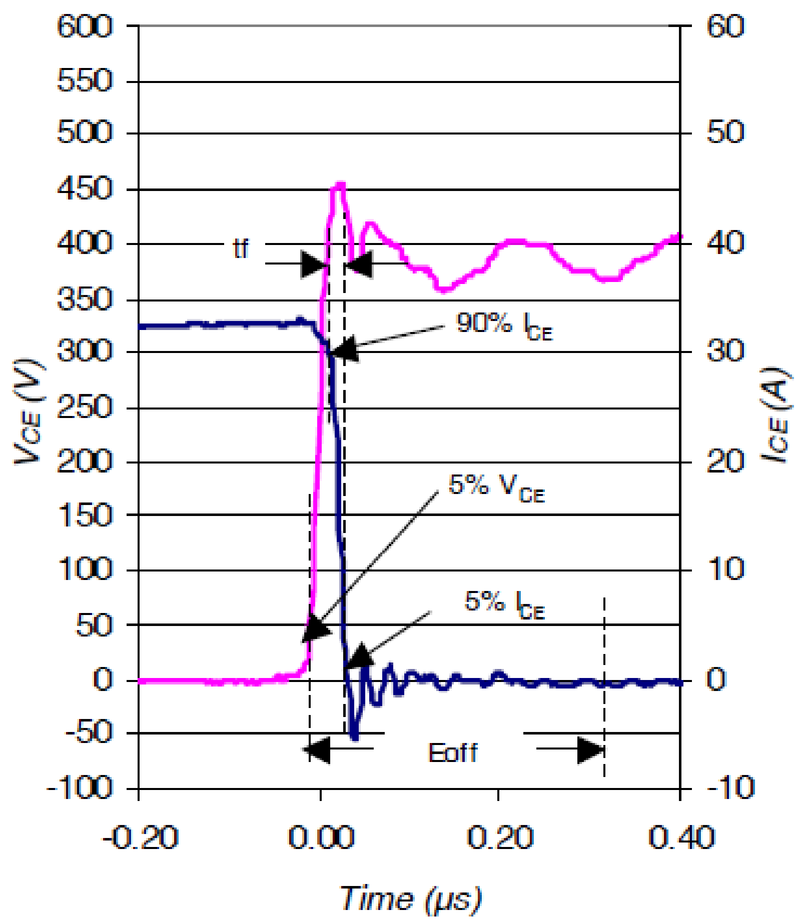
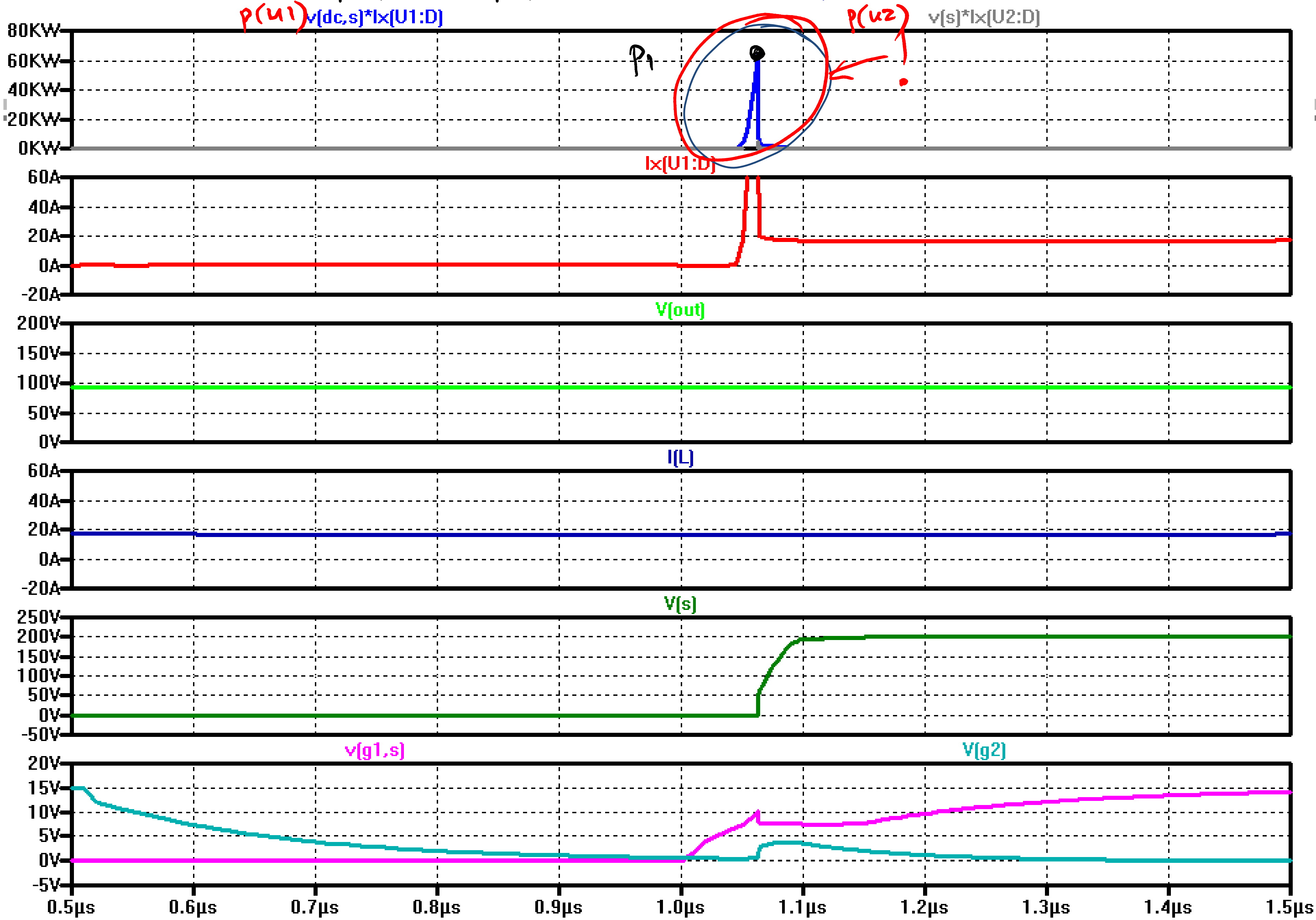


Fig. 11 - Typ. Energy Loss vs. I_C
$T_J = 125°C$; $L = 200μH$; $V_{CE} = 390V$, $R_G = 3.3Ω$; $V_{GE} = 15V$.
Diode clamp used: 30ETH06 (See C.T.3)



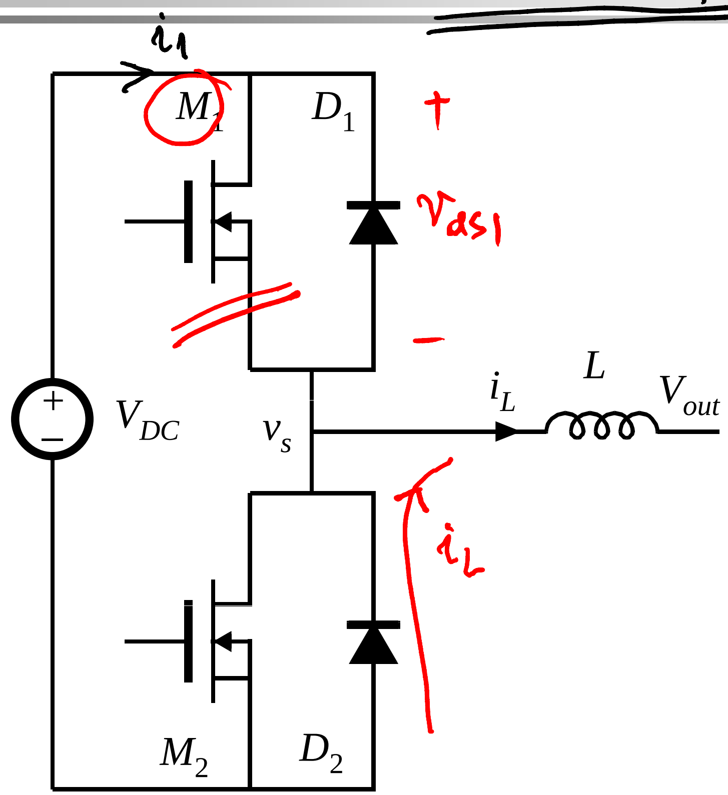
IRGP50B60 (IGBT+diode)

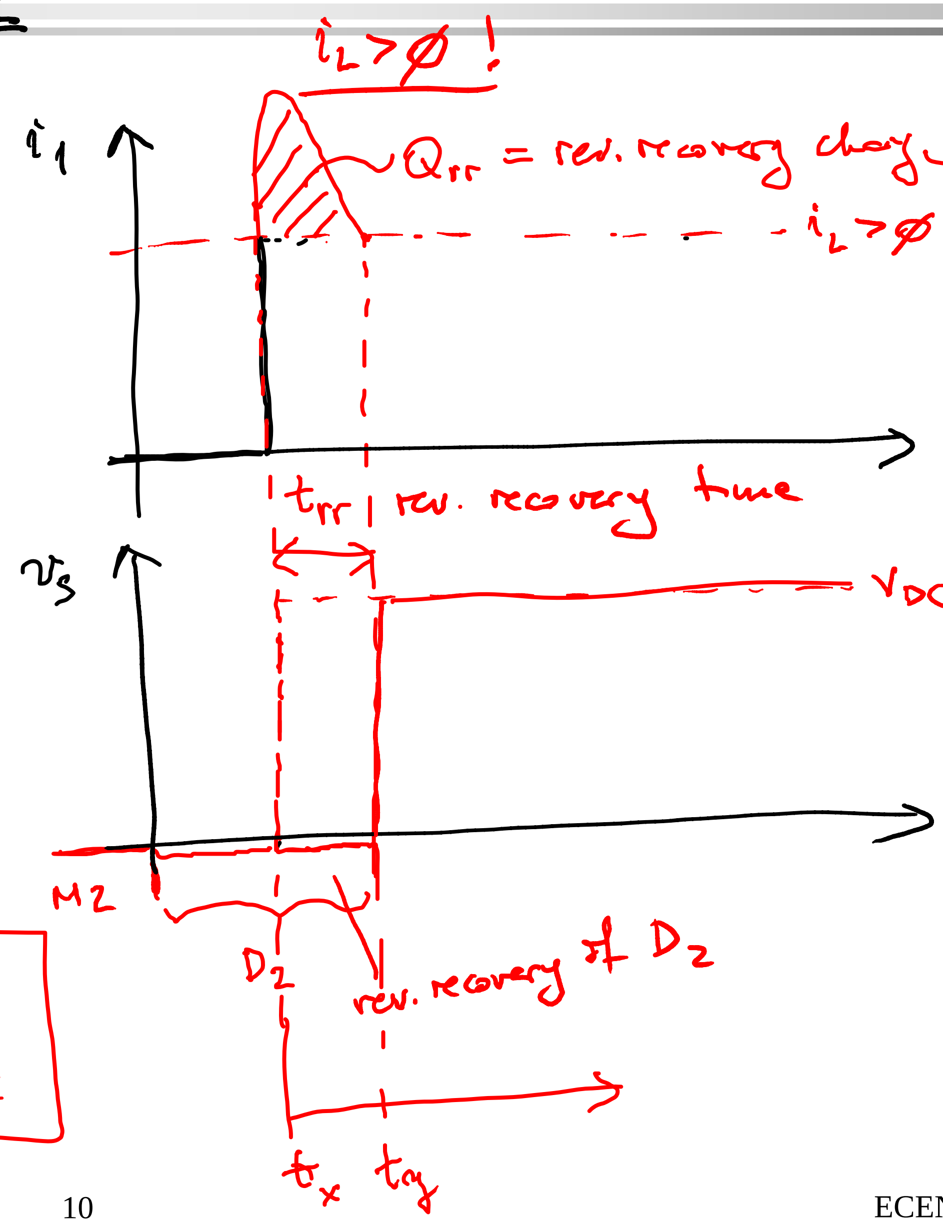
L = 100 μH, C = 10 μF, R = 5 Ω: M2 turn off, M1 turn on transition



Hard-switched: M2 turn-off, M1 turn-on transition

$$P_{on} = E_{on} \cdot f_s$$

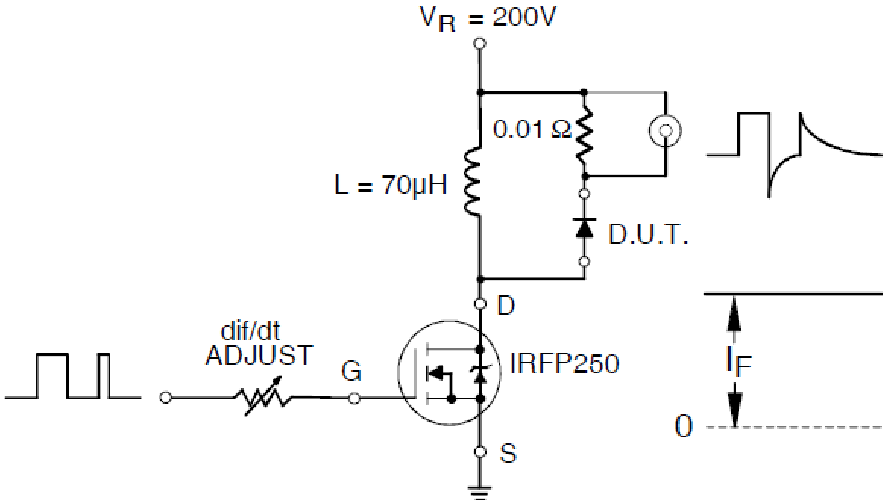




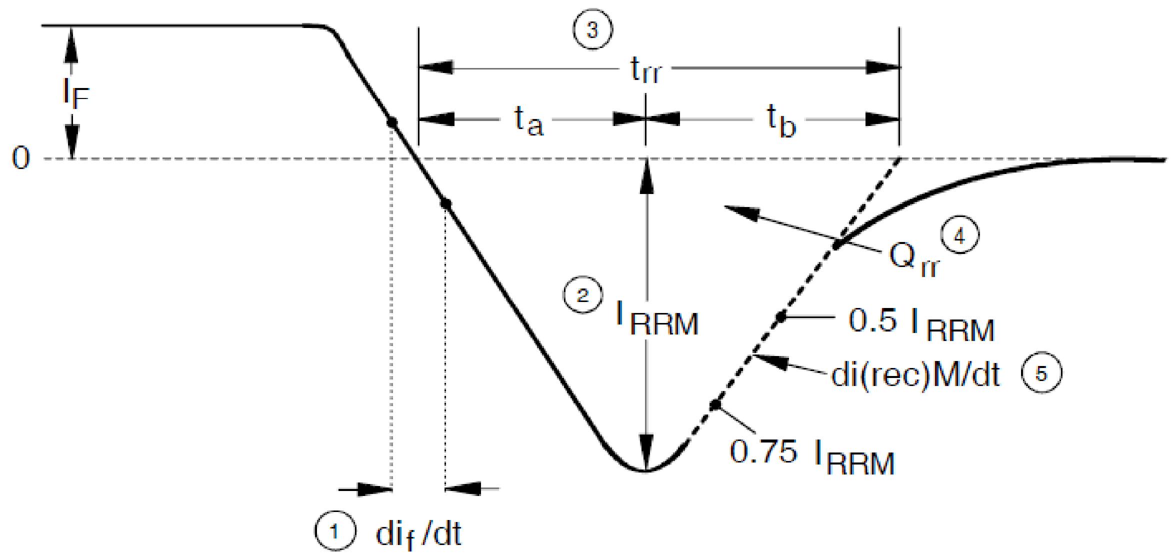
$$p_1 = i_1 v_{ds1} = i_1 (V_{DC} - v_s)$$

$$E_{on} = \int_{t_x}^{t_y} p_1 \, dt = \boxed{i_L t_{rr} \cdot V_{DC} + Q_{rr} \cdot V_{DC}}$$

Diode Stored Charge and Reverse Recovery



Typical test circuit and parameter definitions in diode data sheets



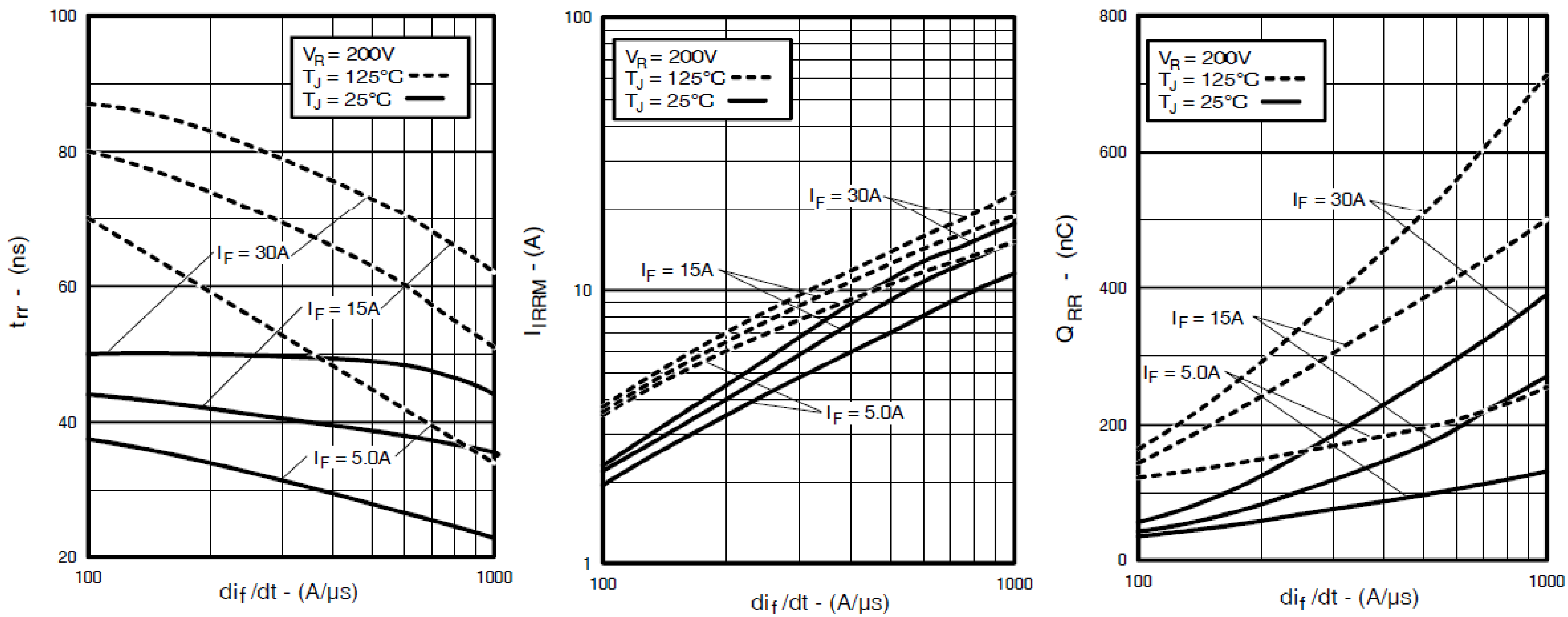
1. di_f/dt - Rate of change of current through zero crossing
2. I_{RRM} - Peak reverse recovery current
3. trr - Reverse recovery time measured from zero crossing point of negative going I_F to point where a line passing through 0.75 I_{RRM} and 0.50 I_{RRM} extrapolated to zero current
4. Q_{rr} - Area under curve defined by t_{rr} and I_{RRM}

$$Q_{rr} = \frac{t_{rr} \times I_{RRM}}{2}$$

5. $di_{(rec)M}/dt$ - Peak rate of change of current during t_b portion of t_{rr}

Example

Diode in IRGP50B60 (IGBT+diode): ultra-fast, “soft recovery”



Reverse recovery time t_{rr}, maximum reverse recovery current I_{RRM}, and reverse recovery charge Q_{rr} depend on diode forward current I_F prior to turn off, rate of current decay di_f/dt, and junction temperature T_J

Circuit Example: Introduction to Soft Switching

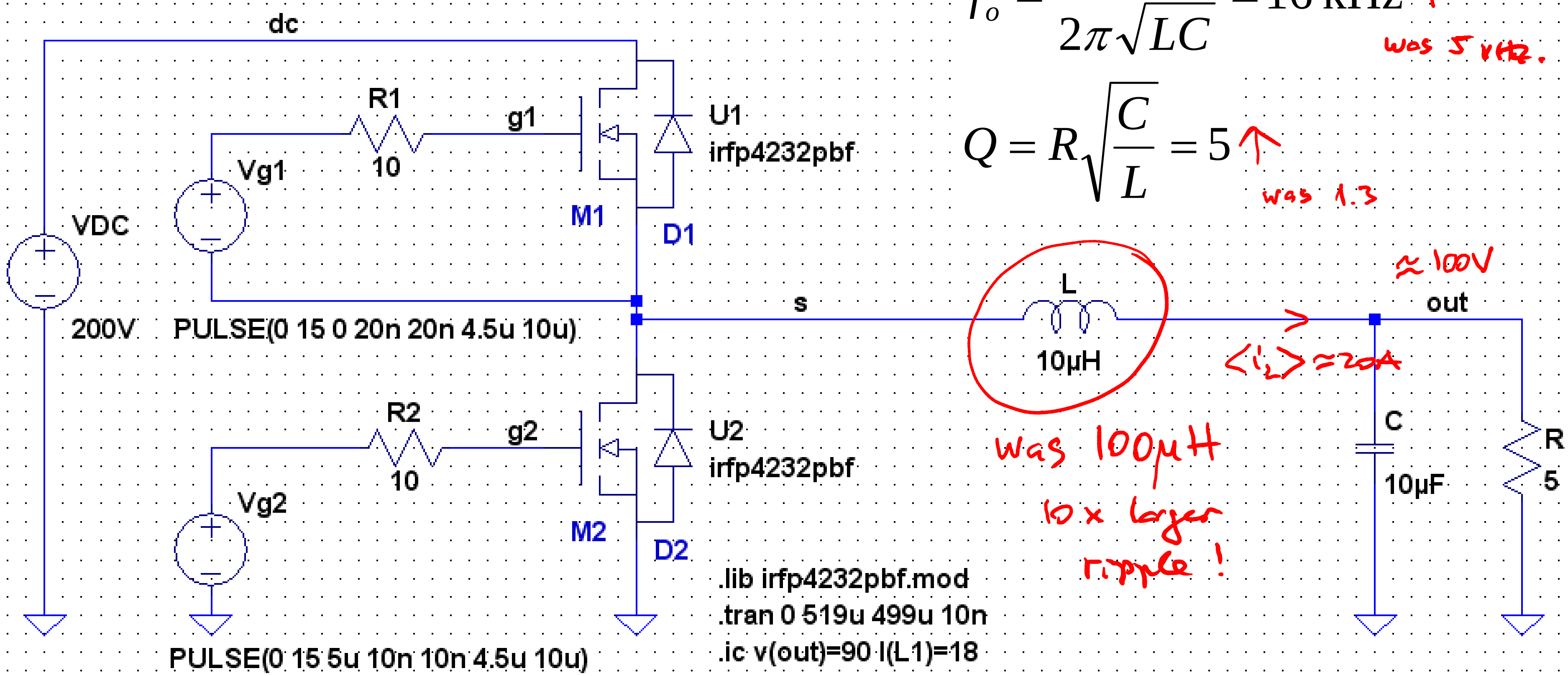
$$f_s = 100\text{ kHz},\ D \approx 0.5$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 16\text{ kHz}$$

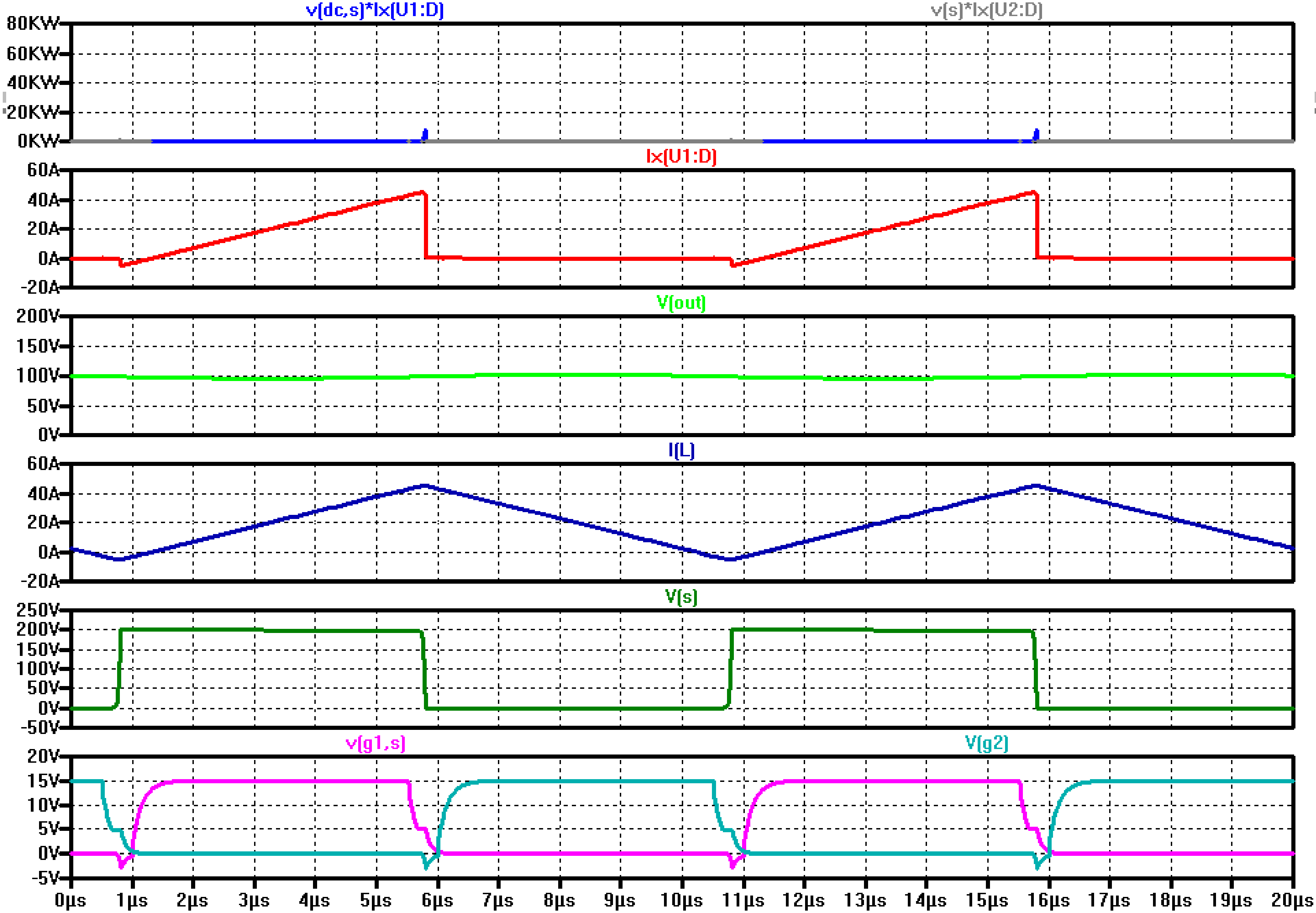
was 5 kHz.

$$Q = R\sqrt{\frac{C}{L}} = 5$$

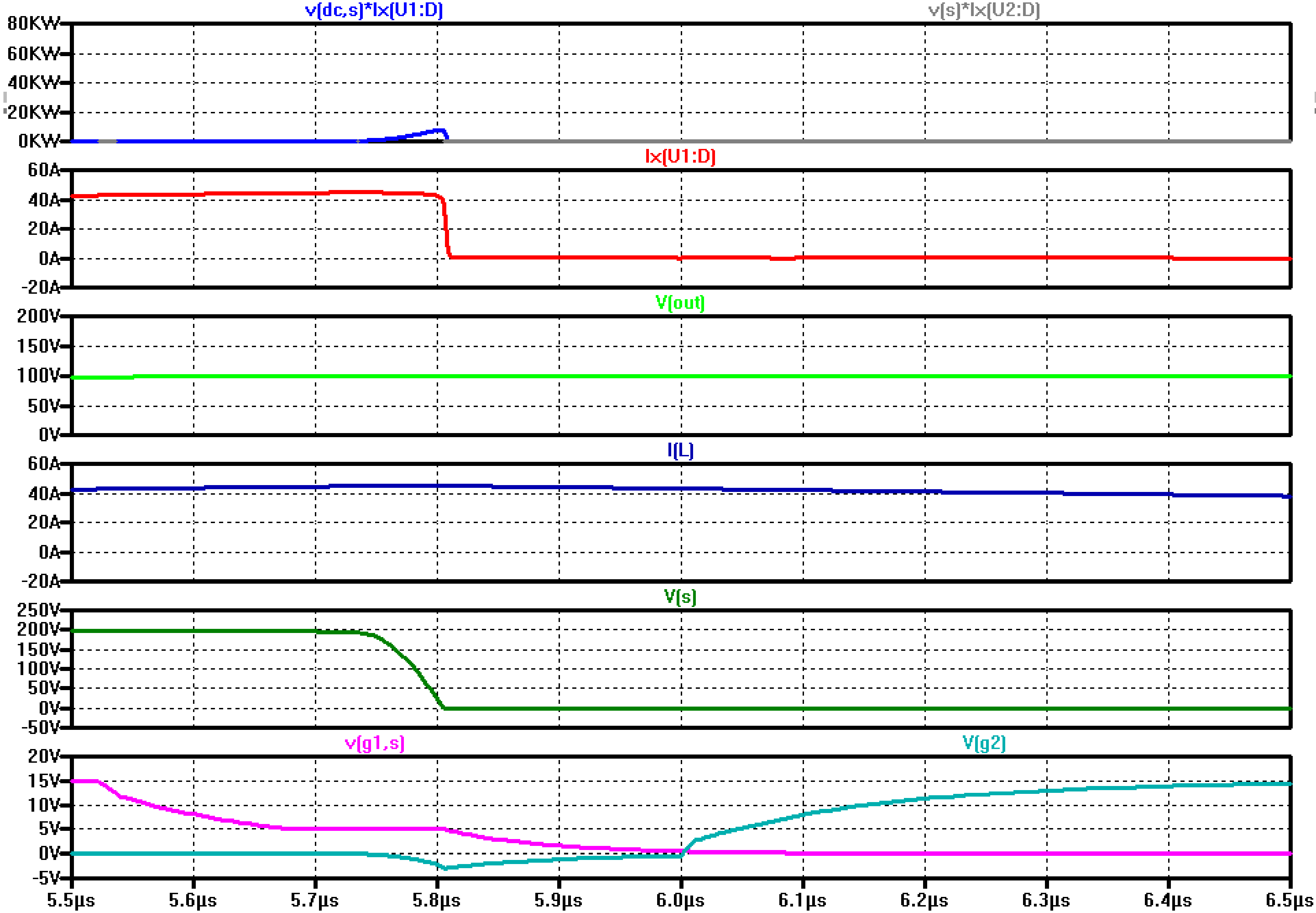
was 1.3



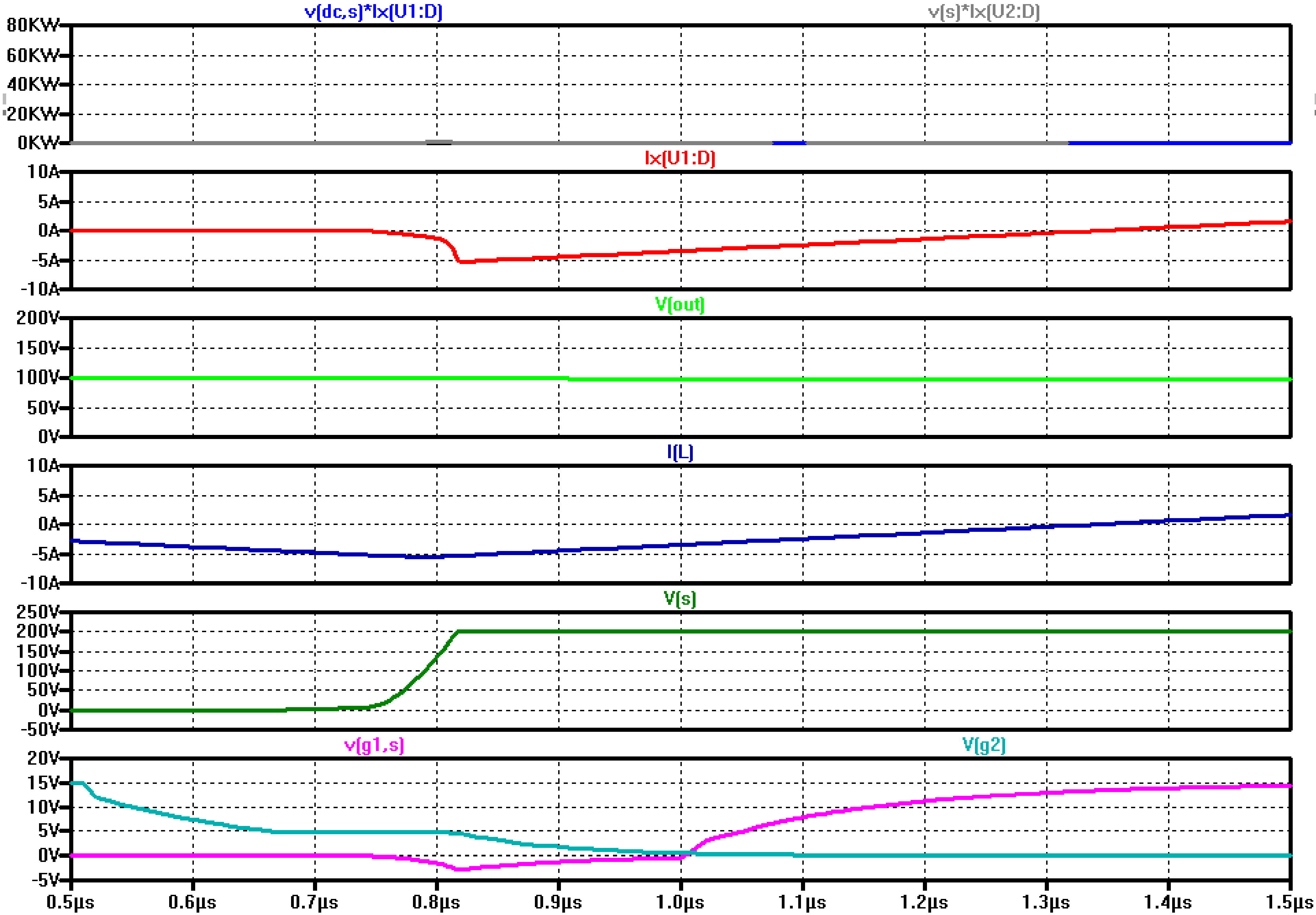
L = 10 μH, C = 10 μF, R = 5 Ω: Zero-Voltage Switching (ZVS) Quasi-Square-Wave Operation



L = 10 μH, C = 10 μF, R = 5 Ω: ZVS-QSW M1 turn-off, M2 turn-on

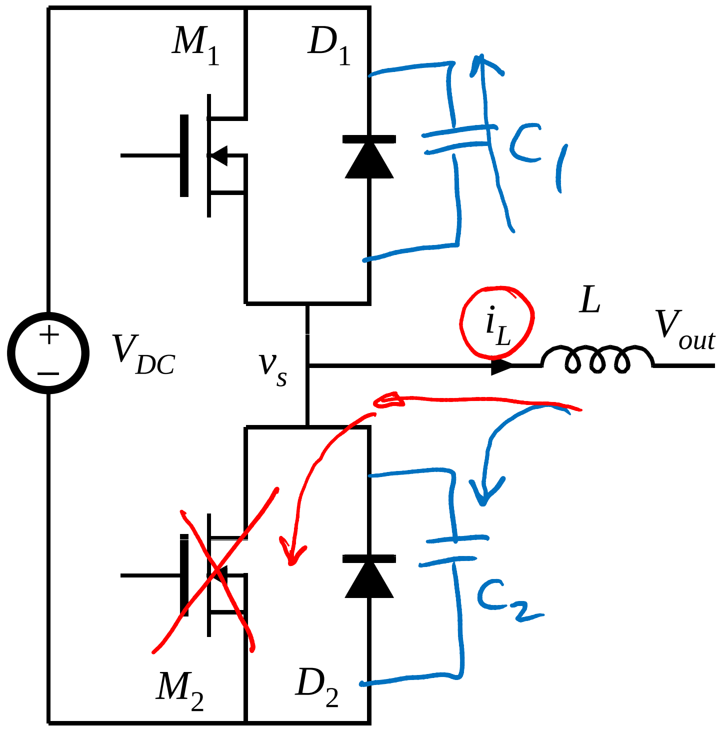


L = 10 μH, C = 10 μF, R = 5 Ω: ZVS-QSW M2 turn-off, M1 turn on



ZVS-QSW: M2 turn-off, M1 turn-on transition

$i_L < \emptyset$



ZVS turn on of M_1

Energy loss $\simeq \emptyset$