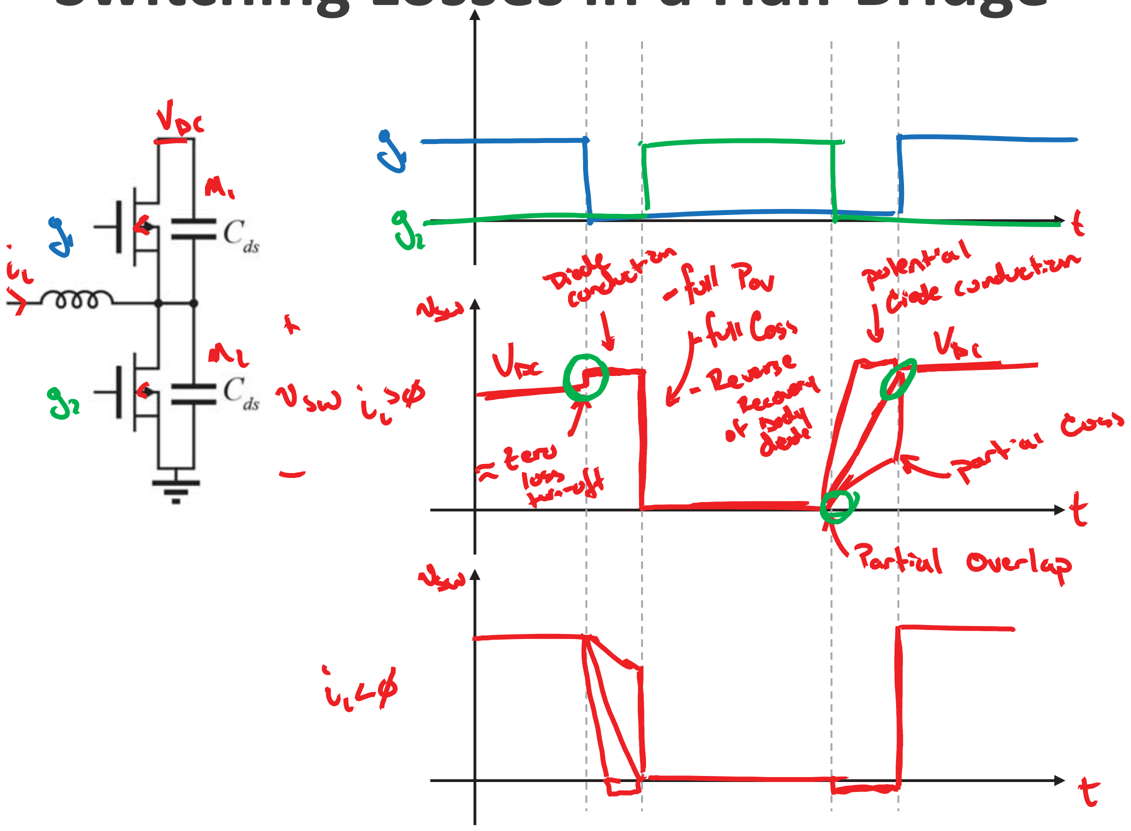
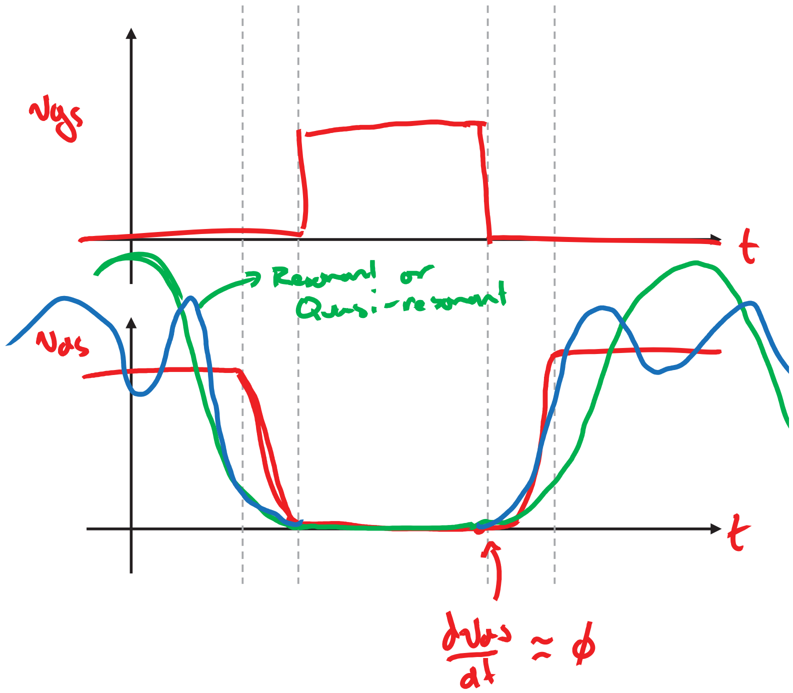
Switching Losses in a Half Bridge



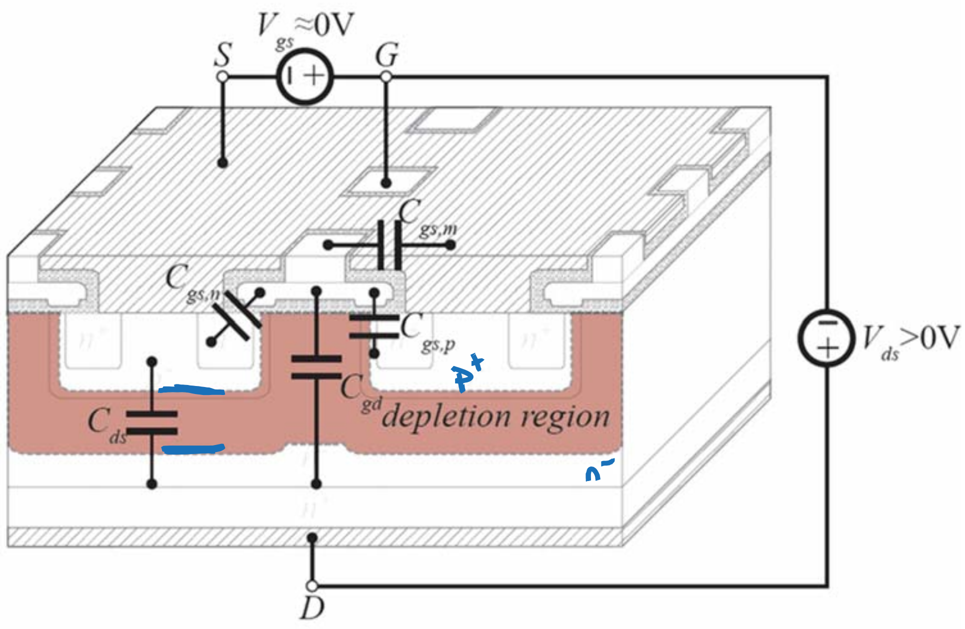
Target Switching Waveforms



Capacitive switching loss

ANALYSIS OF NONLINEAR CAPACITANCES

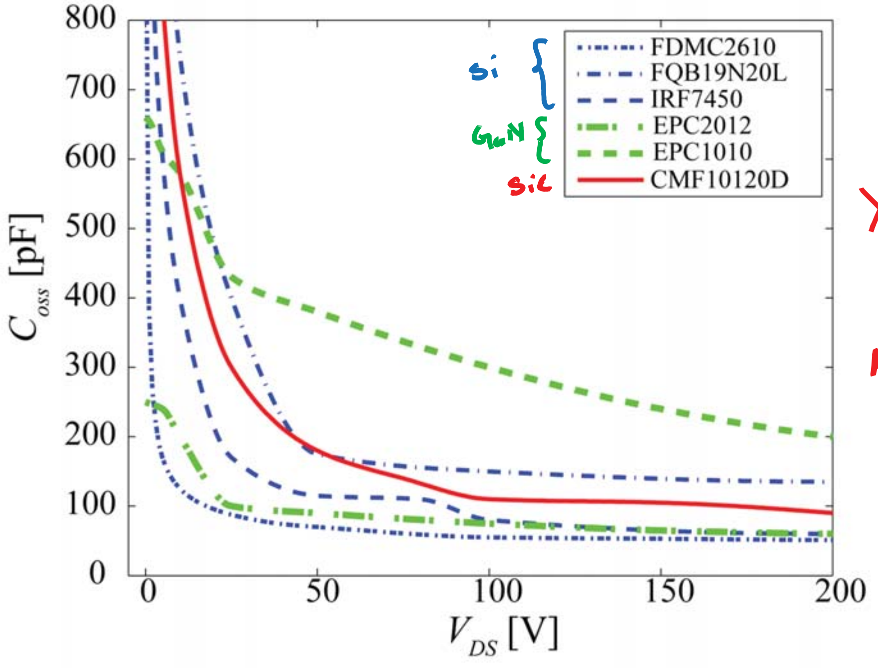
MOSFET Depletion Capacitance



Example Device C_{oss}

C_{oss} is highly nonlinear

$C_{oss} = f(V_{ds})$



C_{oss} is small-signal capacitance

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

$$\Delta q = C_{oss}\Big|_{V_{DS}} \Delta v_{ds}$$

$$X\ \underline{Q_{tot} = C_{oss}\Big|_{V_{DS}} V_{DS}}\ X$$

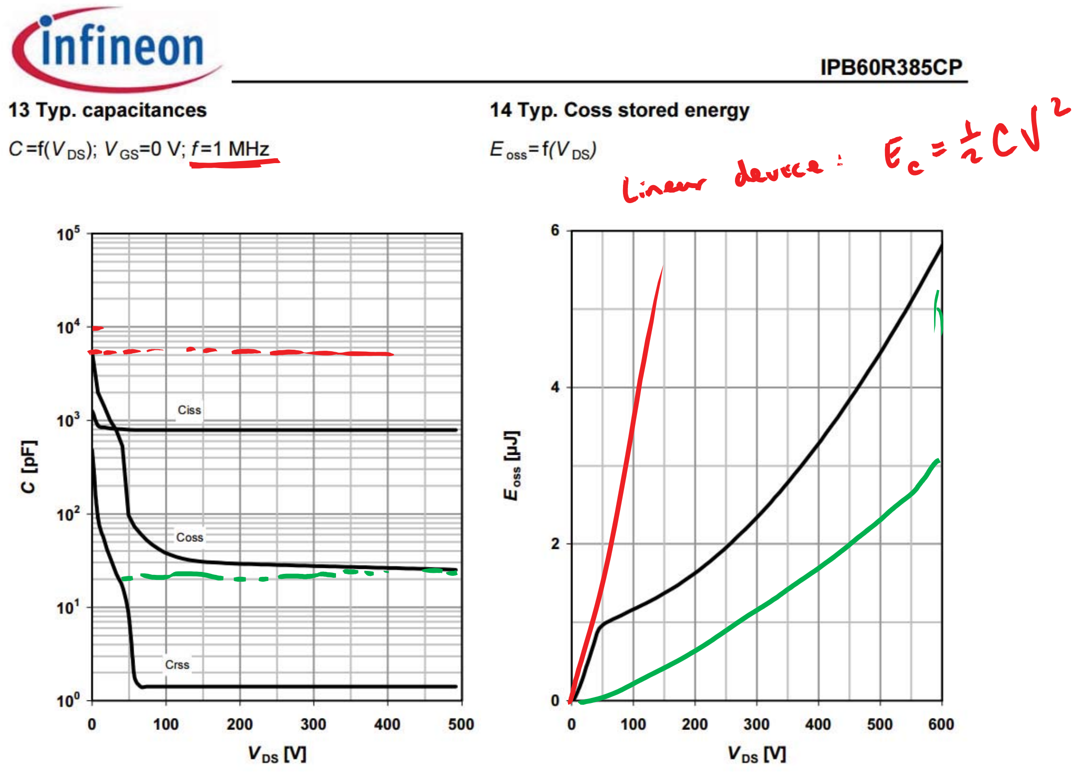
is not correct

Analytical curve fit used in e.g. SPICE

$$C_{oss} \approx \frac{C_{j0}}{\left(1 + \frac{V_{ds}}{V_{j0}}\right)^m}$$

often $m = \frac{1}{2}$

Datasheet Reported Capacitance



IPB60R385CP

13 Typ. capacitances

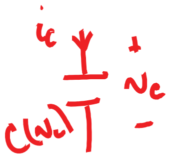
$C = f(V_{DS})$; $V_{GS} = 0$ V; $f = 1$ MHz

14 Typ. Coss stored energy

$E_{oss} = f(V_{DS})$

Linear device: $E_c = \frac{1}{2}CV^2$

Modeling Nonlinear Capacitances



Linear

Charge

$$Q = \int_0^t i_c(t)\,dt$$

$$Q = \int_0^t C(v_c)\,\frac{dv_c}{dt}\,dt$$

$$Q = \int_0^{V_{DC}} C(v_c)\,dv_c$$

$$Q = C\,V_{DC}$$

Energy

$$E = \int_0^t i_c(t)\,v_c(t)\,dt$$

$$E = \int_0^t C(v_c)\,\frac{dv_c}{dt}\,v_c(t)\,dt$$

$$E = \int_0^{V_{DC}} C(v_c)\,v_c(t)\,dv_c$$

$$E = C\left[\frac{v_c^2}{2}\right]_0^{V_{DC}} = \frac{1}{2}C V_{DC}^2$$

Nonlinear

$$Q = \int_0^{V_{DC}} C(v_c)\,dv_c$$

$$E = \int_0^{V_{DC}} C(v_c)\,v_c(t)\,dv_c$$

Cannot simplify further without
(1) Analytical expression for $C(v_c)$
(2) Numerical curves for $C(v_c)$

D. Costinett, D. Maksimovic and R. Zane, "Circuit-Oriented Treatment of Nonlinear Capacitances in Switched-Mode Power Supplies," in *IEEE Transactions on Power Electronics*

Energy and Charge Equivalents

Linear capacitance can model exactly one behavior of the nonlinear $C(v_c)$

Charge

$$Q = CV_{DC} = \int_0^{V_{DC}} C(v_c)\,dv_c$$

$$\boxed{C_{eq,Q} = \frac{1}{V_{DC}}\int_0^{V_{DC}} C(v_c)\,dv_c}$$

Energy

$$E = \frac{1}{2}C V_{DC}^2 = \int_0^{V_{DC}} C(v_c)\,v_c\,dv_c$$

$$\boxed{C_{eq,E} = \frac{2}{V_{DC}^2}\int_0^{V_{DC}} C(v_c)\,v_c\,dv_c}$$

Note:

$$C_{eq,Q} = \langle C(v_c)\rangle\Big|_{V_{DC}}$$