Electrical Drives I

Week 7: Solid state dc drives- open loop DC chopper drives

Power Electronic Converters for DC Drives

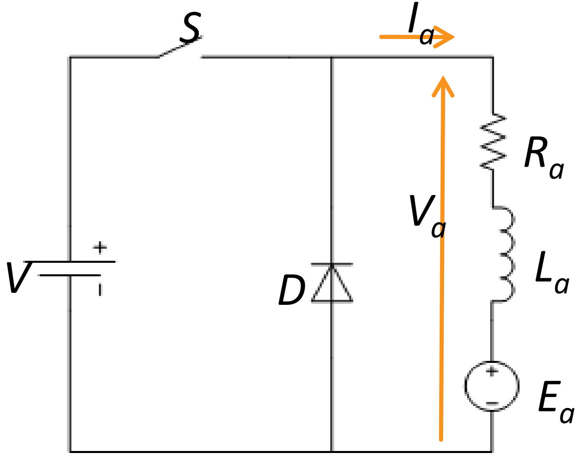
- Power electronics converters are used to obtain variable voltage
  - Highly efficient
  - Ideally lossless
- Type of converter used is depending on voltage source :
  - AC voltage source ⇒ Controlled Rectifiers
  - Fixed DC voltage source ⇒ DC-DC converters (switch mode converters)
- Self-commutated devices preferred (MOSFETs, IGBTs, GTOs) over thyristors
  - Commutated by lower power control signal
  - Commutation circuit not needed
  - Can be switched at higher frequency for same rating
  - Improved motor performance (less ripple, no discontinuous currents, increased control bandwidth)
- Suitable for high performance applications
- Regenerative braking possible up to very low speeds even when fed from fixed DC voltage source

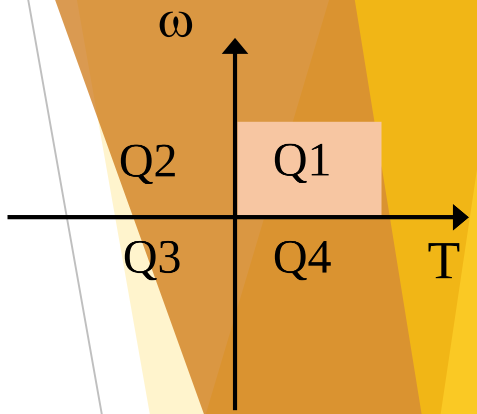
DC – DC Converter Fed Drives: Step Down Class 'A' Chopper

Motoring

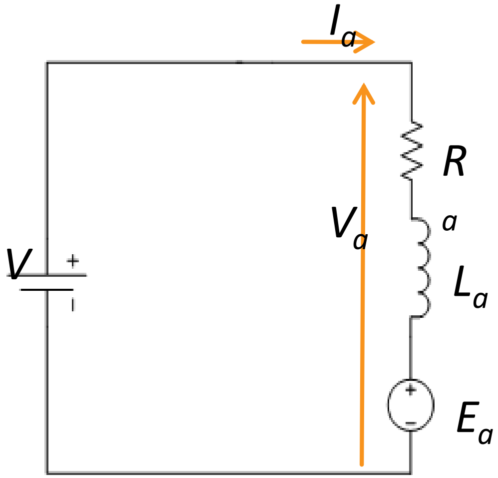
- Provides positive output voltage and current
- Average power flows from source to load (motor)
- Switch (S) operated periodically with period T

Class A choppers are also called step down choppers are most commonly used in dc drives.





S is ON ($0 \leq t \leq t_{on}$)

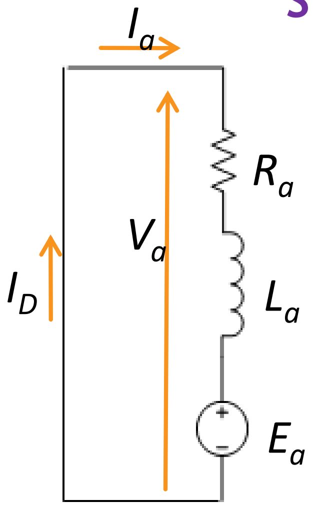


- *Va = V*
- *Ia flows to motor*
- *|Ia| increases*

$$R_a i_a + L_a \frac{di_a}{dt} + E = V$$

Duty cycle Interval
($i_a \uparrow$)

S if OFF ($t_{on} \leq t \leq T$)



- $V_a = 0$
- I_a freewheels through diode D
- $|I_a|$ decreases

$$R_a i_a + L_a \frac{di_a}{dt} + E = 0$$

Freewheeling Interval
($i_a \downarrow$)

DC – DC Converter Fed Drives: Step Down Class ‘A’ Chopper

Motoring

- Duty cycle: $k = \dfrac{t_{on}}{T}$ where $T =$ chopper period
- Under steady-state conditions:

Motor side: $V_a = R_a I_a + E$

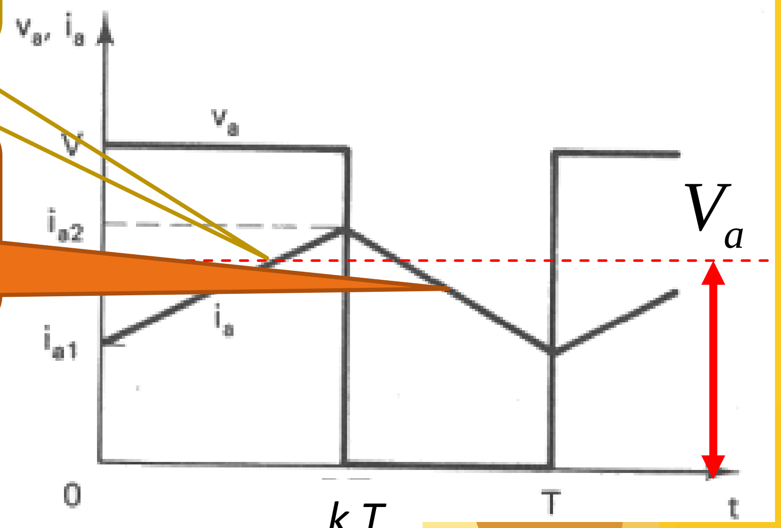
Chopper side, average armature voltage: $V_a = kV$

Therefore:

$$kV = V_a = R_a I_a + E$$

t_{on} affects V_a and thus the speed

average armature current: $I_a = \dfrac{kV - E}{R_a}$

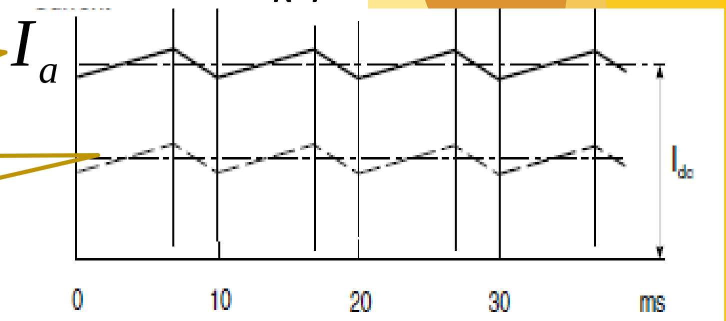


Duty Interval ($i_a \uparrow$)

Freewheeling Interval ($i_a \downarrow$)

full load current produces full rated torque

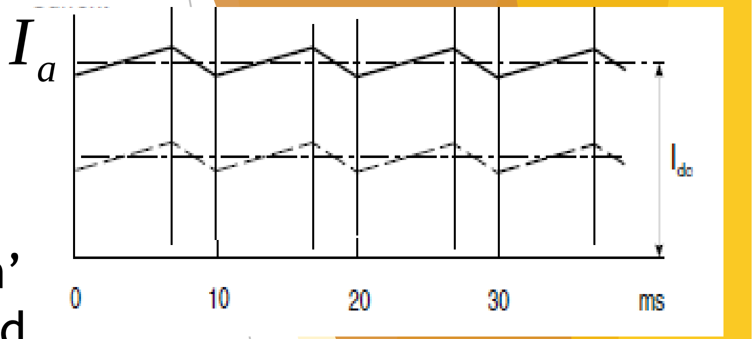
Reduced load current



A chopping frequency of around 100 Hz is typical of medium and large chopper drives, while small drives often use a much higher chopping frequency, and thus have lower ripple current

The speed of the motor is determined by the average armature voltage, which in turn depends on the proportion of the total cycle time (T) for which the transistor is ‘on’

DC – DC Converter Fed Drives: Step Down Class ‘A’ Chopper



- If we ignore resistance, the equation governing the current during the ‘on’ period is

$$V = L_a \frac{di_a}{dt} + E \ , \frac{di_a}{dt} = \frac{1}{L}(V - E)$$

Since V is greater than E, the gradient of the current (di/dt) is positive During this ‘on’ period the battery is supplying power to the motor. Some of the energy is converted to mechanical output power, but some is also stored in the magnetic field associated with the inductance so as the current (i) rises, more energy is stored.

- During the ‘off’ period, the equation governing the current is:

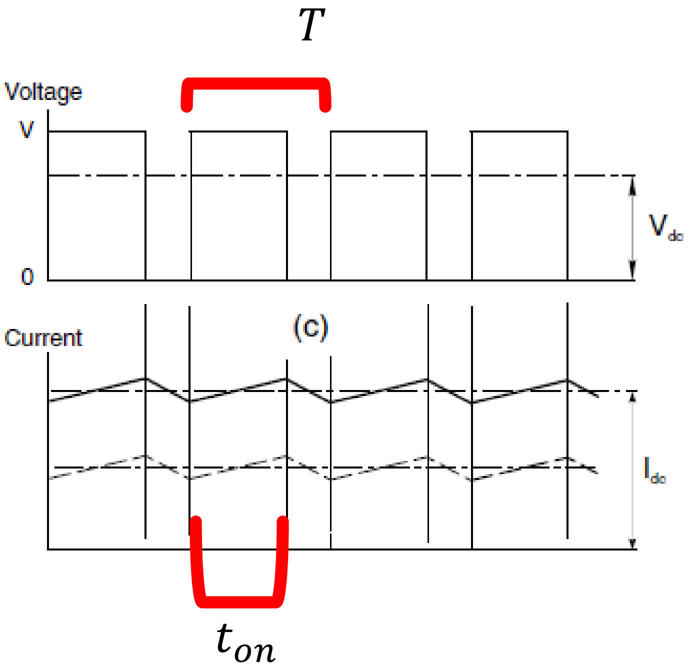
$$0 = L_a \frac{di_a}{dt} + E \ , \frac{di_a}{dt} = \frac{-E}{L}$$

during the ‘off’ time the gradient of the current is negative and it is determined by the motional e.m.f. E. During this period, the motor is producing mechanical output power which is supplied from the energy stored in the inductance.

The rise and fall of the current (i.e. the current ripple) is inversely proportional to the inductance, but is independent of the mean d.c. current, i.e. the ripple does not depend on the load.

DC – DC Converter Fed Drives: Step Down Class ‘A’ Chopper

- When the armature current is continuous the speed falls only slightly with load, because the mean armature voltage remains constant.
- But when the armature current is discontinuous (which is most likely at high speeds and light load) the speed falls off rapidly when the load increases, because the mean armature voltage falls as the load increases.
- **Discontinuous current can be avoided by adding an inductor in series with the armature, or by raising the chopping frequency, but when closed-loop speed control is employed, the undesirable effects of discontinuous current are masked by the control loop.**



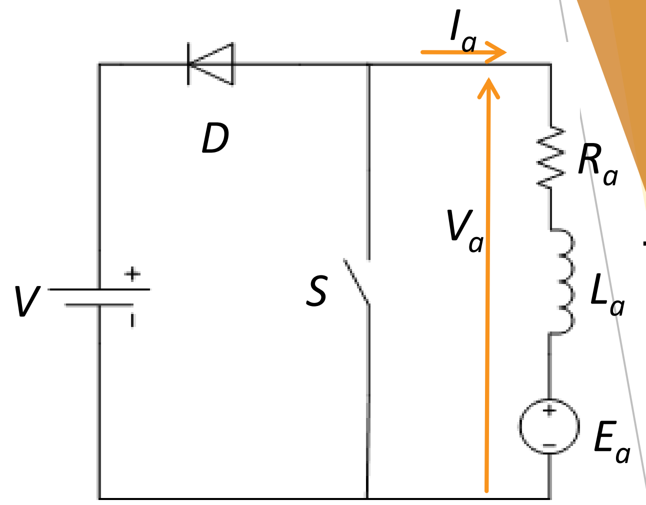
DC – DC Converter Fed Drives: Step Up Class 'B' Chopper

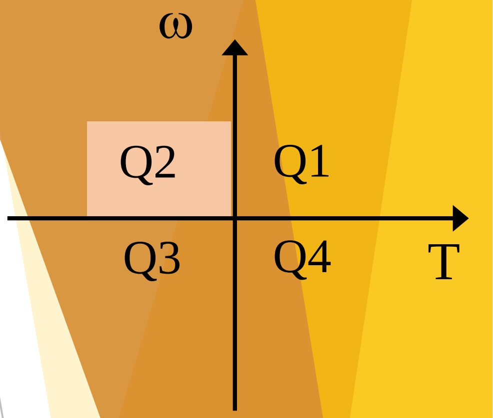
Regenerative Braking

- Provides positive output voltage and negative average output current
- Average power flows from load (motor) to source
- Possible for speed above rated speed and down to nearly zero speed

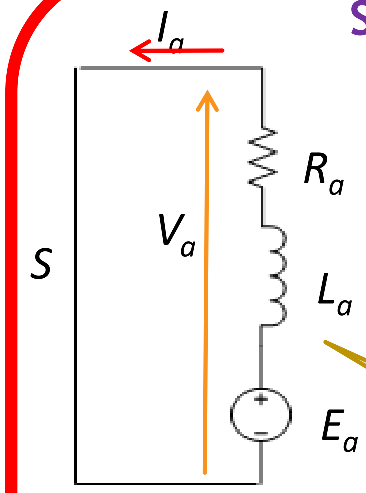
Application:

- Battery operated vehicles
- Regenerated power stored in battery





S is ON ($0 \le t \le t_{on}$)

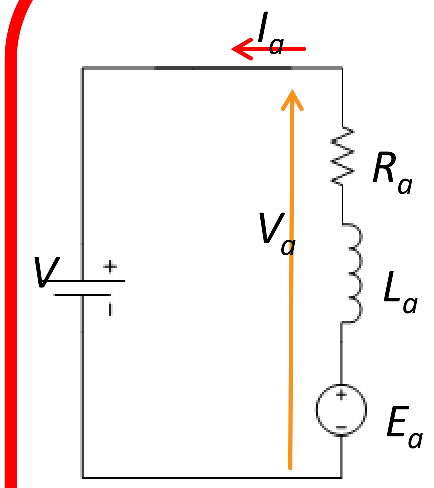


- V_a **= 0** (diode blocks V)
- i_a **increases** due to E (since $E > V_a$)
- Mechanical energy converted to electrical
- Energy stored in L_a
- Any remaining energy dissipated in R_a and S

$$R_a i_a + L_a \frac{di_a}{dt} = E$$

Energy Storage Interval (i_a ↑)

S if OFF ($t_{on} \le t \le T$)



- i_a flows through diode D and source V
- i_a decreases in negative direction
- Energy stored in L_a & energy supplied by machine are fed to the source

$$R_a i_a + L_a \frac{di_a}{dt} + V = E$$

Duty Interval (i_a ↓)

DC – DC Converter Fed Drives: Step Up Class ‘B’ Chopper

Regenerative Braking

- Duty cycle $k = \dfrac{t_{on}}{T}$ where $T =$ chopper period

- Under steady-state conditions

  Generator side: $V_a = E - R_a I_a$

  Chopper side, average armature voltage: $V_a = (1-k)V$

- Therefore, $(1-k)V = V_a = E - R_a I_a$

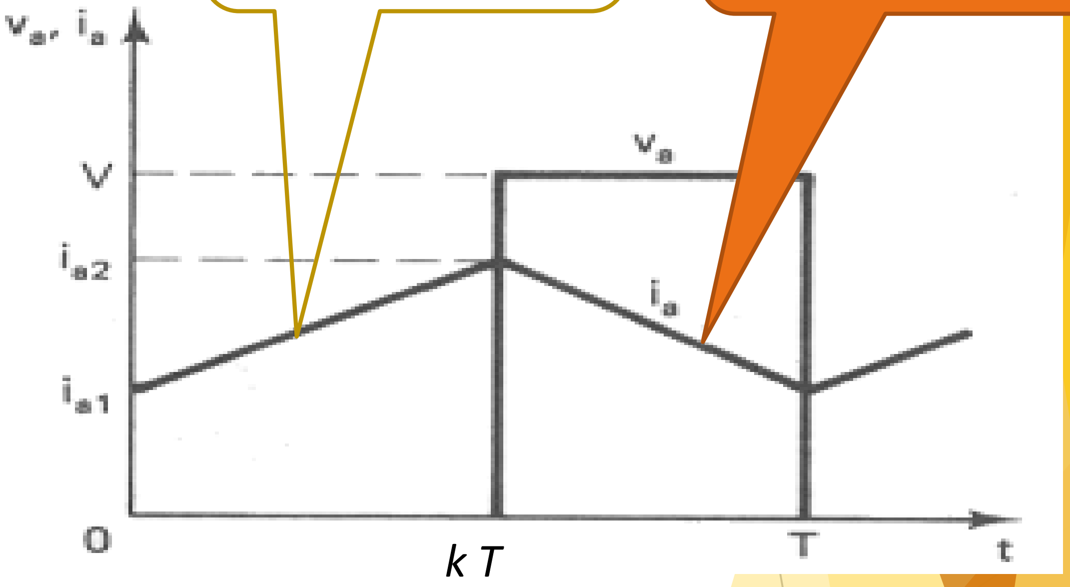
- Hence, average armature current:

$$I_a = \frac{E - (1-k)V}{R_a}$$

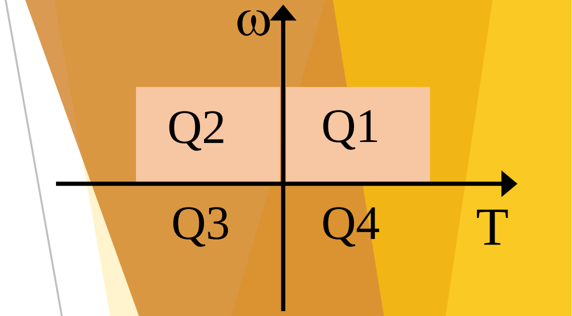
Negative because current flows from motor to source

Energy Storage Interval ($i_a \uparrow$)

Duty Interval ($i_a \downarrow$)

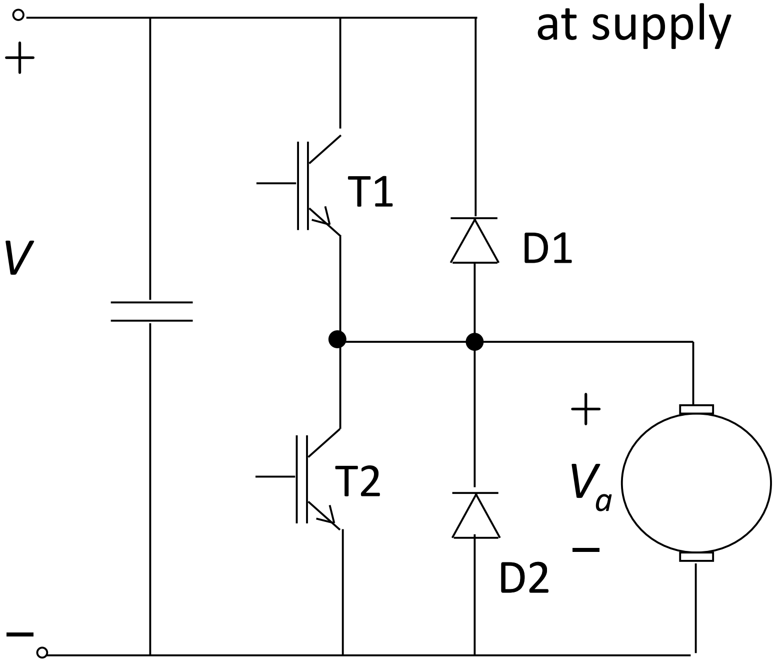


DC – DC Converter Fed Drives: Two-quadrant Control



- Combination of Class A & B choppers
- Forward motoring **Q1 - T1 and D2 (Class A)**
- Forward braking **Q2 - T2 and D1 (Class B)**

- V_a always +ve ⇒ ω always +ve
- I_a can be **+ve or –ve**
- **Do not fire both switches together** ⇒ short circuit at supply

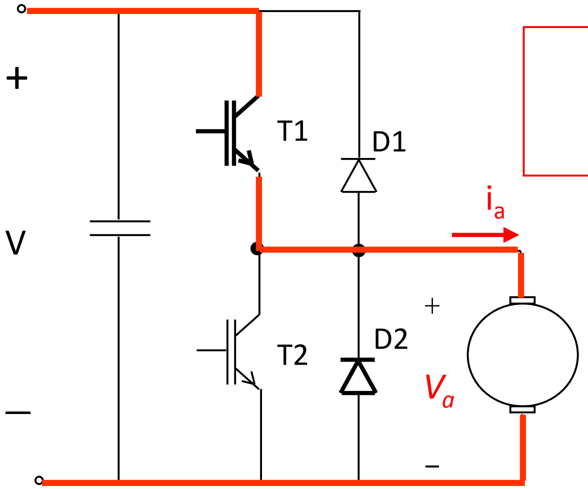


No Speed Reversal

Supply voltage can be obtained from a single/three phase rectified ac source

DC – DC Converter Fed Drives: Two-quadrant Control

- **Forward motoring Q1 - T1 and D2 (Class A)**
  - **T1 conducting:** $V_a = V$ ($i_a \uparrow$)

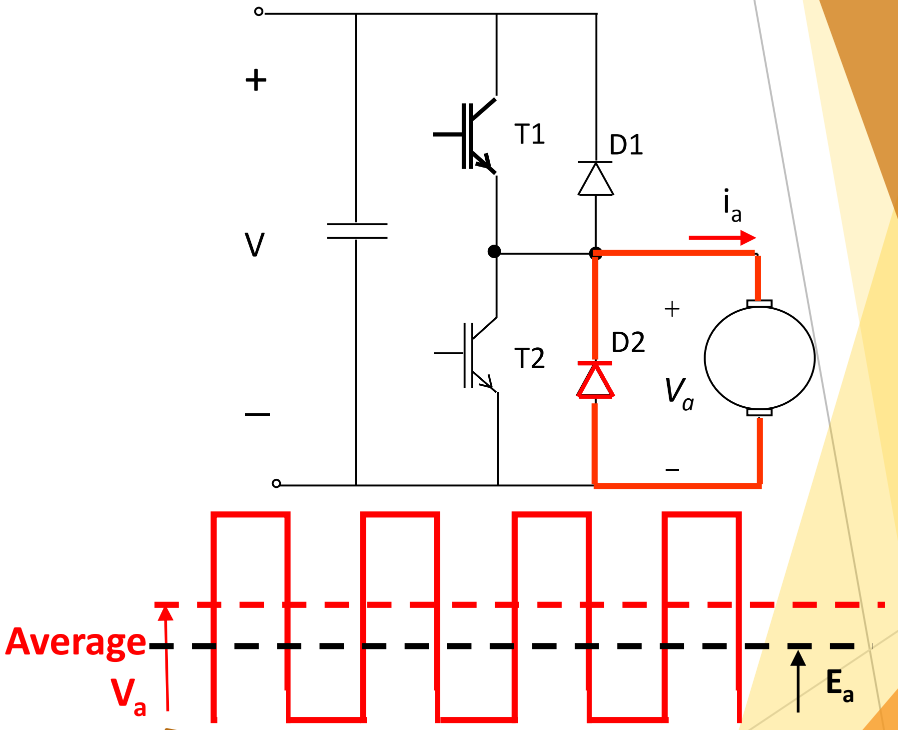


T2 always OFF

$$\boxed{\text{Average } V_a = k_1 V,\quad k_1 = (t_{on\ T1} / T),\ k_2 = 0}$$

T1 chopping ON & OFF

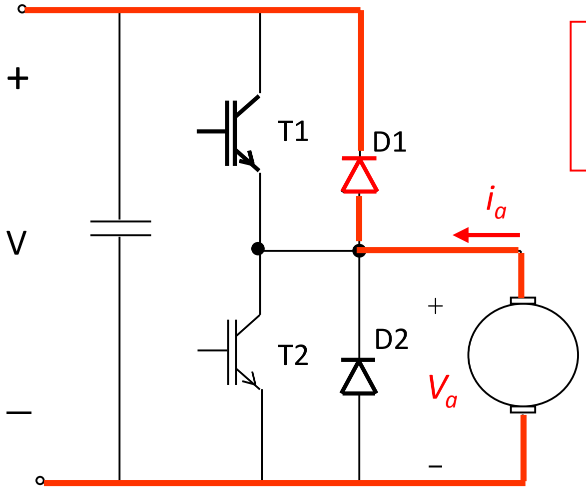
- **D2 conducting:** $V_a = 0$ ($i_a \downarrow$)



- Average V_a positive
- Average V_a made larger than back emf E_a
- I_a positive

DC – DC Converter Fed Drives: Two-quadrant Control

- **Forward braking Q2 - T2 and D1 (Class B)**
  - **D1 conducting:** $V_a = V$ ($i_a \downarrow$)

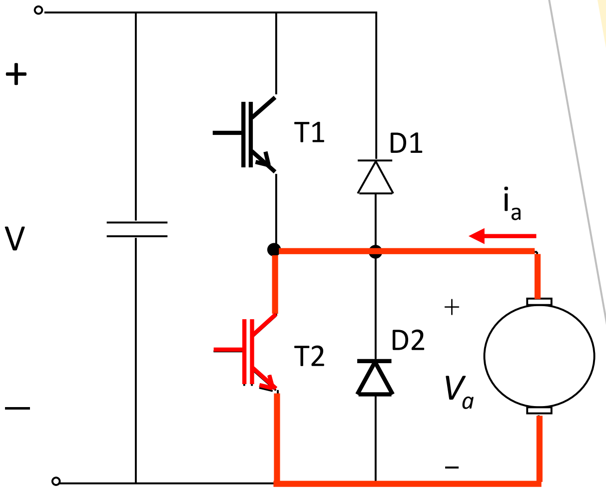


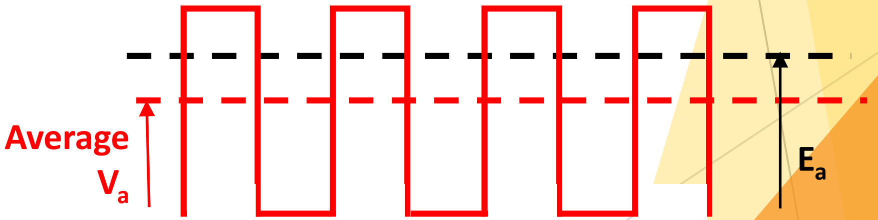
T1 always OFF

Average $V_a = (1 - k_2)V$,
$k_1 = 0$, $k_2 = (t_{on\,T2} / T)$

T2 chopping ON & OFF

- **T2 conducting:** $V_a = 0$ ($i_a \uparrow$)

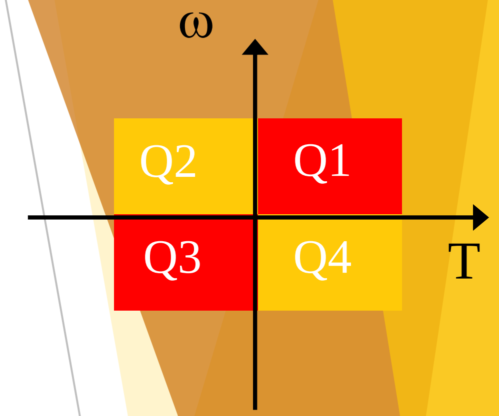


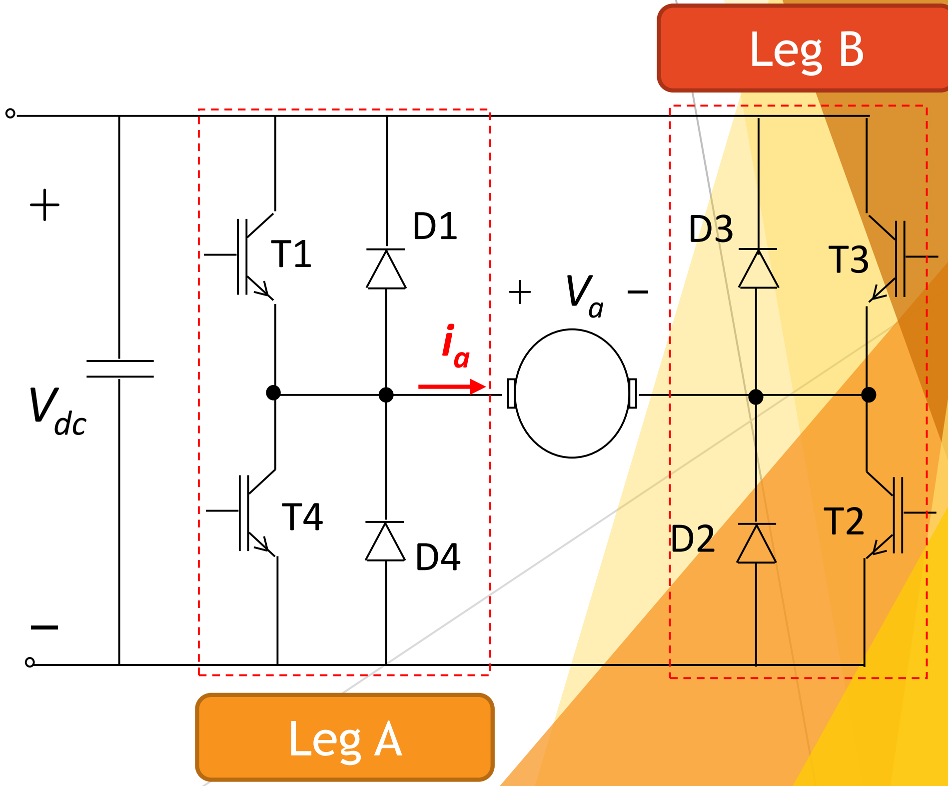


- Average V_a positive
- Average V_a made <u>smaller</u> than back emf E_a
- I_a negative (motor acts as generator)

DC – DC Converter Fed Drives: Four-quadrant Control

- Operation in all four quadrants
  - V_a and I_a can be controlled in magnitude and polarity
  - Power flow can be in either direction
- Speed and torque can be reversed
- When a switch is on (i.e. ‘ON state’) it may or may not conduct current depending on the direction of i_a
- If a switch conducts current, it is in a conducting state
- Converter has two legs (Leg A & Leg B)
- Both switches in each leg, are **alternately switched**
  - If T1 = ON, T4 = OFF
  - If T4 = ON, T1 = OFF

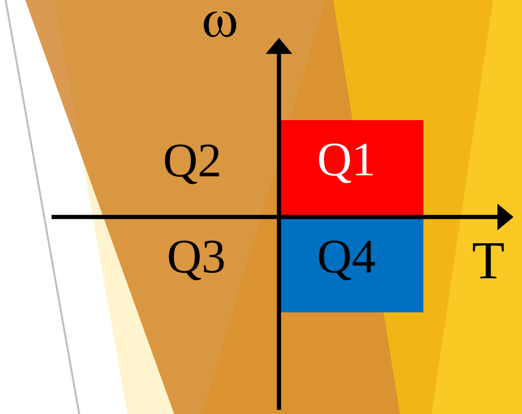


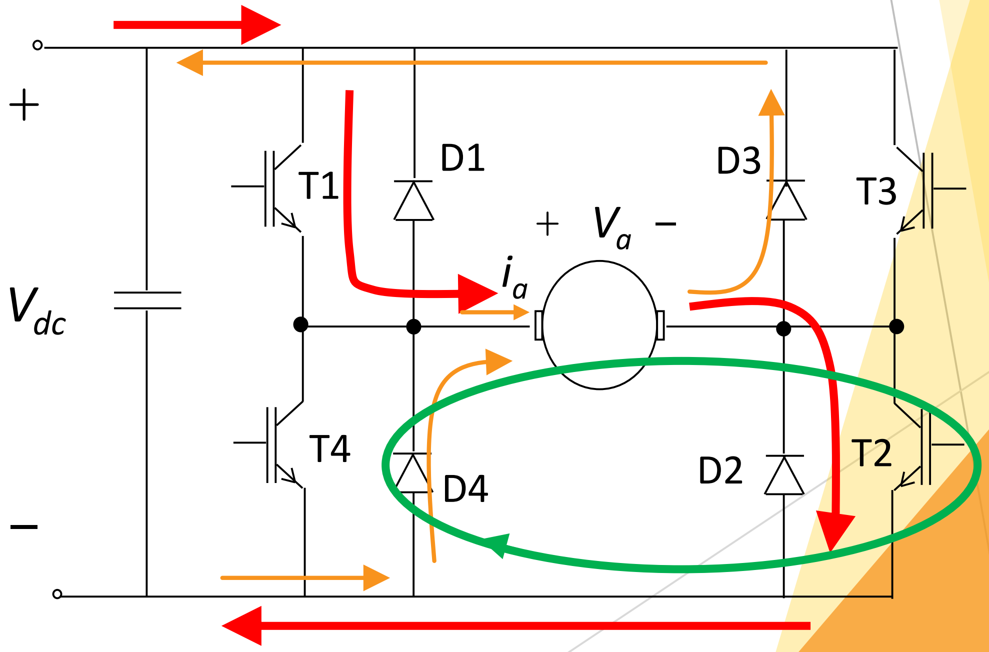


DC – DC Converter Fed Drives: Four-quadrant Control

- **Positive Current ($I_a > 0$)**
  - $V_a = V_{dc}$ when T1 and T2 are ON
    - Current increases
    - Q1 operation
  - $V_a = 0$ when current freewheels throughT2 and D4
    - Current decreases
    - Q1 operation
  - $V_a = -V_{dc}$ when D3 and D4 conducts current
    - Current decreases
    - Energy returned to supply
    - Q4 operation

T3 and T4 off





DC – DC Converter Fed Drives: Four-quadrant Control

- **Negative Current (I_a > 0)**
  - $V_a = -V_{dc}$ when T3 and T4 are ON
    - Current increases in **negative** direction
    - **Q3 operation**
  - $V_a = 0$ when current freewheels through T4 and D2
    - Current decreases
    - **Q3 operation**
  - $V_a = V_{dc}$ when D1 and D2 conducts current
    - Current decreases
    - Energy returned to supply
    - **Q2 operation**

T1 and T2 off