EE 238

Power Engineering - II

Power Electronics

Lecture 5

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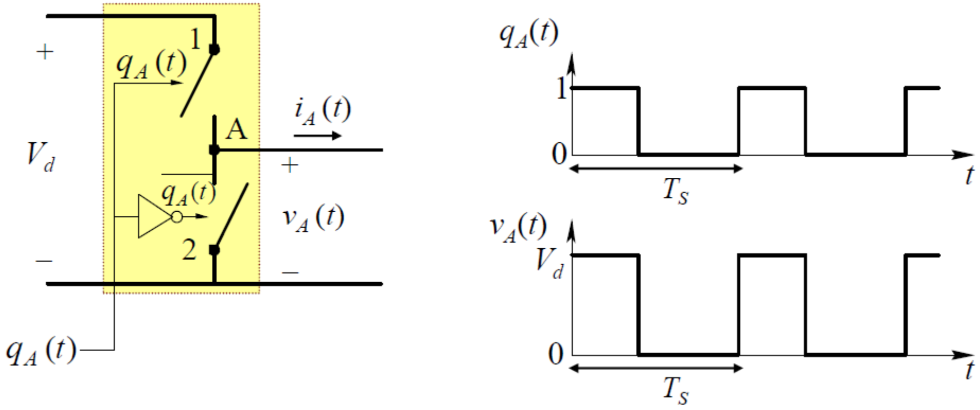
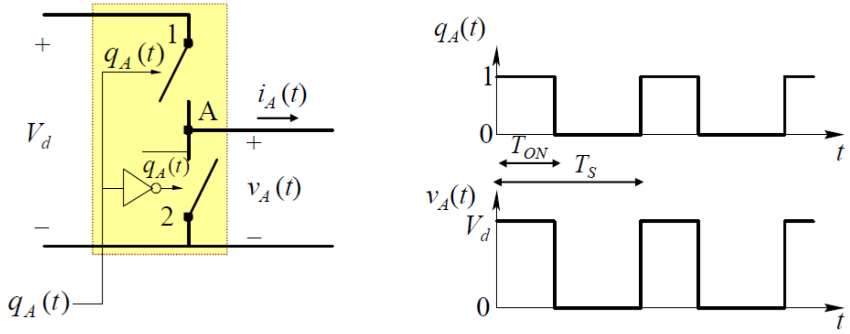
Constant switching frequency



Example:
Switching frequency, f_S = 200 kHz

Period, $T_S = 1/f_S$ = 5 us

Duty ratio



Example:
Frequency, f_S = 200 kHz
Period, $T_S = 1/f_S$ = 5 us

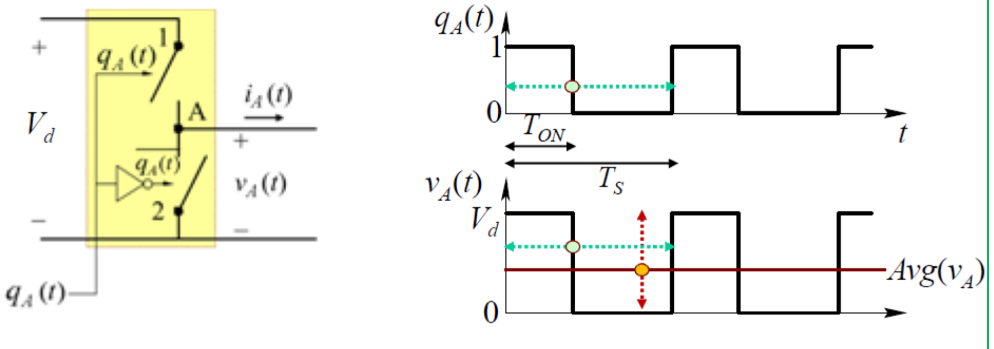
Given T_{ON} = 2 us
d = 0.4

- T_{ON}: duration for which $q_A = 1$ in T_s

$$\text{duty ratio, } d_A = \frac{T_{ON}}{T_S}$$

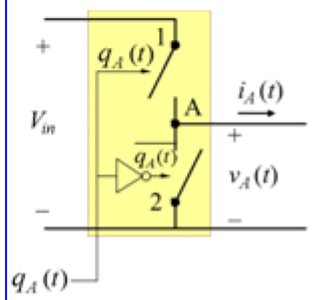
- Duty ratio is the main control variable

Pulse width modulation

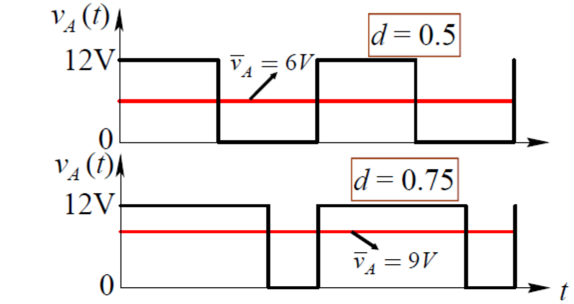


- PWM: Control of average (CCA) quantity by controlling (modulating) the pulse width in a switching cycle (duty ratio control)
- Normally constant switching frequency

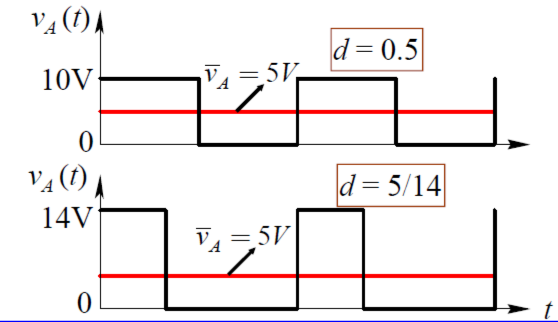
PWM example



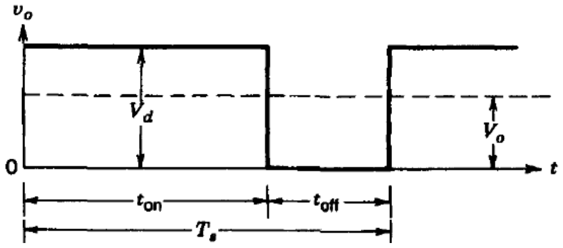
Different output voltages with a fixed input

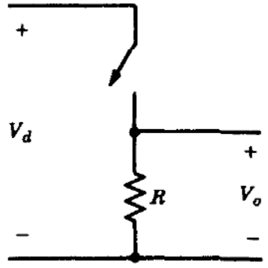


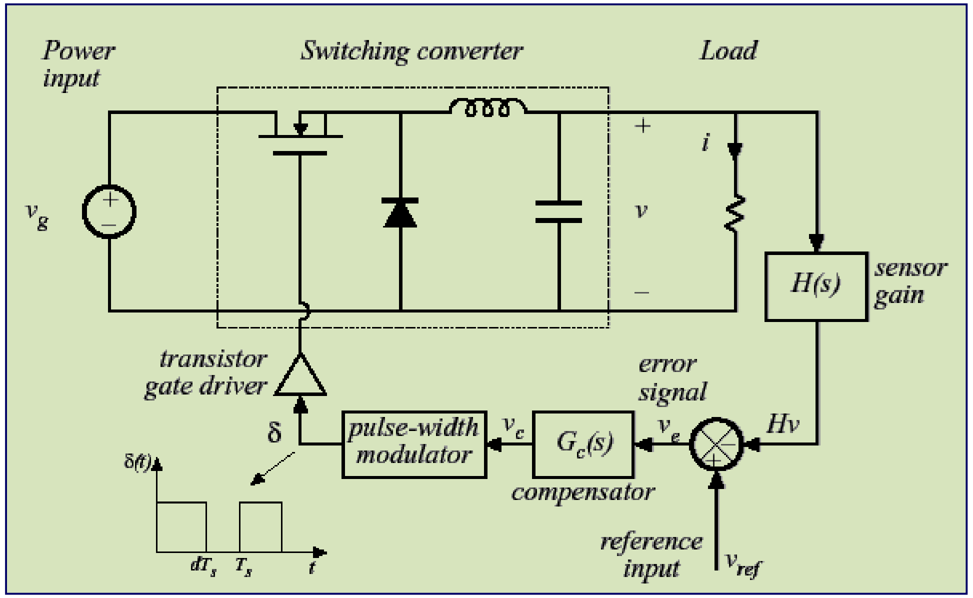
Constant output voltage with varying input

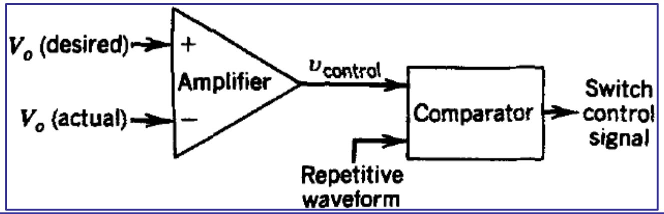


CONTROL OF dc-dc CONVERTERS: PWM Implementation





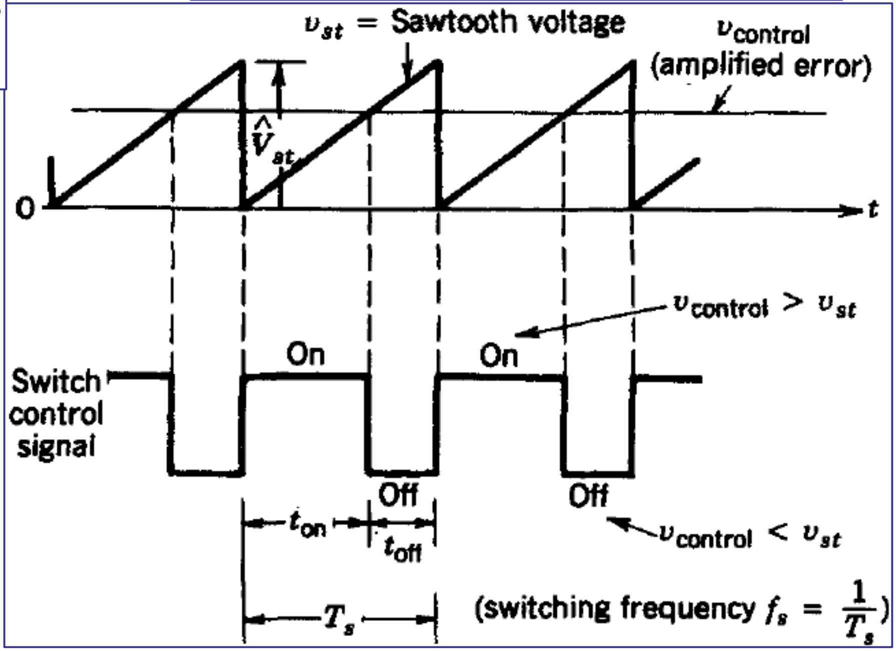




$$D = \frac{t_{on}}{T_s} = \frac{v_{control}}{\hat{V}_{st}}$$

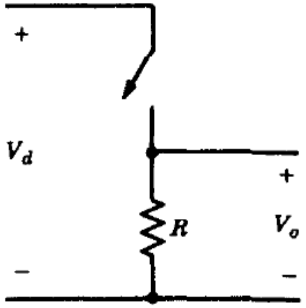
PWM switching:

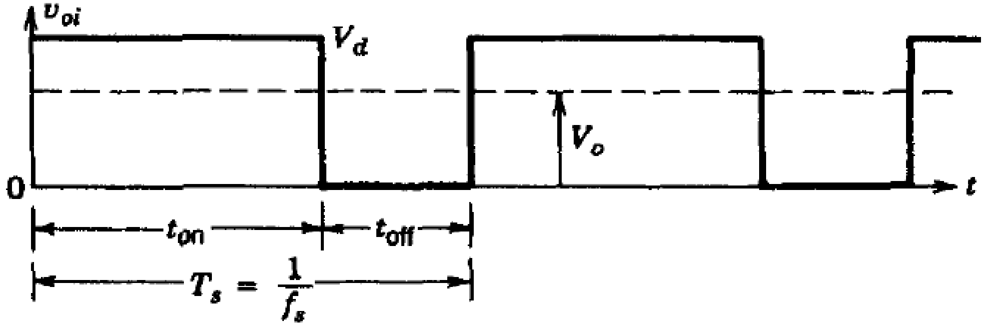
- the switch control signal is generated by comparing a signal-level control voltage *vcontrol*, with a repetitive waveform.
- *vcontrol* is obtained by amplifying the error.
- The frequency of the repetitive waveform with a constant peak establishes *f*.
- *f* is chosen to be in a few kilohertz to a few hundred kilohertz range.



A CHOPPER

Assuming ideal switch, constant *Vd*, and a purely resistive load R.



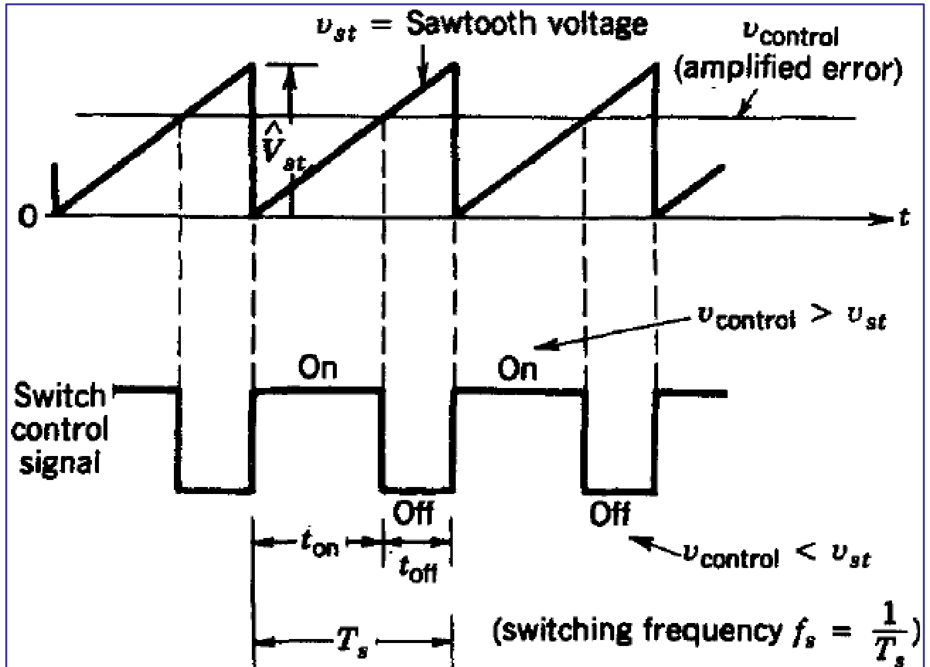


The average output voltage:

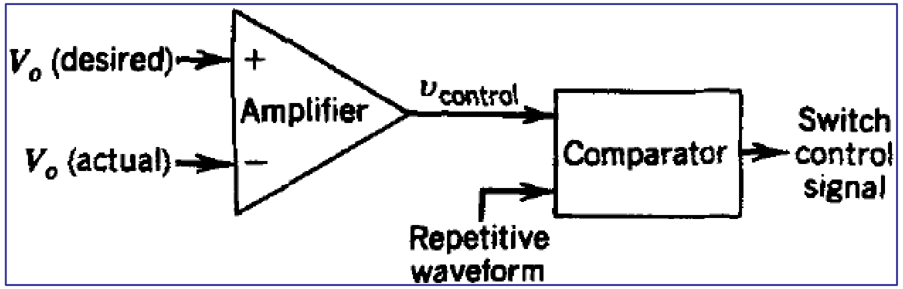
$$V_o = \frac{1}{T_s}\int_0^{T_s} v_o(t)\,dt = \frac{1}{T_s}\left(\int_0^{t_{on}} V_d\,dt + \int_{t_{on}}^{T_s} 0\,dt\right) = \frac{t_{on}}{T_s}V_d = DV_d$$

$$D = \frac{t_{on}}{T_s} = \frac{v_{control}}{\hat{V}_{st}} \qquad V_o = \frac{V_d}{\hat{V}_{st}}v_{control} = kv_{control} \qquad k = \frac{V_d}{\hat{V}_{st}} = \text{constant}$$

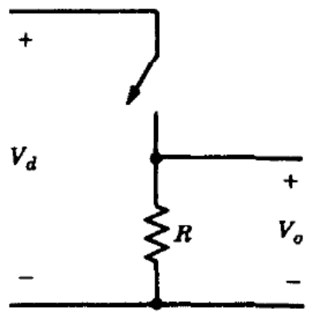
By varying D of the switch, *V0* can be controlled.

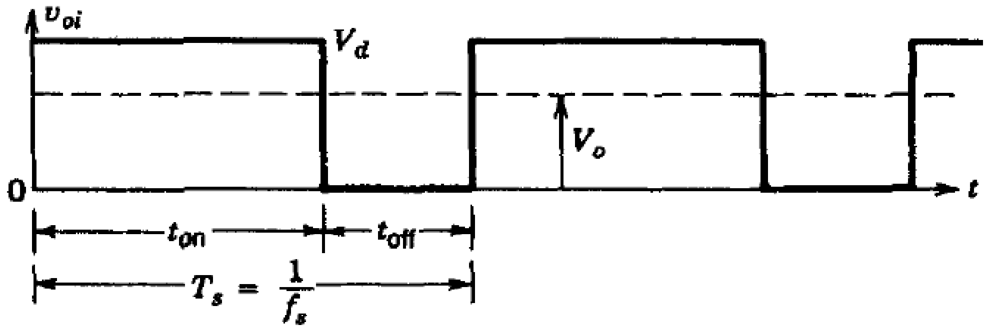


The average output volt. V_0 varies linearly with the $v_{control}$.



A CHOPPER



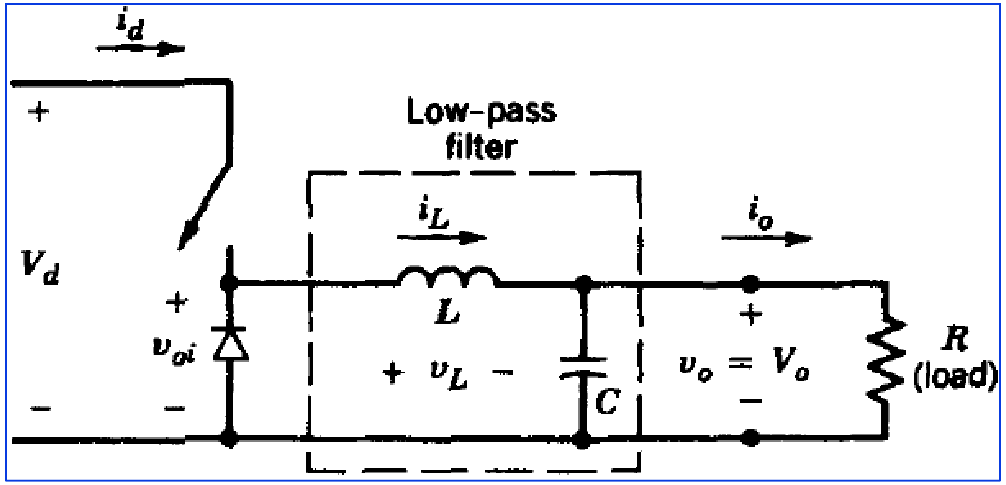


In actual applications, the foregoing circuit has two drawbacks:

(1) In practice the load would be inductive. Even with a resistive load, there would always be certain associated stray inductance. This means that the switch would have to absorb (or dissipate) the inductive energy and therefore it may be destroyed.

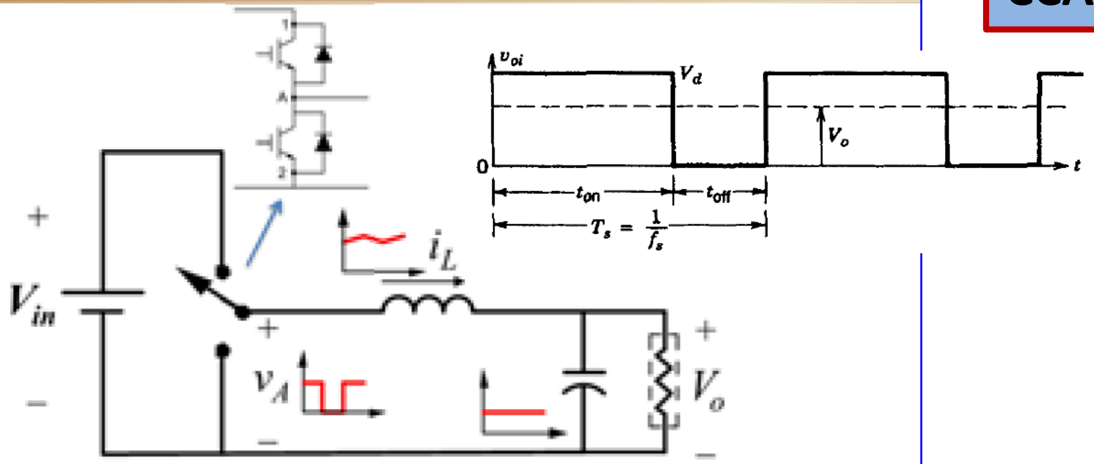
(2) The output voltage fluctuates between zero and *Vd* , which is not acceptable in most applications.

- ✓ The problem of stored inductive energy is overcome by using a diode.
- ✓ The output voltage fluctuations are very much diminished by using a low-pass filter, consisting of C & L.



Step-down converter example

CCA



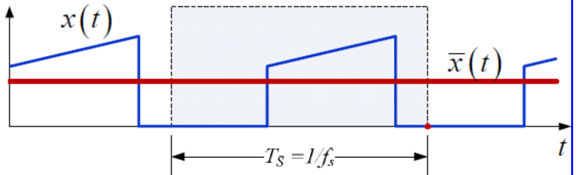
- By controlling the ON/OFF durations of the switches, we control the **periodic average** of bi-positional switch output, and in turn the average values of other quantities
- Most quantities have switching waveforms or high-frequency content, but for most control purposes we are only interested in average value

Cycle-by-cycle averaging (CCA)

- Average over a switching period referred to as cycle-by-cycle average (CCA)
- Control objectives achieved essentially by controlling the CCA value of different quantities
- Average models, steady-state analysis & controller design use CCA quantities

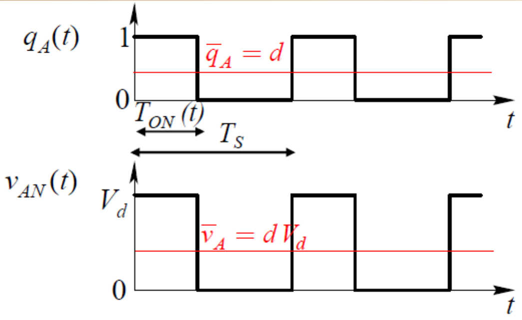
- Average over a switching period
- CCA values denoted by a bar (-) on top, like $\overline{v}_{AN}$, $\overline{i}_d$

$$\overline{x}(t) = \frac{1}{T_s}\int_{t-T_s}^{t} x(\tau)\,d\tau$$



- CCA quantities can be time varying

CCA value of q_A and v_{AN}



$$v_{AN}(t) = V_d\; q_A(t)$$

$$\overline{q}_A(t) = \frac{1}{T_S}\int_{t-T_s}^{t} q_A(t)\,dt = \frac{T_{ON}(t)}{T_S} = d(t)$$

$$\overline{v}_{AN} = \frac{1}{T_S}\int_{t-T_s}^{t} v_{AN}(t)\,dt = \frac{1}{T_S}\int_{t-T_s}^{t} V_d\; q_A(t)\,dt = V_d\; d(t)$$

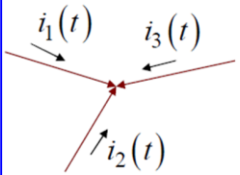
Some properties of CCA

- Just like instantaneous quantities, KCL and KVL apply for CCA quantities too

KCL: $\sum_k \overline{i}_k = 0$ — At a node

KVL: $\sum_k \overline{v}_k = 0$ — Around a loop

Instantaneous	CCA
$v(t) = R\,i(t)$	$\overline{v}(t) = R\,\overline{i}(t)$
$v_L(t) = L\frac{d}{dt}i_L(t)$	$\overline{v}_L(t) = L\frac{d}{dt}\overline{i}_L(t)$
$i_C(t) = C\frac{d}{dt}v_C(t)$	$\overline{i}_C(t) = C\frac{d}{dt}\overline{v}_C(t)$



$$i_1(t) + i_2(t) + i_3(t) = 0$$

Integrating both sides and dividing by T_s

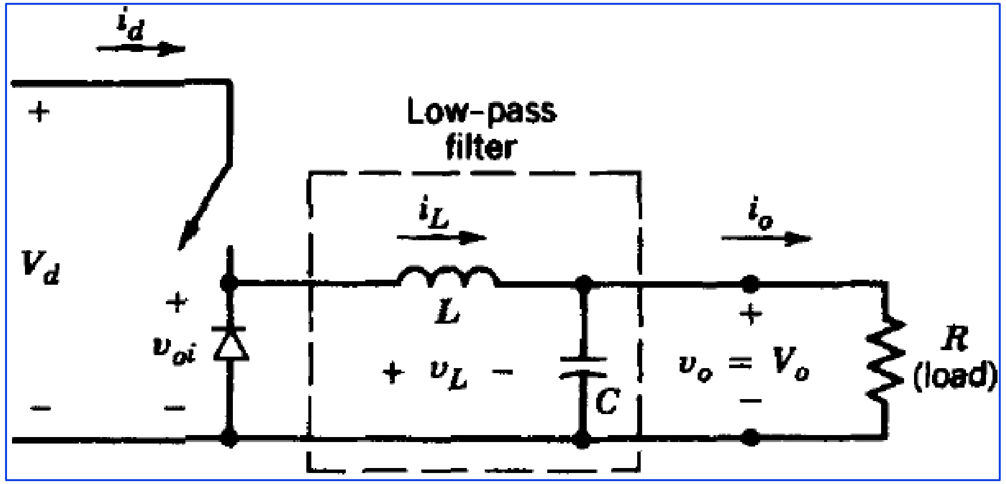
$$\frac{1}{T_S}\int_{t-T_s}^{t} i_1(t)\,dt + \frac{1}{T_S}\int_{t-T_s}^{t} i_2(t)\,dt + \frac{1}{T_S}\int_{t-T_s}^{t} i_3(t)\,dt = 0$$

$$\therefore \overline{i}_1 + \overline{i}_2 + \overline{i}_3 = 0$$

- CCA can be used in both steady-state and transient analysis
- Simulations based on CCA models are sometimes orders of magnitude faster
- Since the process of CCA removes the switching frequency component and its harmonics, phasor analysis can be applied (at fundamental frequency) in sinusoidal applications
- CCA analysis cannot be used for studying switching frequency ripple, switch stress and other high frequency effects

STEP-DOWN (BUCK) CONVERTER

- The converters are analyzed in **steady state**.
- The switches are treated as being **ideal**, and the **losses** in L and C are **neglected**.

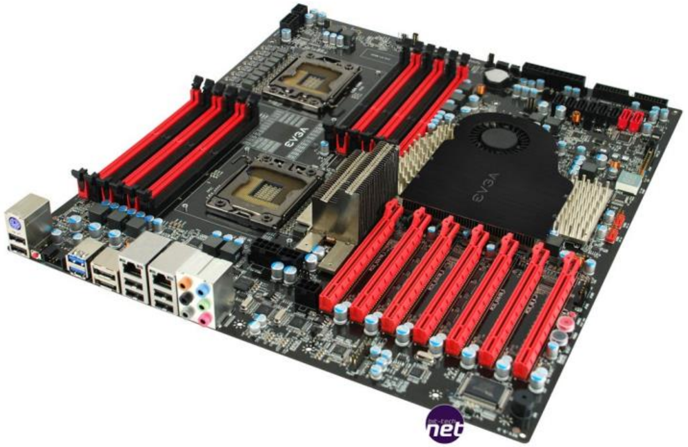


- A small **filter** is treated as an **integral part** in the **output stage** of the converter
- The **output** is assumed to supply a load that can be represented by an equivalent **resistance**. A dc motor load (the other application of these converters) can be represented by a dc voltage in series with the motor winding resistance and inductance.

- The **dc input voltage** to the converters is assumed to have **zero internal impedance**. It could be a battery source.
- However, in most cases, the input is a diode rectified ac line voltage with a large filter capacitance to provide a low internal impedance and a low-ripple dc voltage source.

BUCK CONVERTER APPLICATIONS

POL Converter for PCs and Laptops



USB On-The-Go

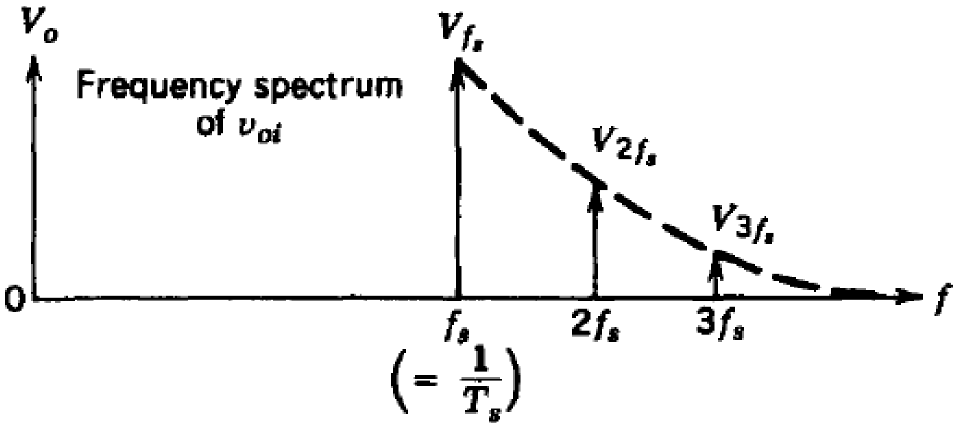
Solar Chargers

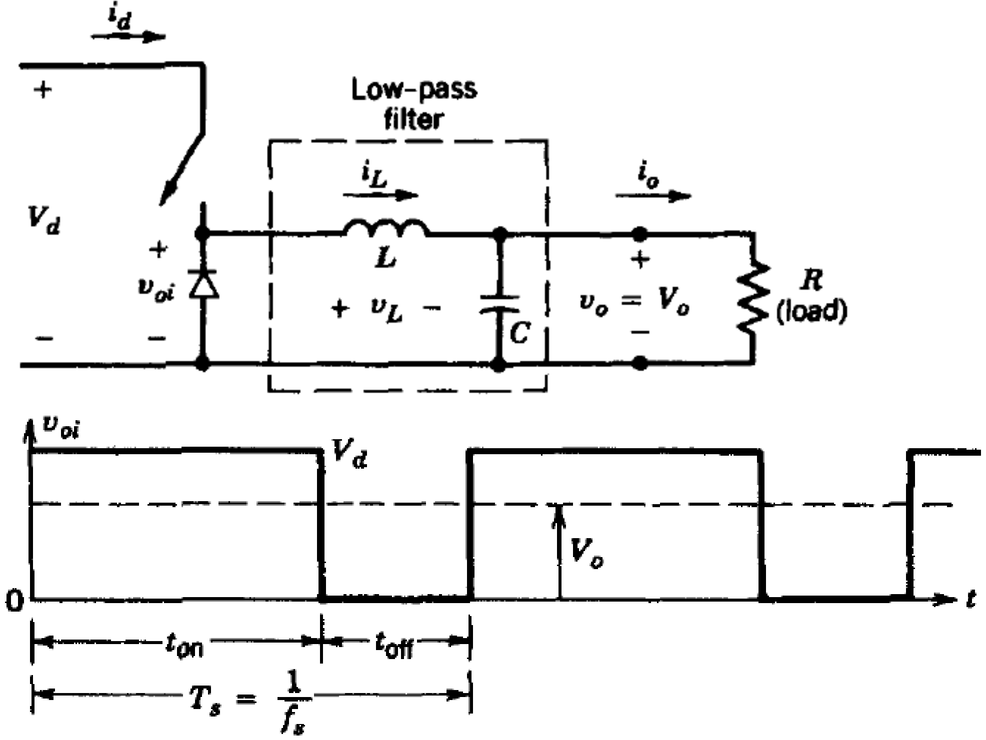
Battery Chargers

Quadcopters

The buck is widely used in low power consumption small electronics to step-down from 24/12V down to 5V. They are sold as a small finish product chip for well less than US$1 having about 95% efficiency.

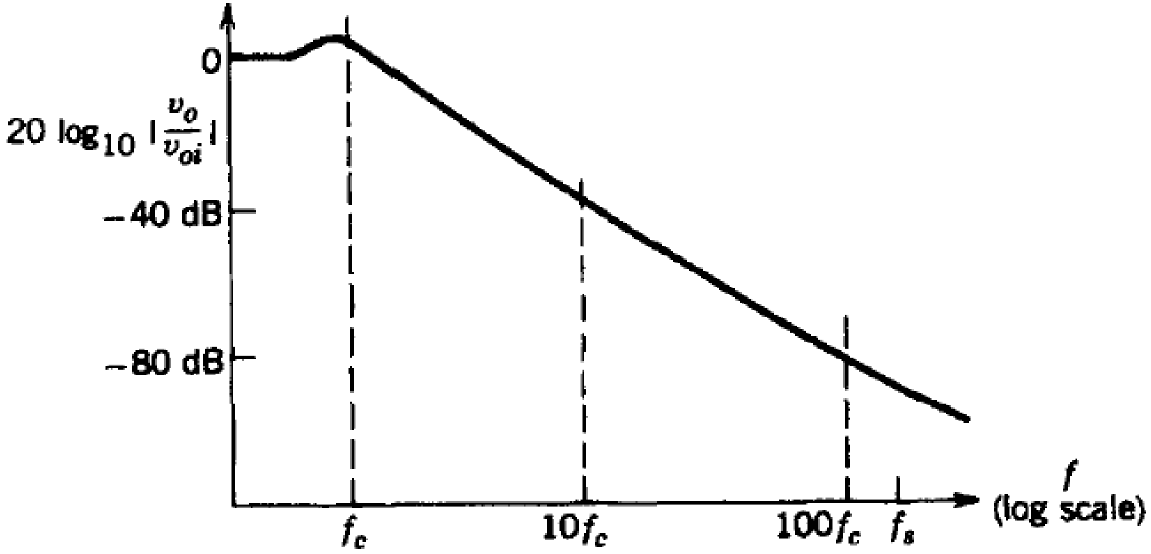
STEP-DOWN (BUCK) CONVERTER





A dc component V_0, and the harmonics at the switching frequency f_s and its multiples,

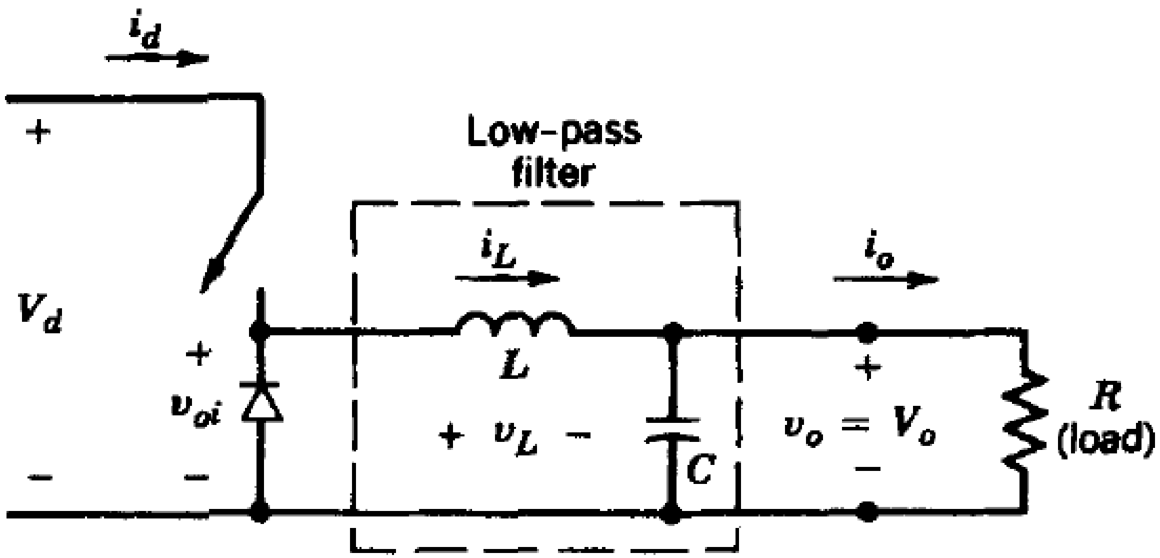
The corner frequency fc of the low-pass filter is selected to be much lower than the switching frequency, thus essentially eliminating the switching frequency ripple in the output voltage.

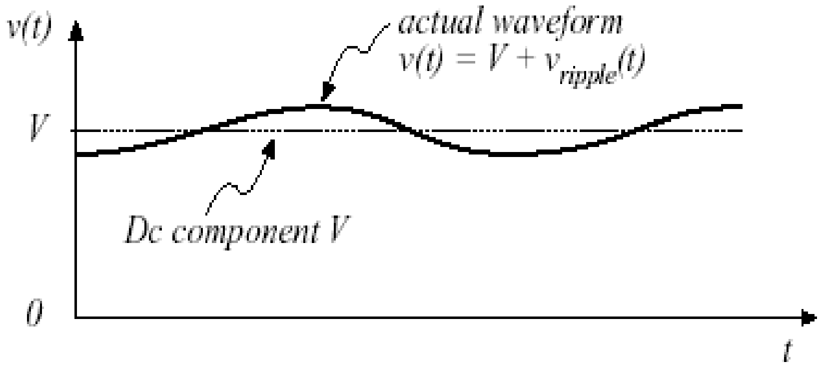


The low-pass filter characteristic

Thought process in analyzing basic DC/DC converters

- Basic operation principle (qualitative analysis)
  - How does current flow during different switching states
  - How is energy transferred during different switching states
- Verification of small ripple approximation
- Derivation of inductor voltage waveform during different switching states
- Quantitative analysis according to inductor volt-second balance or capacitor charge balance



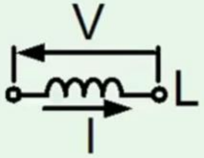


$$\left| v_{ripple} \right| << V$$

$$v(t) \approx V$$

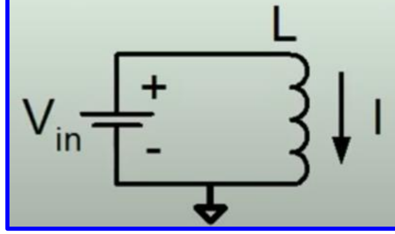
Inductor in Switched-mode Converters

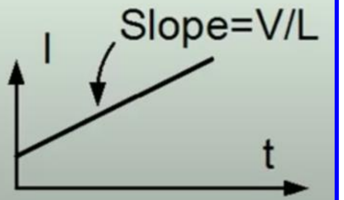
$$\frac{dI}{dt} = \frac{V}{L}$$

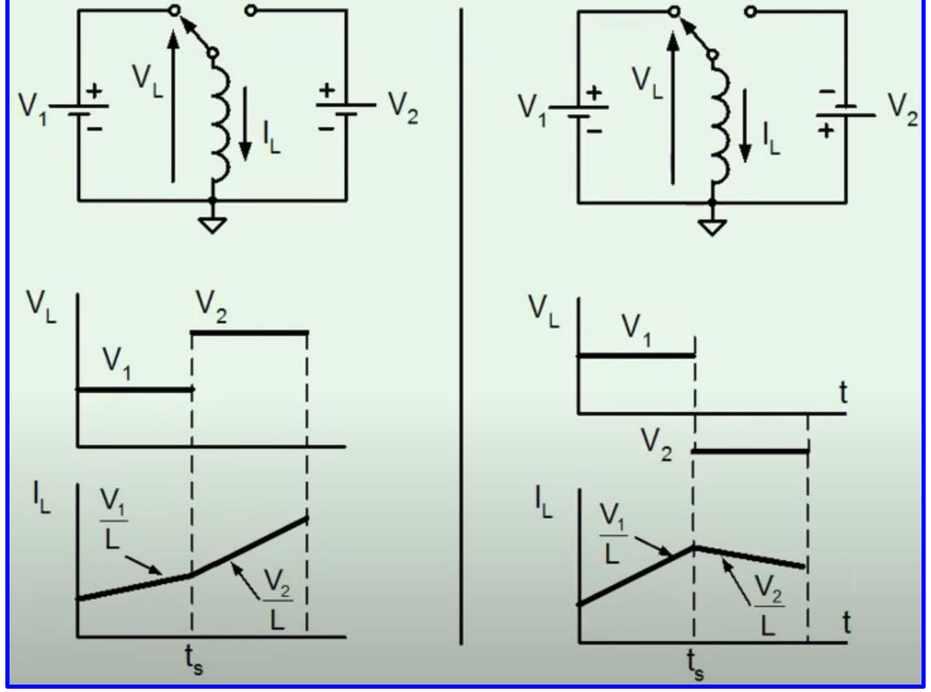


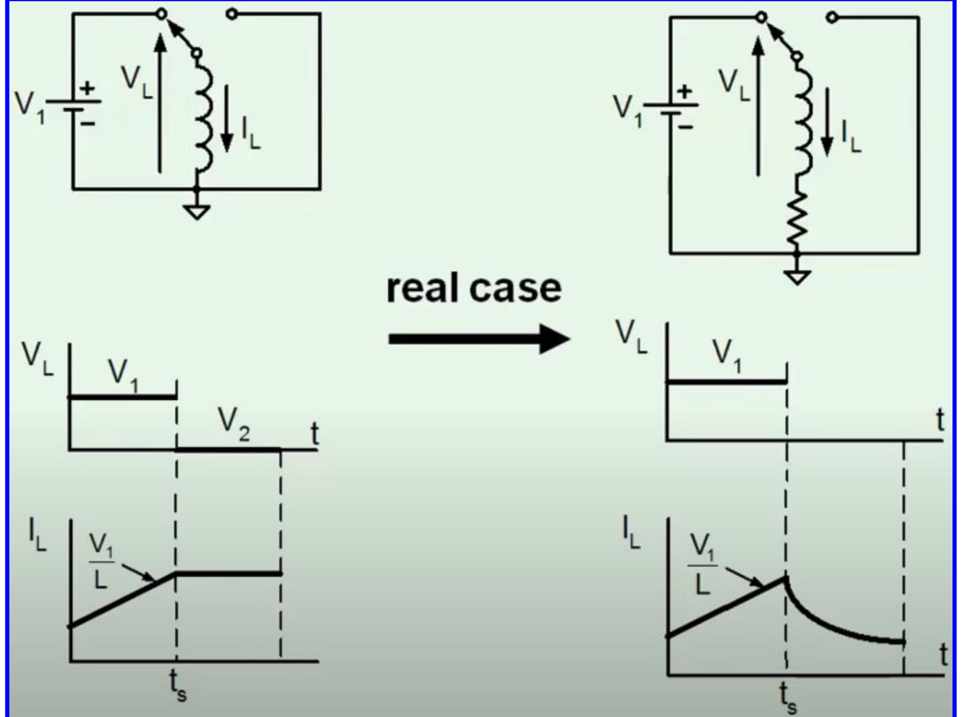
In most Power Electronics cases
V=constant over time period of interest

$$\frac{\Delta I}{\Delta t} = \frac{V}{L}; \qquad \Delta I = \frac{V}{L}\Delta t;$$





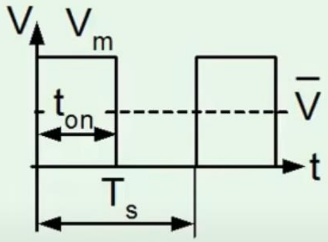


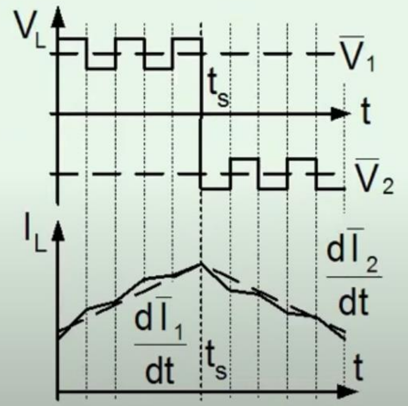


Average Signals

Most important equation in Power Electronics: $\frac{dI}{dt} = \frac{V}{L}$

Correct for average too: $\frac{d\bar{I}}{dt} = \frac{\bar{V}}{L}$





$$\bar{X} = \frac{1}{T}\int_0^T X dt$$

$\bar{X}$ - average

$$\bar{V} = \frac{V_m \cdot t_{on}}{T_s} = V_m D_{on}$$

Implication

For any practical system in steady state:

Average voltage on inductor $\overline{V}_L = 0$

Proof:

If $\overline{V}_L \neq 0$ then $\overline{I}_L \rightarrow \infty$

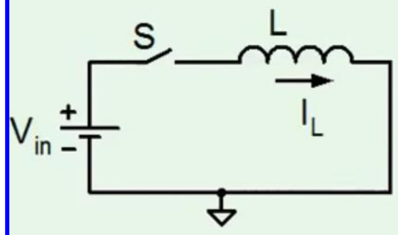
That is:

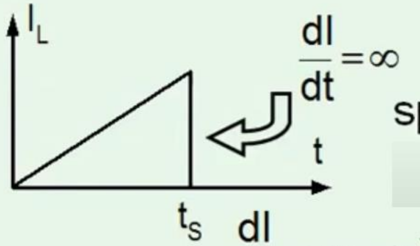
System must be designed such that:

$$\overline{V}_L = 0$$

Inductor in Switched-mode Converters

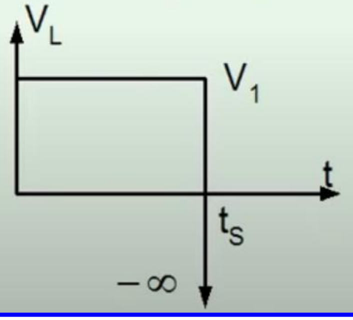
Inductor current interruption





spark

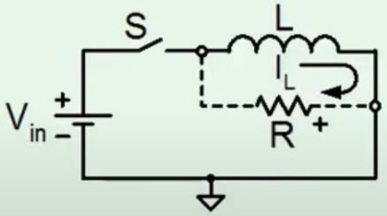
$$\frac{dI}{dt} = \infty \rightarrow V_L = \infty$$

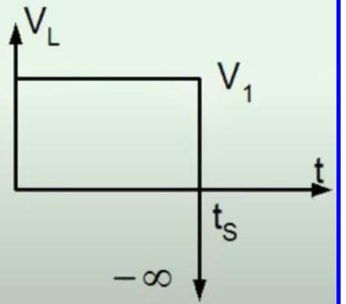


Inductor current interruption

What is the polarity?

The imaginary resistor method





Current continuity