Ideal Switching Waveforms

![Diagram of Ideal Switching Waveforms]

- $v_{gs,2}$ vs. $t$
- $v_{sw}$
- High $dV/dt$ @ turn-off
- Zero $dV/dt$ at turn-off
- Some residual $V_{f(0)}$
Synchronous Simulation (L3)
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Capacitive switching loss

ANALYSIS OF NONLINEAR CAPACITANCES
Example Device $C_{oss}$

\[ C_{oss} = C_{ds} + C_{gd} \approx C_{ds} \]

$C_{oss}$ is a small-signal measurement.

\[ C_{V_{ds}} \quad \frac{dV}{dt} \bigg|_{V_{ds}=V_{ds}} \]

\[ C_{tot} = CV_{ds} \]

\[ \Delta g = C \left| \frac{dV}{dV_{ds}} \right. \]

Curve fit model:

\[ C_{ds} = \left( 1 + \frac{V_{ds}}{V_{d0}} \right)^{-m} \]

Often $m = \frac{1}{2}$.

Empirical model.
Datasheet Reported Capacitance

13 Typ. capacitances
\[ C = f(V_{DS}); \quad V_{GS} = 0 \text{ V}; \quad f = 1 \text{ MHz} \]

14 Typ. Coss stored energy
\[ E_{oss} = f(V_{DS}) \]

\( Q_{c} C \quad V_{BE} = 300 \text{ V} \)

\( \frac{1}{2} CV^2 \)

Less common for datasheets to include for linear cap

\( 1/2 CV^2 \)
Modeling Nonlinear Capacitances

\[ Q_c = \int_{0}^{V_{bc}} C(u_c) \, du_c \]

Linear

\[ Q_c = \int_{0}^{V_{bc}} C \, du_c = CV_{bc} \]

Nonlinear

Cannot simplify further in nonlinear case

Energy

\[ E_c = \int_{0}^{V_{bc}} \frac{1}{2} \frac{dV_c}{dt} \, dt \]

\[ E_c = \int_{0}^{V_{bc}} \frac{dV_c}{dt} \, dt \]

\[ E_c = C \int_{0}^{V_{bc}} V_c \, du_c = C \left. \frac{V_c^2}{2} \right|_0^{V_{bc}} = \frac{1}{2} CV_{bc}^2 \]
Energy and Charge Equivalents

Linear equivalent capacitance can match a single characteristic of the full nonlinear characteristic.

**Charge**

\[ Q_c = \int_0^{V_{dc}} C(V_c) \, dV_c = C_{eq,a} \, V_{dc} \]

\[ C_{eq,a} = \frac{1}{V_{dc}} \int_0^{V_{dc}} C(V_c) \, dV_c \]

Linear capacitance that will have the same total charge stored at \( V_{dc} \) as the nonlinear cap.

**Energy**

\[ E_c = \int_0^{V_{dc}} C(V_c) \, V_c \, dV_c = \frac{1}{2} C_{eq,a} \, V_{dc}^2 \]

\[ C_{eq,e} = \frac{2}{V_{dc}^2} \int_0^{V_{dc}} C(V_c) \, V_c \, dV_c \]

Linear cap with same total energy at \( V_{dc} \) vs. nonlinear cap.

Interesting: \[ C_{eq,a} = \langle C(V_c) \rangle_{V_{dc}} \]

is the average capacitance on the curve.
$C_{oss}$ Losses in a Half Bridge

\[ V_{dc} \]

\[ C_{ds} \]

\[ V_{dc} \]

\[ C_{ds} (V_{dc}) \]

\[ V_{dc} = V_{dc} \]

\[ i.c. \]

$V_{sel}(t=0) = V_{dc}$
$M_2$ Energy Loss

\[ E_R = \int_0^\infty v_{Rc} i_R \, dt \]

\[ i_R = i_e = C_{d2}(v_e) \frac{dv_e}{dt} \]

\[ v_R = -v_{sc} \omega \]

\[ E_R = \int_0^\infty (-v_{sc} \omega) C_{d22}(v_{sc}) \frac{dv_{sc}}{dt} \, dt \]

By insight:

\[ E_R = E_C = \frac{1}{2} C_{d22} v_{sc}^2 \]

\[ C = C_{d2} \]

\[ v_{sc} = v_{sc} \omega \]