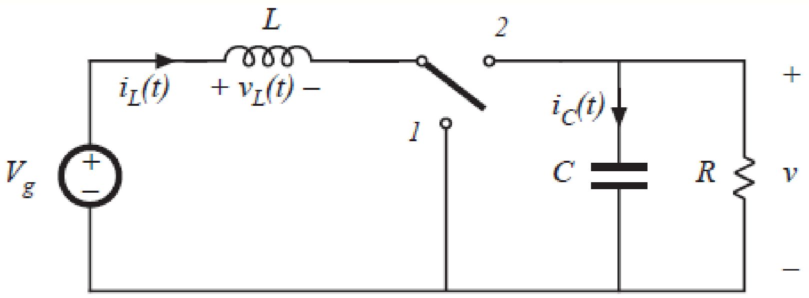
Johns Hopkins Engineering

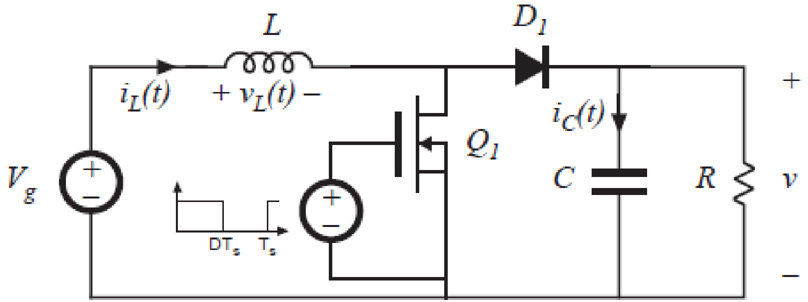
Power Electronics 525.725

Module 2 Lecture 2a

Boost Converter Simulink Simulation

Boost Converter





$$V_g = 48\ \text{V}$$

$$V = 120\ \text{V}$$

$$P_{out} = 150\ \text{W}$$

$$f_{sw} = 100\ \text{kHz}$$

$$\Delta i_L = 20\% I_L$$

$$\Delta v = 100 mV$$

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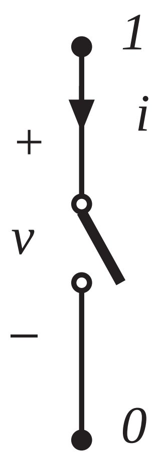
Module 2 Lecture 2b

Switch realization, losses, and efficiency of a Switching Converter

SPST (single-pole single-throw) switches

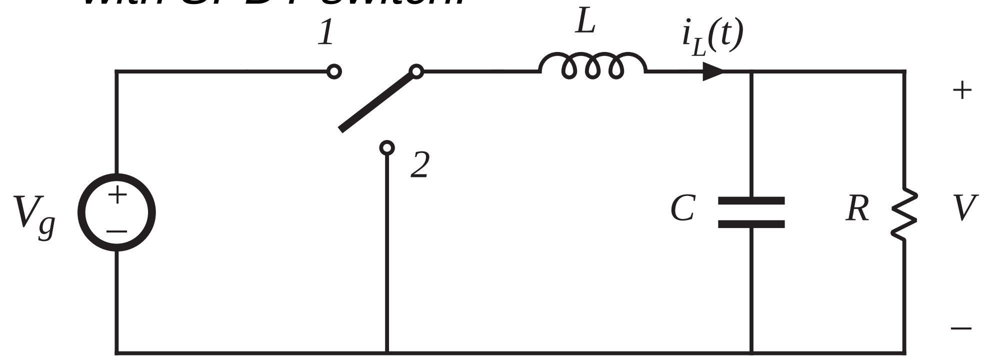
SPST switch, with voltage and current polarities defined



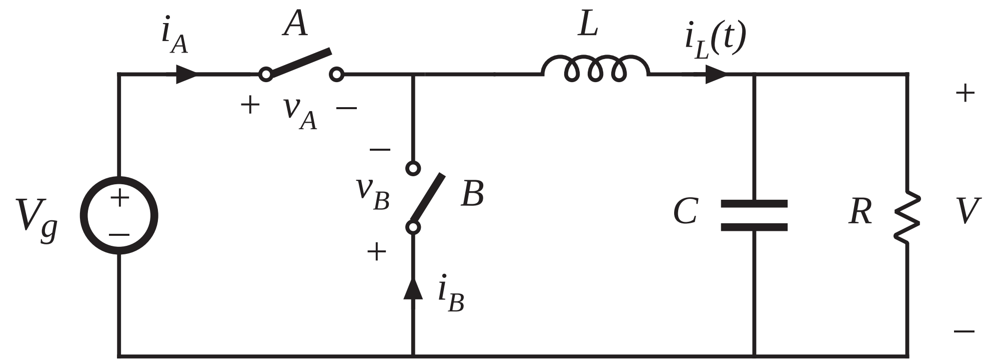
All power semiconductor devices function as SPST switches.

Buck converter

with SPDT switch:



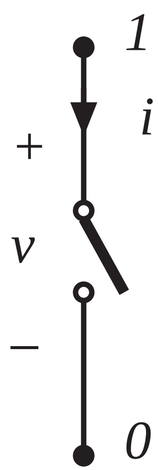
with two SPST switches:

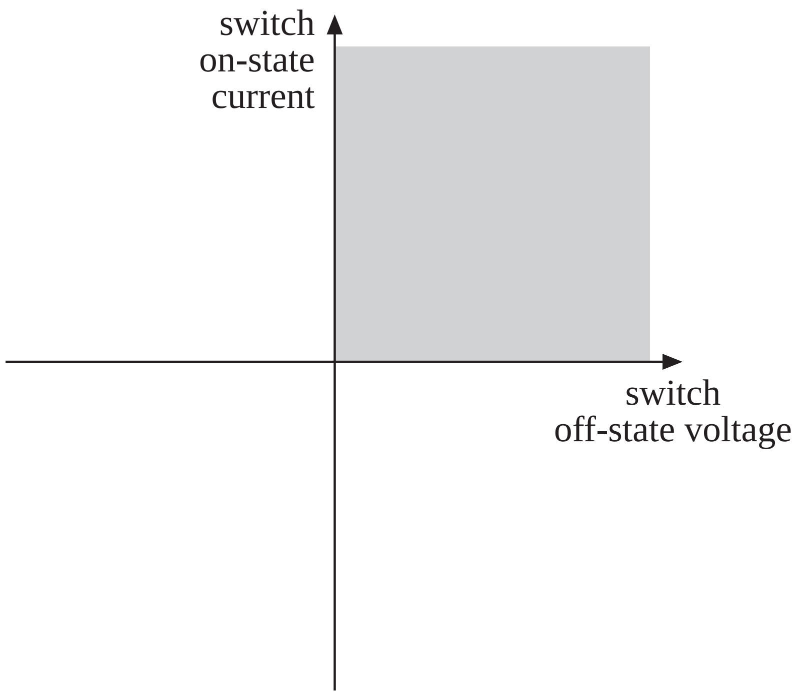


Realization of SPDT switch using two SPST switches

- A nontrivial step: two SPST switches are not exactly equivalent to one SPDT switch
- It is possible for both SPST switches to be simultaneously ON or OFF
- Behavior of converter is then significantly modified
—discontinuous conduction modes (ch. 5)
- Conducting state of SPST switch may depend on applied voltage or current —for example: diode

Quadrants of SPST switch operation





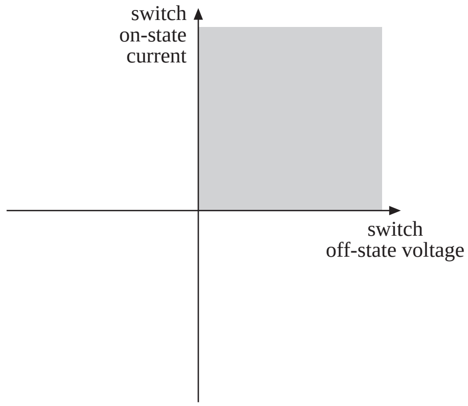
A single-quadrant switch example:

ON-state: $i > 0$

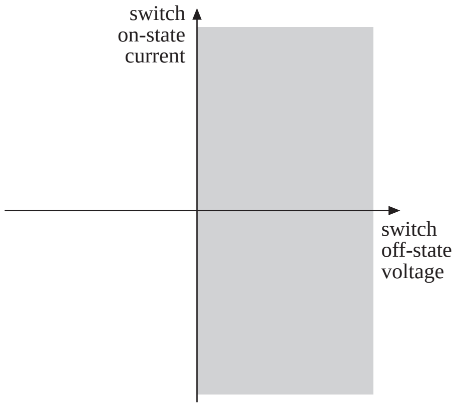
OFF-state: $v > 0$

Some basic switch applications

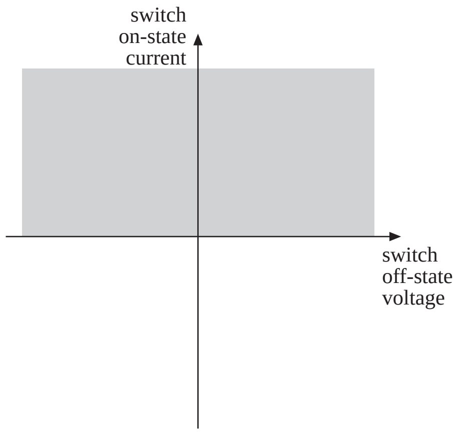
Single-quadrant switch



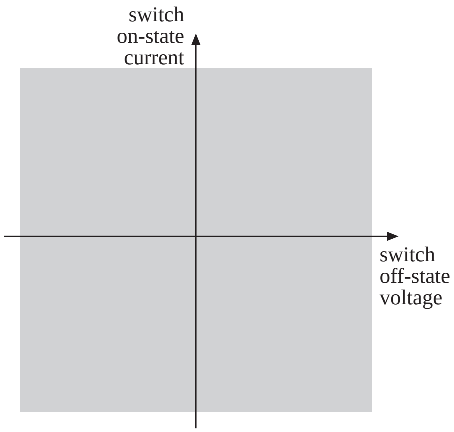
Current-bidirectional two-quadrant switch



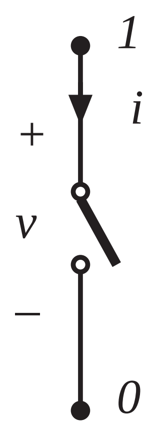
Voltage-bidirectional two-quadrant switch



Four-quadrant switch



4.1.1. Single-quadrant switches



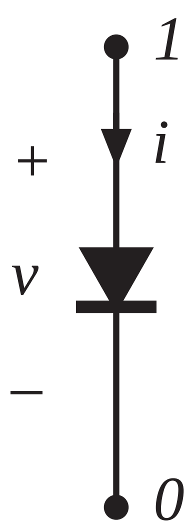
Active switch: Switch state is controlled exclusively by a third terminal (control terminal).

Passive switch: Switch state is controlled by the applied current and/or voltage at terminals *1* and *2*.

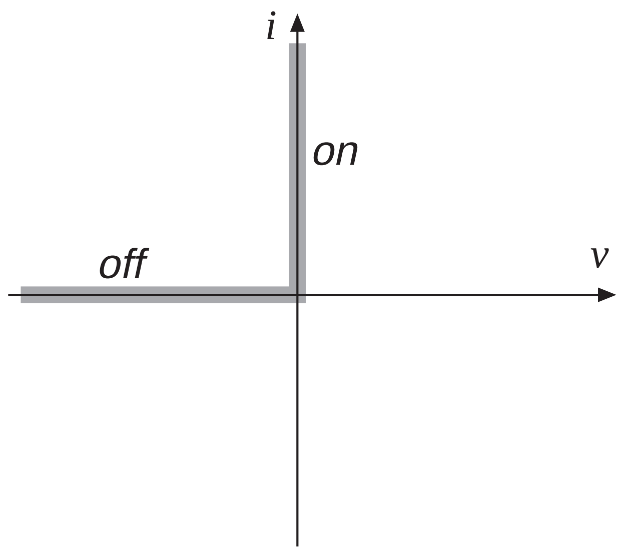
SCR: A special case — turn-on transition is active, while turn-off transition is passive.

Single-quadrant switch: on-state $i(t)$ and off-state $v(t)$ are unipolar.

The diode



Symbol

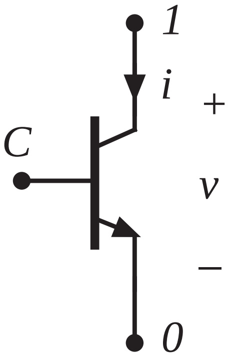


instantaneous i-v characteristic

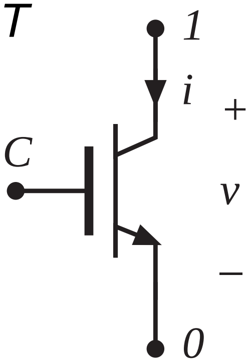
- *A passive switch*
- *Single-quadrant switch:*
- *can conduct positive on-state current*
- *can block negative off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the diode i-v characteristic, then switch can be realized using a diode*

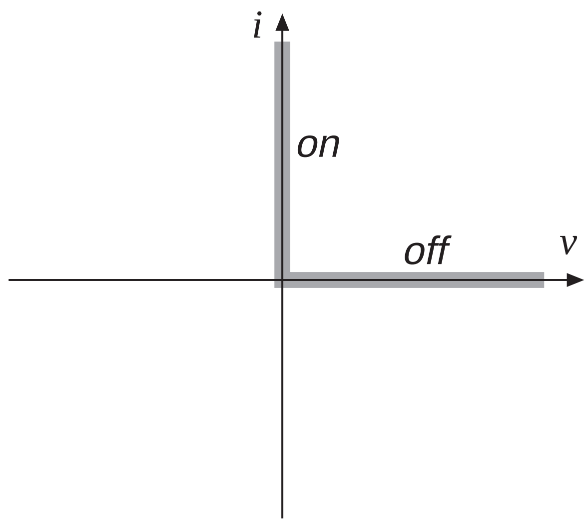
The Bipolar Junction Transistor (BJT) and the Insulated Gate Bipolar Transistor (IGBT)

BJT



IGBT

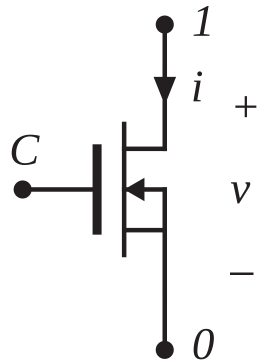




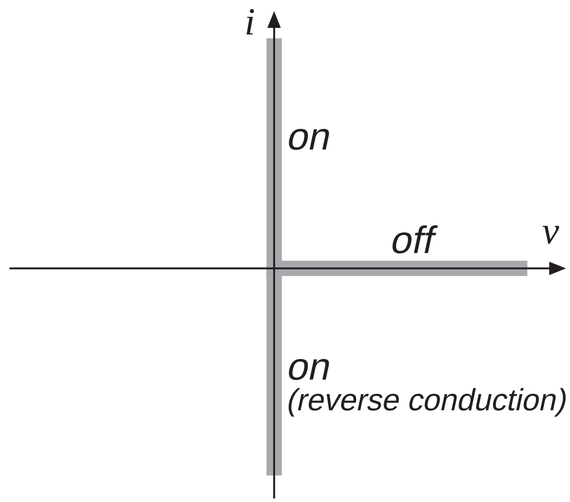
instantaneous i-v characteristic

- *An active switch, controlled by terminal C*
- *Single-quadrant switch:*
- *can conduct positive on-state current*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the transistor i-v characteristic, then switch can be realized using a BJT or IGBT*

The Metal-Oxide Semiconductor Field Effect Transistor (MOSFET)



Symbol

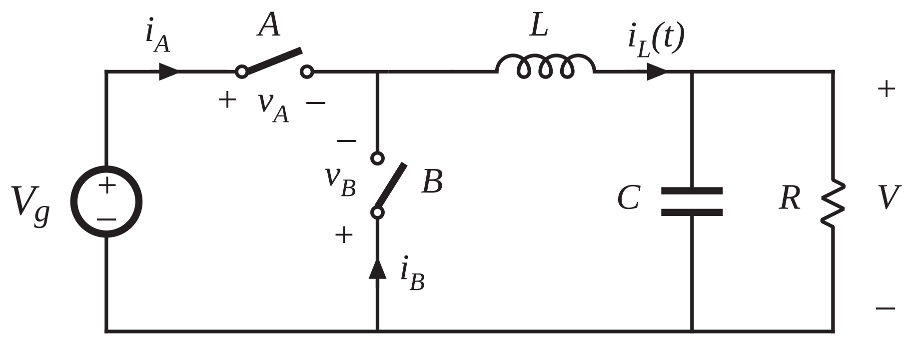


instantaneous i-v *characteristic*

- *An active switch, controlled by terminal* C
- *Normally operated as single-quadrant switch:*
- *can conduct positive on-state current (can also conduct negative current in some circumstances)*
- *can block positive off-state voltage*
- *provided that the intended on-state and off-state operating points lie on the MOSFET* i-v *characteristic, then switch can be realized using a MOSFET*

Realization of switch using transistors and diodes

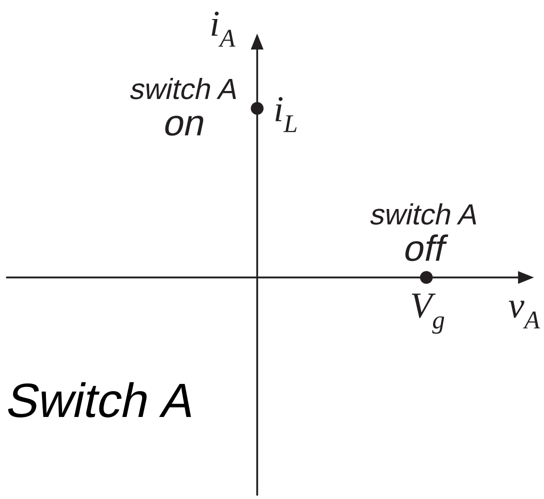
Buck converter example



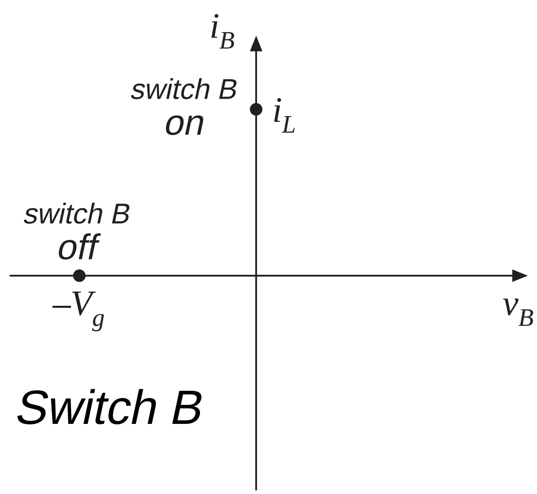
Switch A: transistor

Switch B: diode

SPST switch operating points

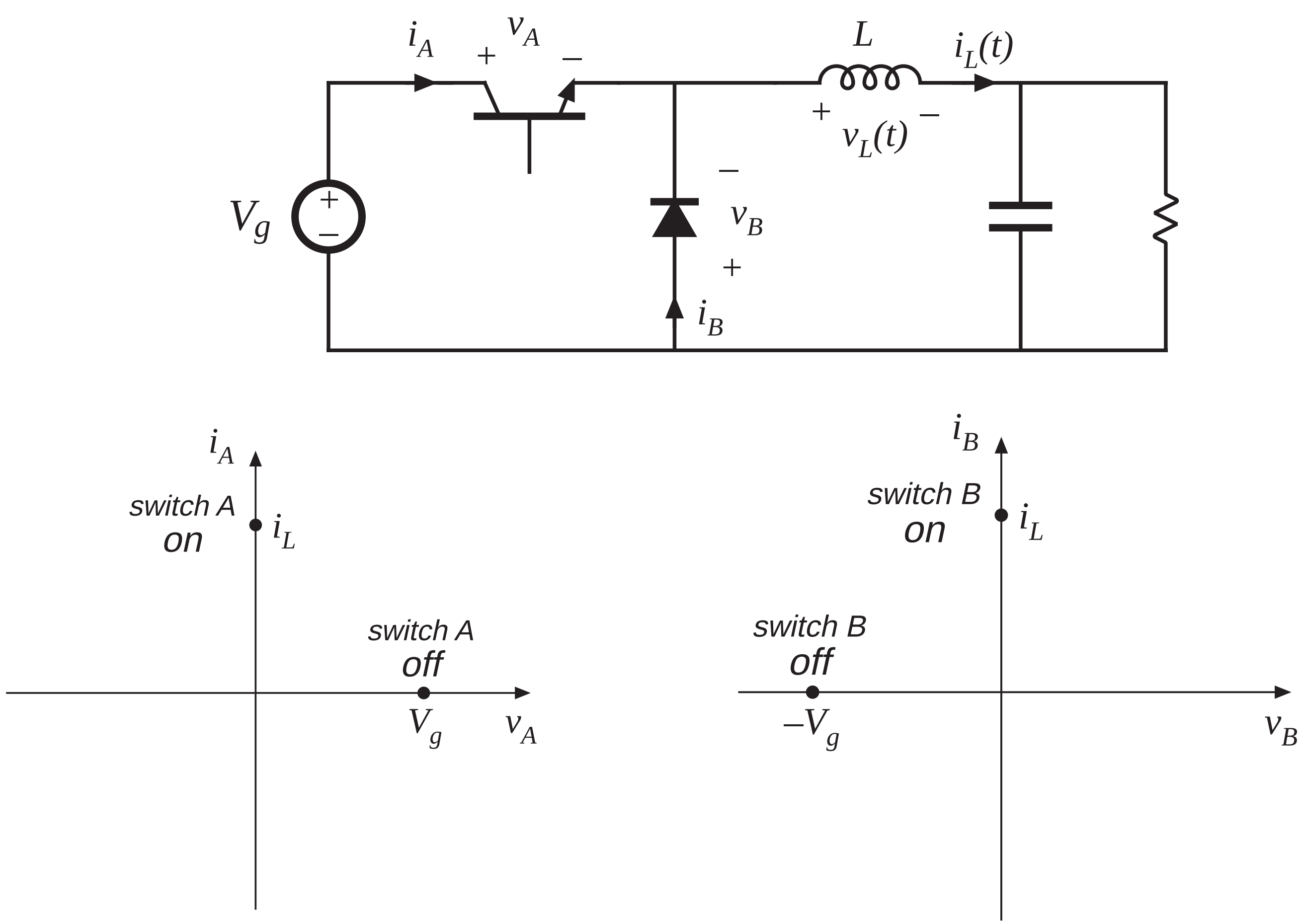


Switch A



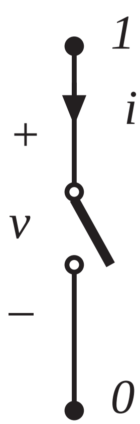
Switch B

Realization of buck converter using single-quadrant switches

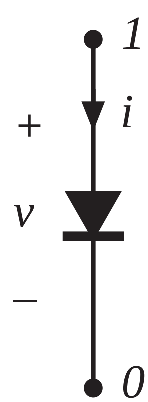


4.1.5. Synchronous rectifiers

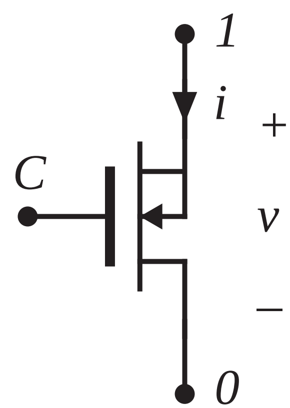
Replacement of diode with a backwards-connected MOSFET,
to obtain reduced conduction loss



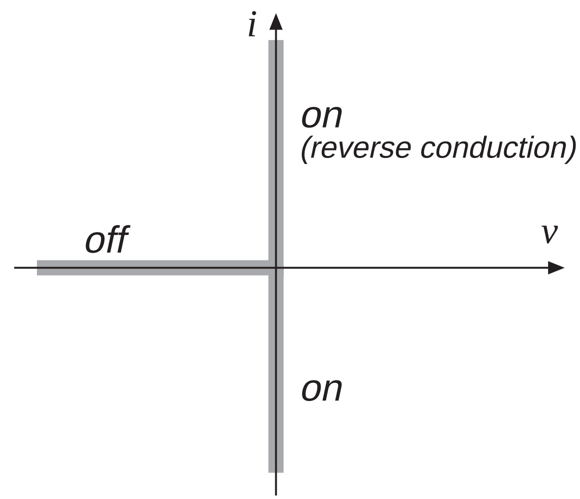
ideal switch



conventional diode rectifier

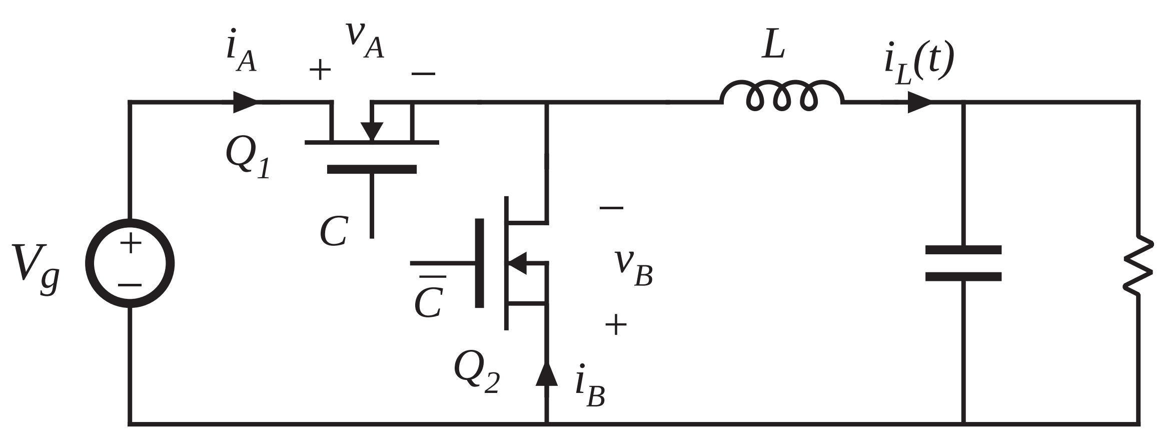


MOSFET as synchronous rectifier



instantaneous i-v characteristic

Buck converter with synchronous rectifier



- MOSFET Q_2 is controlled to turn on when diode would normally conduct
- Semiconductor conduction loss can be made arbitrarily small, by reduction of MOSFET on-resistances
- Useful in low-voltage high-current applications

Converter Efficiency

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} I_{out}}{V_{out} I_{out} + P_{loss}}$$

$$P_{loss} = P_{sw-cond} + P_{sw-switch} + P_{ind-core} + P_{ind-copper}$$

$P_{sw-switch}$: Switching loss of device

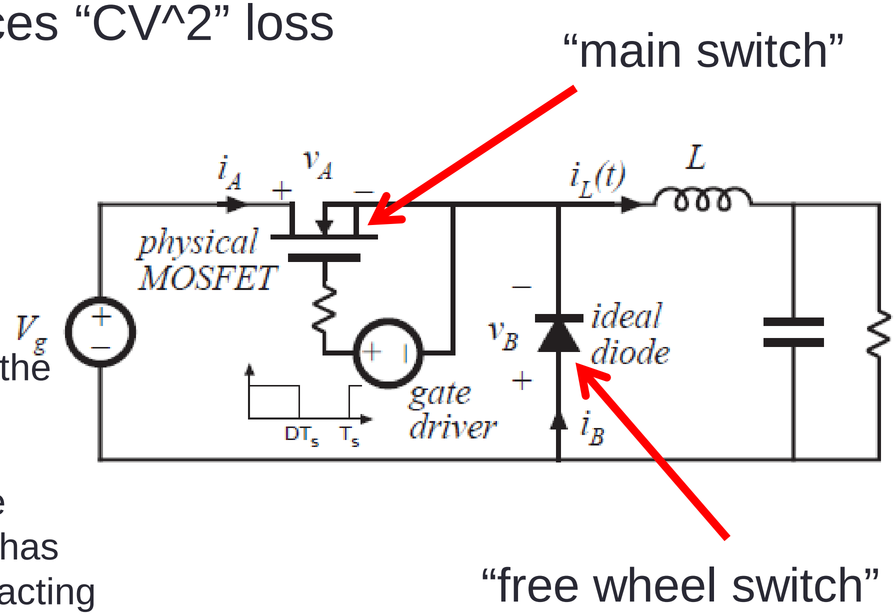
$\mathrm{P}_{\text{sw-cond}}$: Conduction loss of device

$P_{ind-core}$: Inductor core loss

$P_{ind-copper}$: Inductor copper "conduction" loss

Device Loss Contributors

1. **Switching Loss** – Energy is lost during the “**main**” semiconductor switching transitions, via several mechanisms
   - Transistor switching times “Cross-over” loss
   - Diode stored charge “diode recovery” loss”
   - Energy stored in device capacitances “CV^2” loss
2. **Conduction Loss -**
   - I^2xR loss in MOSFET
   - Von x I loss in IGBT and diode

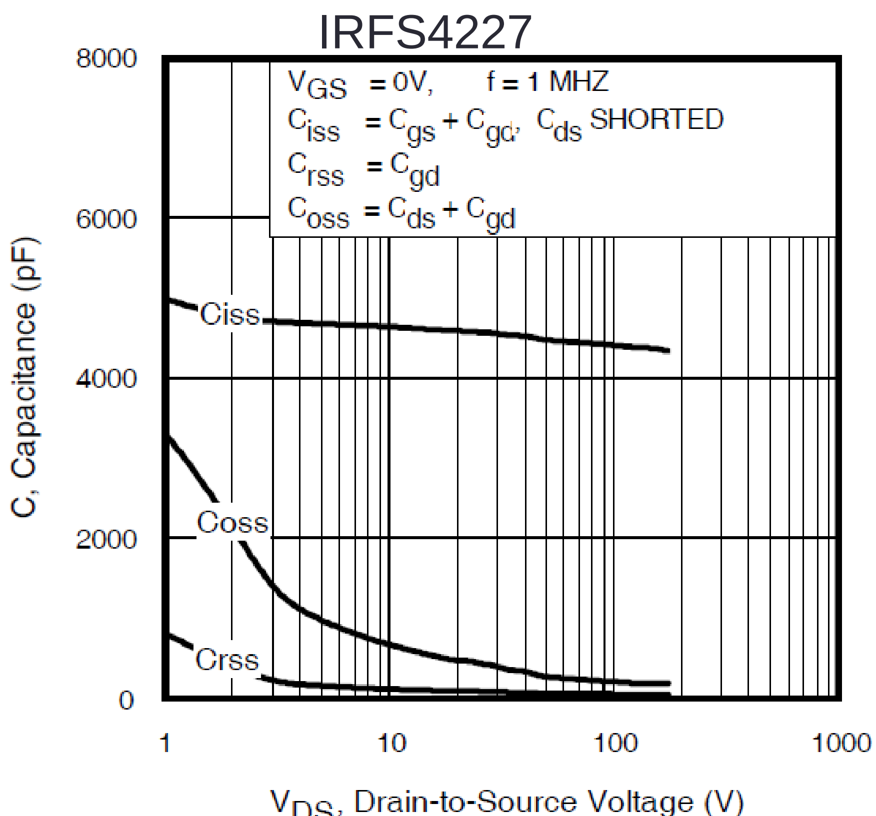


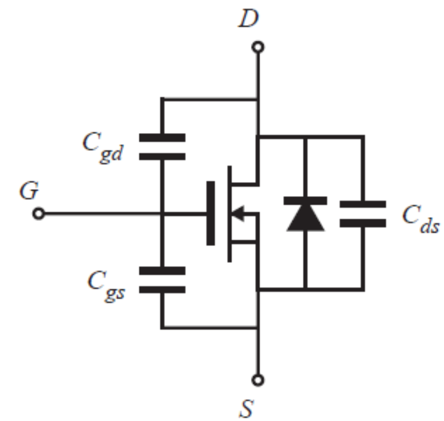
Main Switch:
An active switch which charges or stores energy in the inductor.

Free Wheel Switch:
The free wheel switch is the switch which keeps the current flowing in an inductor once the main switch has turned off and is typically a diode rectifier or switch acting as a synchronous rectifier.

In General, we will only consider switching loss in the main switch and conduction loss in the main and free wheel switch

MOSFET Data Sheet Capacitances





$$C_{iss} = C_{GS} + C_{GD}, C_{DS} \text{ Shorted}$$

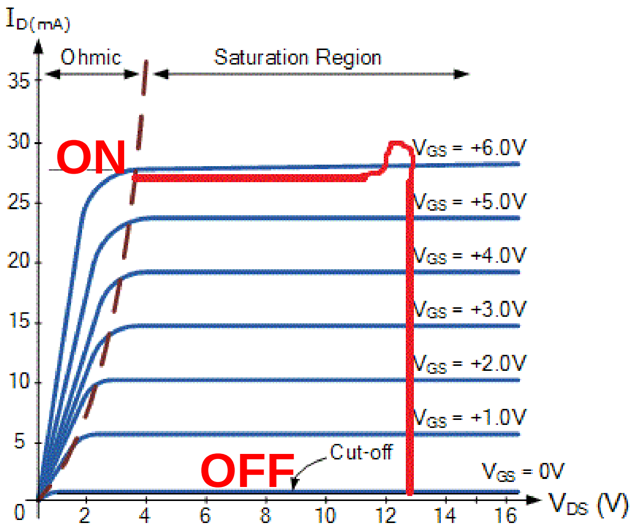
$$C_{rss} = C_{GD} \text{ "Miller Capacitance"}$$

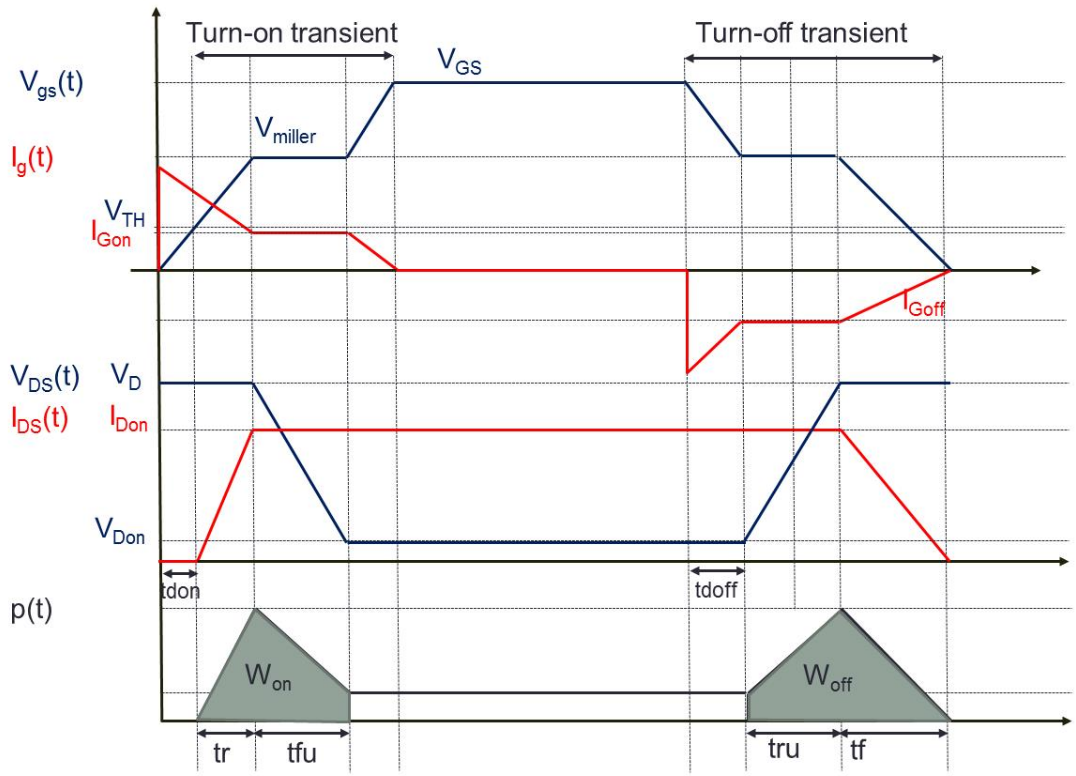
$$C_{oss} = C_{DS} + C_{GD}$$

C_{oss} and C_{rss} VERY nonlinear!!

C_{iss}	Input Capacitance	—	4600	—	pF	V_{GS} = 0V
C_{oss}	Output Capacitance	—	460	—		V_{DS} = 25V
C_{rss}	Reverse Transfer Capacitance	—	91	—		f = 1.0MHz,
C_{oss} eff.	Effective Output Capacitance	—	360	—		V_{GS} = 0V, V_{DS} = 0V to 160V

MOSFET Switching Loss -MOSFET OFF to ON Trajectory





V_D : Main Device Blocking Voltage

V_{Don} : Main Device on-state voltage

V_{TH} : Main Device threshold voltage "voltage at which device starts to conduct"

tdon: The time it takes for the gate tou source voltage to reach the threshold voltage

V_{GS} : Peak applied gate to source voltage

p(t) : Instantaneous power dissipation "$V_{DS}(t)$ x $I_{DS}(t)$"

I_{Don} : Main Switch Peak Current "average inductor current"

"*assume small ripple approximation for main device current when calculating switching loss*"

Calculating Miller and Threshold Voltage

1. Pick two points from curve. Select the drain current values corresponding to vertical lines (less error)
2. Read corresponding gate-to-source voltages on the horizontal axis
3. Calculate miller voltage and threshold voltages and adjust for temperature per the formulas:

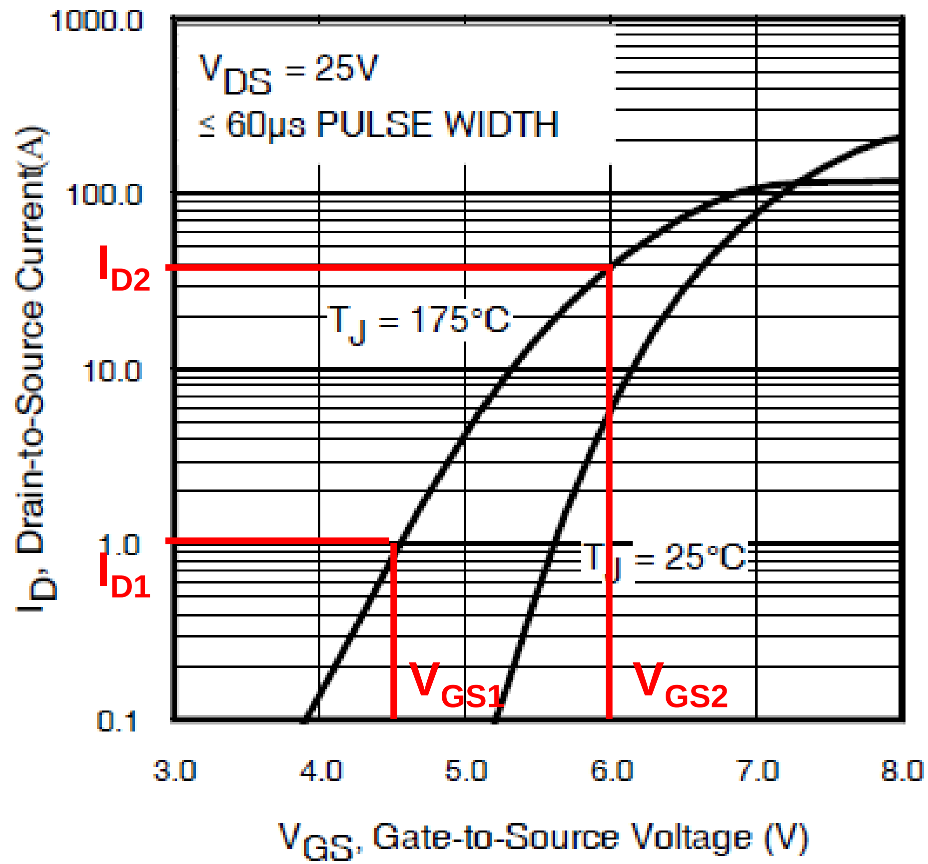
$$I_{D1} = K \cdot \left(V_{GS1} - V_{TH}\right)^2$$

$$I_{D2} = K \cdot \left(V_{GS2} - V_{TH}\right)^2$$

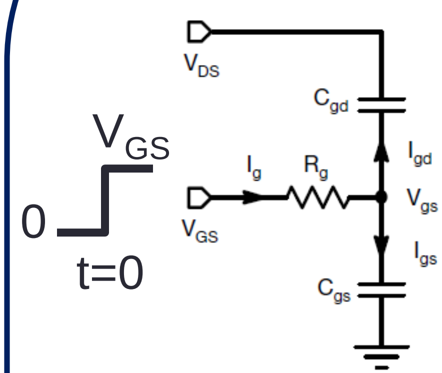
Solve for K and V_{TH}

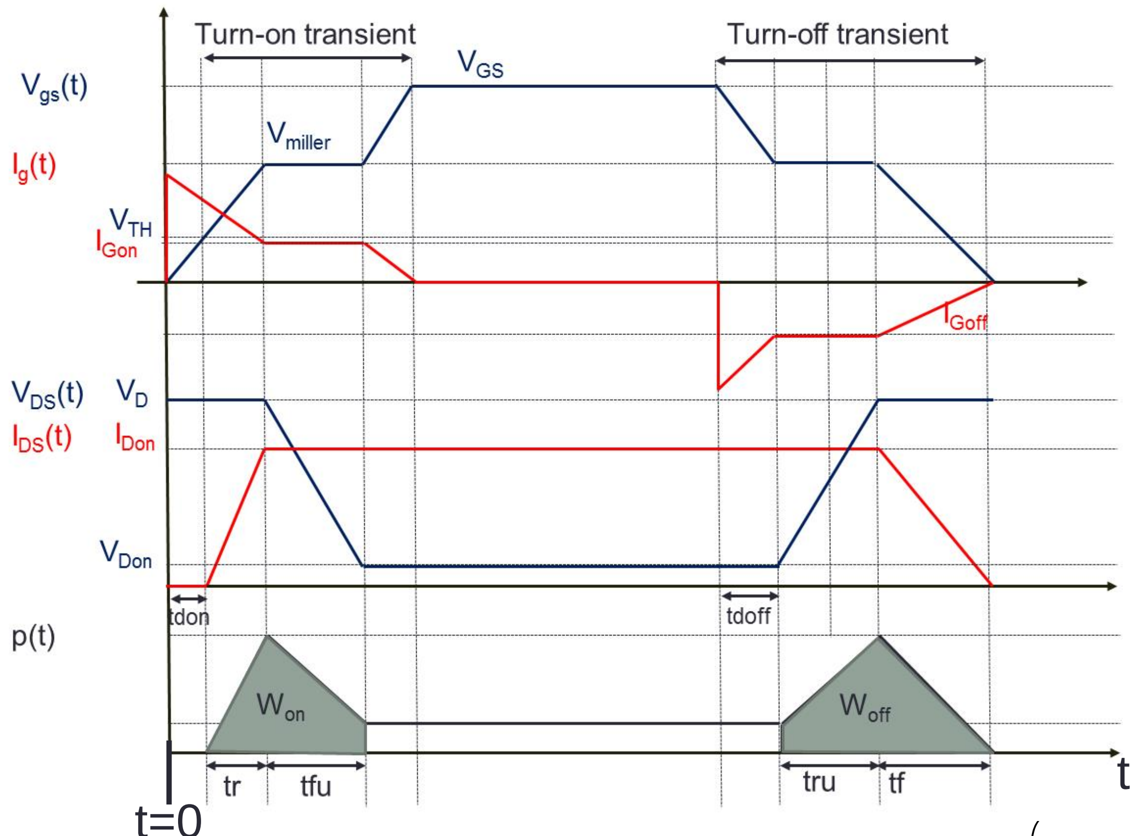
$$V_{miller} = V_{TH} + \sqrt{\frac{I_{load}}{K}}$$

$$\Delta V_{ADJ} = \left(T_j - T_{curve}\right) \cdot T_C$$



MOSFET Switching Loss –Determine Cross-over time





Determine tdon and tr:

$$I_g(t) = \frac{V_{GS} - V_{gs}(t)}{R_g}$$

$$I_g(t) = I_{gs}(t) + I_{gd}(t)$$

$$I_{gs}(t) = \mathrm{C}_{gs}\frac{dV_{gs}(\mathrm{t})}{dt}$$

$$I_{gd}(t) = \mathrm{C}_{gd}\left(V_{DS}\right)\frac{d\left(V_{gs}(\mathrm{t}) - \mathrm{V}_{\mathrm{DS}}(t)\right)}{dt}$$

Since $\mathrm{V}_{\mathrm{DS}}(\mathrm{t})$ is constant during this interval

$$I_{gd}(t) = \mathrm{C}_{gd}\left(V_{DS}\right)\frac{dV_{gs}(\mathrm{t})}{dt}$$

$$I_g(t) = \left(\mathrm{C}_{\mathrm{gs}} + \mathrm{C}_{\mathrm{gd}}\left(V_{DS}\right)\right)\frac{dV_{gs}(t)}{dt}$$

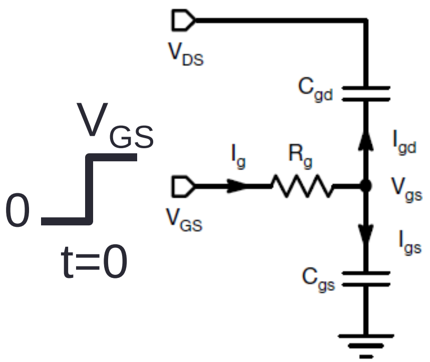
$$I_g(t) = \left(\mathrm{C}_{\mathrm{gs}} + \mathrm{C}_{\mathrm{gd}}\left(V_{DS}\right)\right)\frac{dV_{gs}(t)}{dt}$$

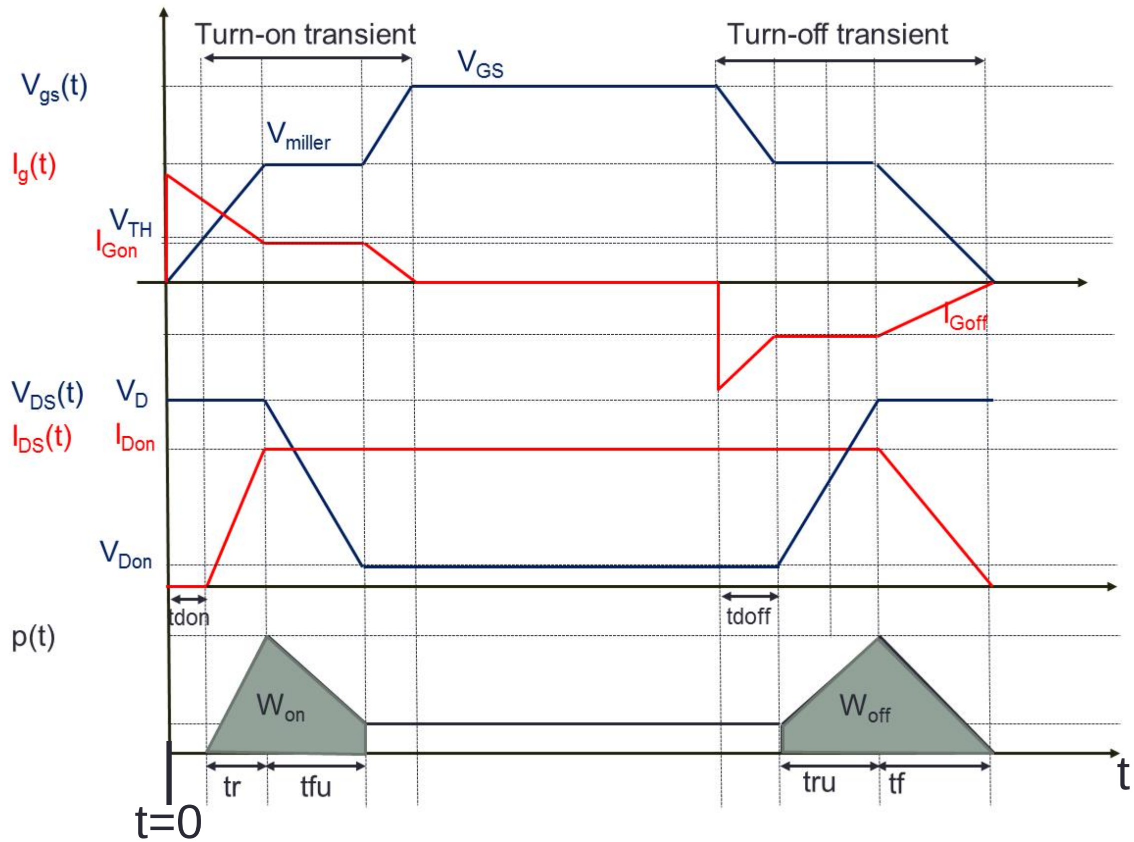
Solving ode

$$V_{gs}(t) = \mathrm{V}_{\mathrm{GS}}\left(1 - e^{-\frac{t}{R_G\, C_{iss}|_{V_{DS}}}}\right)$$

$$t = R_g\, C_{iss}\big|_{V_{DS}} \ln\left(\frac{1}{1 - \frac{V_{gs}(t)}{V_{GS}}}\right)$$

MOSFET Switching Loss –Determine Cross-over time cont.





Determine tdon and tr:

$$tdon = R_g\, C_{iss}\big|_{V_D} \ln\left(\frac{1}{1-\frac{V_{TH}}{V_{GS}}}\right)$$

$$tdon + tr = R_g\, C_{iss}\big|_{V_D} \ln\left(\frac{1}{1-\frac{V_{miller}}{V_{GS}}}\right)$$

$$tr = R_g\, C_{iss}\big|_{V_D} \ln\left(\frac{1}{1-\frac{V_{miller}}{V_{GS}}}\right) - R_g\, C_{iss}\big|_{V_D} \ln\left(\frac{1}{1-\frac{V_{TH}}{V_{GS}}}\right)$$

Similarly for tdoff and tf:

$$tdoff = R_G\, C_{iss}\big|_{V_{Don}} \ln\left(\frac{V_{GS}}{V_{miller}}\right)$$

$$tf = R_G\, C_{iss}\big|_{V_D} \ln\left(\frac{V_{miller}}{V_{TH}}\right)$$

MOSFET Switching Loss –Determine Cross-over time cont.

Determine tfu and recall C_{gs} is a function of V_{DS}:

$$I_g(t) = \frac{V_{GS} - V_{gs}(t)}{R_g} = \frac{V_{GS} - V_{miller}}{R_g} = I_{Gon}$$

$$I_g(t) = \cancel{I_{gs}(t)}^{0} + I_{gd}(t) = \mathrm{C}_{gd}(V_{DS})\frac{d\left(V_{gs}(\mathrm{t}) - \mathrm{V_{DS}}(t)\right)}{dt}$$

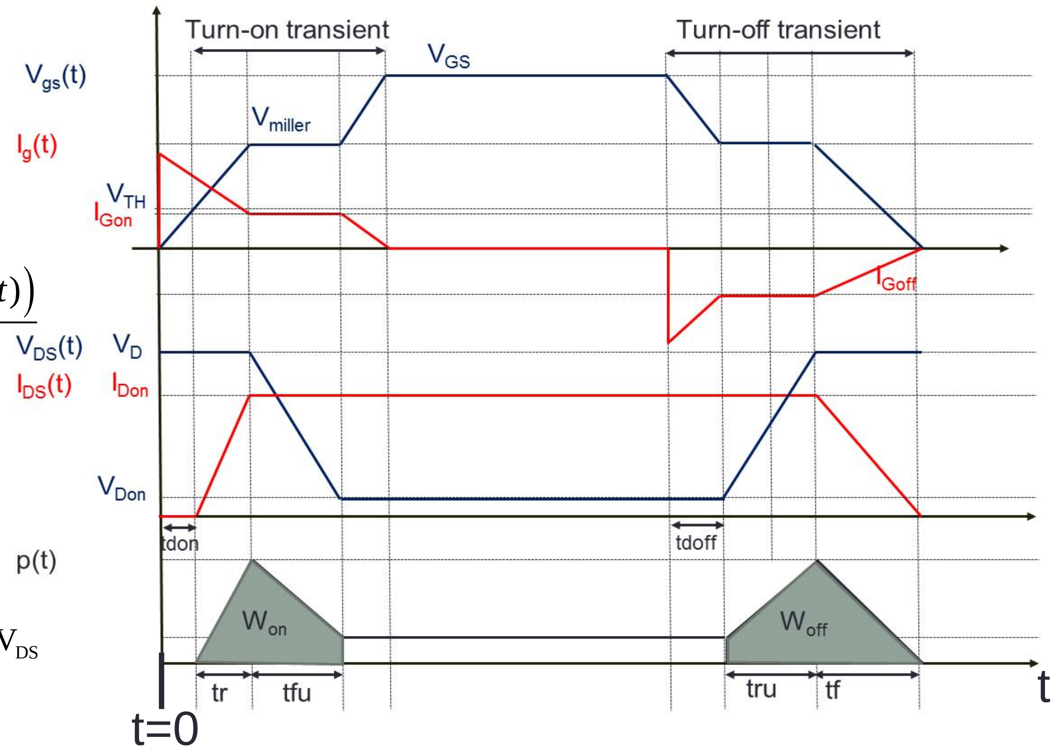
Since $V_{gs}(t)$ is constant during interval

$$\frac{V_{GS} - V_{miller}}{R_g} = -\mathrm{C}_{gd}(V_{DS})\frac{d\,\mathrm{V_{DS}}(t)}{dt}$$

C_{gd} is a function of Vds!!

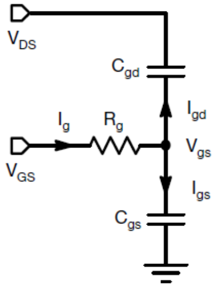
$$\int_{tfu} \frac{V_{GS} - V_{miller}}{R_g}dt = \int_{V_D}^{V_{Don}} -\mathrm{C}_{gd}(V_{DS})d\,\mathrm{V_{DS}} = \int_{V_{Don}}^{V_D} \mathrm{C}_{gd}(V_{DS})d\,\mathrm{V_{DS}}$$

$$\frac{V_{GS} - V_{miller}}{R_g}tfu = \int_{V_{Don}}^{V_D} \mathrm{C}_{gd}(V_{DS})d\,\mathrm{V_{DS}}$$



Similarly for tru:

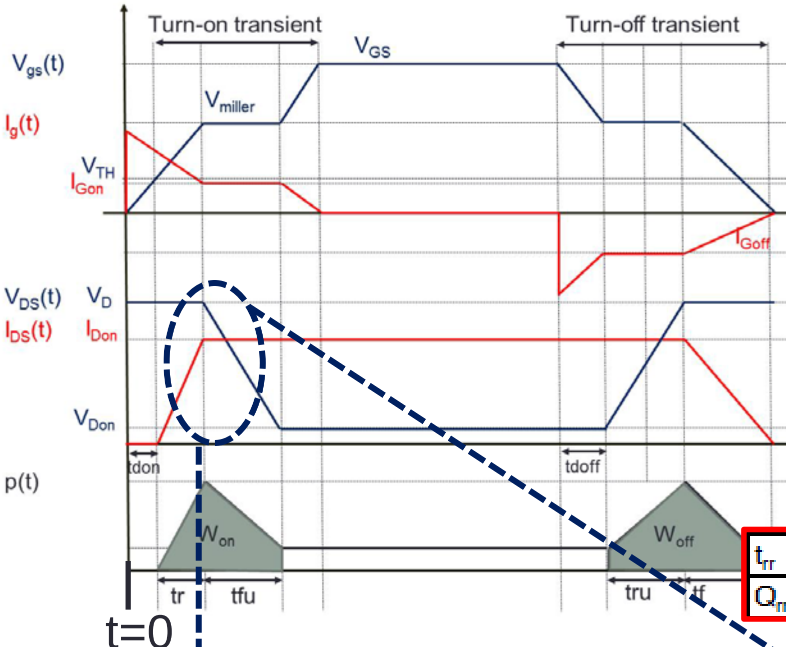
$$tfu = \frac{R_g\int_{V_{Don}}^{V_D} \mathrm{C}_{gd}(V_{DS})d\,\mathrm{V_{DS}}}{V_{GS} - V_{miller}} \qquad tru = \frac{R_g\int_{V_{Don}}^{V_D} \mathrm{C}_{gd}(V_{DS})d\,\mathrm{V_{DS}}}{V_{miller}}$$



Cross-over Switching Energy:

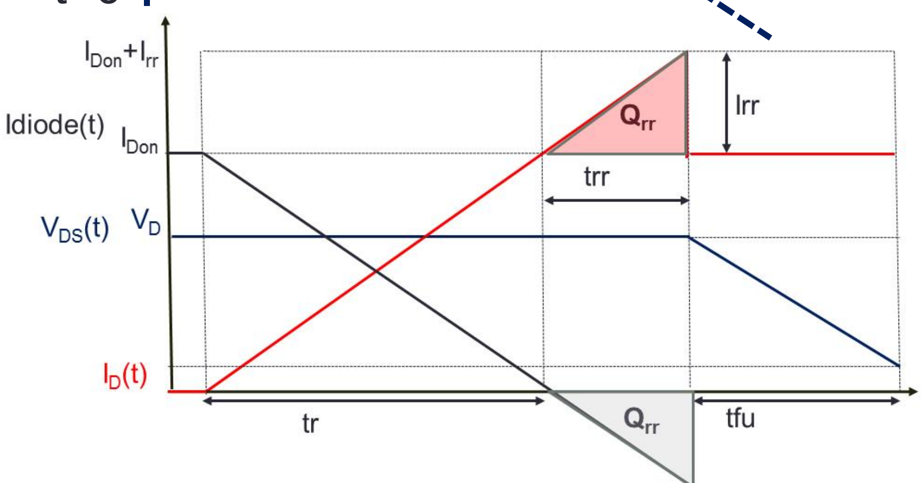
$$\boxed{\begin{aligned} W_{on} &= \frac{1}{2}t_r V_D I_{Don} + \frac{1}{2}t_{fu} V_D I_{Don} \\ W_{off} &= \frac{1}{2}t_{ru} V_D I_{Don} + \frac{1}{2}t_f V_D I_{Don} \end{aligned}}$$

Diode Reverse Recovery



- Reverse Recovery Time (trr) and Recovery Charge (Qrr) from datasheet
- Diode recovery stored charge Qrr flows through transistor during turn-on, inducing additional loss in MOSFET
- Diode does not block voltage until peak reverse recovery current has been reached

t_{rr}	Reverse Recovery Time	—	100	150	ns
Q_{rr}	Reverse Recovery Charge	—	430	640	nC



Reverse Recovery Induced Energy

$$i_{diode}(t) = \frac{dQ}{dt}$$

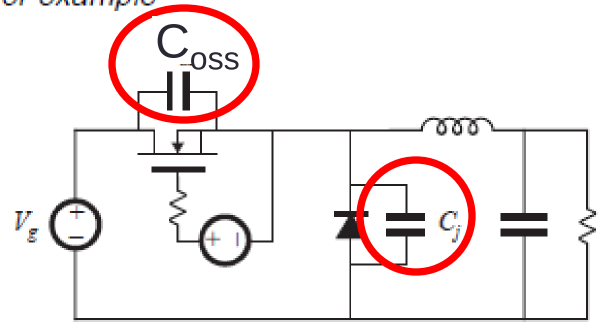
$$\int_{t_{rr}} i_{diode}(t)dt = \int_0^{Q_{rr}} dQ$$

$$\int_{t_{rr}} i_{diode}(t)dt = \frac{1}{2} t_{rr} I_{rr} = Q_{rr} \Rightarrow I_{rr} = \frac{2Q_{rr}}{t_{rr}}$$

$$\boxed{W_{rr} = \frac{1}{2} t_{rr} I_{rr} V_D + V_D I_{Don} t_{rr} = Q_{rr} V_D + V_D I_{Don} t_{rr}}$$

MOSFET Output Capacitance "CV^2 Loss"

Buck converter example



- Capacitances that appear effectively in parallel with switch elements are shorted when the switch turns on. Their stored energy is lost during the switch turn-on transition.

During the switching transition, Coss and Cj are effectiviley in parallel. The energy lost when the MOSFET turns on is:

$$W_c = \frac{1}{2}\left(C_{oss(er)} + C_{j(er)}\right)\left(V_D{}^2 - V_{Don}{}^2\right)$$

Where effective energy related capacitors $C_{oss(er)}, C_{j(er)}$ are linear capacitors with same energy stored at V_D as nonlinear capacitors $C_{oss}(v_{ds}), C_j(v_{ds})$

$$C_{oss(er)} = 2\frac{\int_{V_{Don}}^{V_D} C_{oss}(v_{ds})v_{ds}dv_{ds}}{\left(V_D{}^2 - V_{Don}{}^2\right)}$$

$$C_{j(er)} = 2\frac{\int_{V_{Don}}^{V_D} C_j(v_{ds})v_{ds}dv_{ds}}{\left(V_D{}^2 - V_{Don}{}^2\right)}$$

$$\boxed{W_c = \frac{1}{2}\left(2\frac{\int_{V_{Don}}^{V_D} C_{oss}(v_{ds})v_{ds}dv_{ds}}{\left(V_D{}^2 - V_{Don}{}^2\right)} + 2\frac{\int_{V_{Don}}^{V_D} C_j(v_{ds})v_{ds}dv_{ds}}{\left(V_D{}^2 - V_{Don}{}^2\right)}\right)\left(V_D{}^2 - V_{Don}{}^2\right)}$$

Calculate Total MOSFET Switching Loss

$$p_{sw}(t) = i_{sw}(t) \cdot v_{sw}(t)$$

$$W_{sw} = \int_{T_{sw}} i_{sw}(t) \cdot v_{sw}(t) dt$$

$$p_{sw-avg} = \frac{1}{T_{sw}} W_{sw} = f_{sw} W_{sw}$$

The switching loss is directly proportional to the switching frequency

$$W_{m-sw} = \underbrace{W_{on} + W_{off}}_{\text{crossover}} + \underbrace{W_{rr}}_{\text{diode recovery}} + \underbrace{W_c}_{CV\wedge 2}$$

$$W_{on} = \frac{1}{2} t_r V_D I_{Don} + \frac{1}{2} t_{fu} V_D I_{Don}$$

$$W_{off} = \frac{1}{2} t_{ru} V_D I_{Don} + \frac{1}{2} t_f V_D I_{Don}$$

$$W_{rr} = Q_{rr} V_D + V_D I_{Don} t_{rr}$$

$$W_c = \frac{1}{2} \left(C_{oss(er)} + C_{j(er)} \right) \left(V_D{}^2 - V_{Don}{}^2 \right)$$

$$p_{sw-avg} = W_{m-sw} f_{sw}$$

MOSFET Conduction Loss

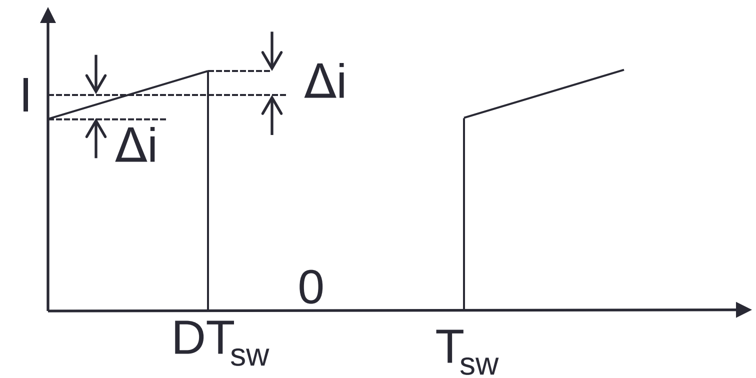
- After MOSFET is fully turned on, it behaves as a resister, given by R_{dson}

$$v_{ds}(t) = i(t) \cdot R_{dson}$$

$$p_c(t) = i(t)^2 \cdot R_{dson}$$

$$p_{c-avg} = \frac{1}{T_{sw}} \left(\int_0^{DT_{sw}} i(t)^2 \cdot R_{dson} dt + \int_{DT_{sw}}^{T_{sw}} 0 dt \right)$$

<u>Typical Switch Current waveform during conduction</u>



$$p_{c-avg} = \frac{1}{T_{sw}} \left(\int_0^{DT_{sw}} \left((I - \Delta i) + \frac{2\Delta i}{DT_{sw}} t \right)^2 \cdot R_{dson} dt + \int_{DT_{sw}}^{T_{sw}} 0 dt \right)$$

$$p_{c-avg} = \frac{1}{3} R_{dson} D \left(3I^2 + \Delta i^2 \right)$$

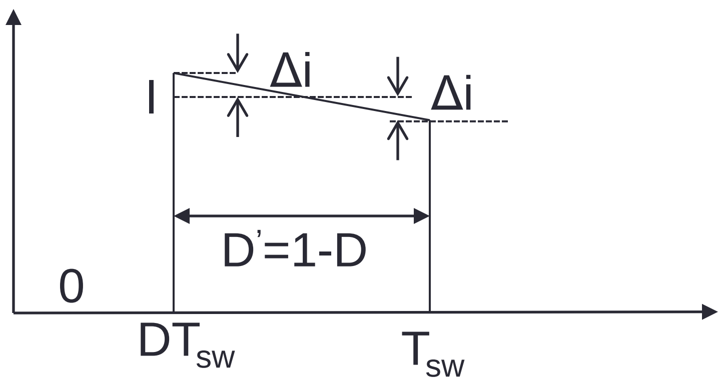
in general:

$$p_{c-avg} = I_{rms}{}^2 R_{dson}$$

can also use simulation to calcualte rms current in switch

Diode Loss – Conduction Loss only

- Diode turns on without cross over loss in most cases
- Majority loss in diode comes from conduction loss
- Reverse recovery loss is induced in the adjacent switch



$$v_{diode}(t) = v_{on}$$

$$p_{cd}(t) = i(t) \cdot v_{on}$$

$$p_{cd-avg} = \frac{1}{T_{sw}}\left(\int_{0}^{DT_{sw}} 0dt + \int_{DT_{sw}}^{T_{sw}} i(t) \cdot v_{on} dt \right)$$

$$p_{cd-avg} = \frac{1}{T_{sw}}\left(\int_{0}^{DT_{sw}} 0dt + \int_{DT_{sw}}^{T_{sw}} \left(I + \Delta i - \left(\frac{2\Delta i}{D'T_{sw}} \right)\left(t - DT_{sw} \right) \right) \cdot v_{on} dt \right)$$

$$p_{cd-avg} = \left(1 - D\right) I v_{on}$$

Total Loss Summary

- MOSFET Total loss
  - Switching
  - Conducting
- Diode Total loss
  - Conducting
- If using MOSFET in replace of free-wheel diode
  - Conducting (I_{rms}^2)R_{dson}

$$p_{mloss} = p_{sw-avg} + p_{c-avg}$$

$$p_{dloss} = \cancelto{0}{p_{sw-avg}} + p_{cd-avg}$$

Converter Efficiency

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} I_{out}}{V_{out} I_{out} + P_{loss}}$$

$$P_{loss} = P_{sw-cond} + P_{sw-switch} + P_{ind-core} + P_{ind-copper}$$

$P_{sw-switch}$: Switching loss of device = p_{sw-avg}

$\mathrm{P}_{\text{sw-cond}}$: Conduction loss of device = $\mathrm{p}_{c-avg} + \mathrm{p}_{cd-avg}$

$P_{ind-core}$: Inductor core loss

$P_{ind-copper}$: Inductor copper "conduction" loss

Inductor Loss

- Inductor Copper “conduction” loss

$$P_{ind-copper} = I^2{}_{ind-rms} \times R_{ind-esr}$$ (esr-Equivalent series resistance)

$$I_{ind-rms} = I\sqrt{1+\frac{1}{3}\left(\frac{\Delta i}{I}\right)^2}$$ "Appendix A of Erickson Fig. A.2"

Assume:

$$P_{ind-core} = P_{ind-copper}$$