Introduction to Power Electronics

ECEN 2060

Spring 2008

References:

- ECEN4797/5797 Intro to Power Electronics
  ece.colorado.edu/~ecen5797
- Textbook: R.W.Erickson, D.Maksimovic, *Fundamentals of Power Electronics*, 2nd ed., Springer 2000,
  http://ece.colorado.edu/~pwrelect/book/SecEd.html

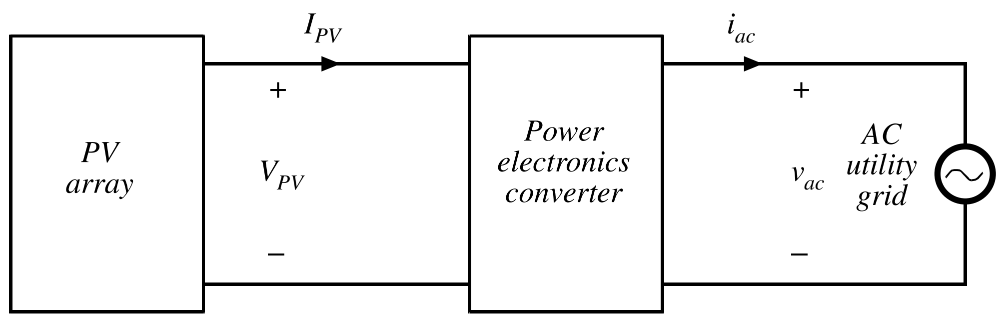
Example: Grid-Connected PV System

One possible grid-connected PV system architecture

DC input

$$V_{PV},\ I_{PV}$$

$$P_{PV} = V_{PV} I_{PV}$$



AC output

$$v_{ac}(t) = \sqrt{2} V_{RMS} \sin(\omega t)$$

$$i_{ac}(t) = \sqrt{2} I_{RMS} \sin(\omega t)$$

$$P_{ac} = V_{RMS} I_{RMS}$$

$$p_{ac}(t) = v_{ac} i_{ac} = V_{RMS} I_{RMS} \left(1 - \cos(2\omega t)\right)$$

Functions of the power electronics converter

- Operate PV array at the maximum power point (MPP) under all conditions
- Generate AC output current in phase with the AC utility grid voltage
- Achieve power conversion efficiency close to 100%

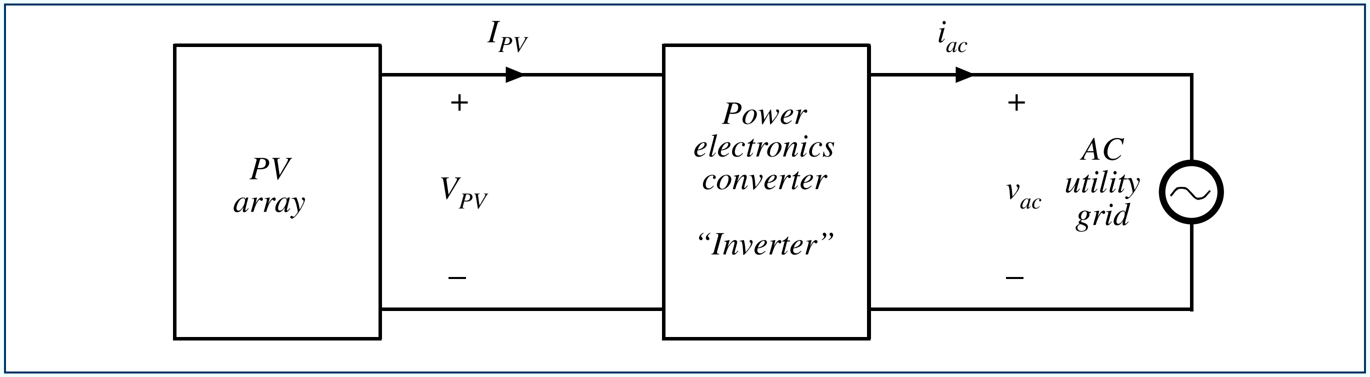
$$\eta_{converter} = \frac{P_{ac}}{P_{PV}} = \frac{V_{RMS} I_{RMS}}{V_{PV} I_{PV}}$$

- Provide energy storage to balance the difference between P_{PV} and $p_{ac}(t)$

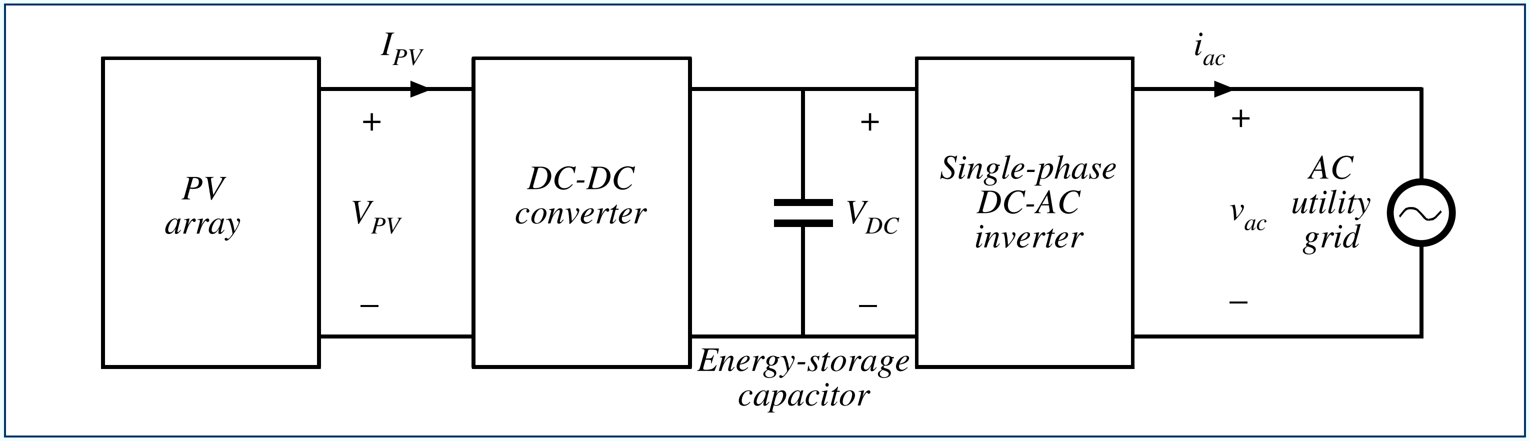
Desirable features

- Minimum weight, size, cost
- High reliability

Power electronics converter

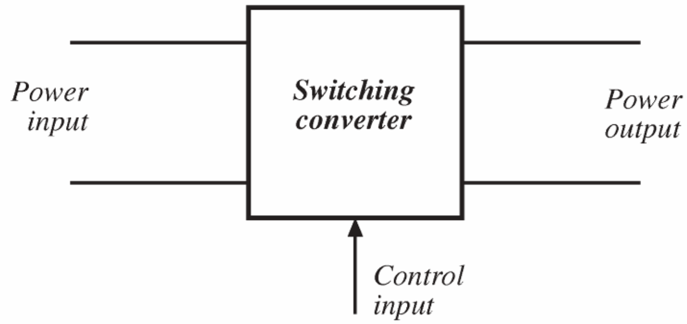


One possible realization:



Class objectives: introduction to circuits and control of a DC-DC converter and a single-phase DC-AC inverter

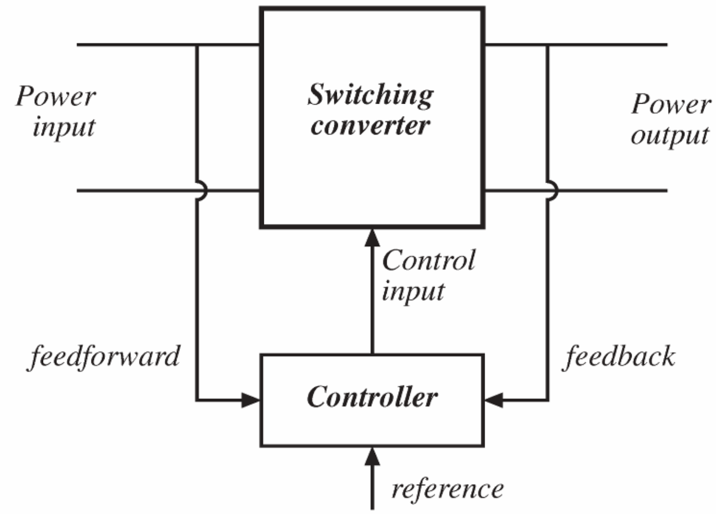
Introduction to electronic power conversion



Dc-dc conversion:	Change and control voltage magnitude
Ac-dc rectification:	Possibly control dc voltage, ac current
Dc-ac inversion:	Produce sinusoid of controllable magnitude and frequency
Ac-ac cycloconversion:	Change and control voltage magnitude and frequency

Four types of power electronics converters

- Control is invariably required
- In the PV system, for example:
  - Control input voltage of the DC-DC input voltage to operate PV at MPP
  - Control shape of the DC-AC output current to follow a sinusoidal reference
  - Control current amplitude to balance the input and output power



High efficiency is essential

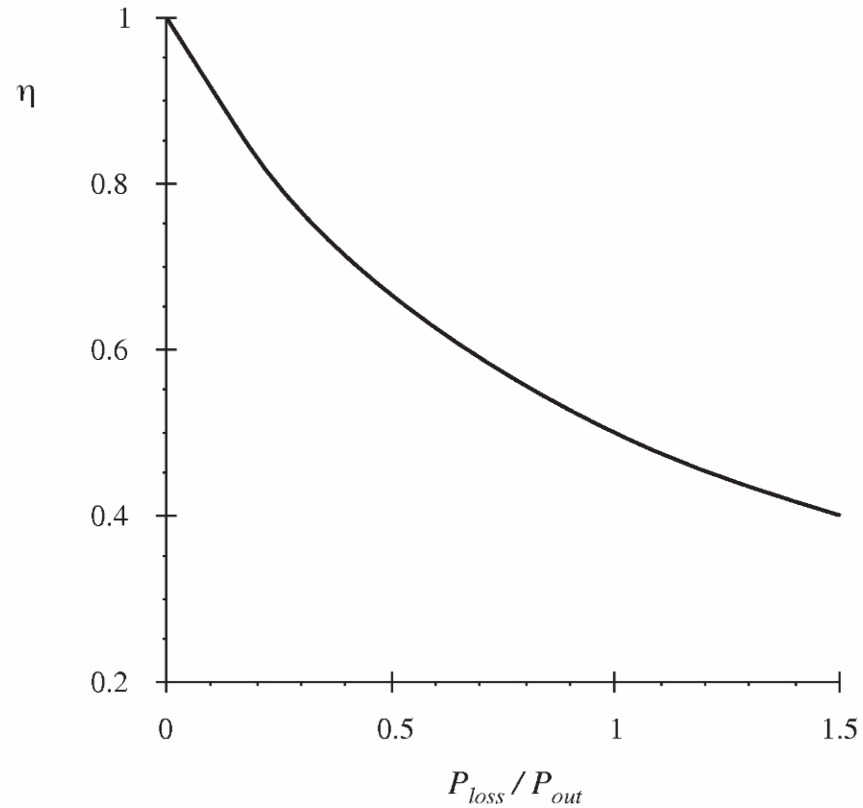
$$\eta = \frac{P_{out}}{P_{in}}$$

$$P_{loss} = P_{in} - P_{out} = P_{out}\left(\frac{1}{\eta} - 1\right)$$

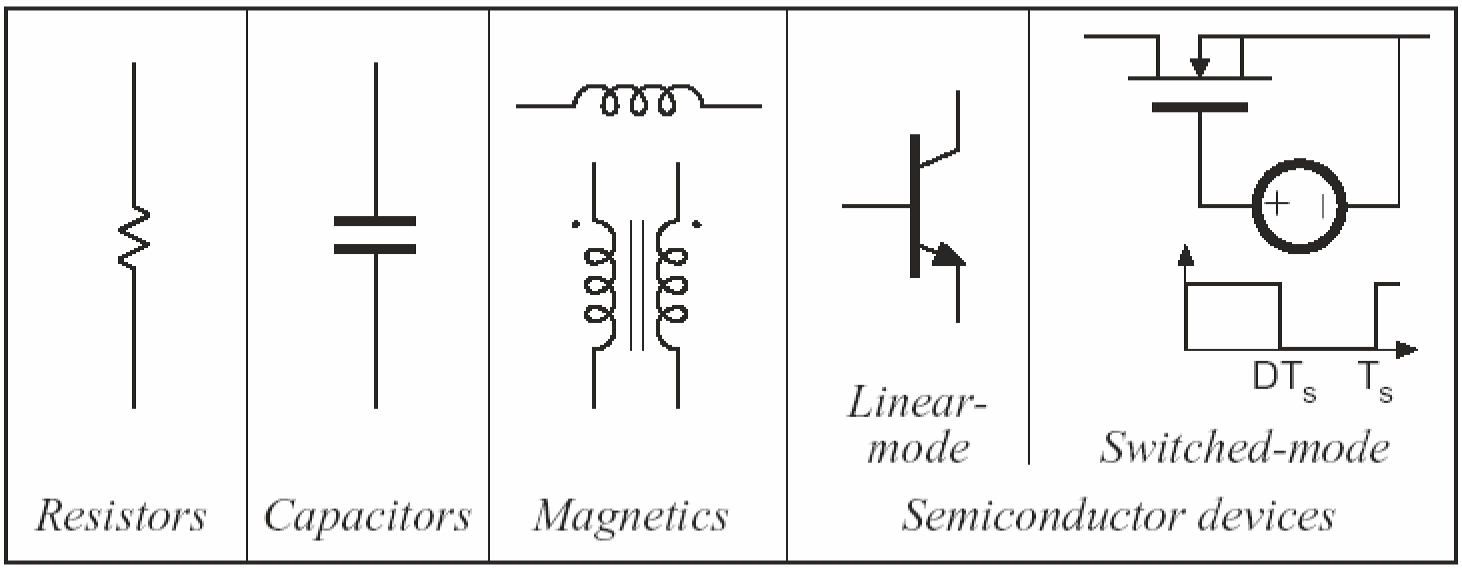
High efficiency leads to low power loss within converter

Small size and reliable operation is then feasible

Efficiency is a good measure of converter performance



Circuit components for efficient electronic power conversion ?



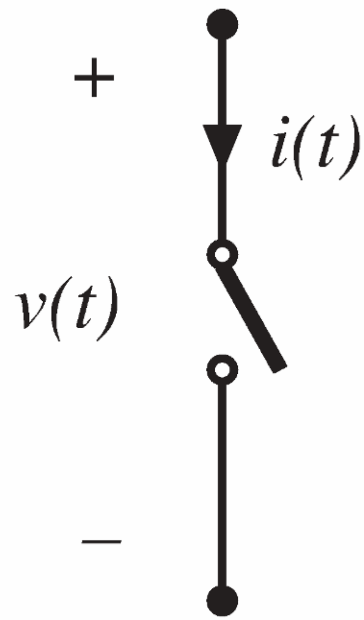
Ideal switch

Switch closed: $v(t) = 0$

Switch open: $i(t) = 0$

In either event: $p(t) = v(t)\, i(t) = 0$

Ideal switch consumes zero power



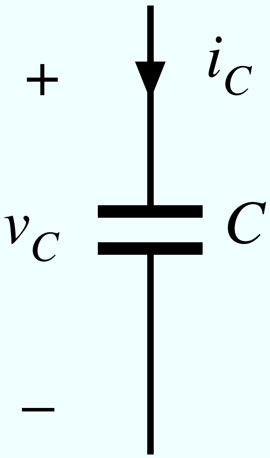
Power semiconductor devices (e.g. MOSFETs, diodes) operate as near-ideal power switches:

- When a power switch is ON, the voltage drop across it is relatively small
- When a power switch is OFF, the switch current is very close to zero

Capacitor

$$i_C = C\frac{dv_C}{dt}$$

$$p_C(t) = v_C(t)i_C(t)$$



For periodic $v_C(t)$, $i_C(t)$:

No losses (average capacitor power = 0)

$$P_C = \frac{1}{T}\int_0^T p_C(t)dt = \frac{C}{T}\int_{v_C(0)}^{v_C(T)} v_C(t)dv_C = \frac{C}{2T}\left(v_C^2(T) - v_C^2(0)\right) = 0$$

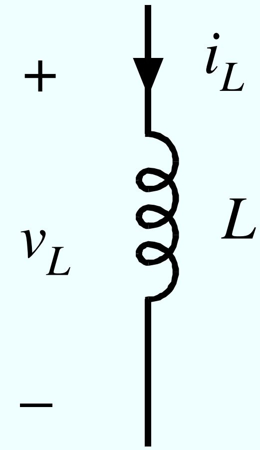
Capacitor charge balance (average capacitor current = 0)

$$I_C = \frac{1}{T}\int_0^T i_C(t)dt = \frac{C}{T}\int_{v_C(0)}^{v_C(T)} dv_C = \frac{C}{T}\left(v_C(T) - v_C(0)\right) = 0$$

Inductor

$$v_L = L\frac{di_L}{dt}$$

$$p_L(t) = v_L(t) i_L(t)$$



For periodic $v_L(t)$, $i_L(t)$:

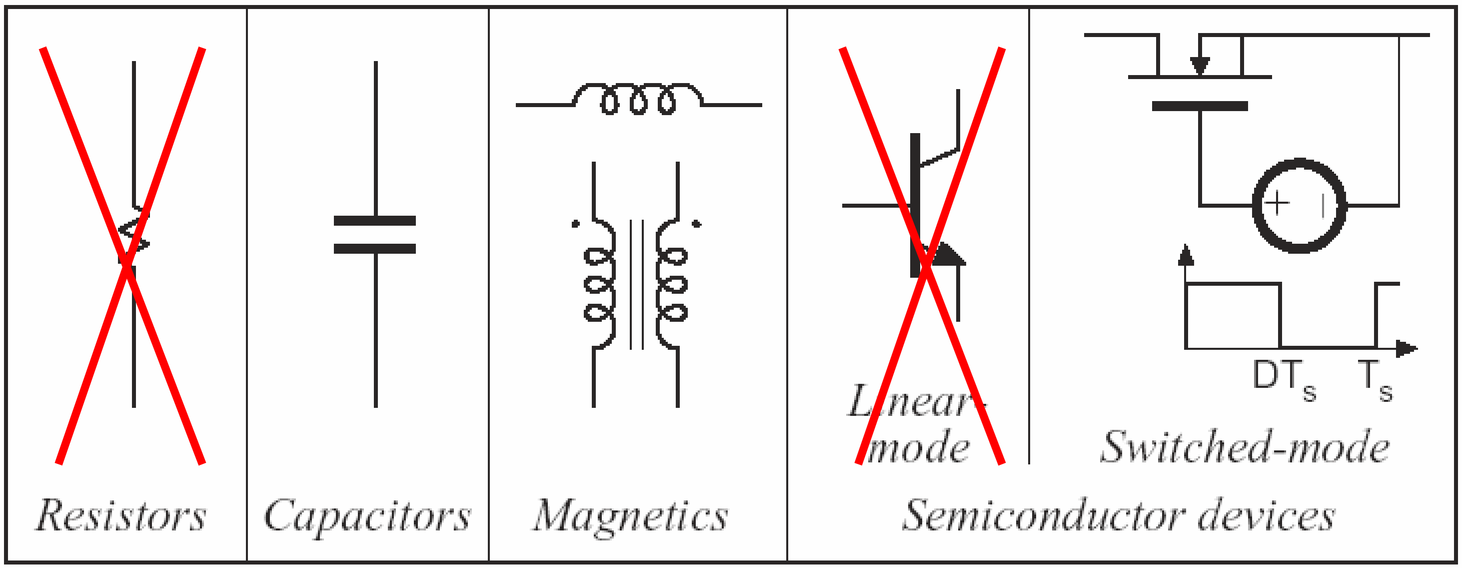
No losses (average inductor power = 0)

$$P_L = \frac{1}{T}\int_0^T p_L(t)dt = \frac{L}{T}\int_{i_L(0)}^{i_L(T)} i_L(t)di_L = \frac{L}{2T}\left(i_L^2(T) - i_L^2(0)\right) = 0$$

Inductor volt-second balance (average inductor voltage = 0)

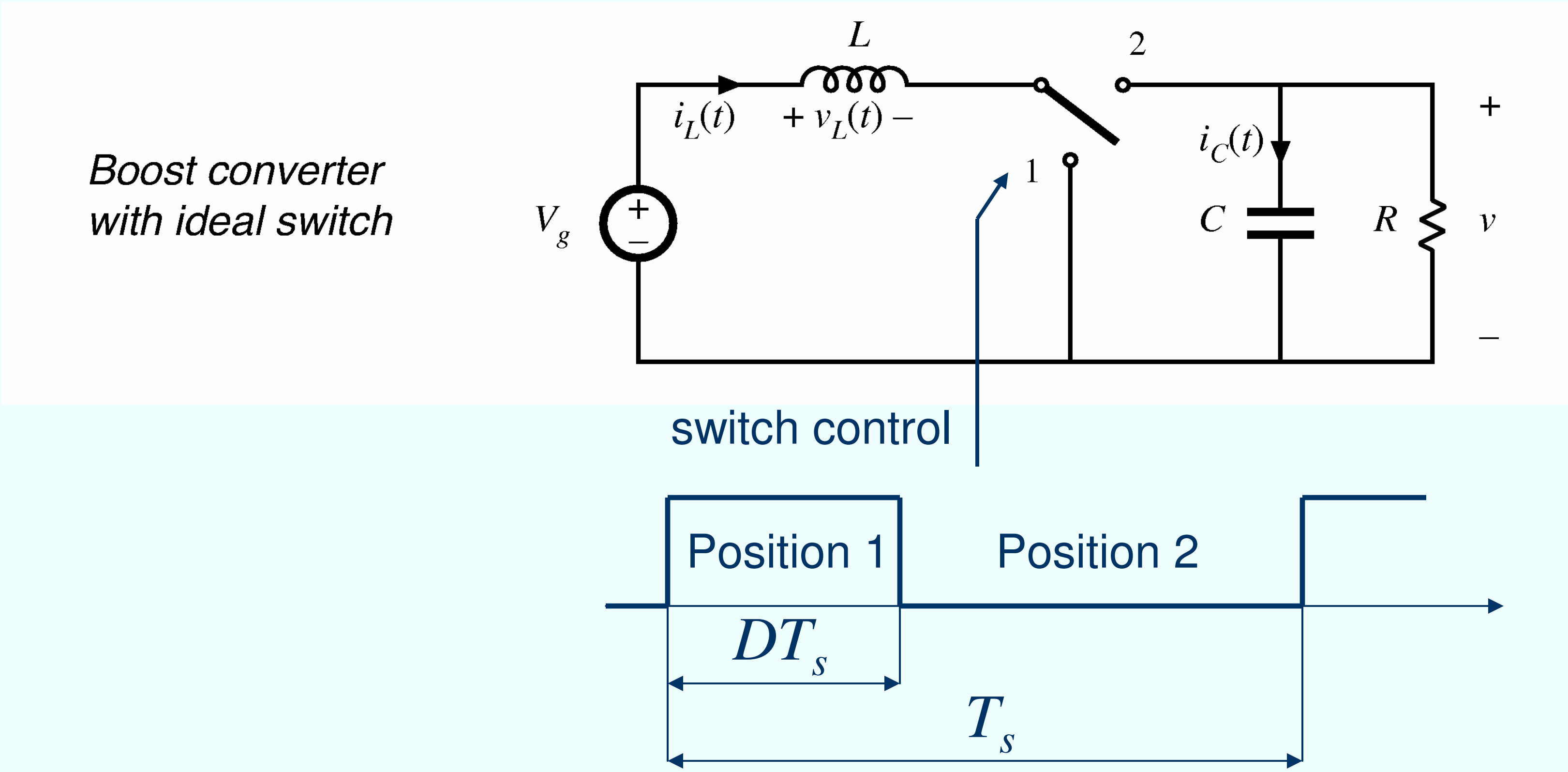
$$V_L = \frac{1}{T}\int_0^T v_L(t)dt = \frac{L}{T}\int_{i_L(0)}^{i_L(T)} di_L = \frac{L}{T}\left(i_L(T) - i_L(0)\right) = 0$$

Circuit components for efficient electronic power conversion



Power electronics converters are circuits consisting of semiconductor devices operated as (near-ideal) switches, capacitors and magnetic components (inductors, transformers)

Boost (step-up) DC-DC converter



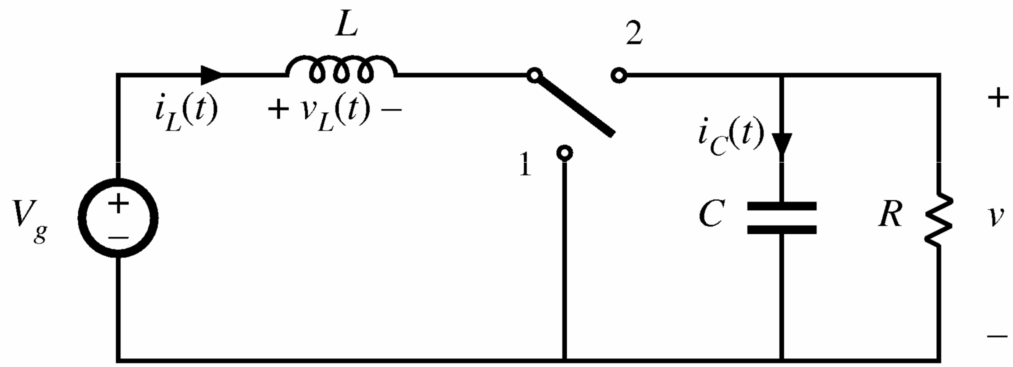
T_s = switching period

$f_s = 1/T_s$ = switching frequency

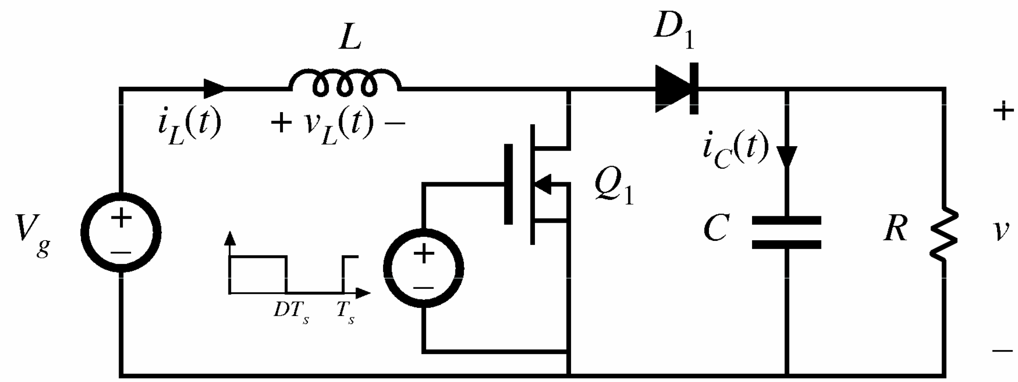
D = switch duty ratio (or duty cycle), $0 \leq D \leq 1$

Boost converter circuit

Boost converter with ideal switch



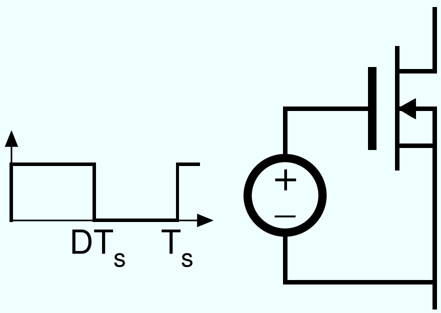
Realization using power MOSFET and diode



Power MOSFET and diode operate as near-ideal switches

Power MOSFETs and diodes

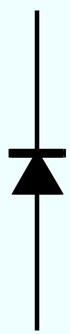
Characteristics of several commercial power MOSFETs



Part number	Rated max voltage	Rated avg current	R_{on}	Q_g (typical)
IRFZ48	60V	50A	0.018Ω	110nC
IRF510	100V	5.6A	0.54Ω	8.3nC
IRF540	100V	28A	0.077Ω	72nC
APT10M25BNR	100V	75A	0.025Ω	171nC
IRF740	400V	10A	0.55Ω	63nC
MTM15N40E	400V	15A	0.3Ω	110nC
APT5025BN	500V	23A	0.25Ω	83nC
APT1001RBNR	1000V	11A	1.0Ω	150nC

Low on-resistance implies low conduction losses

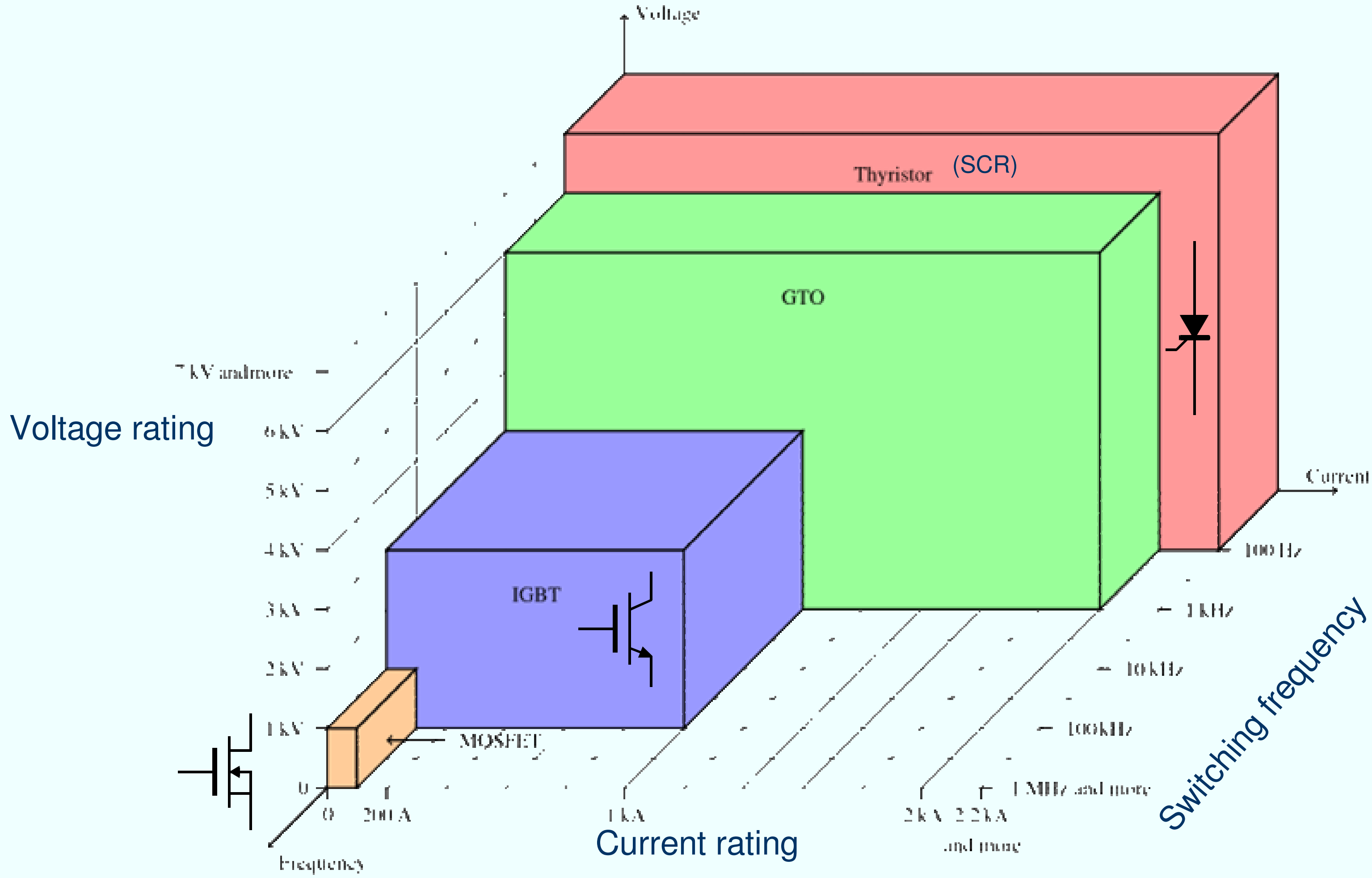
Fast switching enables high switching frequencies, e.g. 100's of kHz to MHz



Part number	Rated max voltage	Rated avg current	V_F (typical)	t_r (max)
Ultra-fast recovery rectifiers				
MUR815	150V	8A	0.975V	35ns
MUR1560	600V	15A	1.2V	60ns
RHRU100120	1200V	100A	2.6V	60ns
Schottky rectifiers				
MBR6030L	30V	60A	0.48V	
444CNQ045	45V	440A	0.69V	
30CPQ150	150V	30A	1.19V	

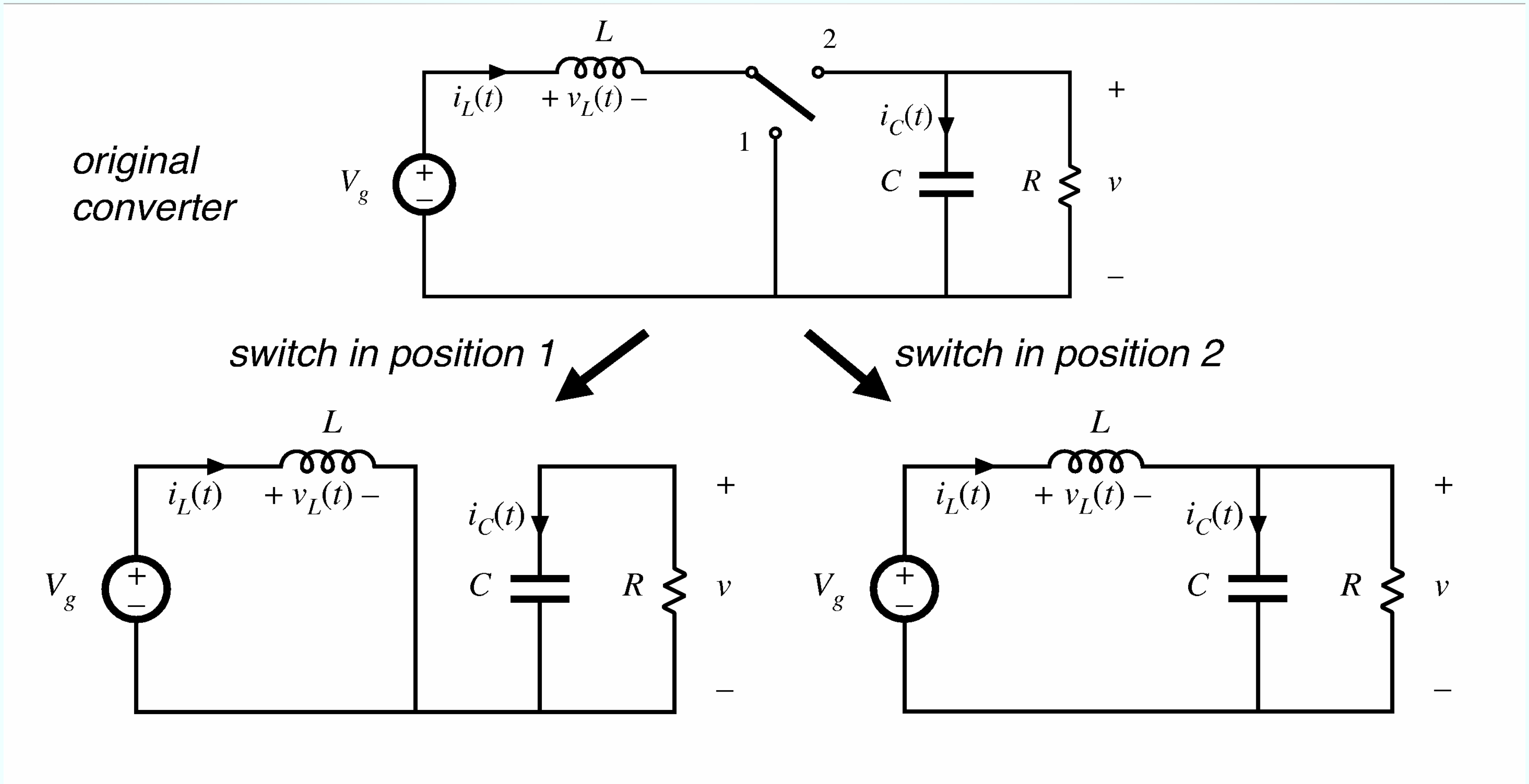
Characteristics of several commercial switching power diodes

Voltage, current and frequency ratings of power semiconductor devices



MOSFET: Metal Oxide Semiconductor Field Effect Transistor
IGBT: Insulated Gate Bipolar Transistor
SCR (or Thyristor): Silicon Controlled Rectifier
GTO: Gate Turn Off thyristor

Boost converter analysis



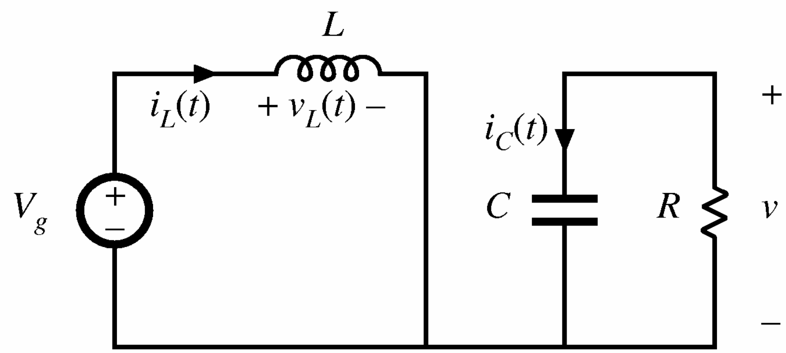
Position 1

Inductor voltage and capacitor current

$$v_L = V_g$$
$$i_C = -v / R$$

Small ripple approximation:

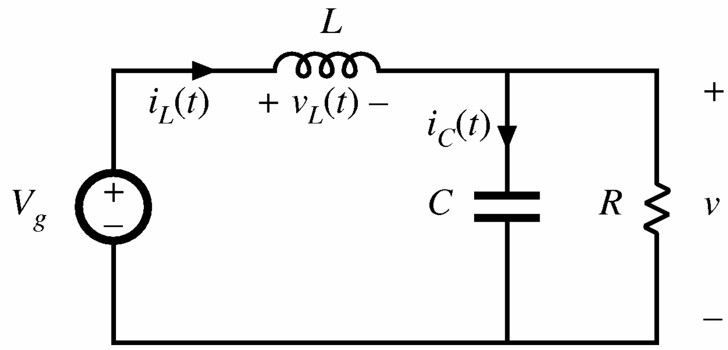
$$v_L = V_g$$
$$i_C = -V / R$$



Position 2

Inductor voltage and capacitor current

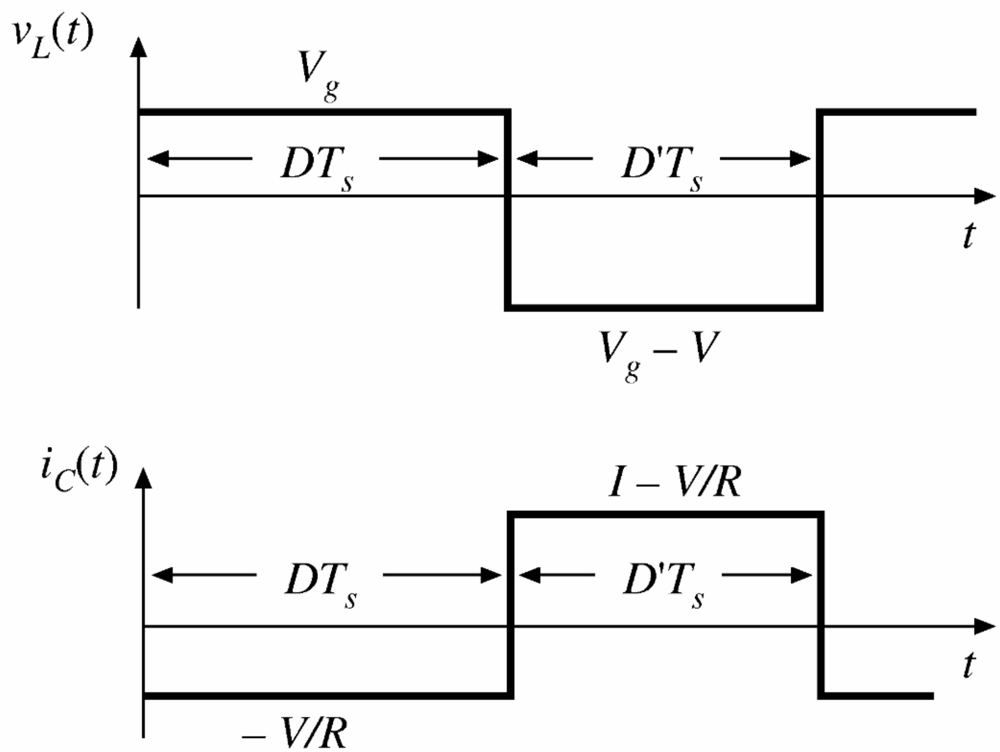
$$v_L = V_g - v$$
$$i_C = i_L - v / R$$



Small ripple approximation:

$$v_L = V_g - V$$
$$i_C = I - V / R$$

Inductor voltage and capacitor current waveforms

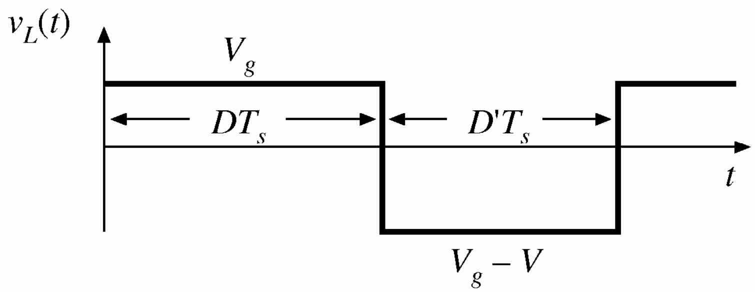


D' = 1-D

Periodic steady-state operation

- Inductor volt-second balance: average inductor voltage = 0
- Capacitor charge balance: average capacitor current = 0

Inductor volt-second balance



Net volt-seconds applied to inductor over one switching period:

$$\int_0^{T_s} v_L(t)\, dt = (V_g)\, DT_s + (V_g - V)\, D'T_s$$

Equate to zero and collect terms:

$$V_g\,(D + D') - V\, D' = 0$$

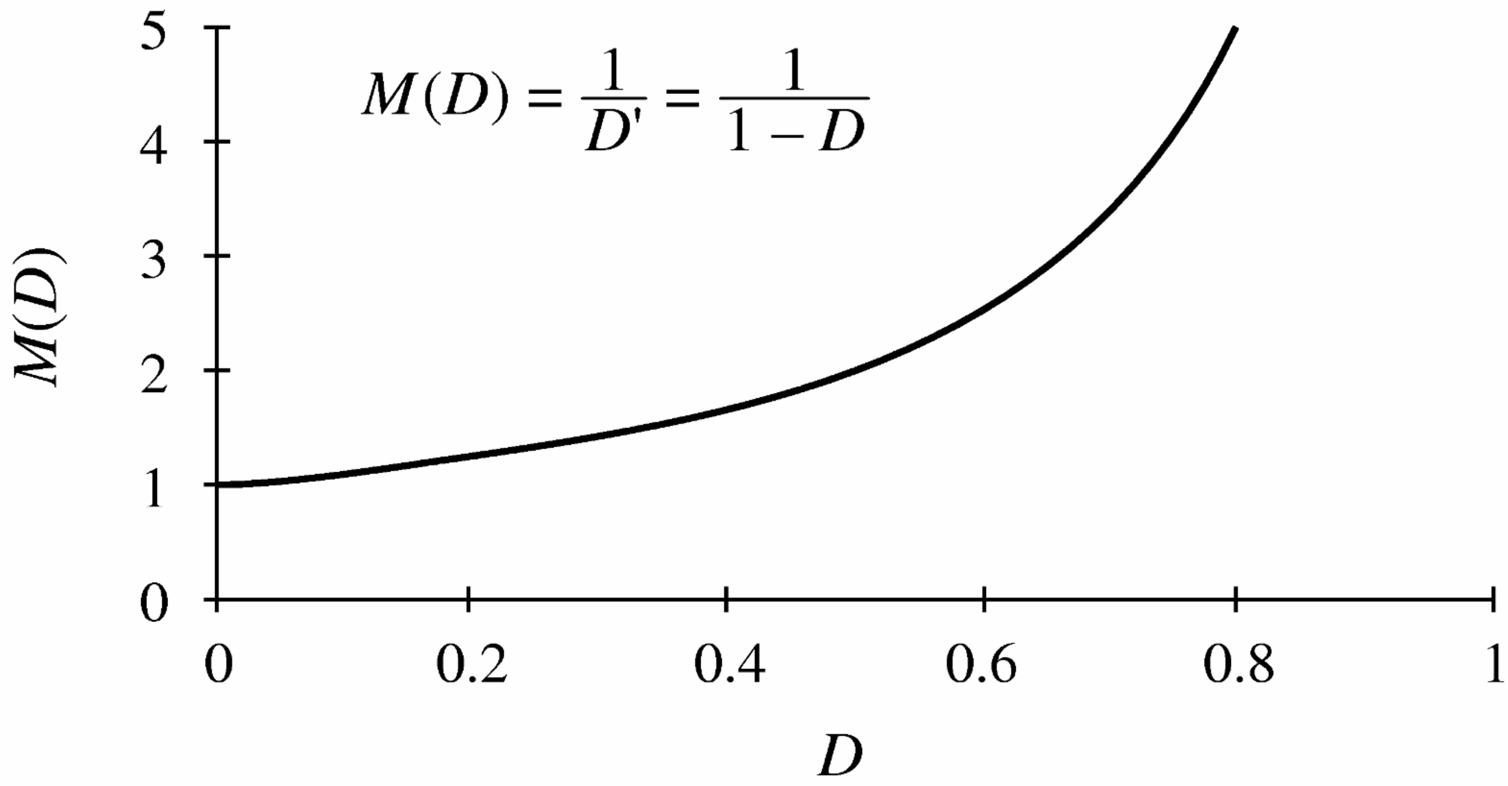
Solve for V:

$$V = \frac{V_g}{D'}$$

The voltage conversion ratio is therefore

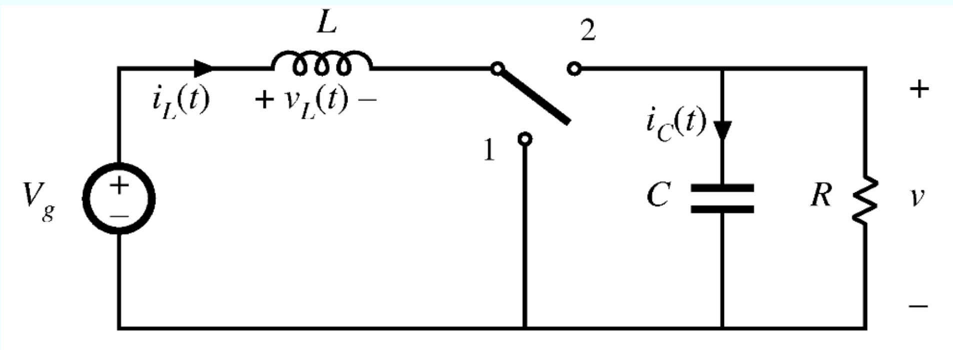
$$M(D) = \frac{V}{V_g} = \frac{1}{D'} = \frac{1}{1 - D}$$

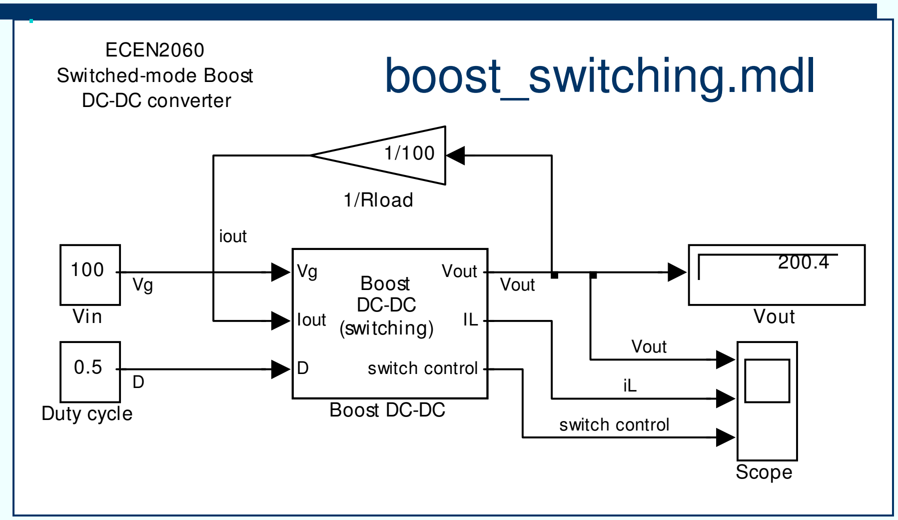
Boost DC voltage conversion ratio $M = V_{out}/V_g$



Boost DC-DC converter steps-up a DC input voltage by a ratio M which is electronically adjustable by changing the switch duty ratio D

Simulink model





Input voltage $V_g = 100$ V

Inductance $L = 200$ µH

Capacitance $C = 10$ µF

Load resistance $R = 100$ Ω

Switch duty cycle $D = 0.5$

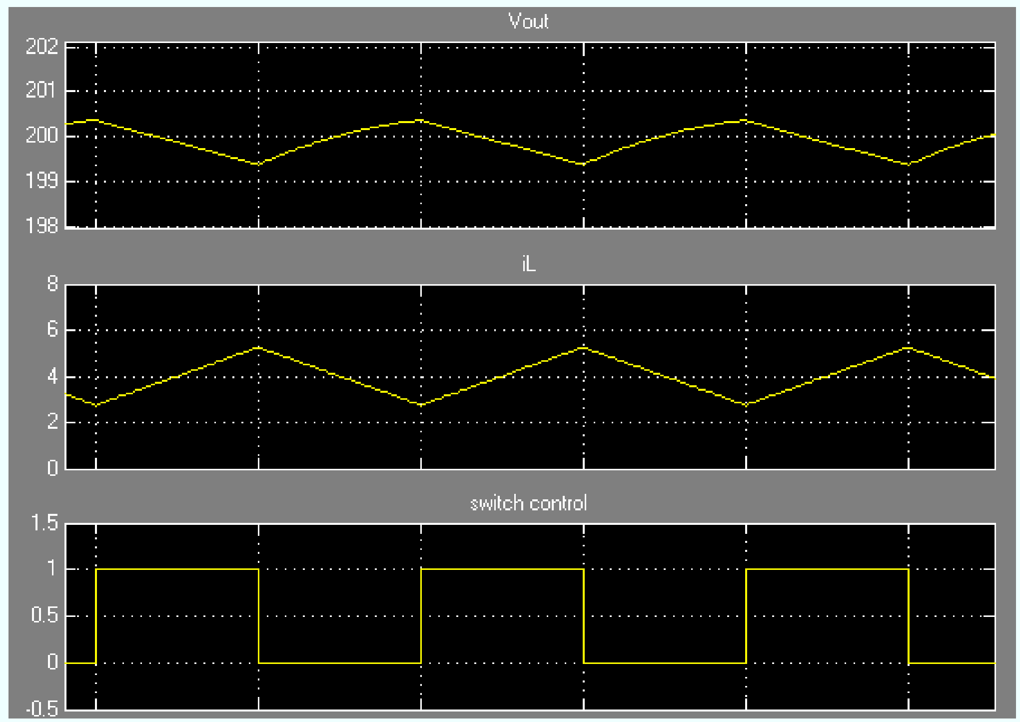
Output voltage $V_{out} = 200$ V

Input current $I_g = I_L = 4$ A

Power $P = 400$ W

Switching frequency $f_s = 100$ kHz

Switching period $T_s = 10$ µs



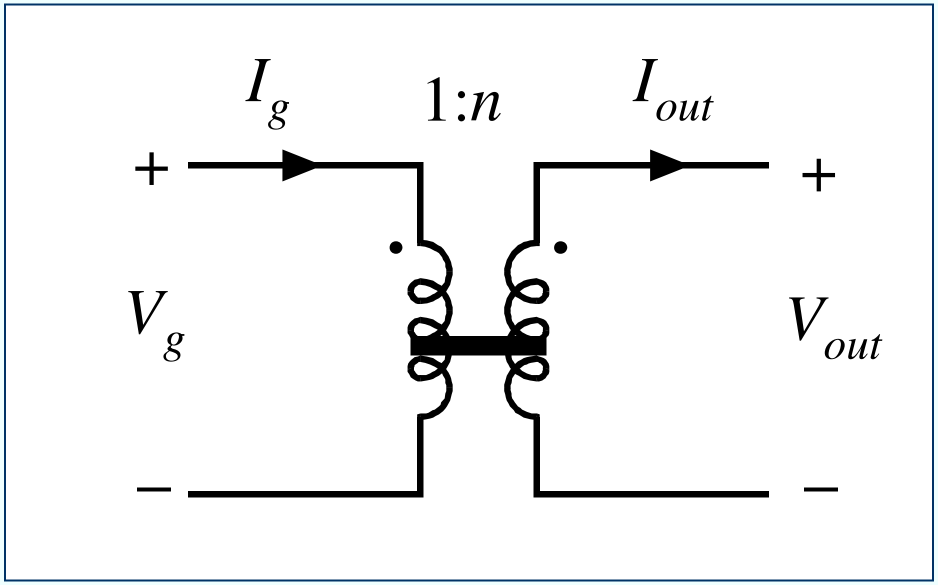
Averaged (DC) model

No losses:

$$V_{out} = \frac{1}{1-D} V_g \qquad I_g = \frac{1}{1-D} I_{out}$$

$$V_g I_g = V_{out} I_{out}$$

Ideal boost DC-DC converter works as an *ideal DC transformer with an electronically adjustable step-up ratio*



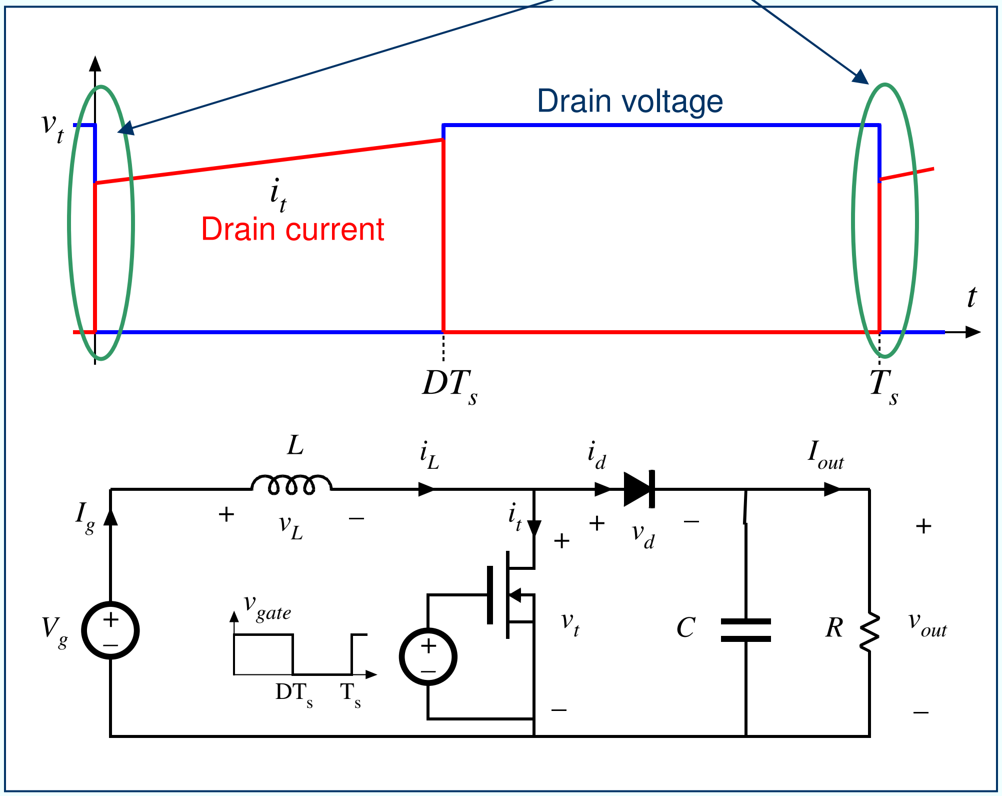
$$n = M(D) = \frac{1}{1-D}$$

Modeling of losses

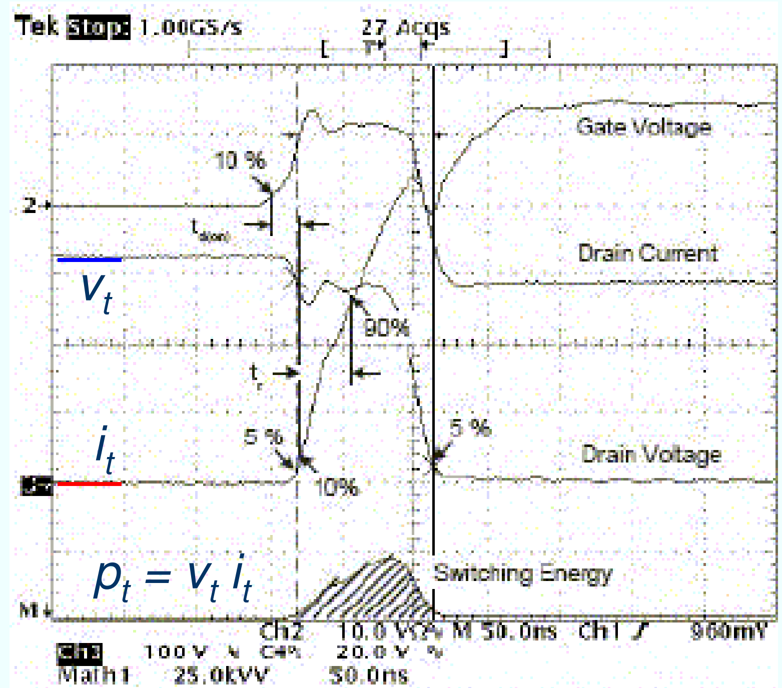
- Losses in switched-mode power converters:
  - Conduction losses, due to voltage drops across inductor winding resistance, and across power semiconductor switches when ON
    - Conduction losses depend strongly on the output power
  - Switching losses, due to energy lost during ON/OFF transitions
    - Switching losses are not strongly dependent on output power; a portion of switching loss remains even at zero output power
    - Switching losses are proportional to the switching frequency
  - Other losses, including:
    - Losses in magnetic cores
    - Power needed to operate control circuitry

Switching waveforms and switching losses

MOSFET turn-on transition



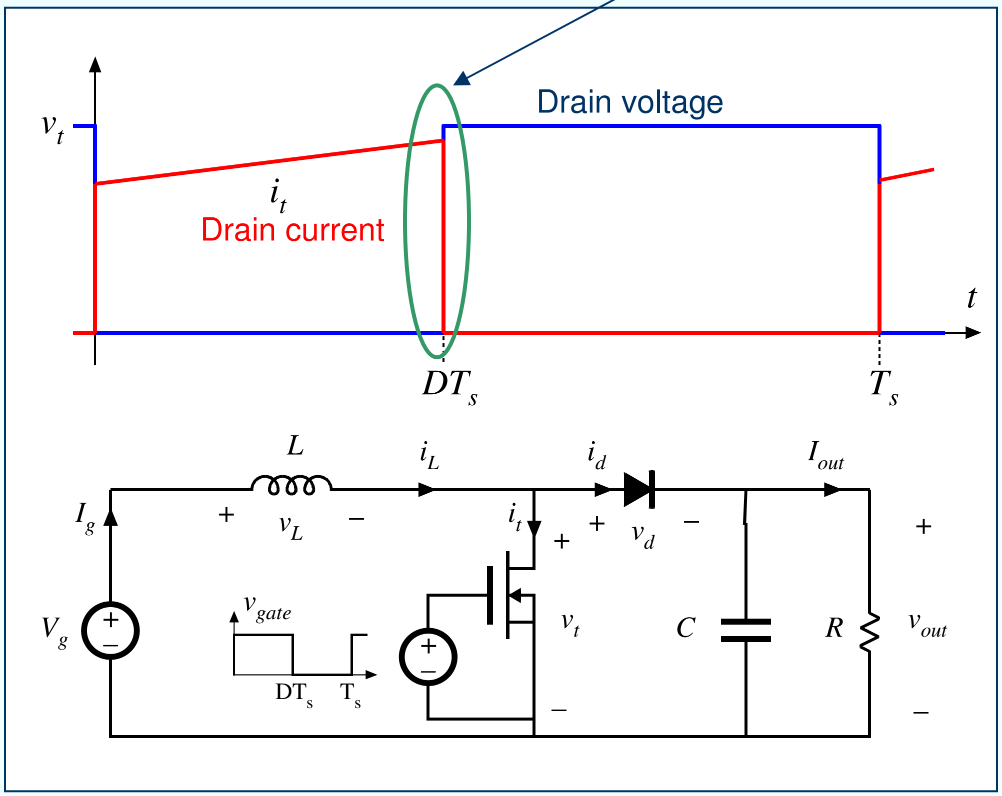
zoom-in



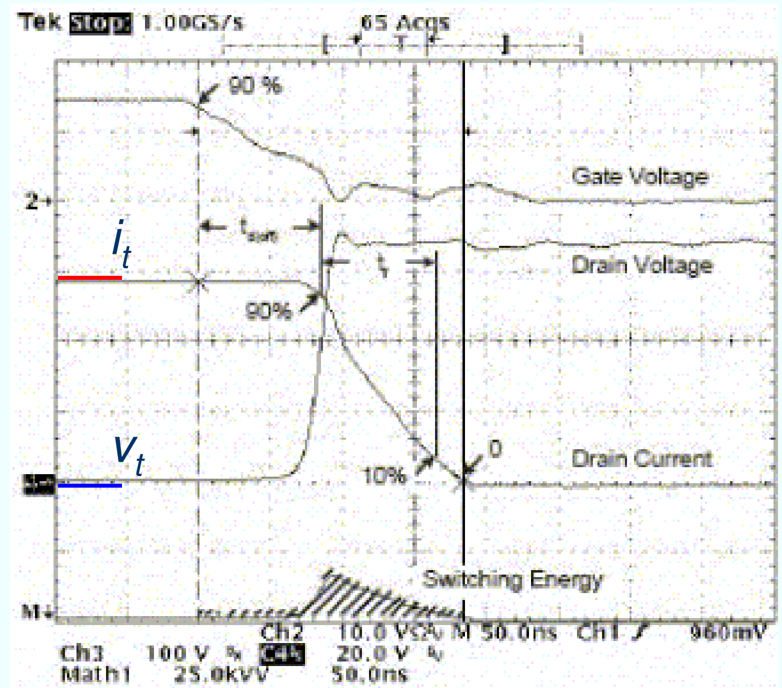
Switching power loss = Transition energy loss * Switching frequency

Switching waveforms and switching losses

MOSFET turn-off transition

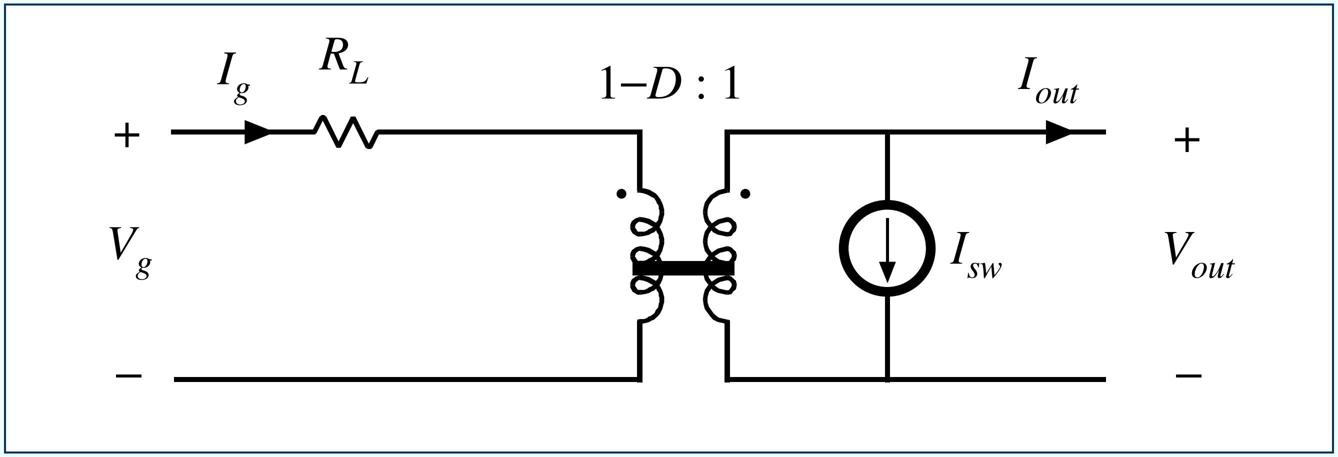


zoom-in



Switching power loss = Transition energy loss * Switching frequency

Averaged (DC) model with losses



- Small R_L models conduction losses due to inductor winding resistance and power switch resistances
- Small I_{sw} models switching and other load-independent losses
- Efficiency with losses, when the load current I_{out} is known:

$$\eta = \frac{1}{1 + \frac{R_L}{(1-D)^2} \frac{(I_{out} + I_{sw})^2}{V_{out} I_{out}} + \frac{I_{sw}}{I_{out}}}$$

Example: efficiency for various R_L

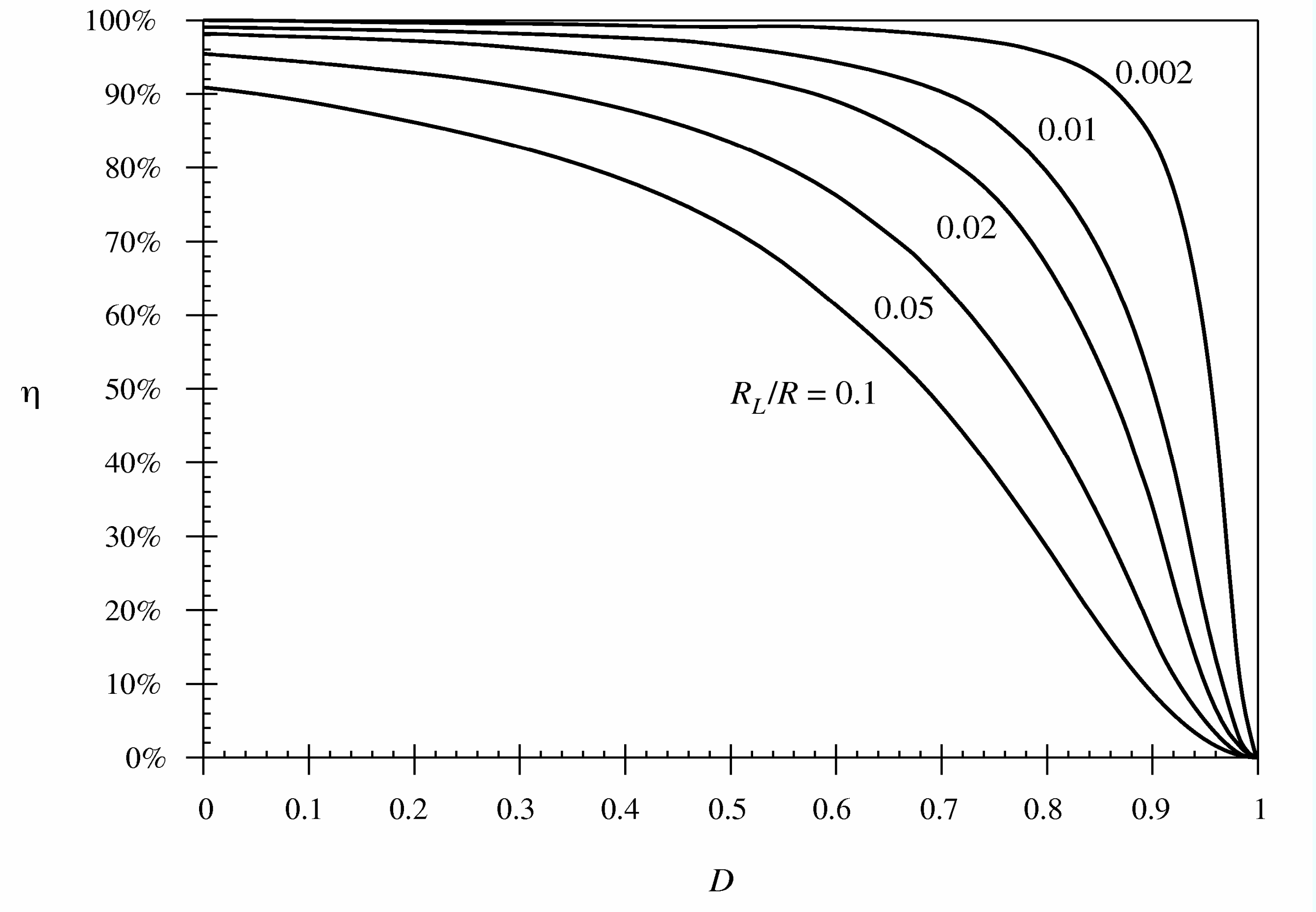
Assume:

- Resistive load

  $R = V_{out}/I_{out}$

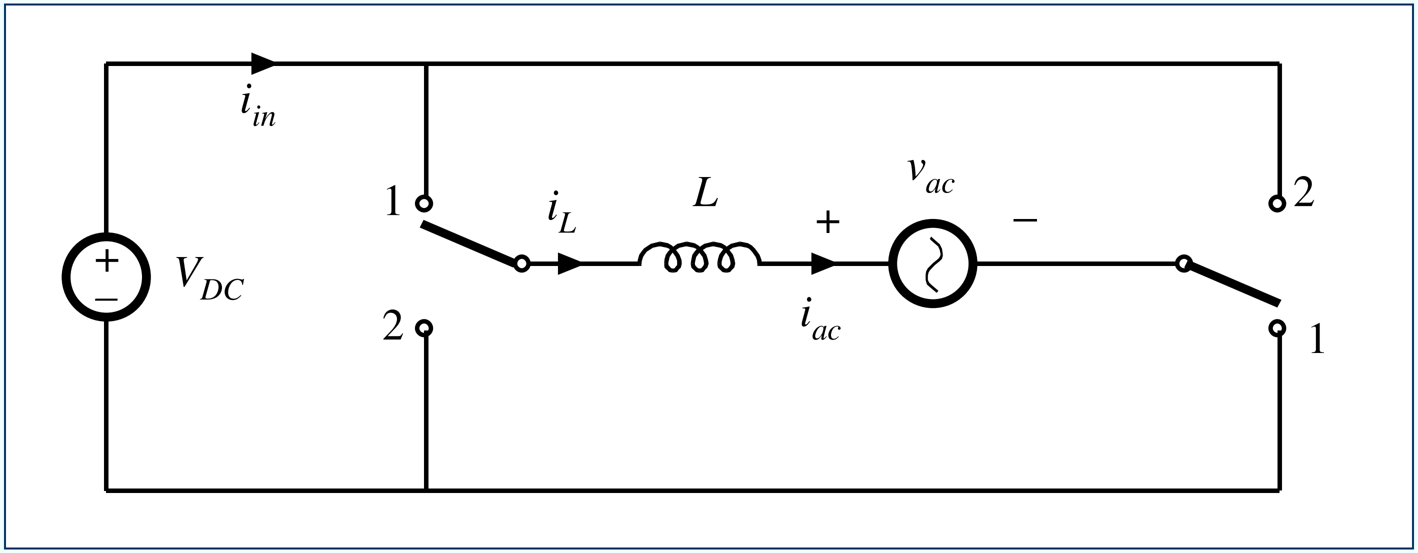
- $I_{sw} = 0$

$$\eta = \frac{1}{1 + \frac{R_L}{(1-D)^2}\frac{1}{R}}$$



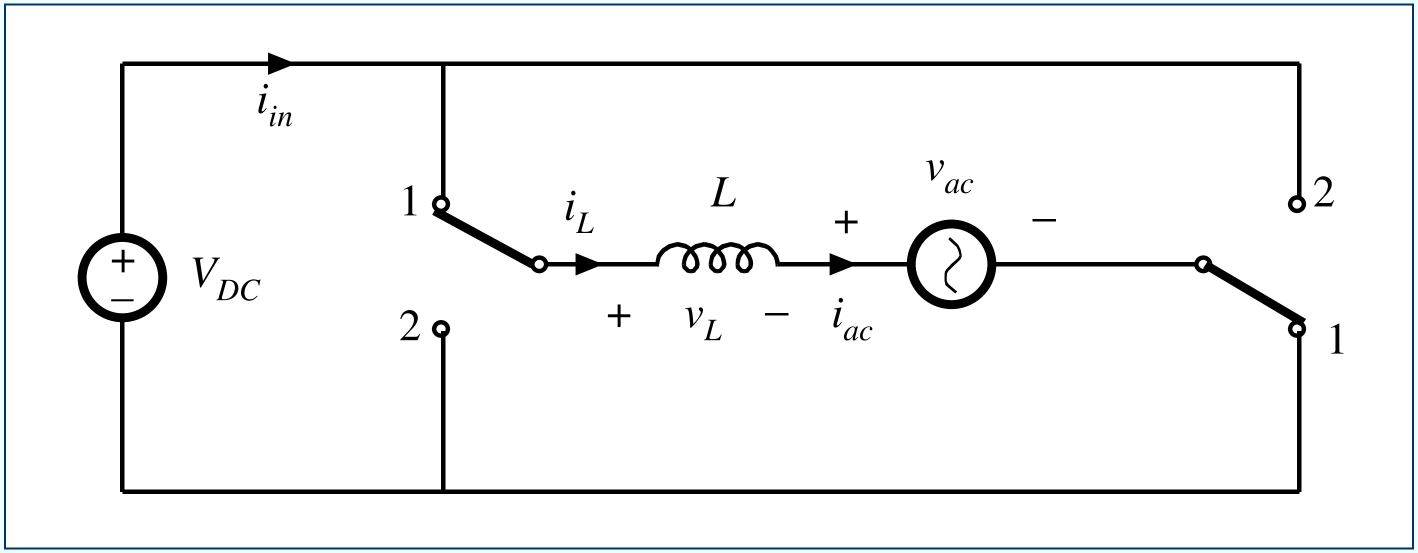
Note that it is more difficult to achieve high efficiency if a large step-up ratio is required (i.e. if duty-ratio D is close to 1)

Single-phase DC-AC grid-connected inverter



- Switches in position 1 during DT_s, in position 2 during $(1-D)T_s$
- Switching frequency f_s is much greater than the AC line frequency (60 Hz or 50 Hz)
- By controlling the switch duty ratio D, it is possible to generate a sinusoidal AC current i_{ac} (+ small switching ripple) in phase with the AC line voltage, as long as the input DC voltage V_{DC} is sufficiently high, i.e. as long as V_{DC} is greater than the peak AC line voltage

Position 1

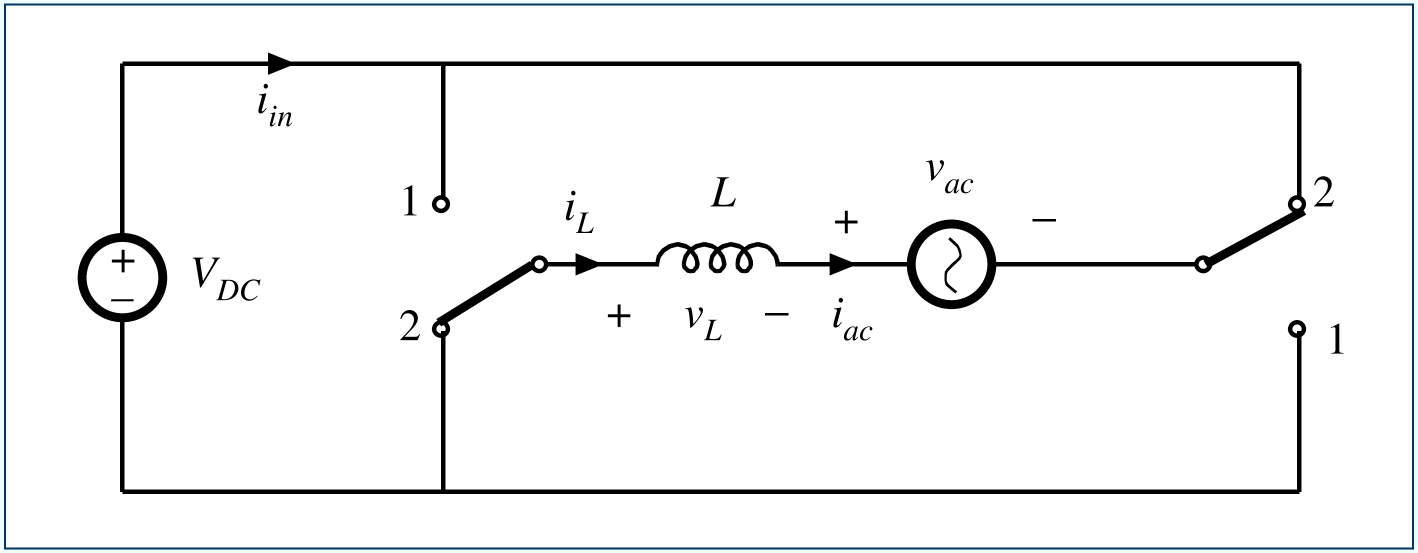


$$v_L = V_{DC} - v_{ac}$$

$$i_L = i_{ac}$$

$$i_{in} = i_L$$

Position 2



$$v_L = -V_{DC} - v_{ac}$$

$$i_L = i_{ac}$$

$$i_{in} = -i_L$$

Inductor volt-second balance

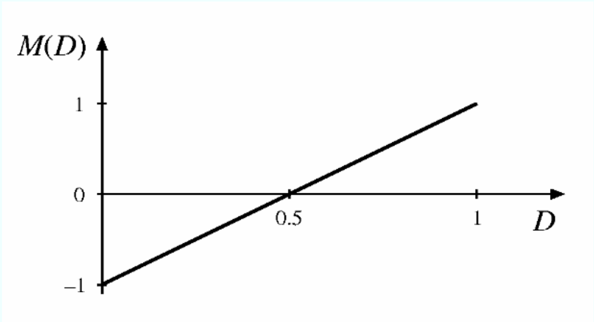
- Note that switching frequency f_s >> ac line frequency
- Over a switching period, $v_{ac}(t) \approx$ const.

$$v_L = \begin{cases} +V_{DC} - v_{ac}, & 0 \le t \le DT_s \\ -V_{DC} - v_{ac}, & DT_s < t \le T_s \end{cases}$$

$$V_L = \frac{1}{T_s}\int_0^{T_s} v_L(t)dt = D(V_{DC} - v_{ac}) + (1-D)(-V_{DC} - v_{ac}) = (2D-1)V_{DC} - v_{ac} = 0$$

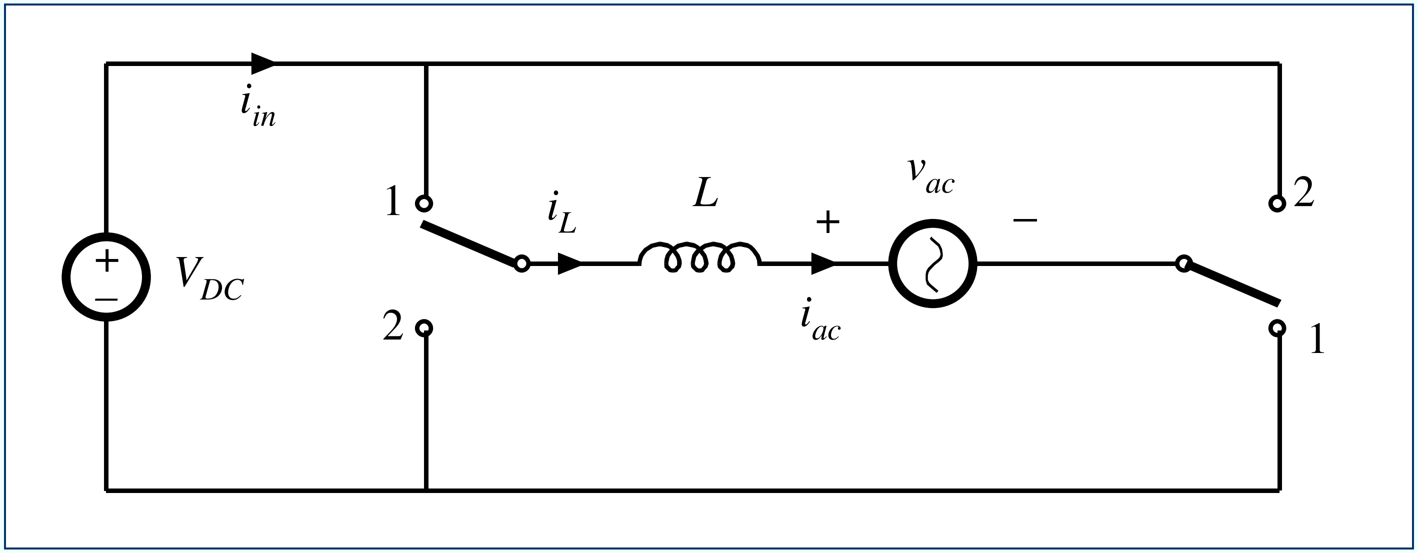
$$M(D) = \frac{v_{ac}}{V_{DC}} = 2D - 1$$

$$-1 \le M(D) \le 1$$



V_{DC} must be greater than the peak of v_{ac}

Control of AC line current



Control objectives:

- $i_{ac} = I_M \sin(\omega t)$, in phase with AC line voltage $v_{ac}(t)$
- Amplitude I_M (or RMS value) adjustable to control power delivered to the AC line

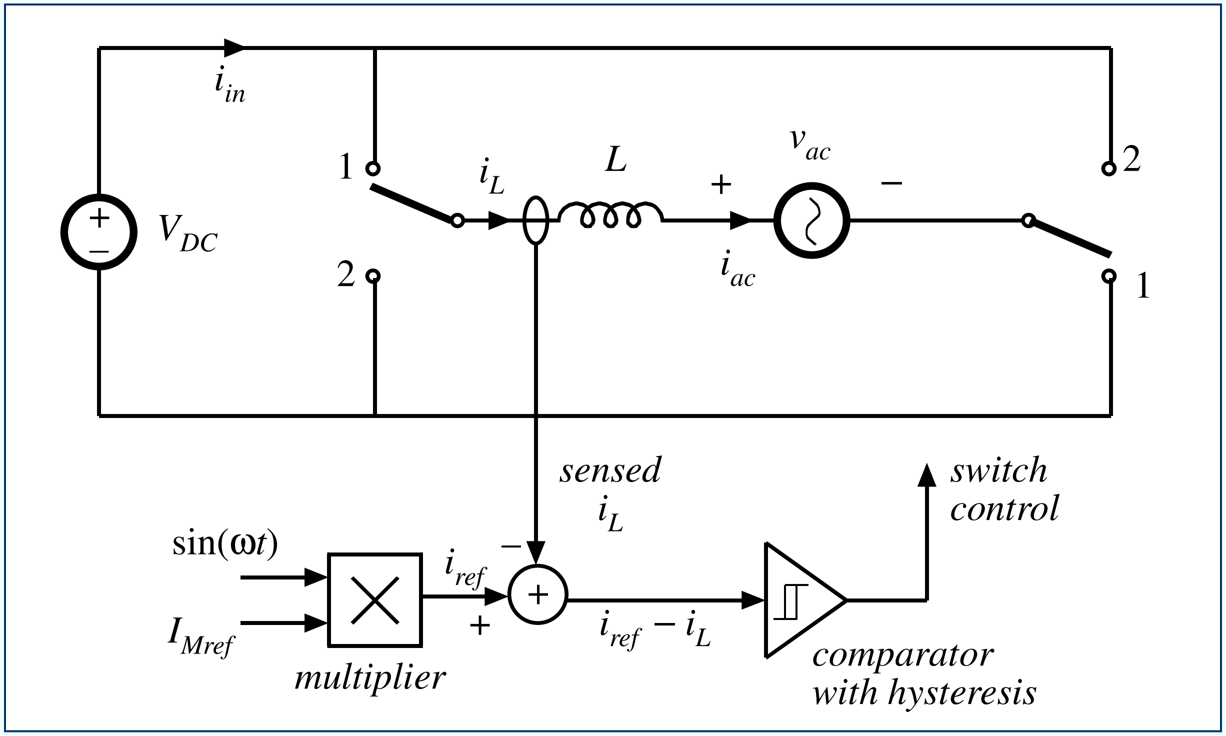
$$v_{ac}(t) = \sqrt{2}V_{RMS}\sin(\omega t)$$

$$i_{ac}(t) = \sqrt{2}I_{RMS}\sin(\omega t)$$

$$p_{ac}(t) = v_{ac}i_{ac} = V_{RMS}I_{RMS}(1-\cos(2\omega t))$$

$$P_{ac} = V_{RMS}I_{RMS}$$

A simple current controller

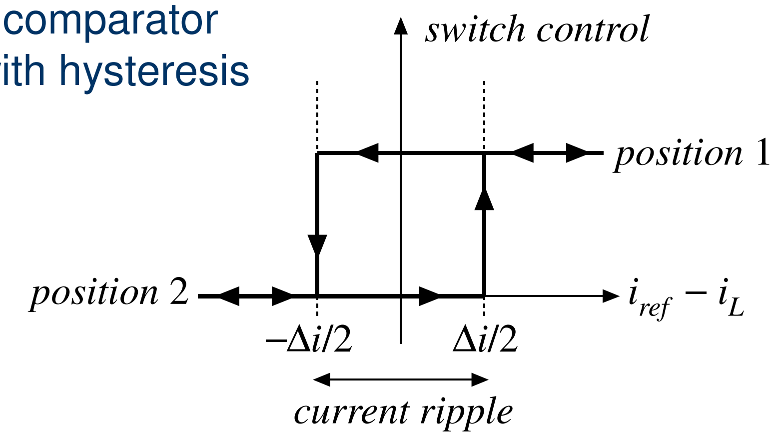


$$i_{ref} = I_{Mref} \sin(\omega t)$$

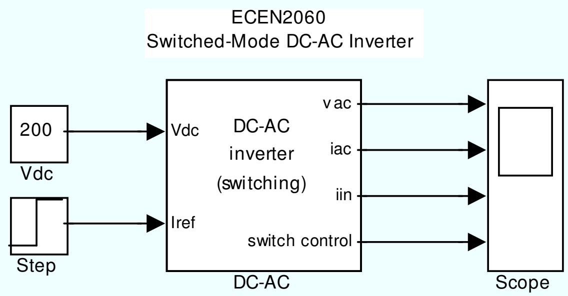
$i_L < i_{ref} - \Delta i/2$: position 1

$i_L > i_{ref} + \Delta i/2$: position 2

i_L is always within $\Delta i/2$ of i_{ref}

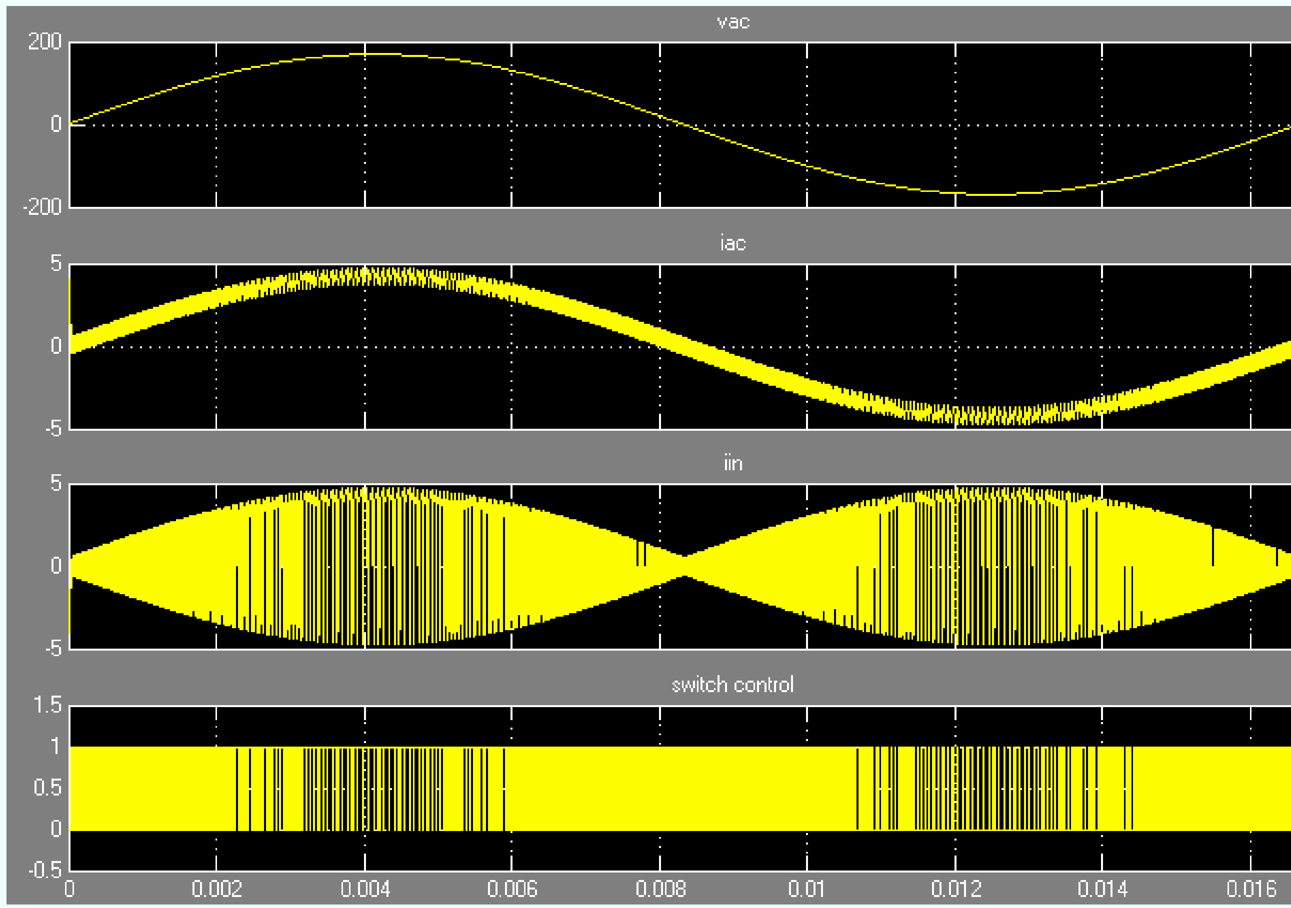


Simulink model



dcac_switching.mdl

Waveforms $v_{ac}(t)$, $i_{ac}(t)$, $i_{in}(t)$, and switch control over one AC line period (1/60 s)



Input voltage

V_{DC} = 200 V

Inductance L = 2 mH

AC: 120Vrms, 60Hz

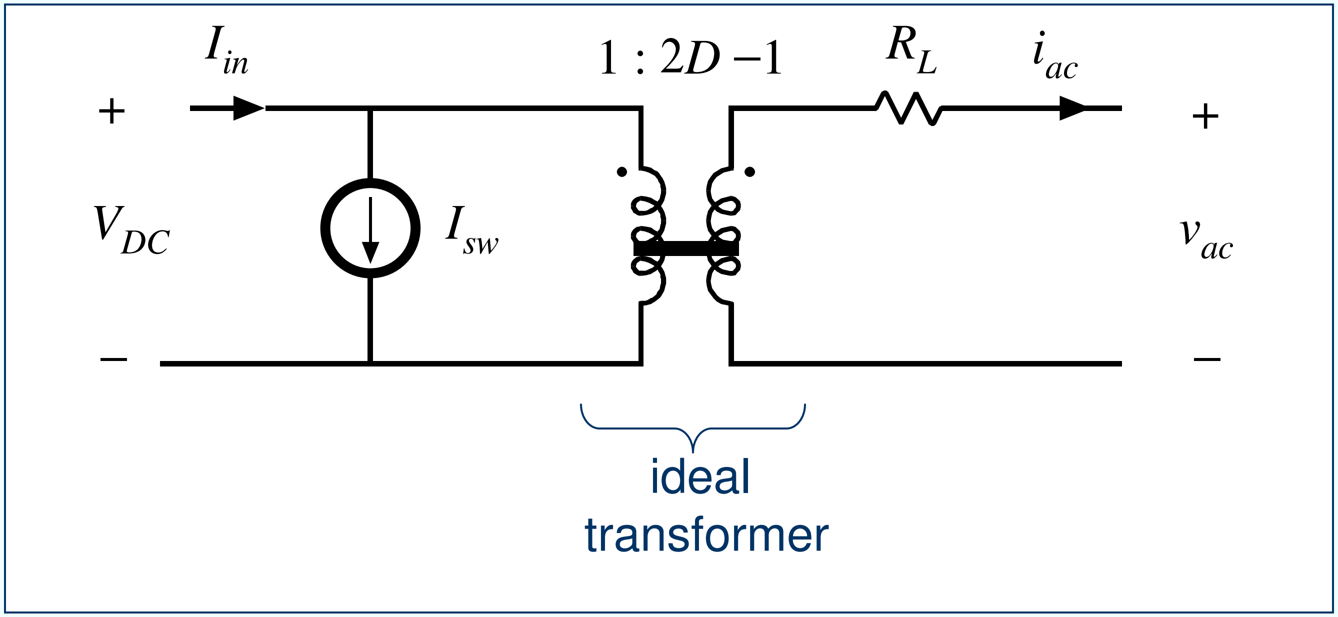
$I_{Mref} = 3\sqrt{2} = 4.2$ A

Δi_L = 1 A

P_{ac} = 360 W

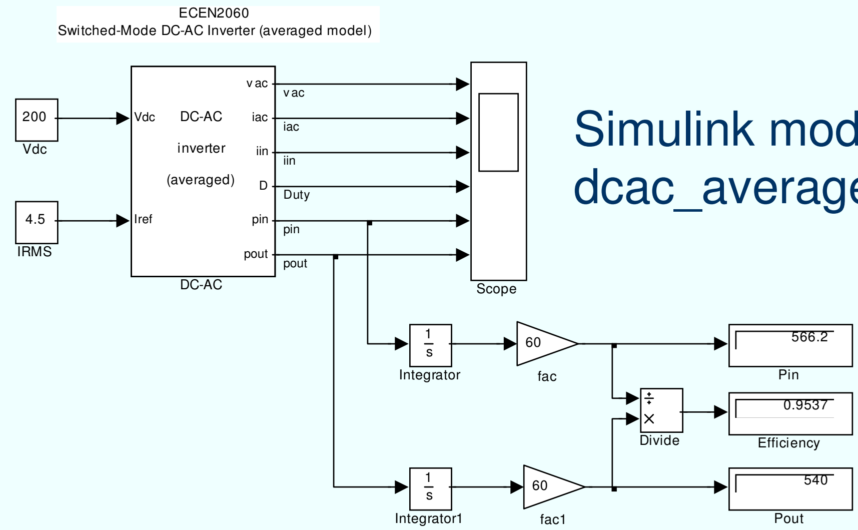
With this simple controller, switching frequency is variable

Averaged DC-AC inverter model with losses



- Small R_L models inductor winding resistance and power switch resistances
- Small I_{sw} models switching and other losses

DC-AC inverter efficiency example



Simulink model
dcac_averaged.mdl

Input voltage V_{DC} = 200 V

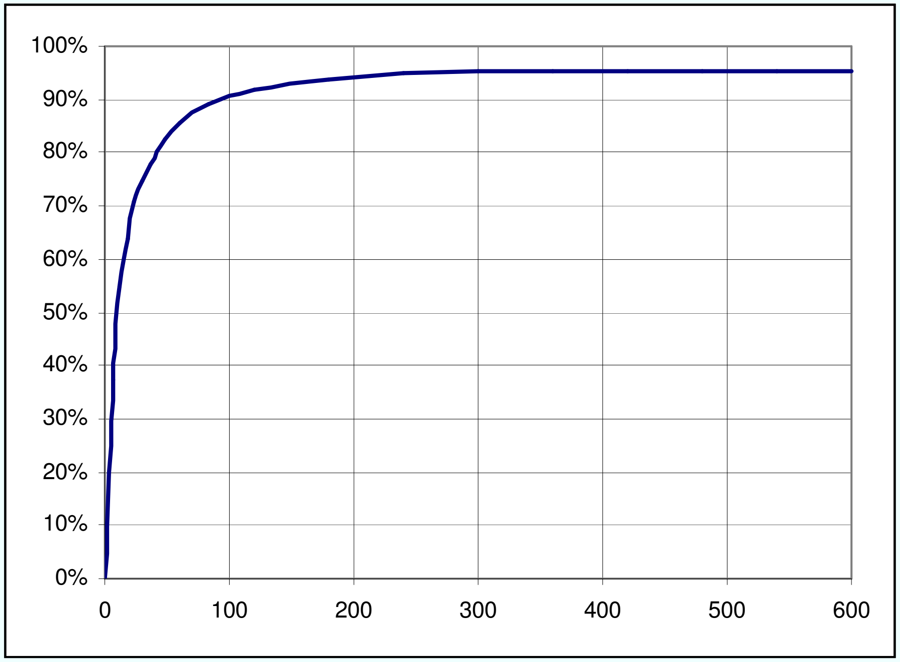
AC: 120Vrms, 60Hz

R_L = 0.8 Ω

I_{sw} = 50 mA

P_{ac} = 0 to 600 W

- Inverter efficiency of about 95% is typical
- At high power levels, conduction losses due to R_L dominate
- At low power levels, efficiency drops due to switching and other fixed losses



P_{ac} [W]