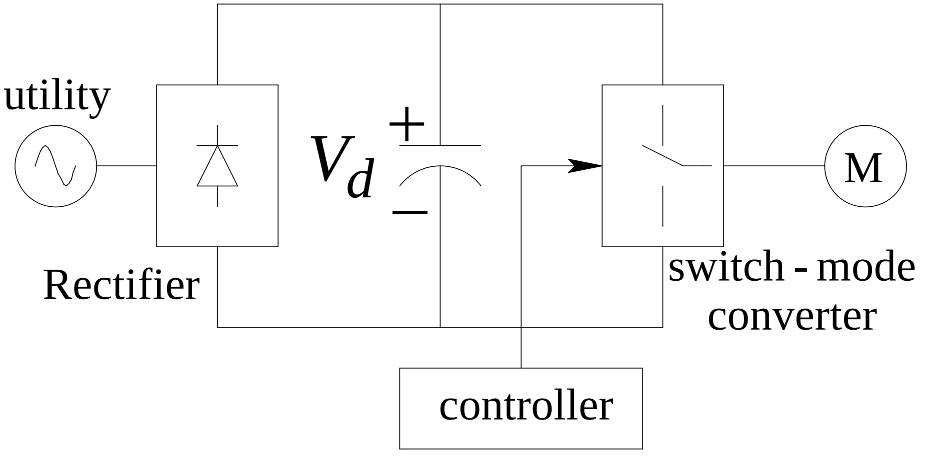
Chapter 4

Basic Understanding of Power Processing in Electric Drives and Non-Isolated Dc-dc Converters

Power Processing Unit (PPU)

- ❑ Efficient conversion of power from line frequency AC to appropriate form required by the motor

Sub-blocks of PPUs

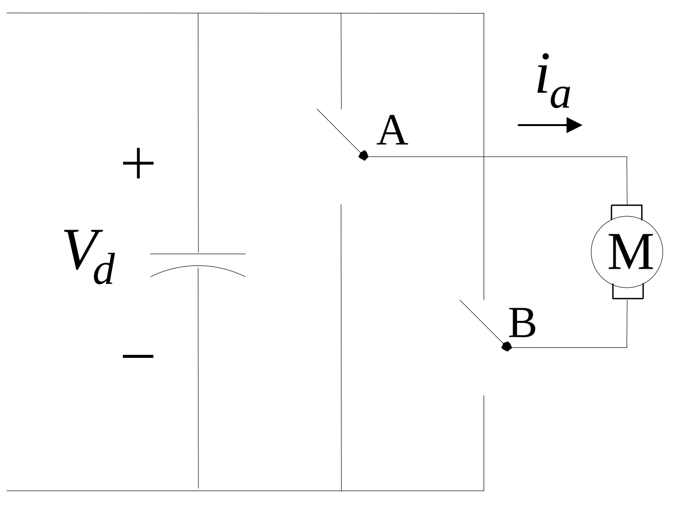


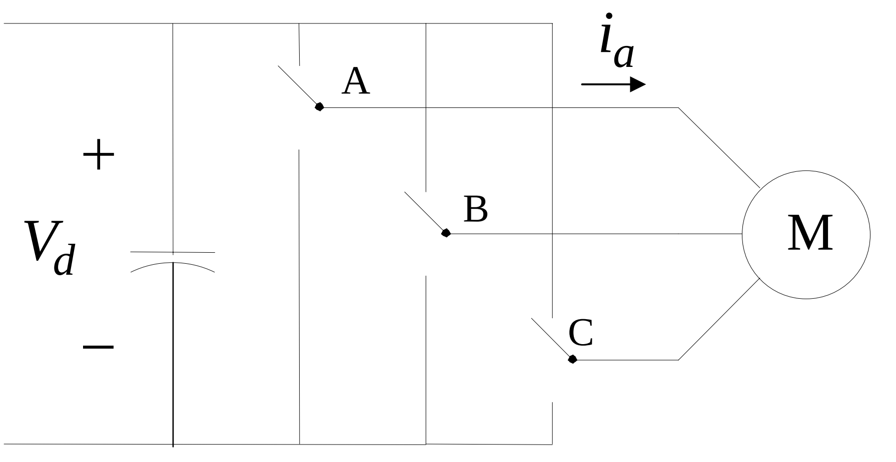
- ❑ Rectifier: Line frequency AC to DC
- ❑ Switch-Mode Converter: DC to form required by motor

Linear vs. Switch-mode Power

- Advantages of switchers vs. linears
  - Size, weight, efficiency
    - Higher frequency => smaller *L*s and *C*s
    - Motors: 1 to 20 kHz
    - DC-DCs: 10 kHz to > MHz (VRMs)
- Disadvantages of switchers vs. linears
  - Electrical ripple and noise (EMI)
  - Slower response (lower bandwidth)

Switch-Mode Converters for dc- and ac-motor drives



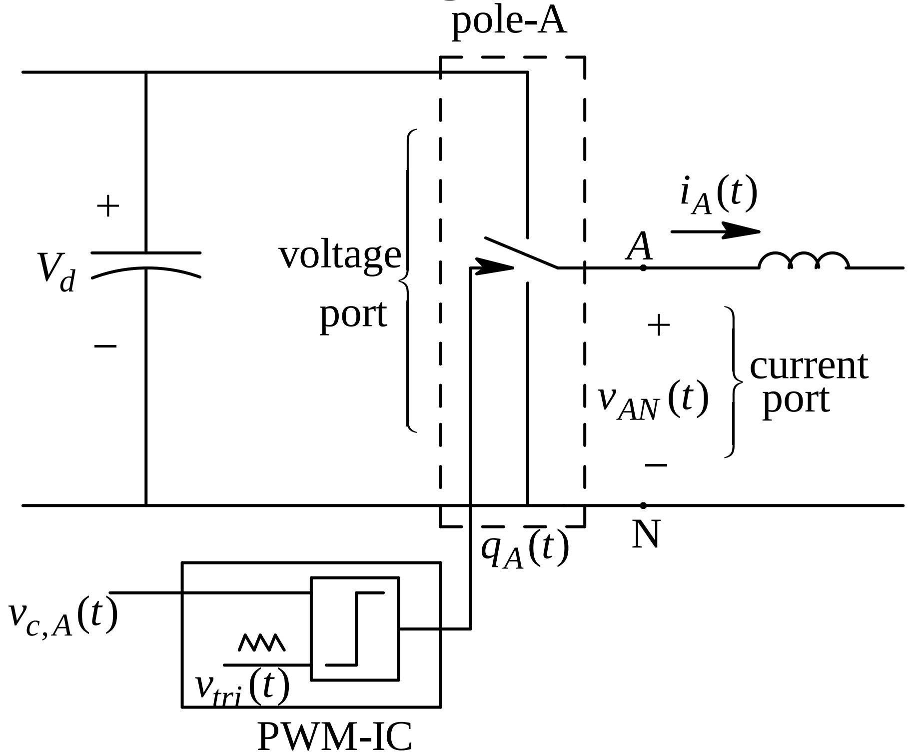


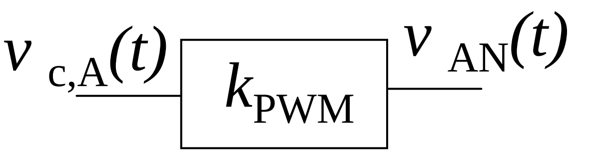
For DC Drives: 2-pole. Controls applied voltage and current

For AC Drives: 3-pole, 3 phase. Controls applied voltage, current, and frequency

Analysis of Switch-Mode Converters

- Pole as a Building Block



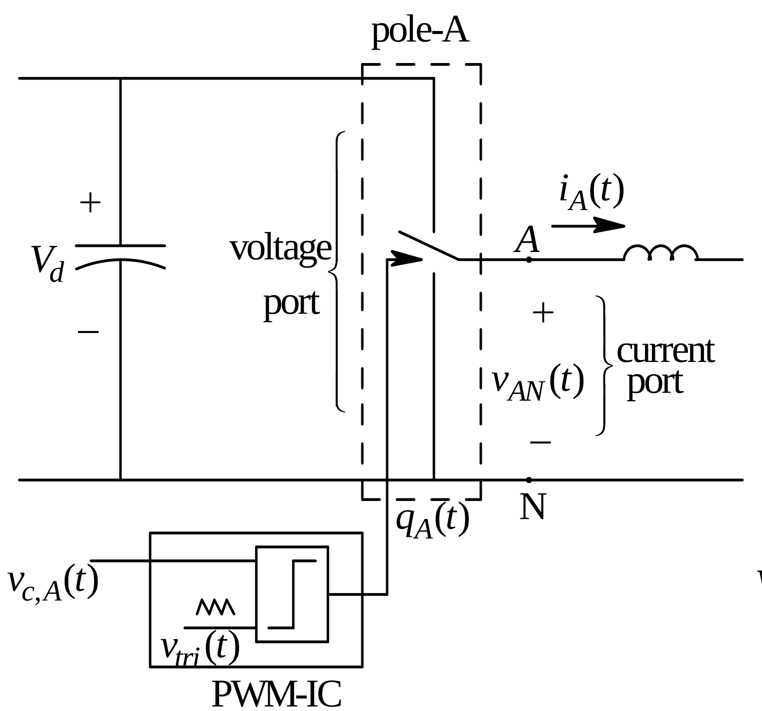


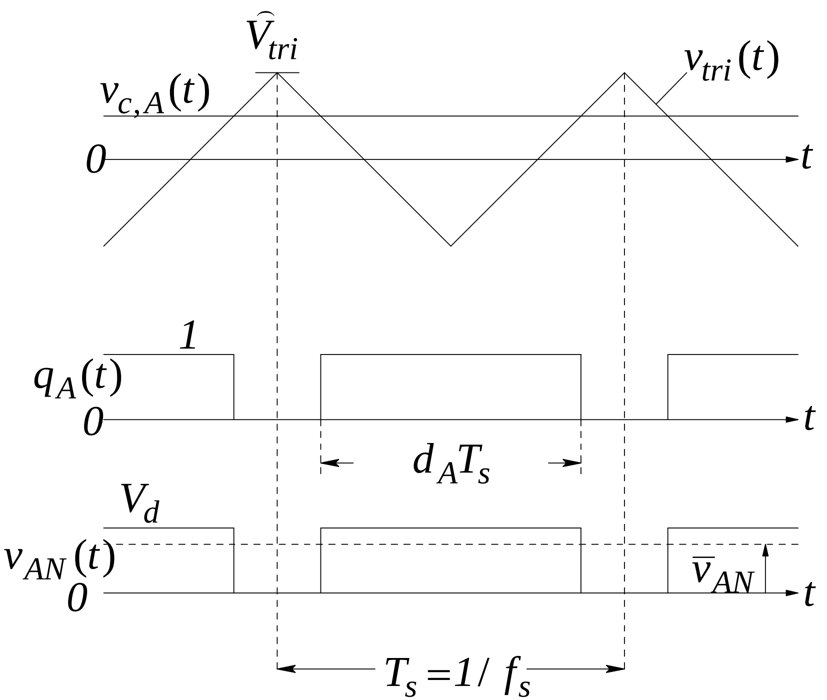
- V_d uncontrolled e.g. ac-dc rectifier, battery, fuel cell
- $v_{c,A}$: control voltage depicting desired output voltage
- Switch modulated to produce desired average voltage v_{AN}

Pulse Width Modulation (PWM)

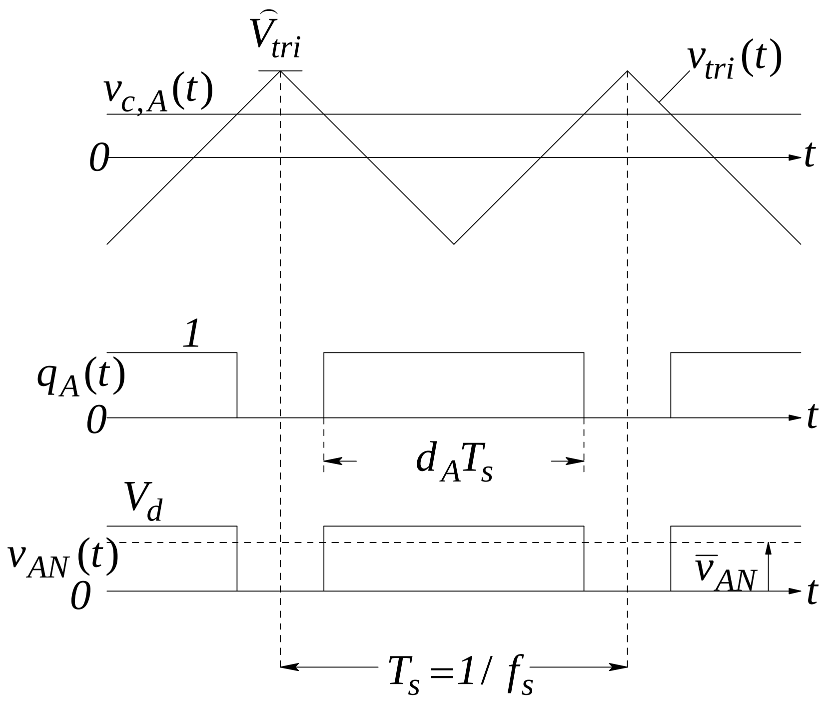
if $v_{c,A}(t) > v_{tri}(t) \Rightarrow q_A(t) = 1 \Rightarrow$ switch "up" $\Rightarrow v_{AN}(t) = V_d$

if $v_{c,A}(t) < v_{tri}(t) \Rightarrow q_A(t) = 0 \Rightarrow$ switch "down" $\Rightarrow v_{AN}(t) = 0$





Derivation of duty ratio, *d*



Let d_A be the ratio of the time $q_A = 1$ to the period of switching T_s

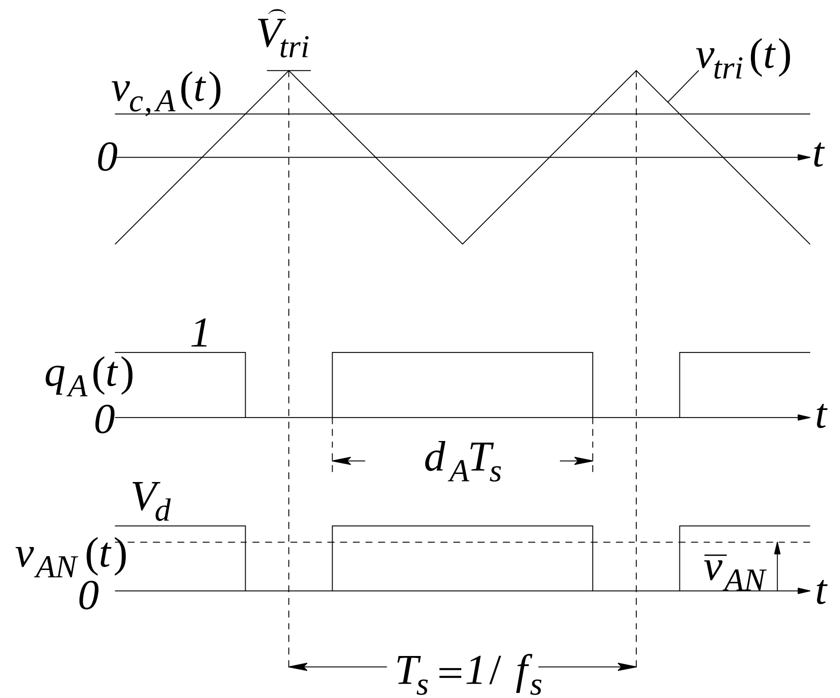
Let $(x, y) = (v_{cA}, d_A)$

d_A changes linearly with v_{cA} between the limits $(-\hat{V}_{tri}, 0)$ *and* $(+\hat{V}_{tri}, 1)$

Average Representation of a Pole

Output Voltage

Average output voltage over one switching cycle



Duty ratio $d_A = \frac{1}{2} + \frac{1}{2}\frac{v_{c,A}}{\hat{V}_{tri}}$

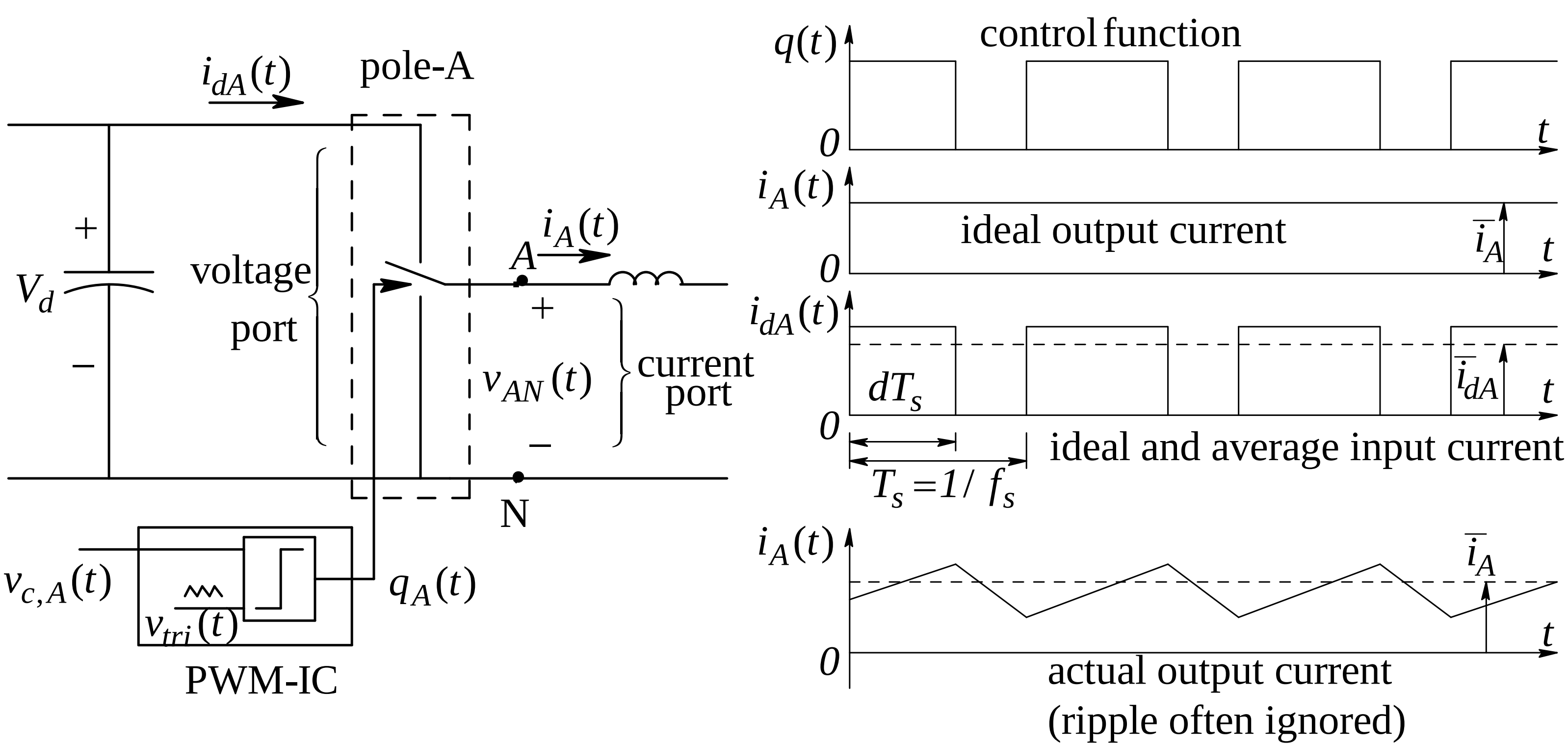
Pole gain

Pulsating $v_{AN}(t)$, relatively smooth $i_A(t)$

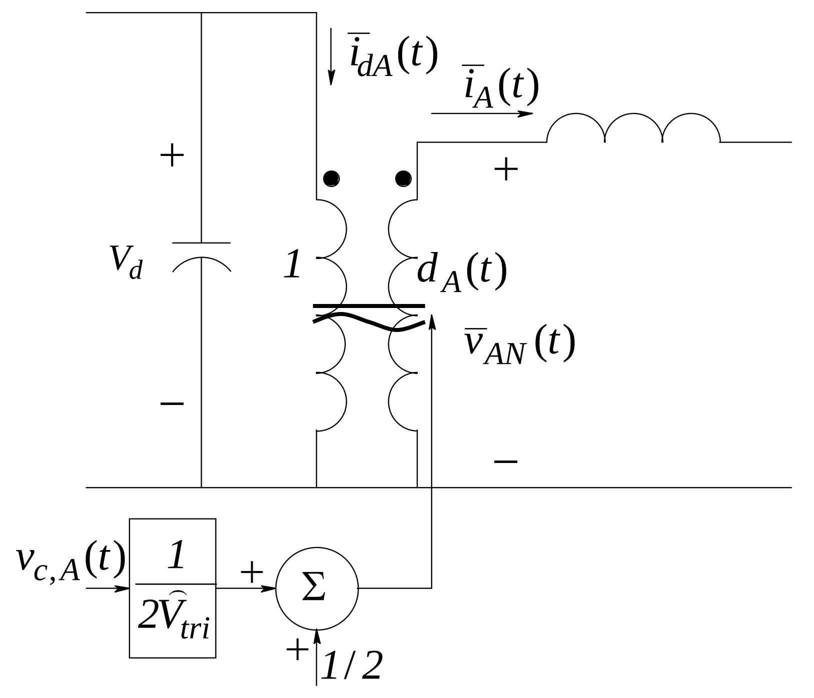
Average Representation of a Pole

Input and Output Currents

❑ Assuming ripple in $i_A(t)$ to be negligible, i.e. $i_A(t) = \bar{i}_A(t)$ average values of input and currents can be related as,

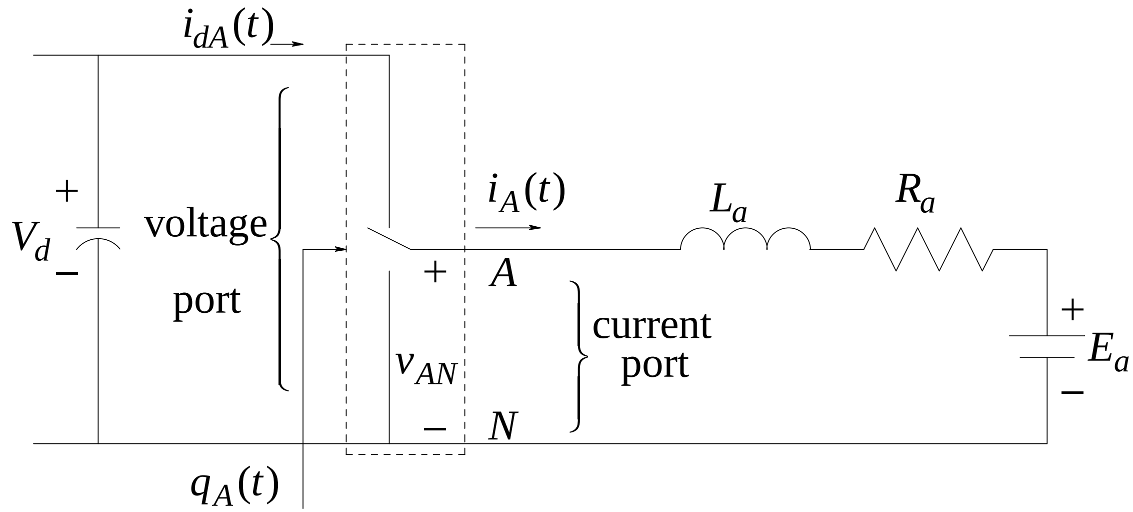


Average Representation of a Pole as An Ideal Transformer



- Transformer turns-ratio is adjustable via Pulse Width Modulation
- This Transformer can pass AC and DC currents but only unipolar voltages

Pole as a Two Quadrant Converter



- ❑ v_{AN} always positive
- ❑ i_A can reverse
  - ◆ $i_A > 0$ if $v_{AN} > E_a$

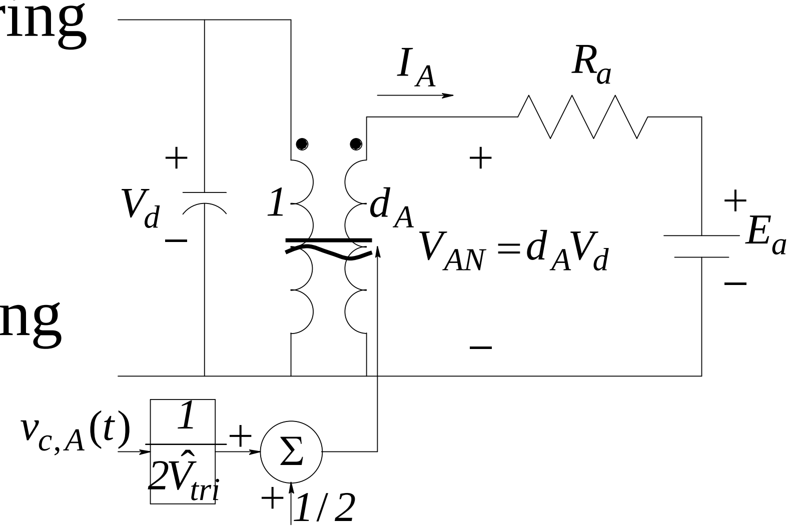
    power $V_d \rightarrow E_a$

    $\Rightarrow$ Buck Mode – forward motoring
  - ◆ $i_A < 0$ if $v_{AN} < E_a$

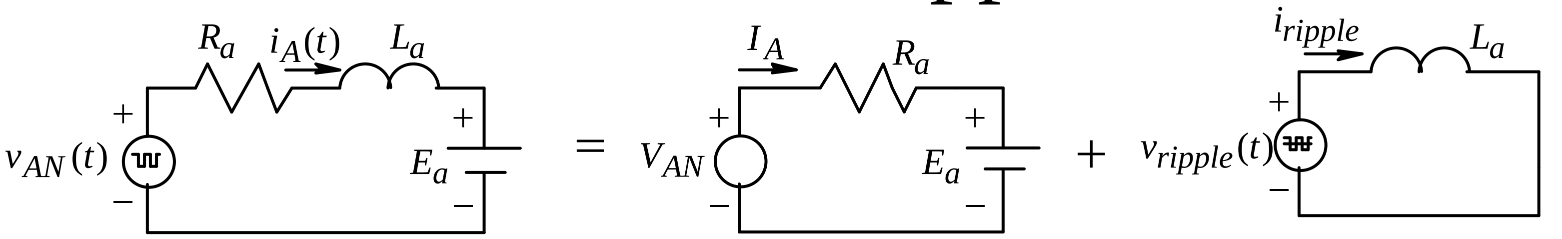
    power $E_a \rightarrow V_d$

    $\Rightarrow$ Boost Mode – forward braking

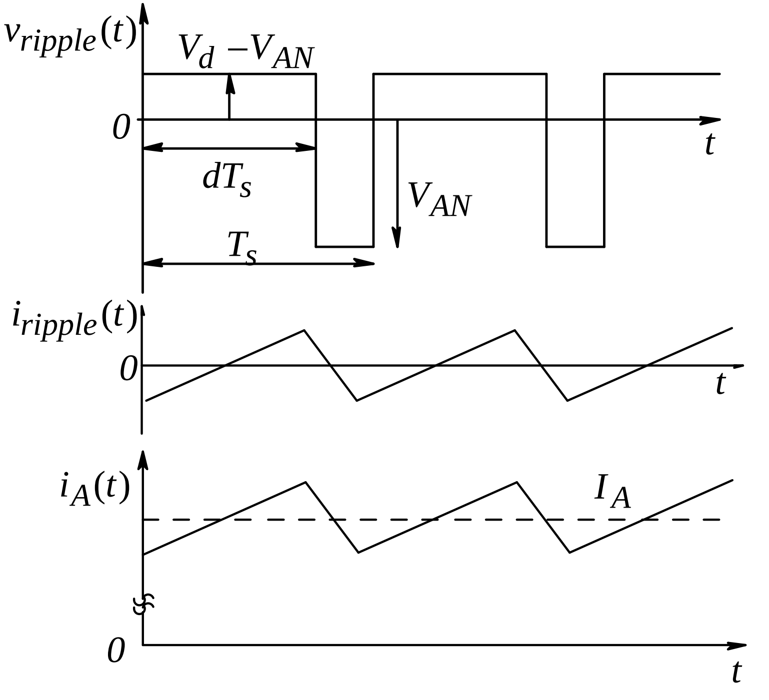
    (generating)



Calculation of Ripple Current

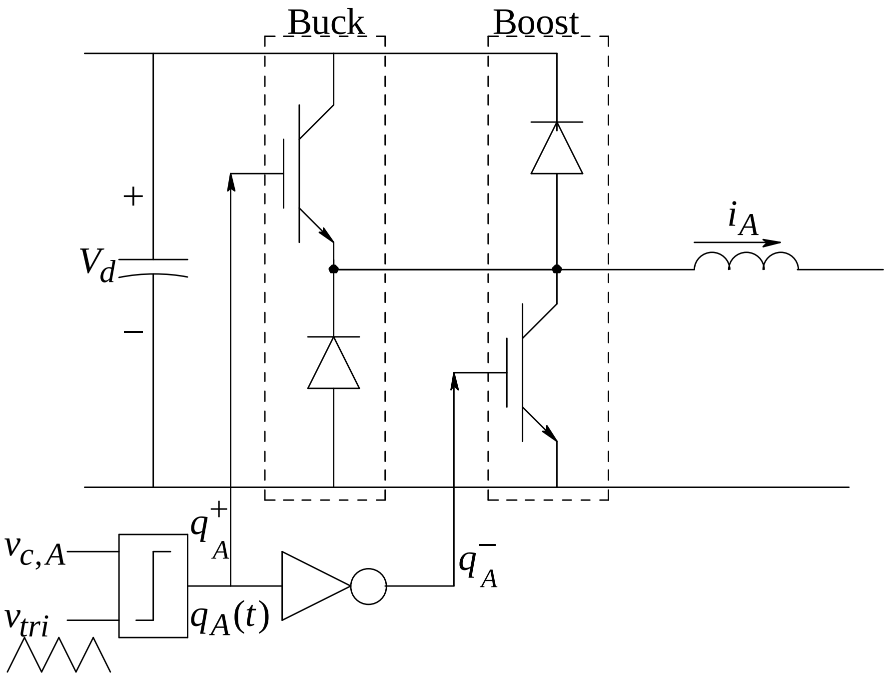


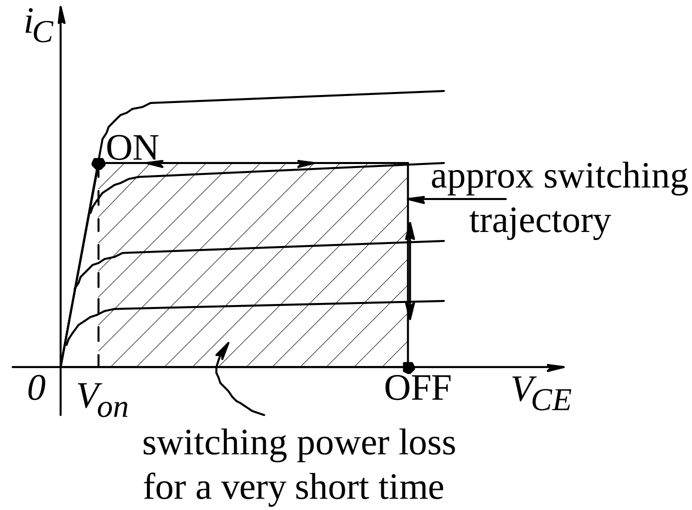
$$i_A(t) = I_A + i_{ripple}(t)$$



$i_{ripple}(t) =$ sawtooth with zero DC average

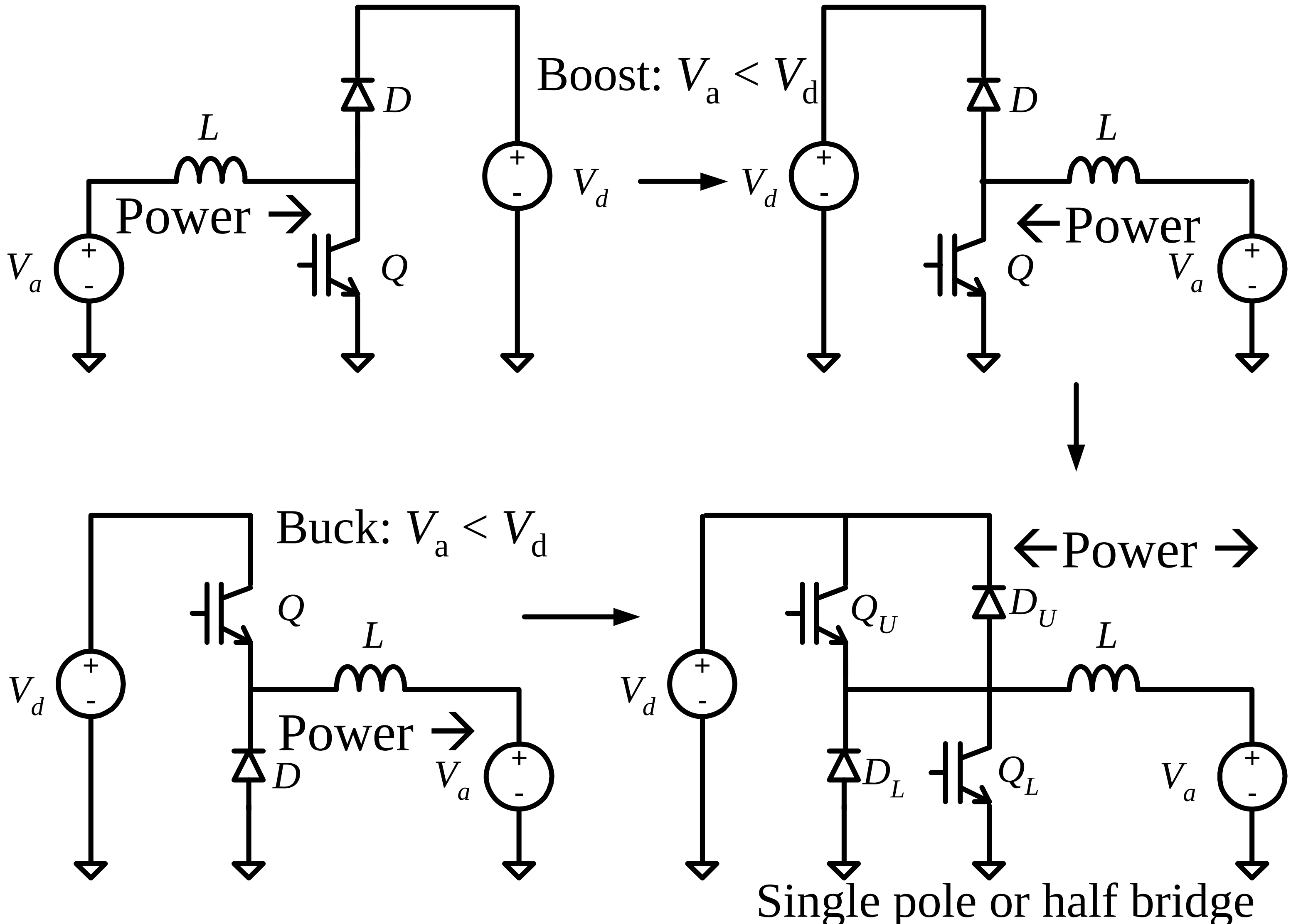
Implementation of Bi-Positional Switches



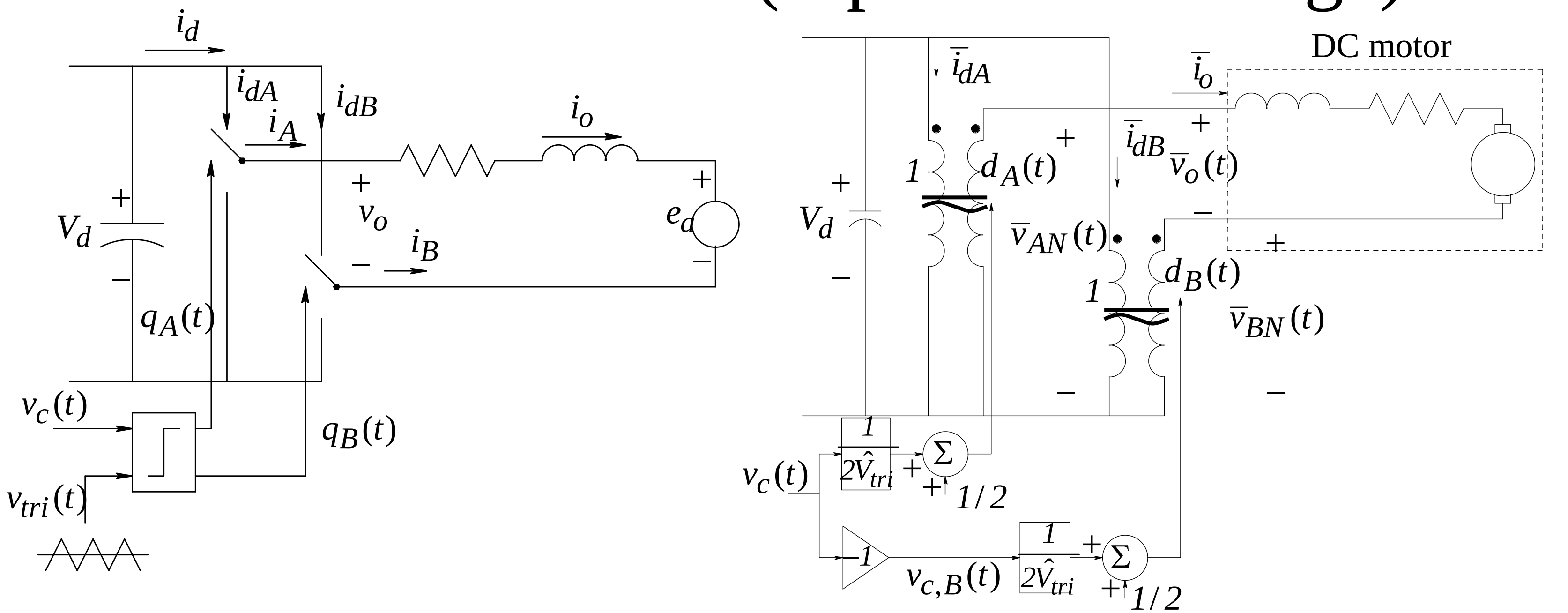


- ❑ Switching frequency 6 kHz to 50 kHz for drives
- ❑ Switching power loss: kept low by fast switching devices
- ❑ Conduction loss: kept low by having switches fully ON or fully OFF
- ❑ Gate drives omitted above

Buck + Boost = Bidirectional Pole

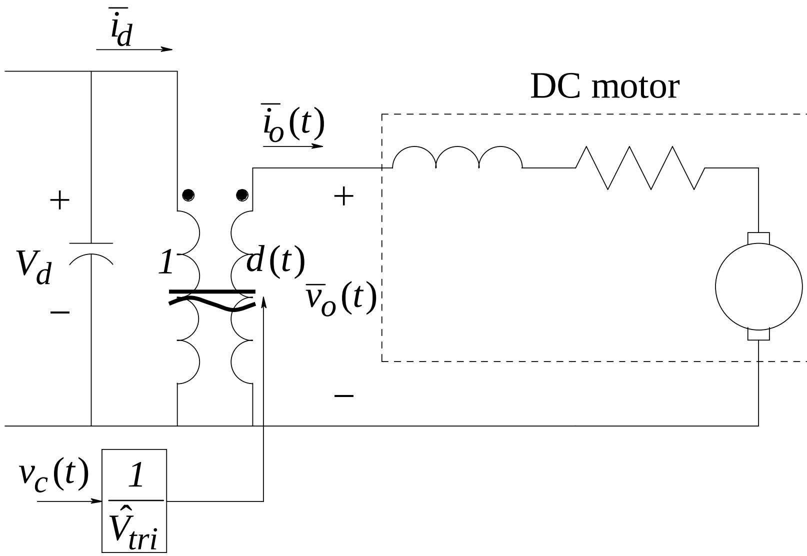


Switch-Mode Converters for DC-Motor Drives (2-pole or H-bridge)



❑ Output voltage can be positive or negative

Analysis of DC-Motor Drives Based on Average Quantities



- ❑ Combined transformer
- ❑ Four quadrant capability
- ❑ Transformer can pass AC or DC currents and voltages

Buck Converter – O/P voltage ripple

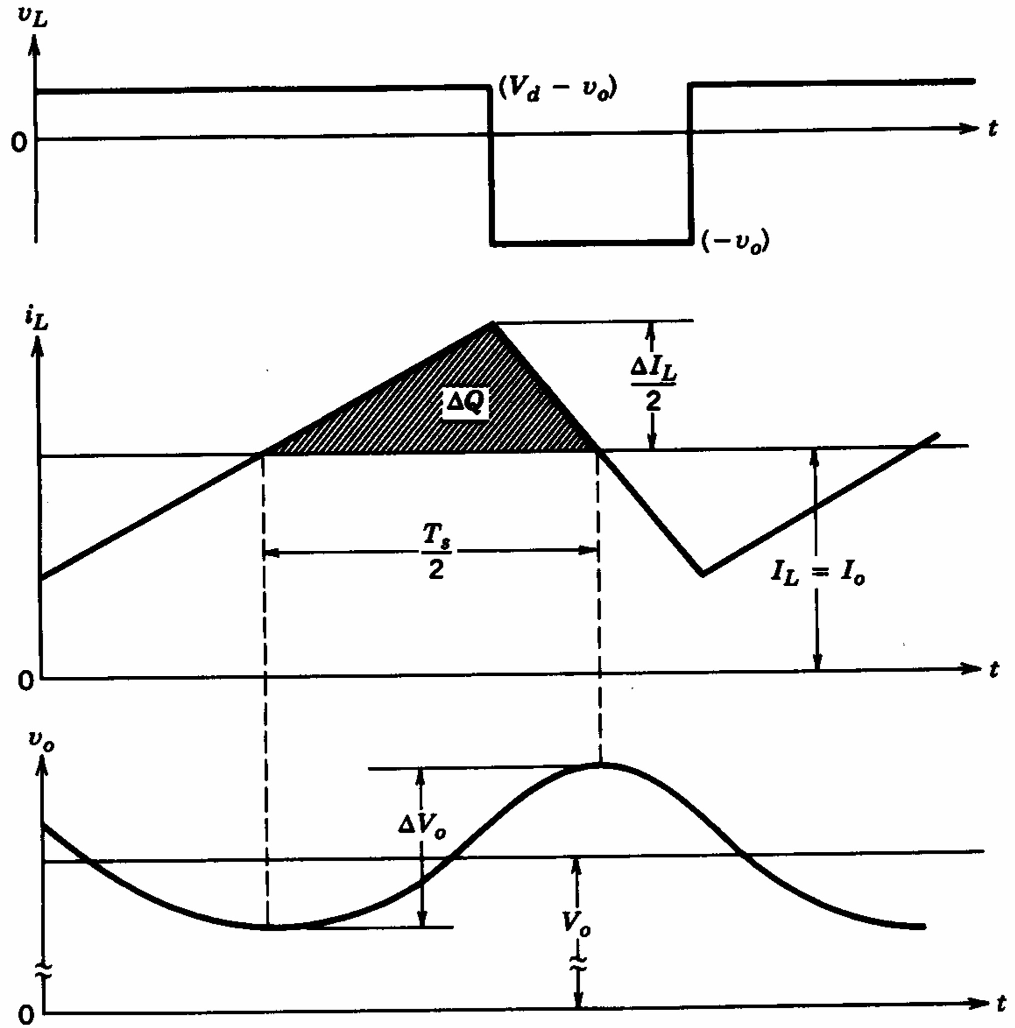
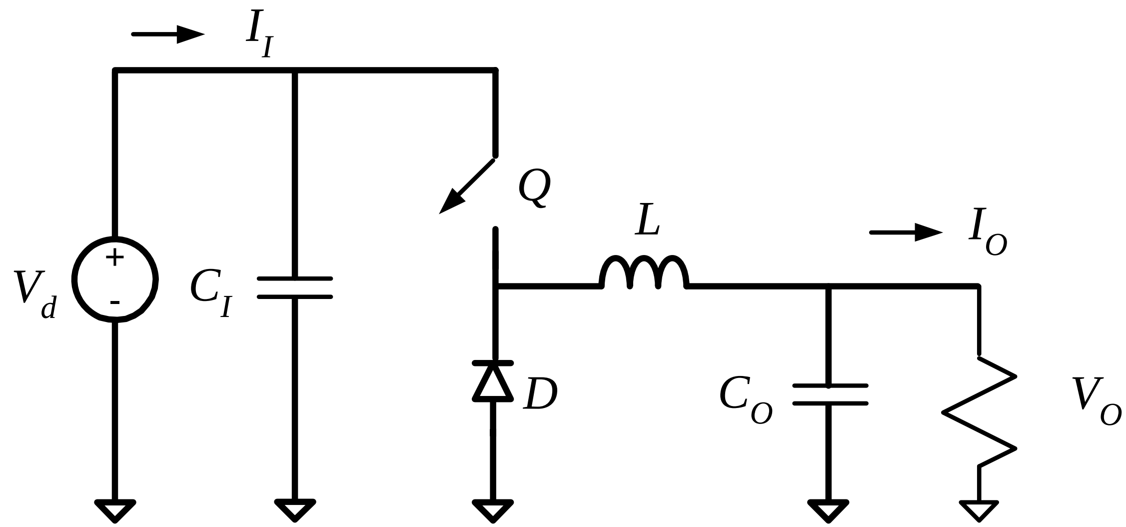


Figure 7-10 Output voltage ripple in a step-down converter.

Buck converter – Switch currents

Power MOSFET:



Power IGBT: $V_{CE} = V_{CE(knee)} + R_{slope} I_{CE}$

$$I_{Q(rms)} = \sqrt{d}\, I_{L(rms)}$$

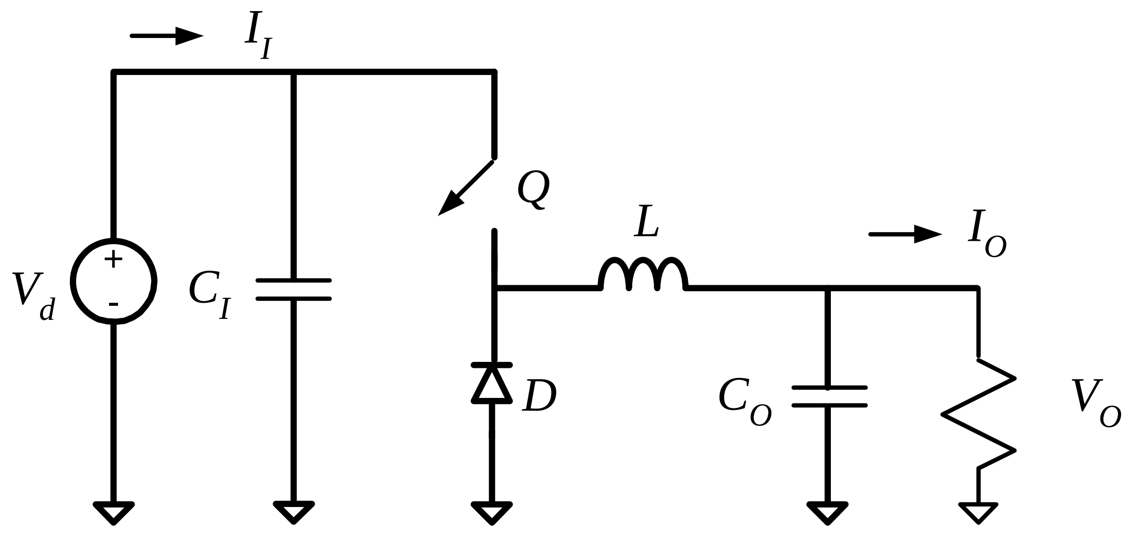
Power diode: $V_f = V_{knee} + R_f I_f$

$$I_{D(rms)} = \sqrt{(1-d)}\, I_{L(rms)}$$

Exit

Buck converter – I/P currents

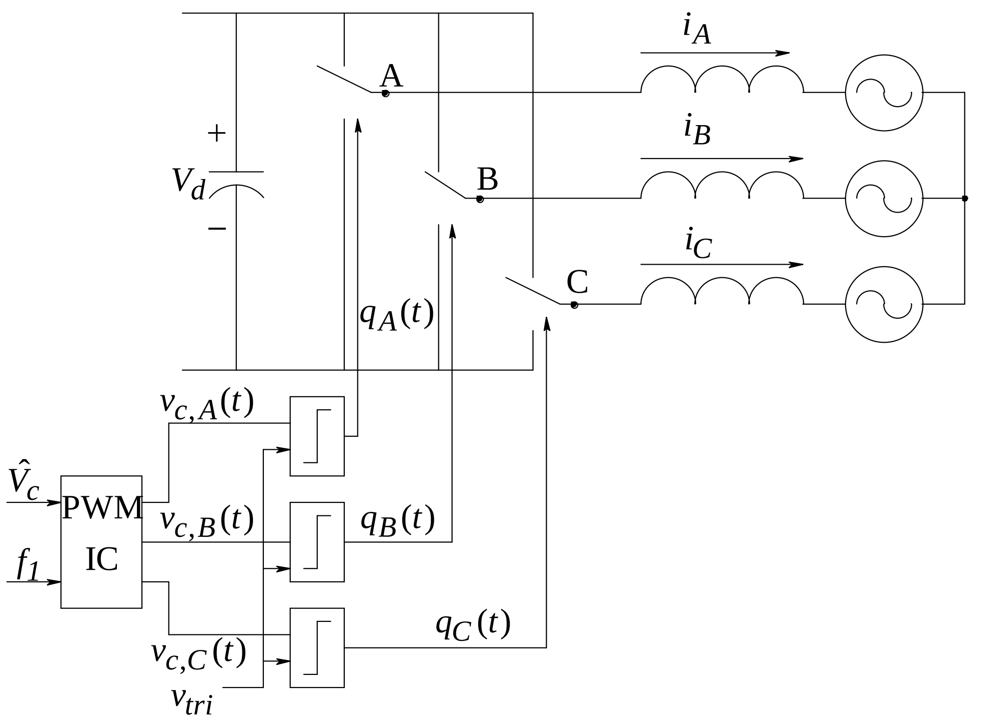
Input:

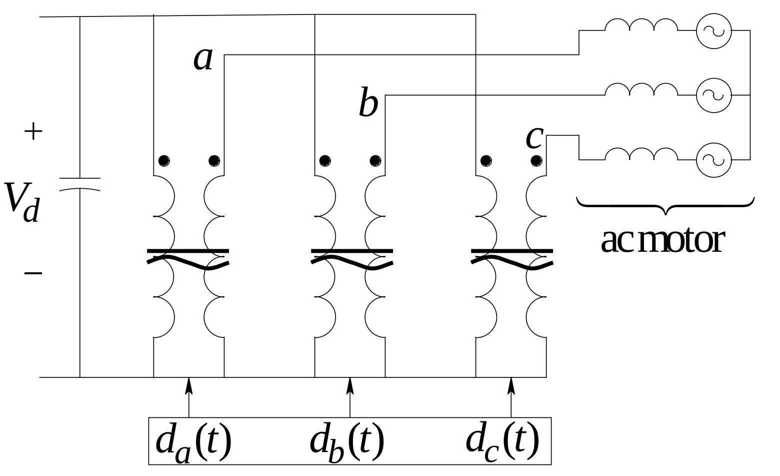


Input capacitor:

(assuming all the ripple comes from the cap)

Three Phase Inverter AC-Motor Drives



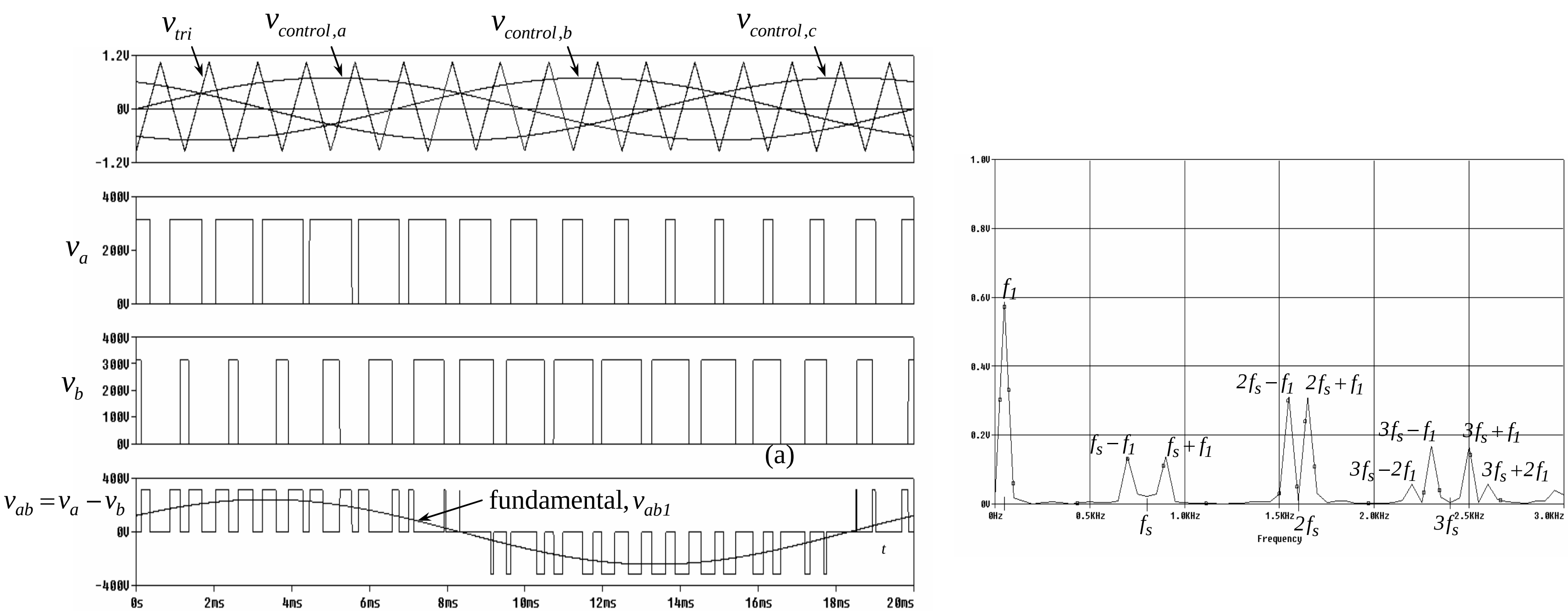


$$v_{c,A}(t) = \hat{V}_c \sin(\omega_1 t)$$

$$v_{c,B}(t) = \hat{V}_c \sin(\omega_1 t - 120^0)$$

$$v_{c,C}(t) = \hat{V}_c \sin(\omega_1 t - 240^0)$$

Harmonics in PPU



- PPU with switching frequency of 800 Hz generating a fundamental sine wave of 50 Hz
- Frequency spectrum shows large 50 Hz component and smaller components at higher frequencies due to switching
- These higher frequency components add to the losses in the motor

Transformer Equivalent of a Three Phase Converter

Voltages with respect to to N

$$\bar{v}_{AN}(t) = \frac{V_d}{2} + \frac{V_d}{2}\frac{\hat{V}_c}{\hat{V}_{tri}}\sin(\omega_1 t)$$

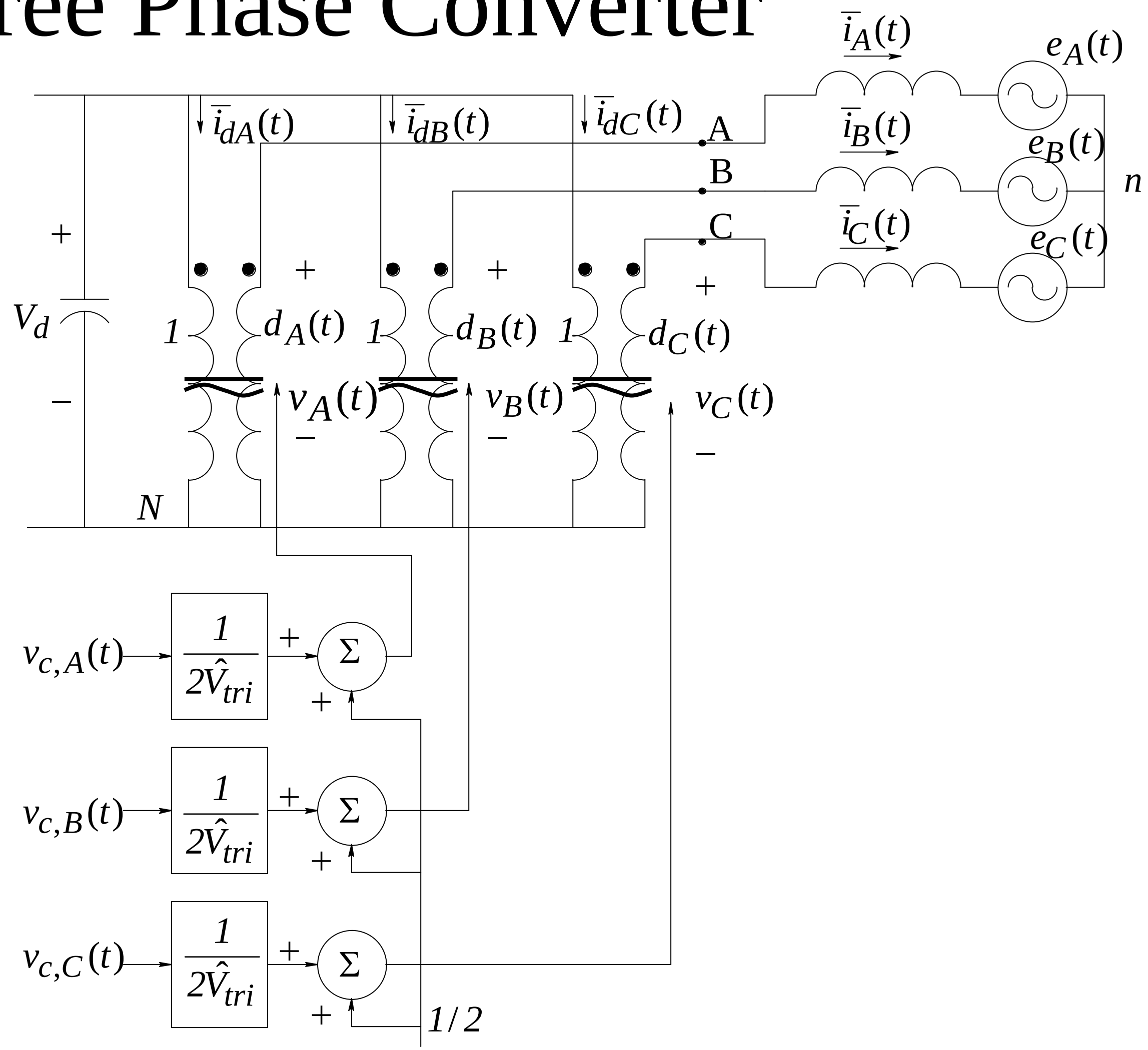
$\vdots$

Voltages with respect to load-neutral n

$$\bar{v}_{An}(t) = \underbrace{\frac{V_d}{2\hat{V}_{tri}}}_{k_{pole}} \hat{V}_c \sin(\omega_1 t)$$

$$= k_{pole} \hat{V}_c \sin(\omega_1 t)$$

$\vdots$



DC offset voltages disappear when voltages are with respect to load neutral

Sinusoidal PWM

Control:

Duty ratio:

Pole:

Phase:

Line:

Modulation Index, *m*

$$m = \frac{\hat{V}_d}{\hat{V}_{Tri}}$$

Phase voltage $v_{An}(t) = V_{ph} = \frac{V_d}{2} m \sin(\omega t)$

Sinewave modulation $m < 1; \quad \hat{V}_c \leq \hat{V}_{Tri}$

Max. Sinewave

Over modulation $m > 1; \quad \hat{V}_c > \hat{V}_{Tri}$

Max. = Squarewave
(inc. 40 % THD)

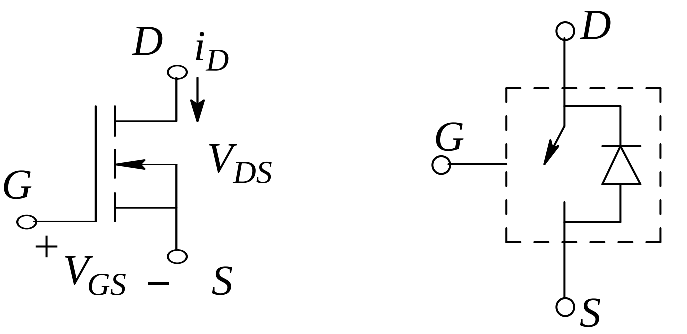
(RMS of 1st harmonic)

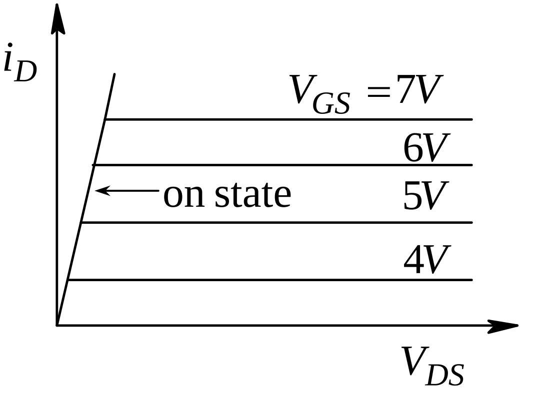
Power Devices

❑ Voltage rating	up to 9kV
❑ Current rating	~ kA
❑ Switching items	~ 0.1 μs
❑ On-State voltage drop	1V to 3V
❑ Cost	

Controlled Switches

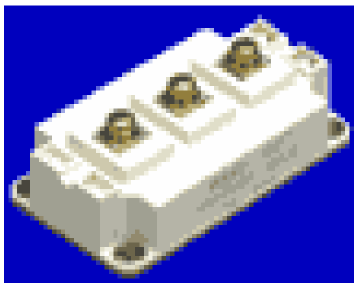
❑ MOSFET

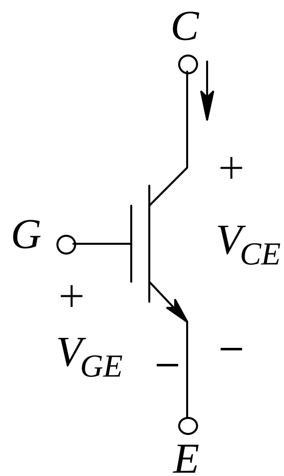


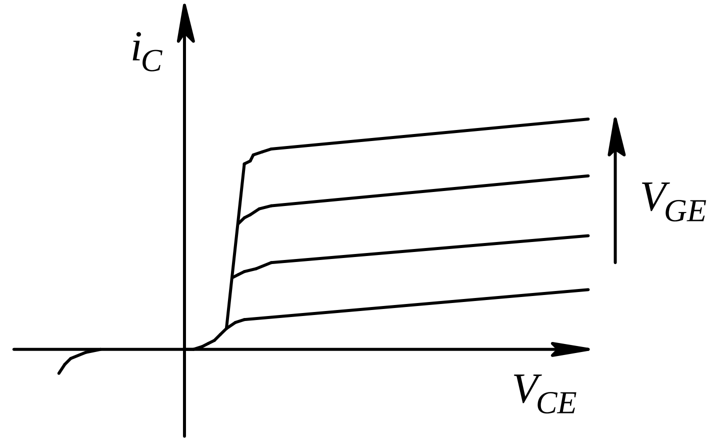


- Insulated gate for low gate requirements
- Built-in free diode
- r_{ds} increases exponentially with voltage rating
- Good for low voltage, high frequency

❑ IGBT - Insulated Gate Bipolar Transistor



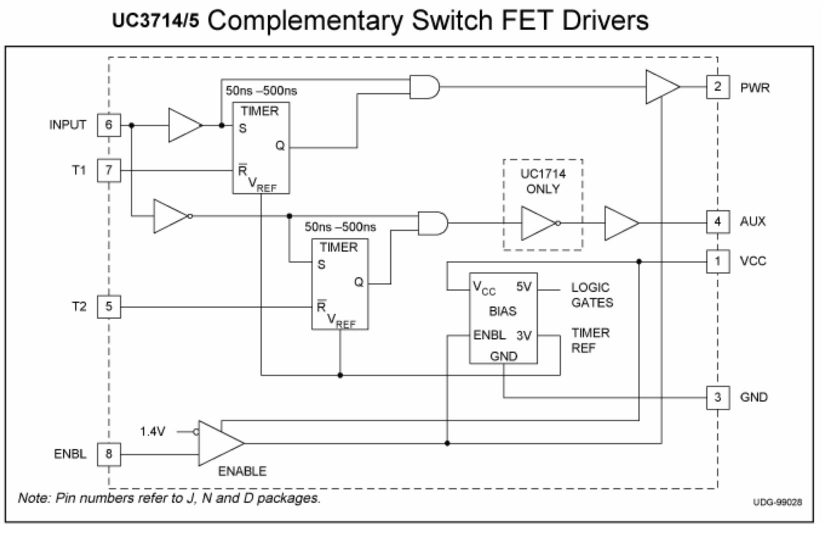




- Insulated Gate for low drive requirements
- Moderately high switching frequency
- Lower conduction losses than MOSFETs in high voltage devices
- Higher voltage (up to several kV) and current rating in the kA range
- Short-circuit capability – very important in drives

❑ Smart Power Modules

- Gate Driver ICs
- Power Modules with Gate drivers



Summary

- What is the function of PPUs?
- What are the sub-blocks of PPUs?
- What are the roles of the rectifier and the filter-capacitor sub-blocks?
- Qualitatively, how does a switch-mode amplifier differ from a linear amplifier?
- Why does operating transistors as switches result in much smaller losses compared to operating them in their linear region?
- How is a bi-positional switch realized in a converter pole?
- What is the gain of each converter pole?
- How does a switch-mode converter pole approach the output of a linear amplifier?
- What is the meaning of $\bar{v}_{AN}(t)$?

Summary

- ❑ How is the pole output voltage made linearly proportional to the input control signal?
- ❑ What is the physical significance of the duty-ratio, for example $d_A(t)$?
- ❑ How is pulse-width-modulation (PWM) achieved and what is its function?
- ❑ Instantaneous quantities on the two sides of the converter pole, for example pole-A, are related by the switching signal $q_A(t)$. What relates the average quantities on the two sides?
- ❑ What is the equivalent model of a switch-mode pole in terms of its average quantities?
- ❑ How is a switch-mode dc-dc converter which can achieve an output voltage of either polarity and an output current flowing in either direction realized?

Summary

- What is the frequency content of the output voltage waveform in dc-dc converters?
- In a dc-drive converter, how is it possible to keep the ripple in the output current small, despite the output voltage pulsating between 0 and V_d, or 0 and $-V_d$, during each switching cycle?
- What is the frequency content of the input dc current? Where does the pulsating ripple component of the dc-side current flow through?
- How is bi-directional power flow achieved through a converter pole?
- What makes the average of the dc-side current in a converter pole related to the average of the output current by its duty-ratio?

Summary

- How are three-phase, sinusoidal ac output voltages synthesized from a dc voltage input?
- What are the voltage and current ratings and the switching speeds of various power semiconductor devices?