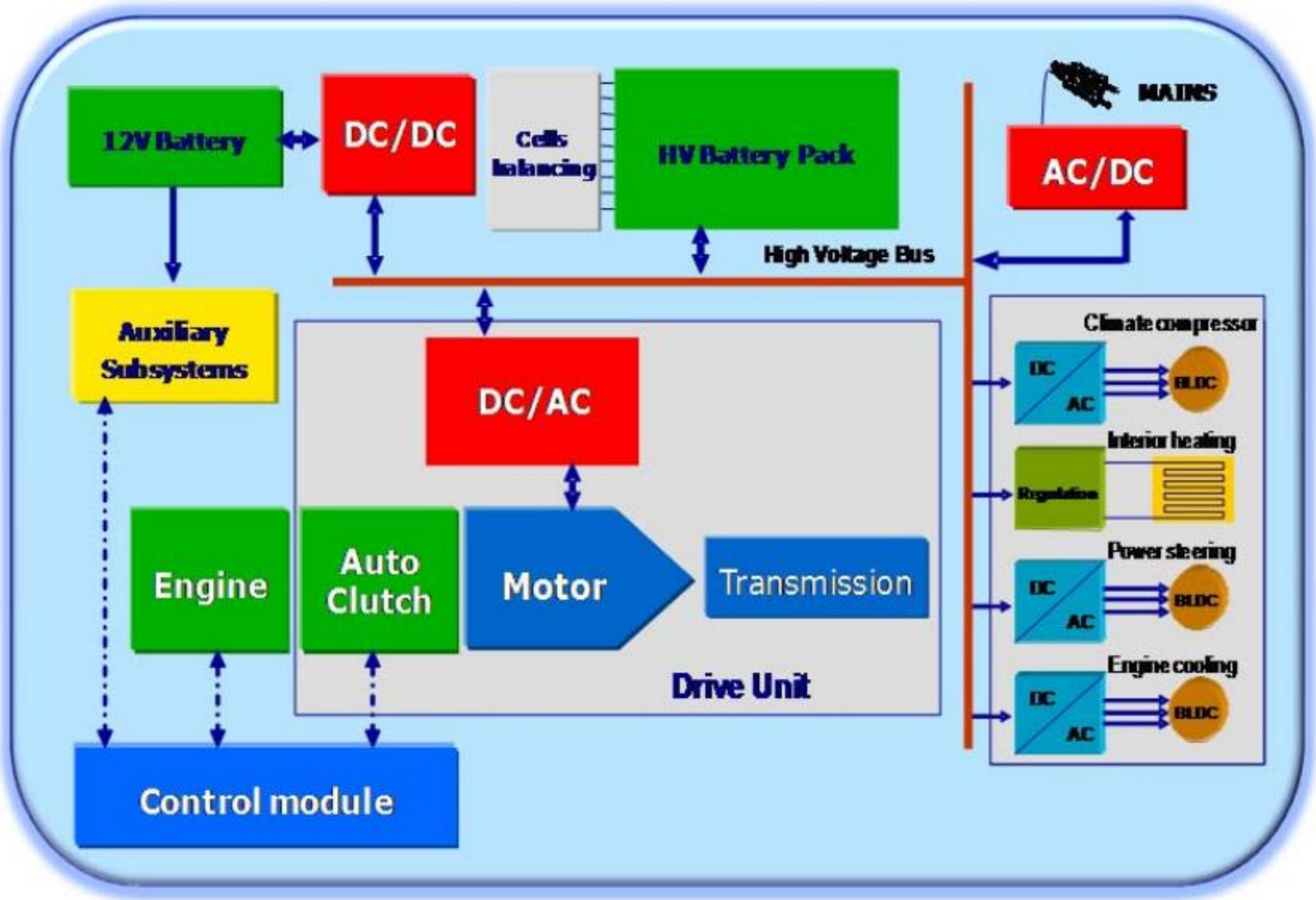
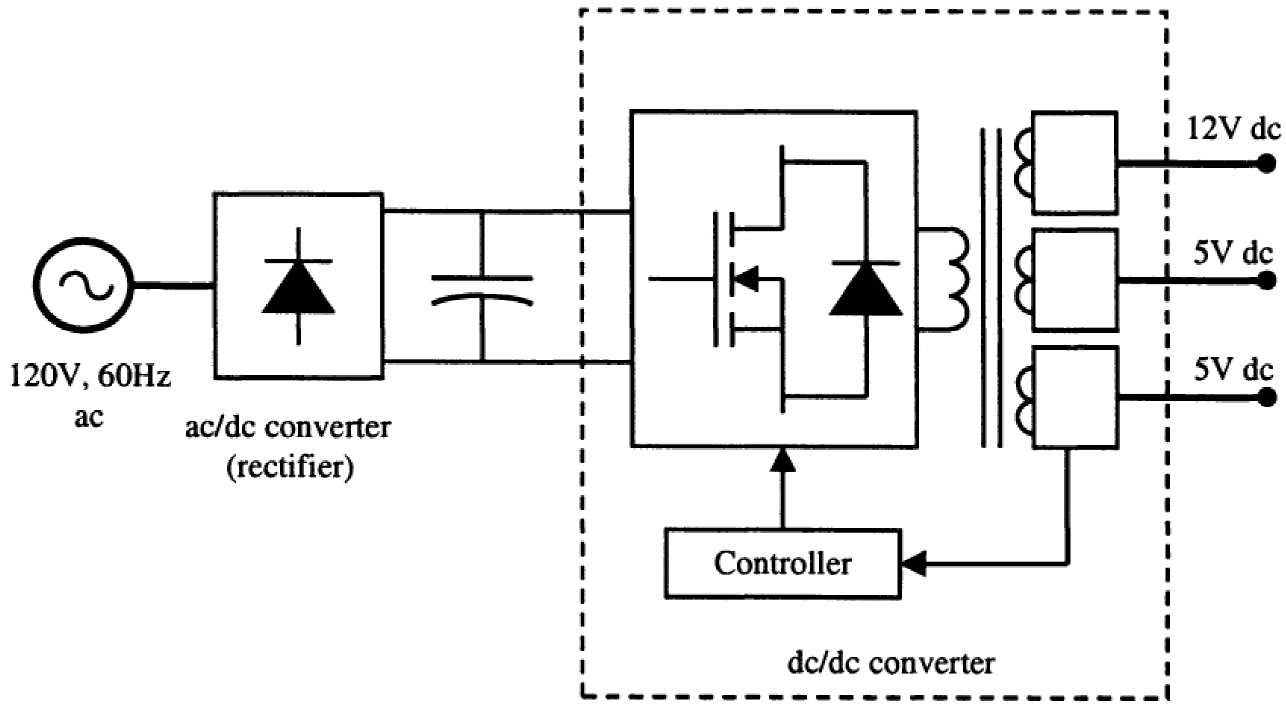
ELG4139
Power Electronics

Switching-Mode Power Supply (SMPS)
Switching-Mode Buck Converter Design

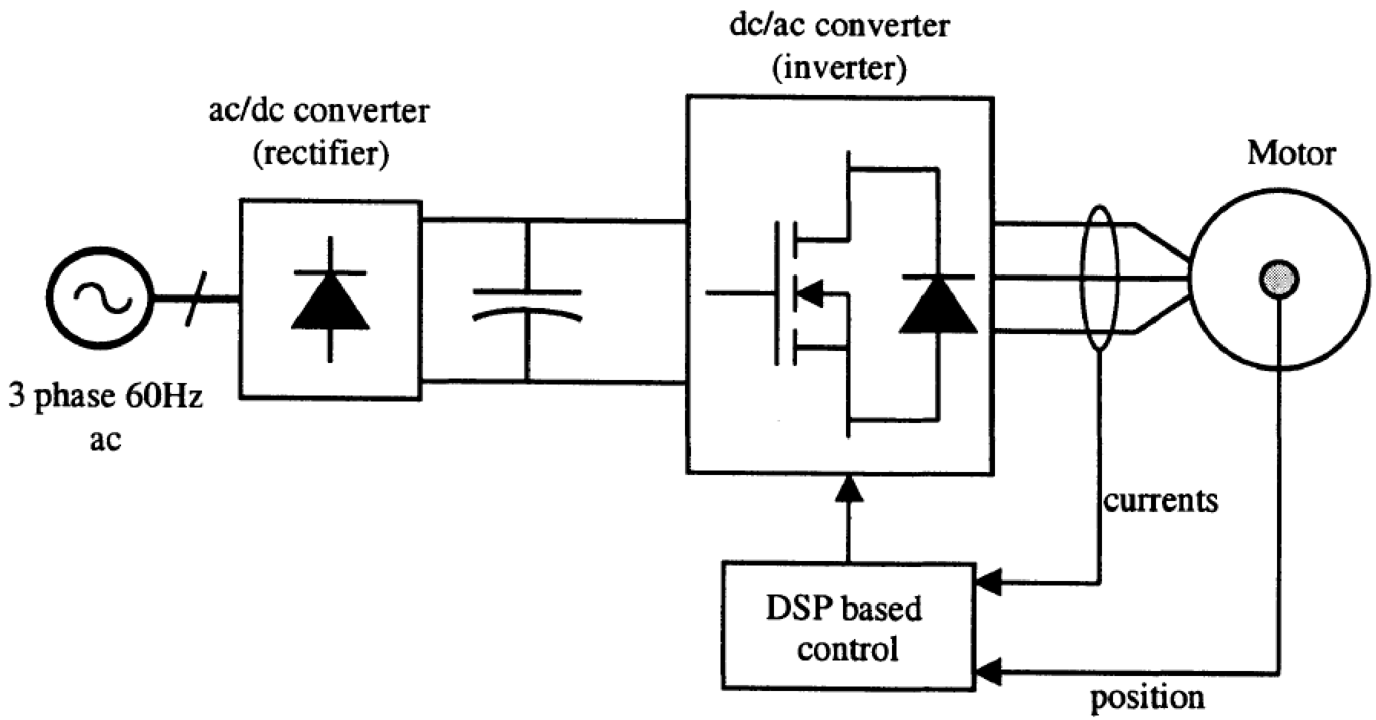
Power Train of a Hybrid Car



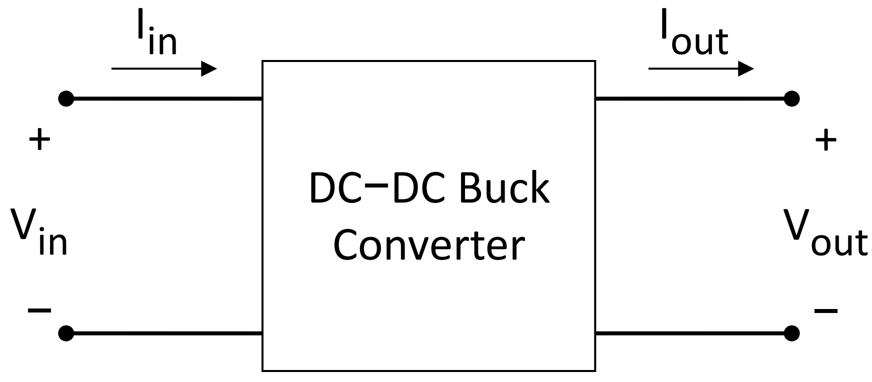
Example: Computer Power Supply



Example: Adjustable Motor Speed Drive



DC-DC Conversion: To efficiently Reduce DC Voltage

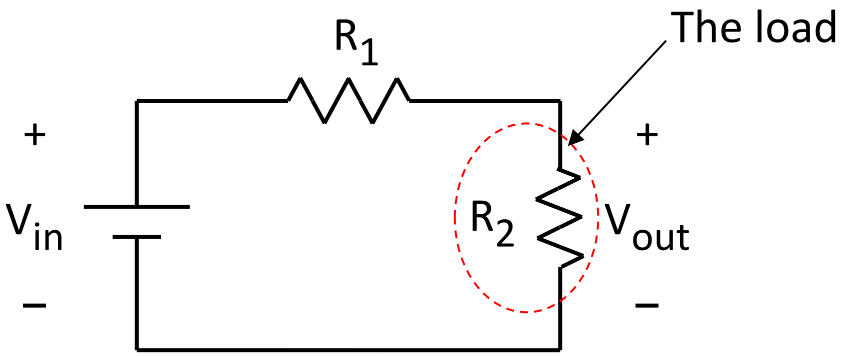


Lossless objective: $P_{in} = P_{out}$, which means that $V_{in}I_{in} = V_{out}I_{out}$

$$\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}}$$

DC–DC Converter: Non-Efficient Way!

Linear regulator is a type of power supply which instead of using switches, employs voltage divider network for adjusting output voltage.



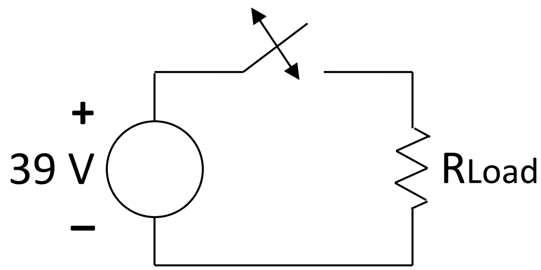
$$V_{out} = V_{in} \bullet \frac{R_2}{R_1 + R_2}$$

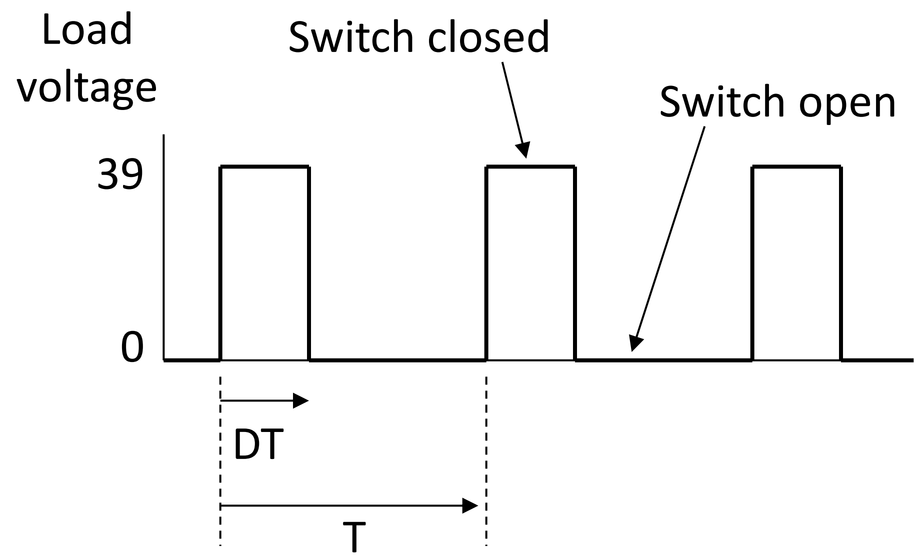
Voltage Divider

$$\eta = \frac{R_2}{R_1 + R_2} = \frac{V_{out}}{V_{in}}$$

If V_{in} = 39V, and V_{out} = 13V, efficiency η is only 33%!

Another Technique: Lossless Conversion





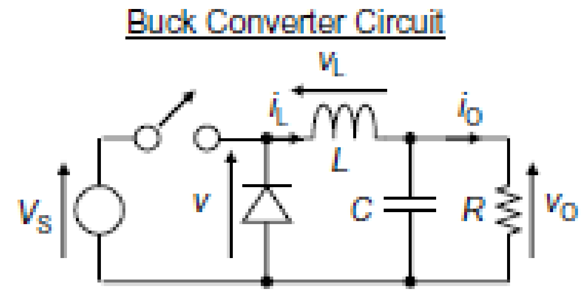
Switch state, Load voltage

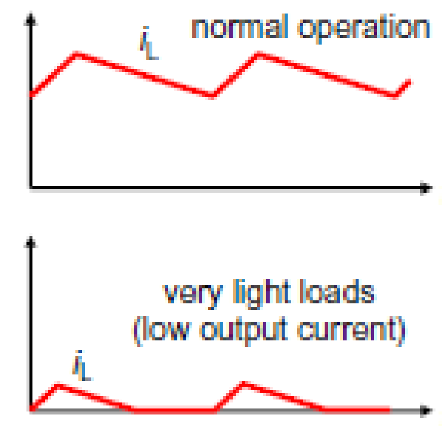
Closed, 39 V

Open, 0 V

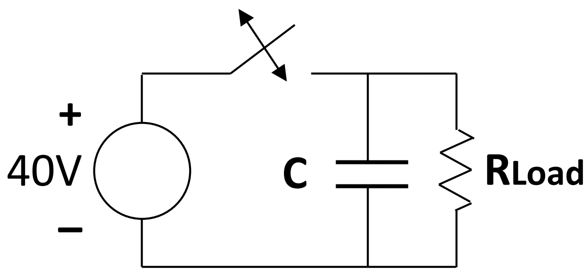
Buck (Step Down) Converter in Brief

- Step down converter
- Switch
- Low-pass LC filter
- Diode
- Transition Between
  - Continuous conduction
  - Discontinuous conduction

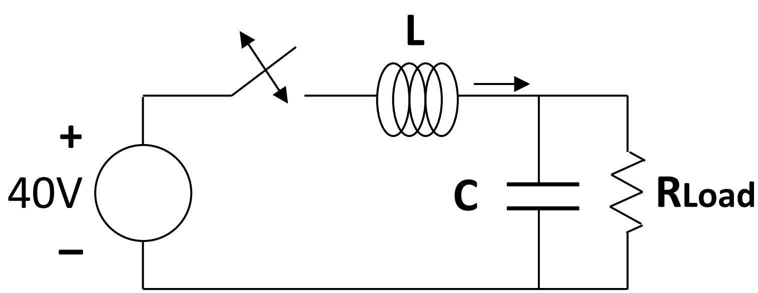




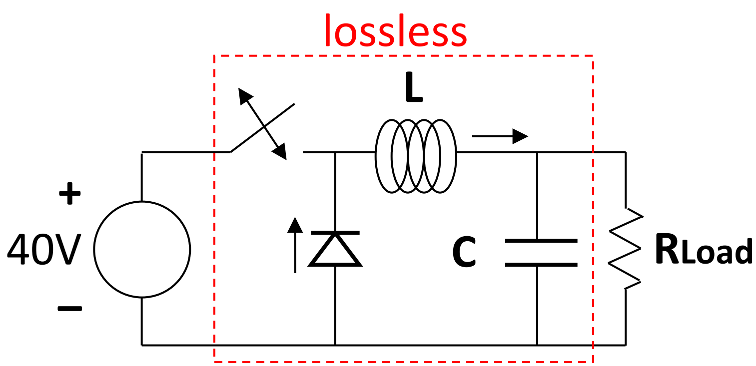
Examples of DC Conversion



Try adding a large C in parallel with the load to control ripple. But if the C has 13Vdc, then when the switch closes, the source current spikes to a huge value and burns out the switch.



Try adding an L to prevent the huge current spike. But now, if the L has current when the switch attempts to open, the inductor's current momentum and resulting *Ldi/dt* burns out the switch.

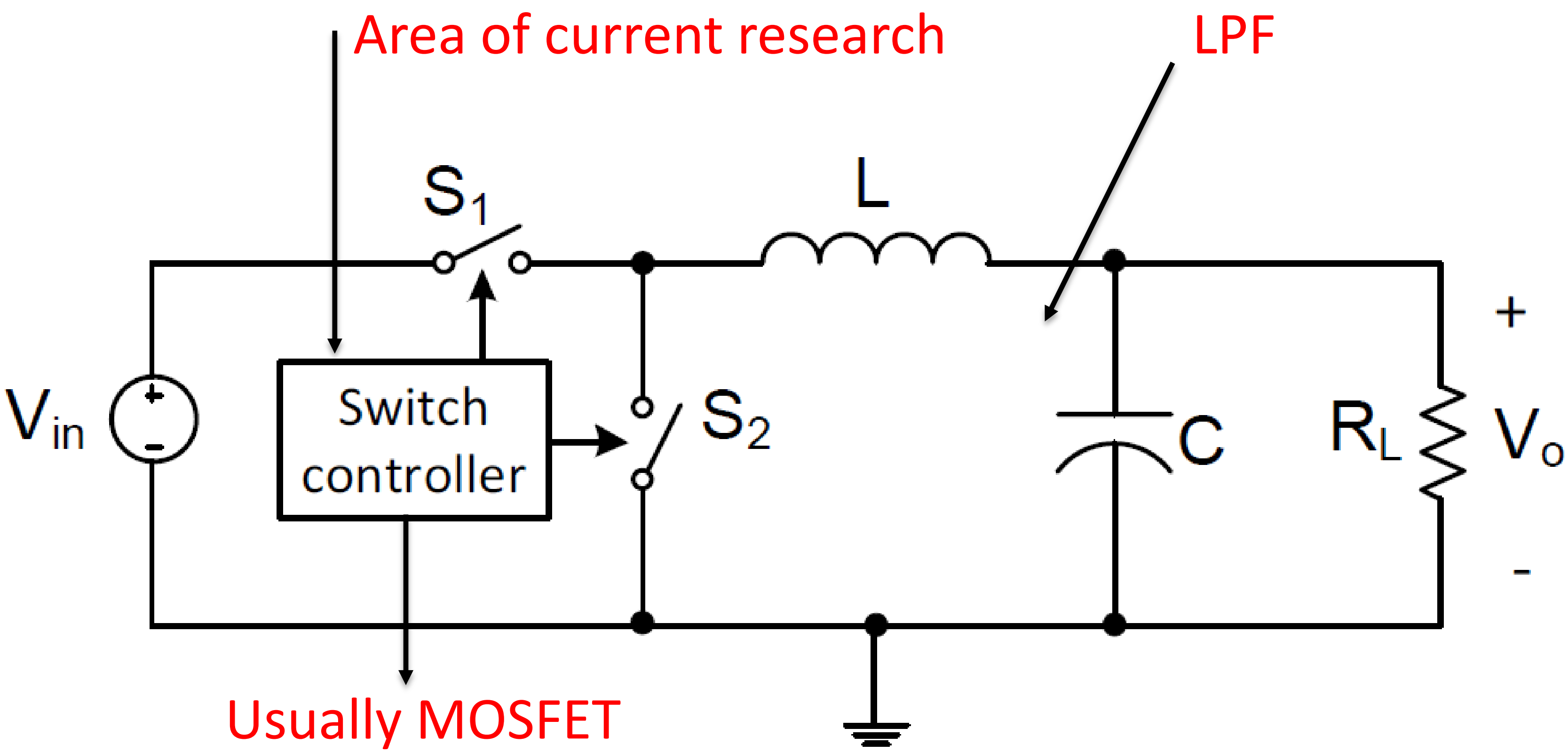


A DC-DC Buck Converter

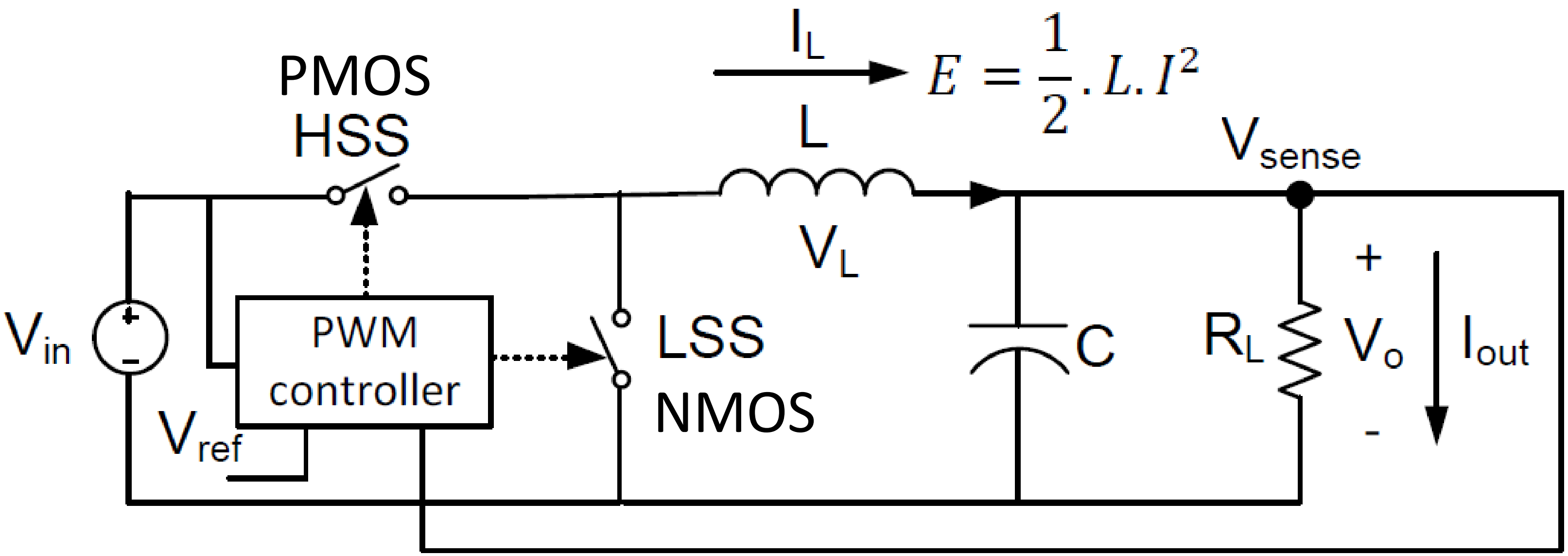
By adding a "free wheeling" diode, the switch can open and the inductor current can continue to flow. With high-frequency switching, the load voltage ripple can be reduced to a small value.

Buck Converter Circuit

The circuit of SMPS Buck converter consists of two main parts: power stage and control stage



Buck Converter with Feedback Loop



$$D = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on} + t_{off}} = f_{sw}.t_{on}$$

Power Loss and Efficiency of Buck Converter

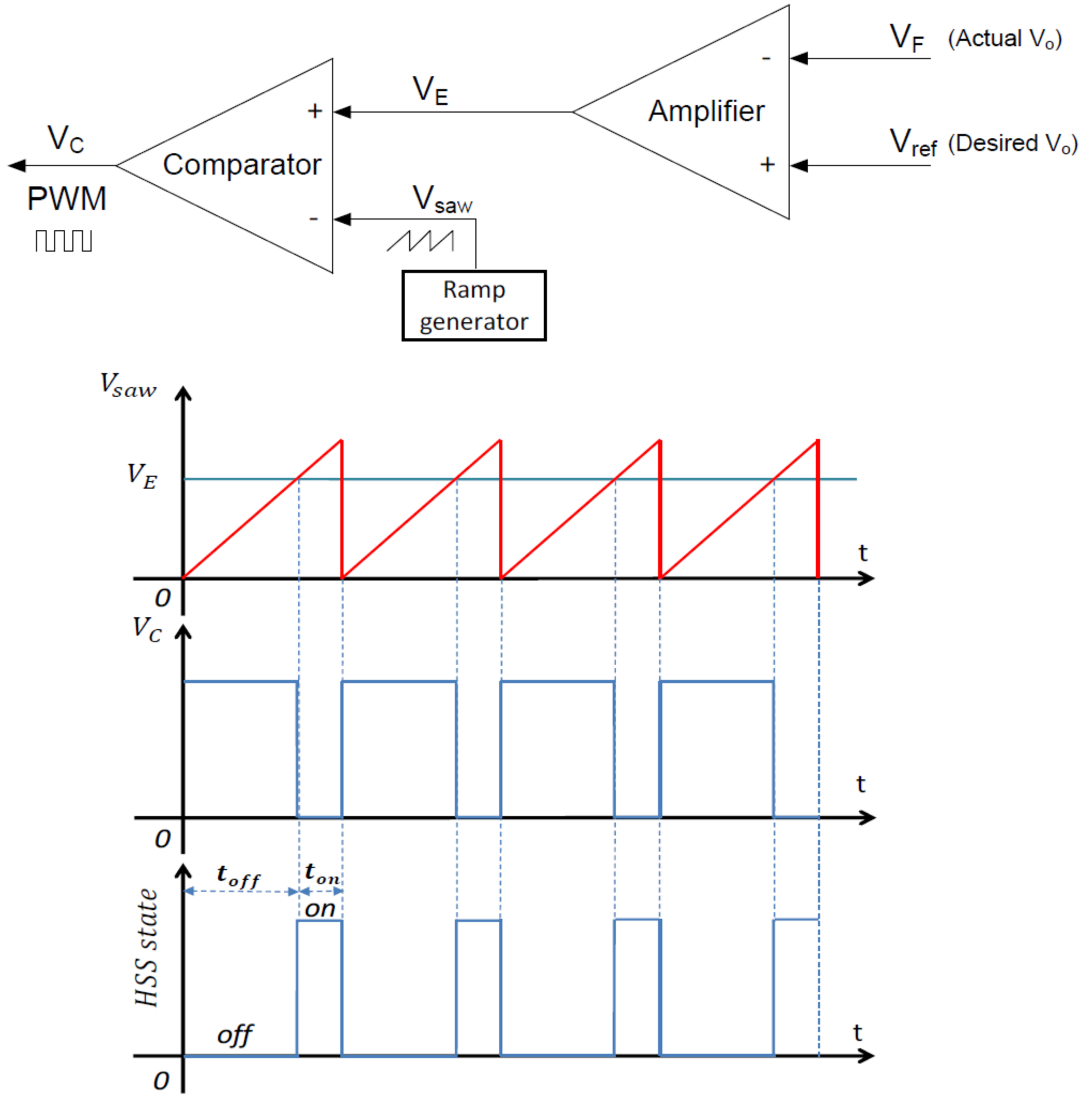
$$P_{loss} = P_{con} + P_{sw}$$

$$P_{loss_{HS}} = \underbrace{R_{DS(on)} . I_{out}{}^{2} . D}_{\boldsymbol{P_{con}}} + \underbrace{\frac{(V_{in} . I_{out})}{2}\left(t_r + t_f\right) . f_{sw} + C_{oss} . f_{sw} . V_{in}{}^{2}}_{\boldsymbol{P_{sw}}}$$

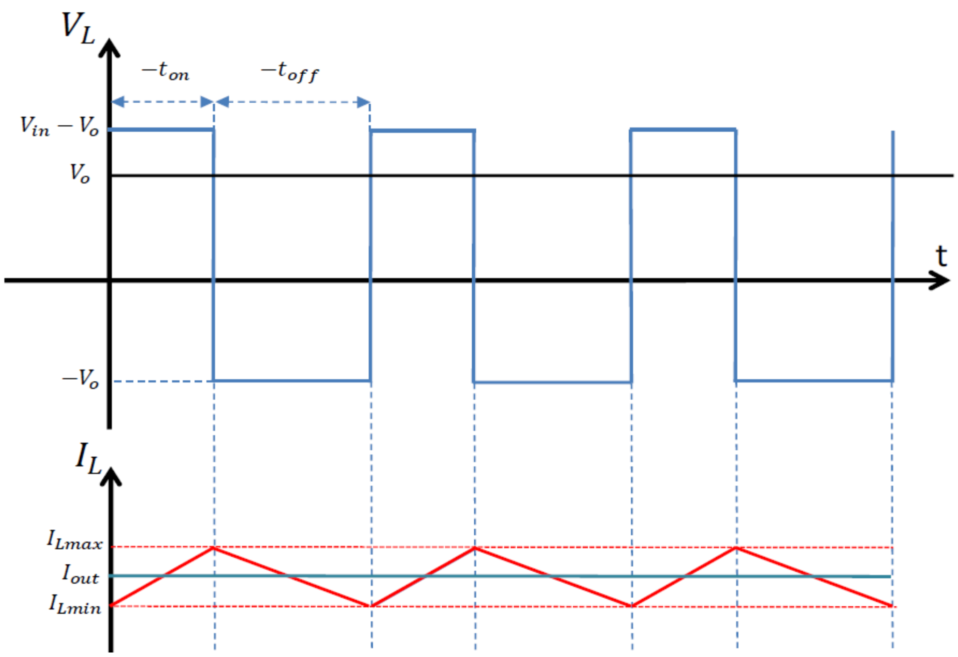
$$P_{loss_{LS}} = R_{DS(on)} . I_{out}{}^{2} . (1 - D)$$

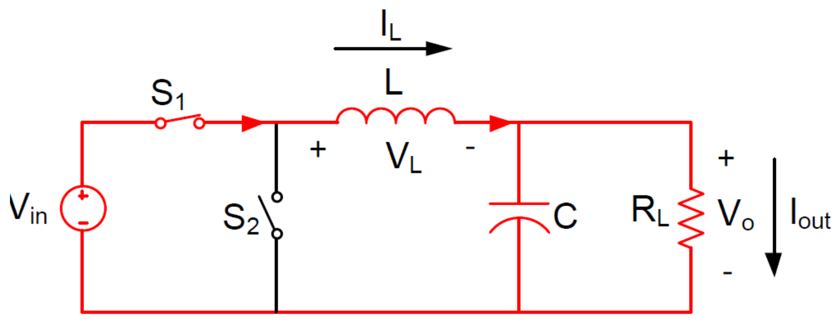
Where $R_{DS(on)}$ is the MOSFET drain-source on-state resistance, I_{out} is the output current, D is the power switch's duty cycle, V_{in} is the input voltage, t_r is the MOSFET rise time, t_f is the MOSFET fall time, f_{sw} is the switching frequency and C_{oss} is the MOSFET output capacitance $(C_{DS} + C_{DG})$

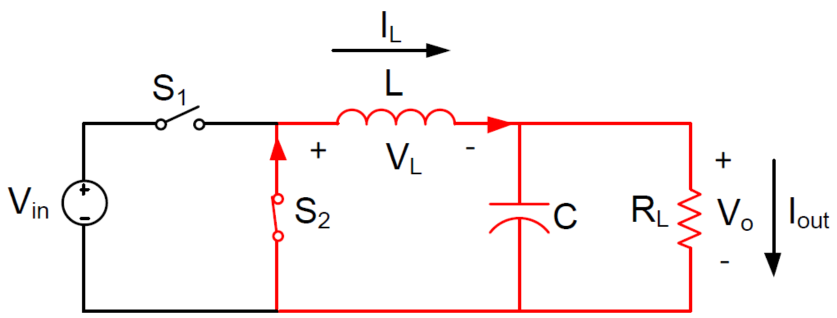
PWM Generator



Duty Cycle Calculation for Buck Converter







$$I_{L_{t_0}} = I_{L_T}$$

$$\Delta I_{L_{ON}} = \int_0^{t_{ON}} \frac{V_L}{L} dt = \frac{(V_{in}-V_o)}{L} t_{ON}$$

$$\Delta I_{L_{OFF}} = \int_0^{t_{OFF}} \frac{V_L}{L} dt = \frac{(-V_o)}{L} t_{OFF}$$

It means that energy stored in inductor at the end of cycle is equal to energy which is stored at the start of cycle, so from equation

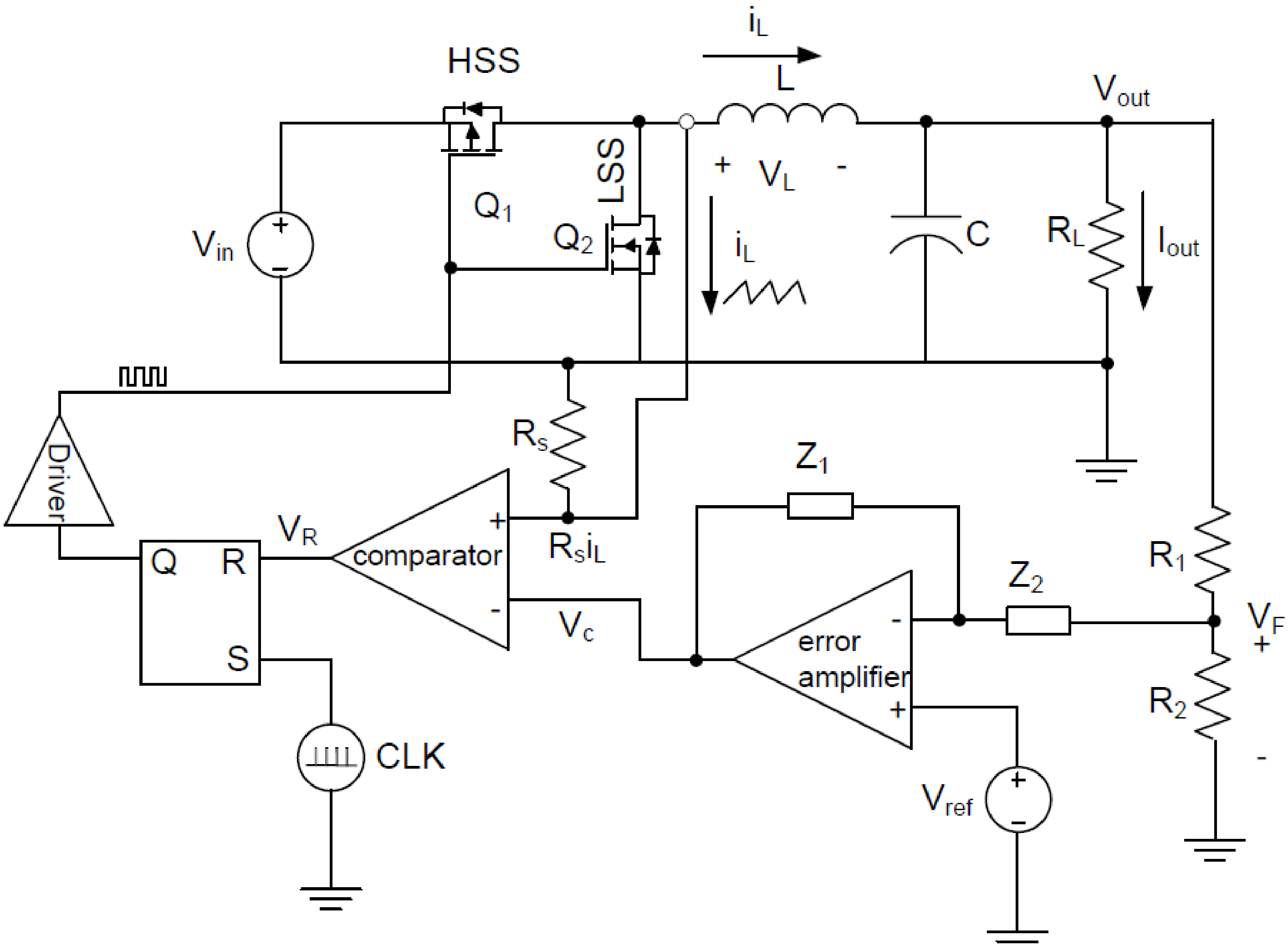
$$t_{ON} = D.T$$

$$\frac{(V_{in}-V_o)}{L} t_{ON} - \frac{V_o}{L} t_{OFF} = 0$$

$$t_{OFF} = (1-D)T$$

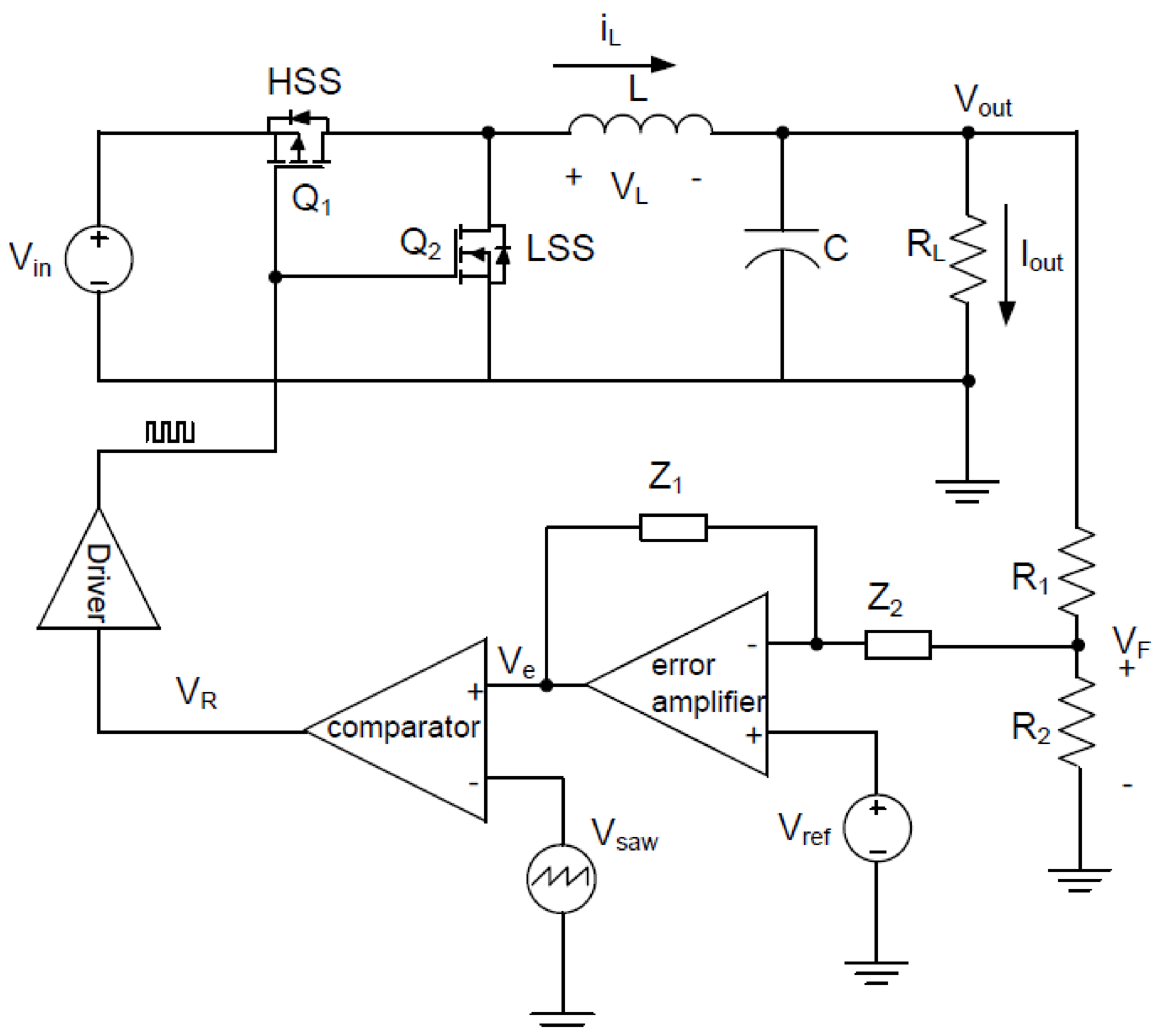
$$D = \frac{V_o}{V_{in}}$$

PWM Buck Converter with Current Mode Control (CMC)



Naim Safari: **Design of a DC/DC buck converter for ultra-low power applications in 65nm CMOS Process**

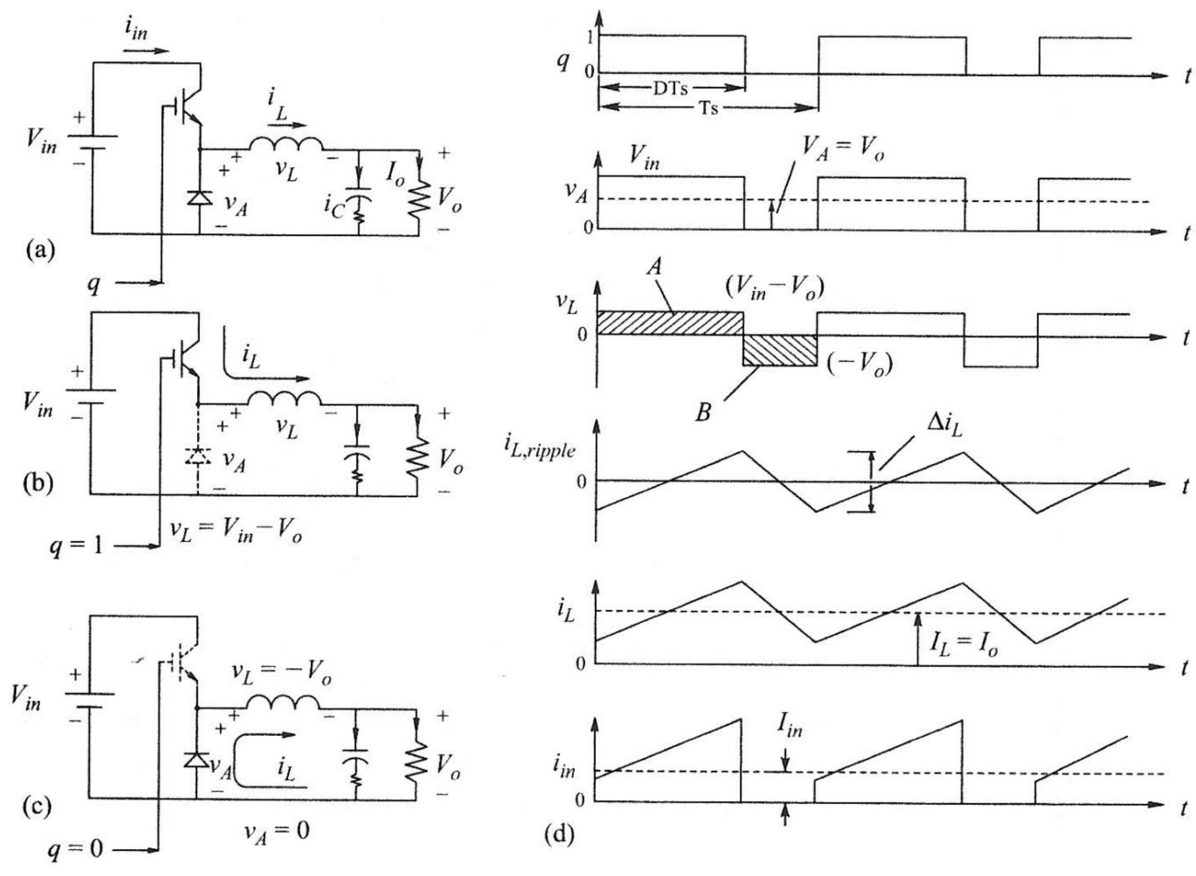
PWM Buck Converter with Voltage Mode Control (VMC)



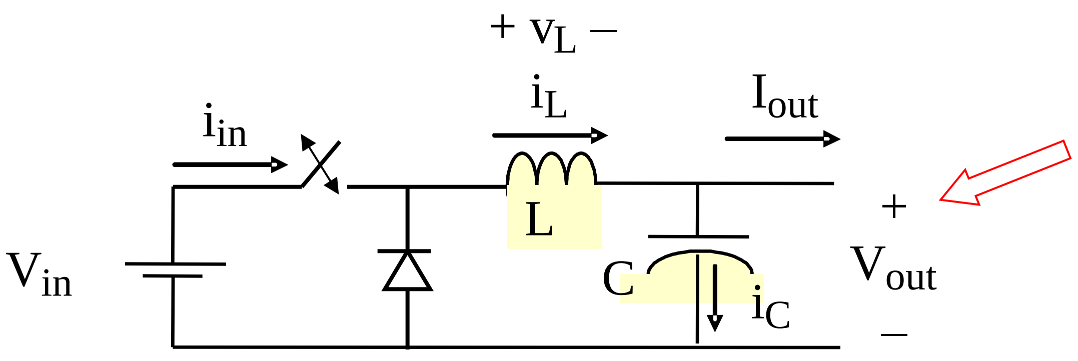
Naim Safari: Design of a DC/DC buck converter for ultra-low power applications in 65nm CMOS Process

Buck Converter Analysis

- $V_o = V_A = DV_{in}$; D = switch duty ratio
- $\Delta_{iL} = \frac{1}{L}(V_{in} - V_o)DT_s = \frac{1}{L}V_o(1-D)T_s$
- $I_L = Io = \frac{Vo}{R}$

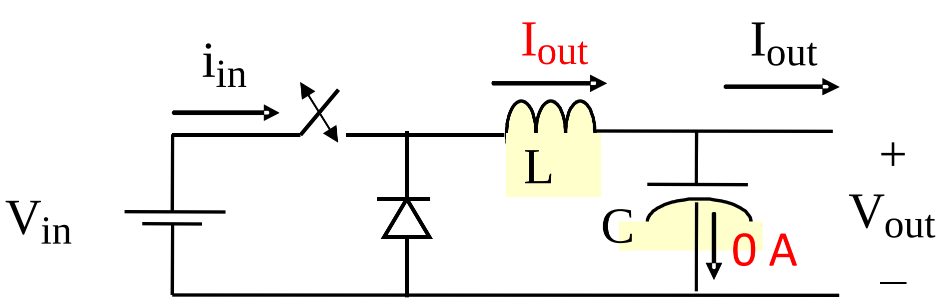


Buck (step Down) Converter



- Assume large C so that V_{out} has very low ripple
- Since V_{out} has very low ripple, then assume I_{out} has very low ripple

What do we learn from inductor voltage and capacitor current in the average sense?



Designing a Buck Converter

- Design Criteria
  - Calculate the required inductor
  - Calculate the output capacitor
  - Select the input capacitor
  - Select the diode
  - Choose the MOSFET
  - Calculate the converter Efficiency
- For a Buck DC-DC converter we first calculate the required inductor and output capacitor specifications. Then determine the input capacitor, diode, and MOSFET characteristics. With the selected components, we will calculate the system efficiency.

Design Criteria

- Input voltage
- Output voltage
- Output current
- Output power
- Switching frequency
- Allowed ripple voltage
- Allowed ripple current
- Minimum efficiency
- Inductor size
- Capacitor size

Inductor and Capacitor Size

$$\Delta i_L = i_L(DT) = \frac{(V_i - V_o)}{L} D.T = \frac{V_o(1-D)}{L.f_s}$$

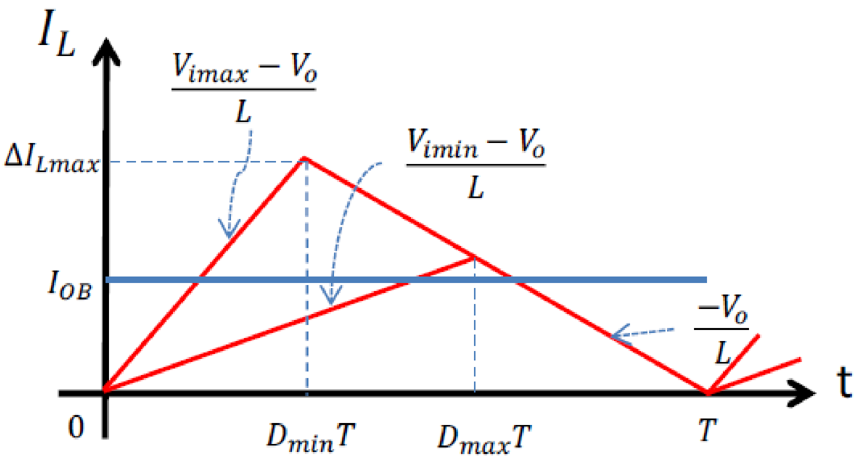
$$\Delta i_{Lmax} = \frac{V_o(1-D_{min})}{L_{min}.f_s}$$

$$L_{min} = \frac{V_o(1-D_{min})}{f_s \Delta i_{Lmax}}$$

$$V_{Cpp} = \frac{\Delta Q}{C} = \frac{\Delta i_{Lmax}}{8 f_s C}$$

$$V_{Cpp} = \frac{V_o(1-D_{min})}{8LC.f_s^{\,2}} \qquad f_{LC} = \frac{1}{2\pi\sqrt{LC}}$$

$$V_{Cpp} = \frac{V_o(1-D_{min})\pi^2 f_{LC}^{\,2}}{2 f_s^{\,2}} \qquad C_{min} = \frac{\Delta i_{Lmax}}{8 f_s V_{Cpp}} = \frac{V_o(1-D_{min})}{8 L f_s^{\,2} V_{Cpp}}$$



Designing a Buck Converter

Assume:

V_{in} = 12 V

V_{OUT} = 5 volts

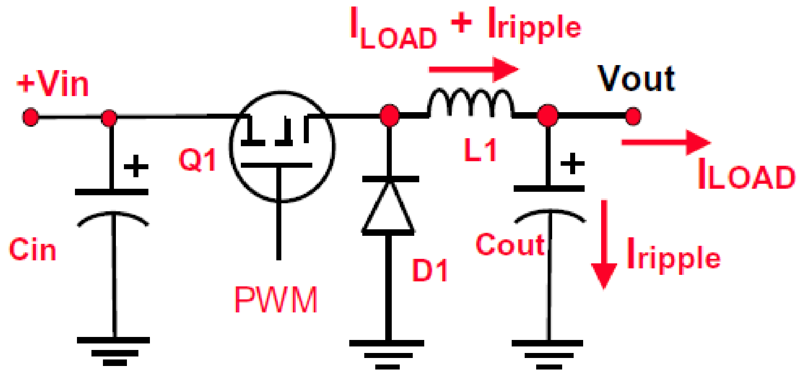
I_{LOAD} = 2 amps

F_{sw} = 400 KHz

D = V_{in} / V_{out} = 5V /12V = 0.416

Define Ripple current:

$I_{ripple} = 0.3 \bullet I_{LOAD}$ (typically 30%)



For an Inductor: $V = L \bullet \Delta I / \Delta T$

Rearrange and substitute:

L = (Vin – Vout) • (D / Fsw) / Iripple

Calculate:

L = 7 V • (0.416 / 400 kHz) / 0.6A

L = 12.12 uh

Select C, Diode (Schottky), and the MOSFET

Calculate the Efficiency

Example

- In **Buck** converter, L = 24μF (steady-state): V_{in} = 20V; D = 0.6; P_o = 14V; f_s = 200 kHz. Calculate and draw the waveform.