Control of Electrical Machines

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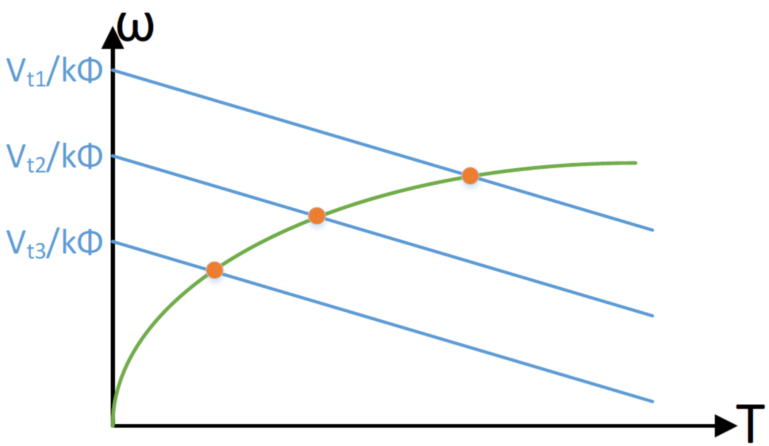
Electric Machines Speed Control

$$\omega = \frac{V_t}{K_a\phi} - \frac{R_a}{(K_a\phi)^2}T$$

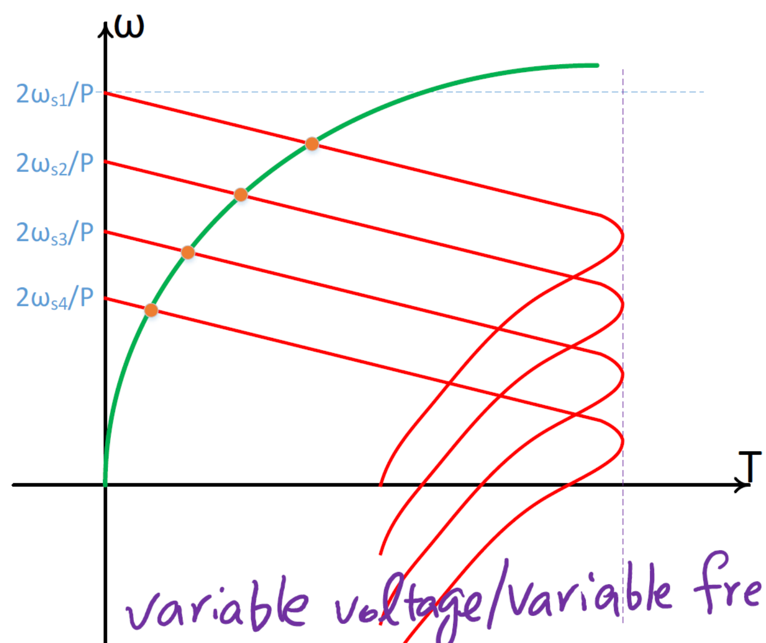
- DC Machines – Variable Voltage Power Supply
- AC Machines – Variable Voltage / Variable Frequency Power Supply

- DC-Machine



Variable voltage supply

- AC-Machine

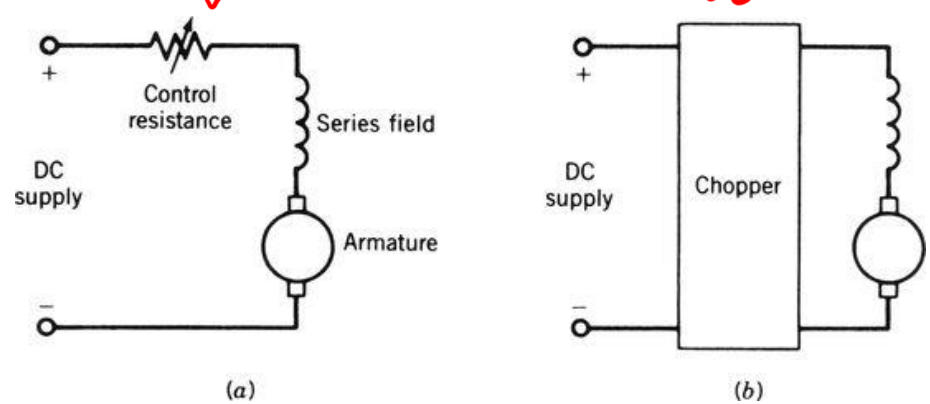


variable voltage/variable frequency power supply

Power Electronic Converters → o/P will be variable DC

- The control of electric machines is using new technology now.
- For example, DC series motors are used to propel the subway cars
- The speed of these cars has been controlled for many years by inserting resistances in series with the DC motors as shown in Figure (a)
- In recent years, solid state choppers (which can convert a fixed DC voltage into a variable DC voltage) have been used for this purpose, as shown in Figure (b)

power Electronics based DC-DC converter



Power Electronic Converters

power Electronics based devices

- Solid state control is smooth and efficient , high switching freq.

on state off -state
losses are very small

Converters:

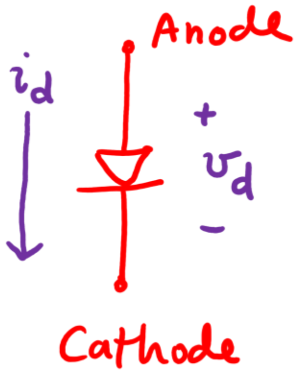
1. AC voltage controller (AC to AC) – converts a fixed voltage to a variable voltage (only magnitude)
2. Chopper (DC to DC)

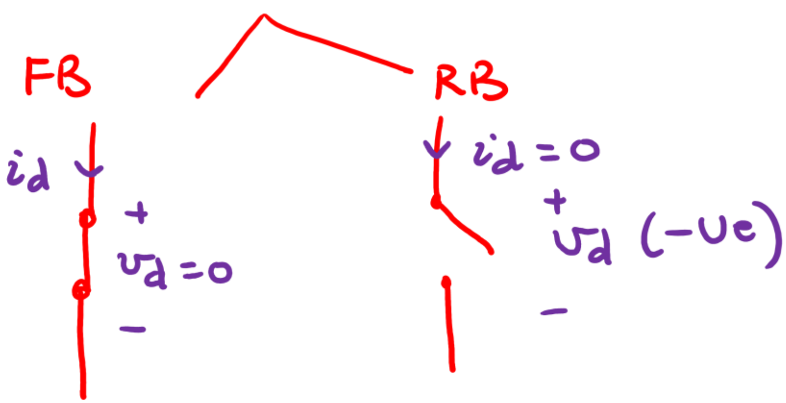
project

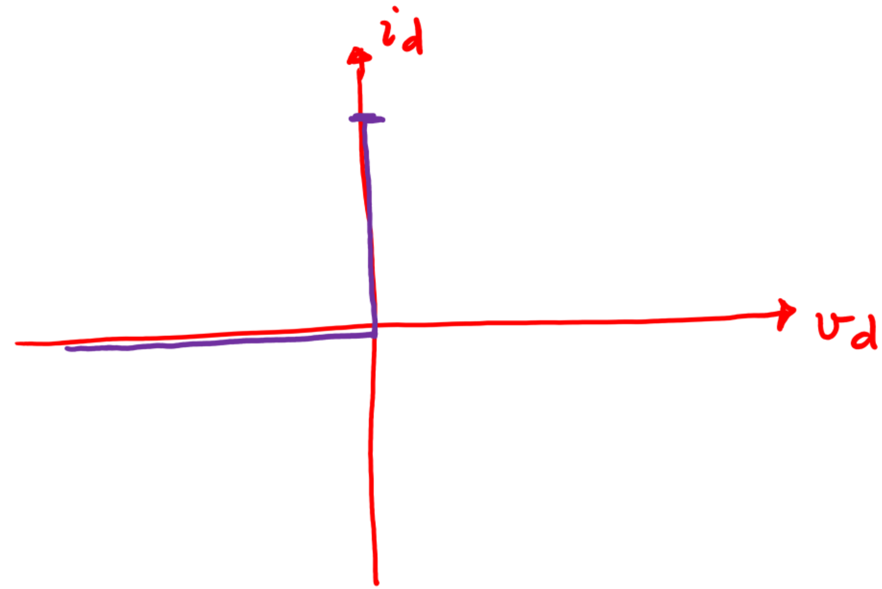
3. Controlled Rectifier (AC to DC)
4. Inverter (DC to AC)
5. Cycloconverter (AC to AC) – converts a fixed voltage and fixed frequency AC to a variable voltage and variable frequency AC

Power Semiconductor Devices

- Power Diodes







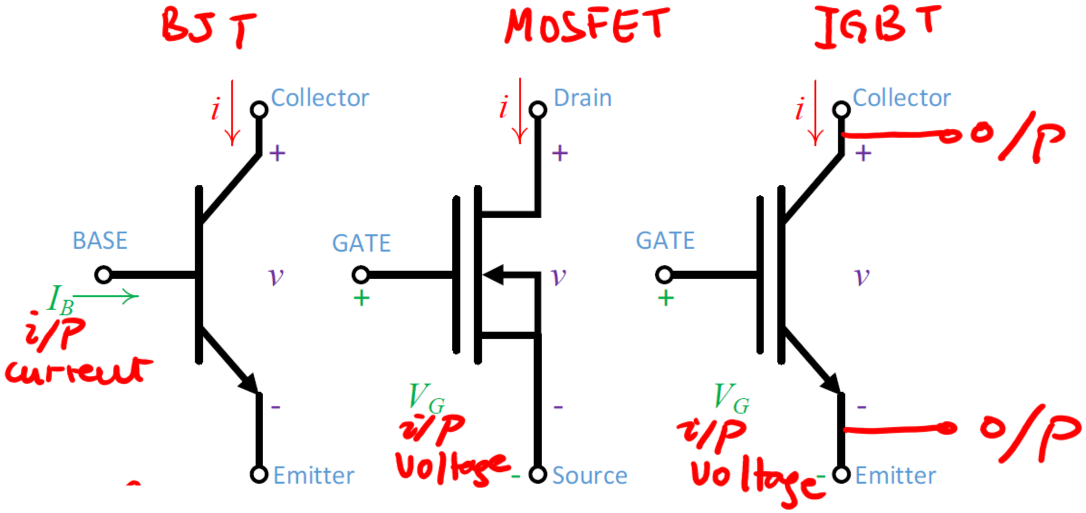
Ideal diodes

Power Semiconductor Devices

- Power Transistors
  - BJT (current controlled)
  - MOSFET (voltage controlled)
  - IGBT (voltage controlled)

Power Semiconductor Devices

- Power Transistors - common characteristics



1. They can be turned ON by the application of a relatively low power command signal to their third terminals, gate or base. The removal of this signal results in turning the switch OFF

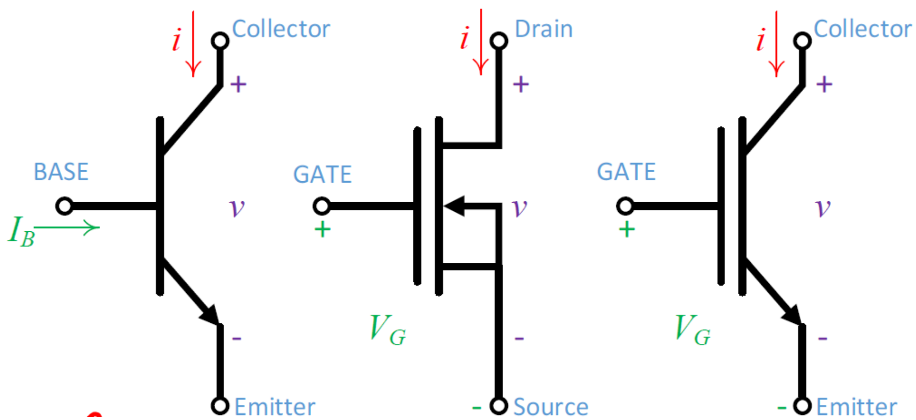
2. When ON, the switches act as closed circuits with small voltage drop (similar to the diodes)

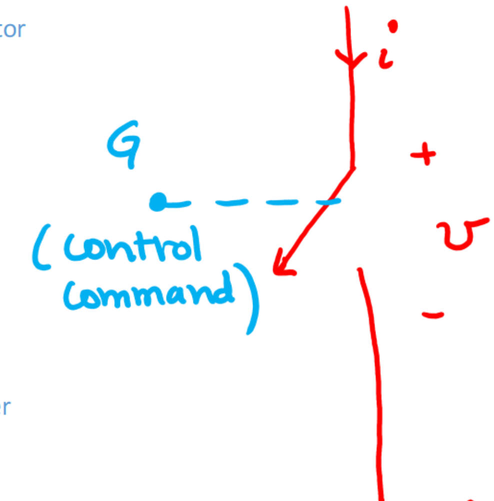
3. When OFF, they can withstand a positive voltages, however they should not be subjected to negative voltages

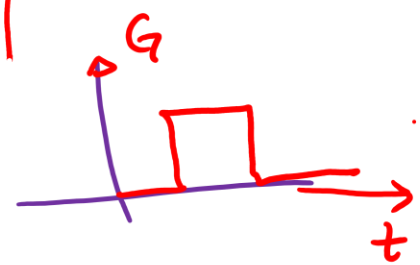
4. When OFF, the switch current is very small (typically zero)

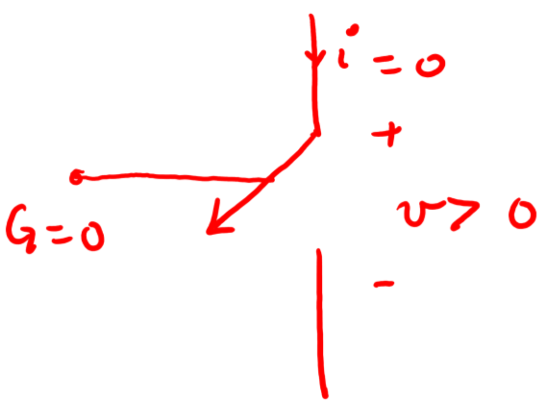
Power Semiconductor Devices

- Power Transistors – Generic Symbol

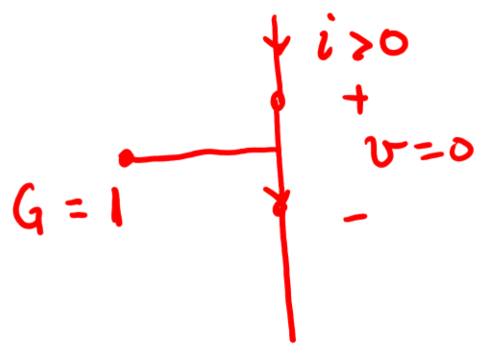








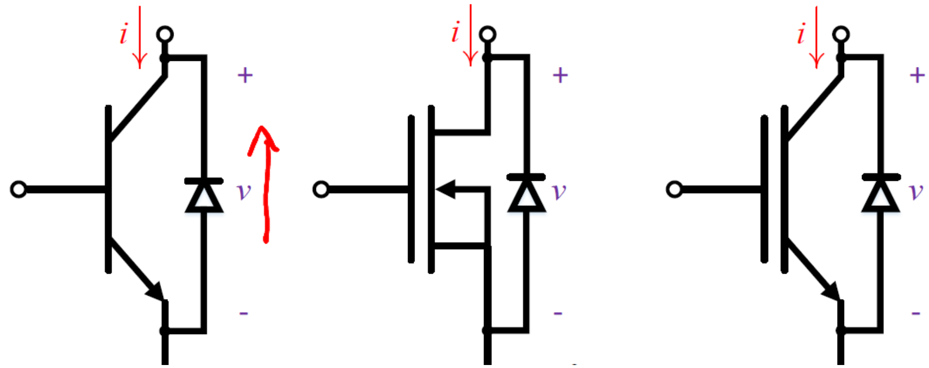
open switch



closed switch

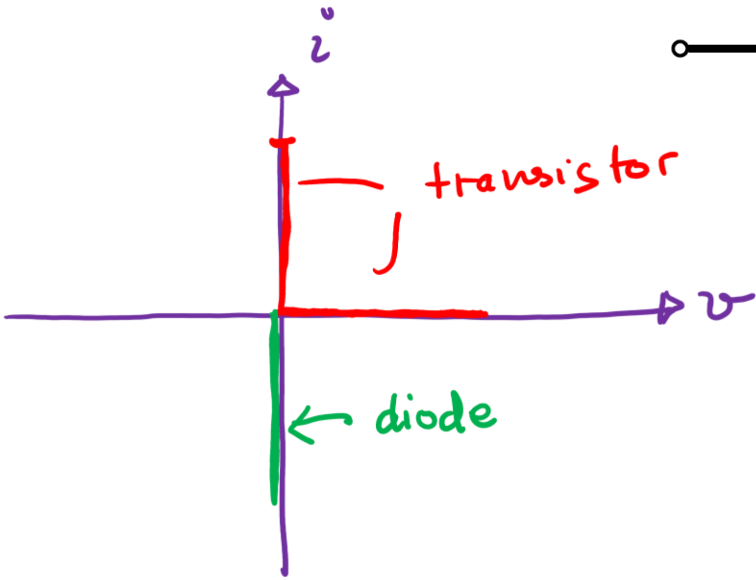
Power Semiconductor Devices

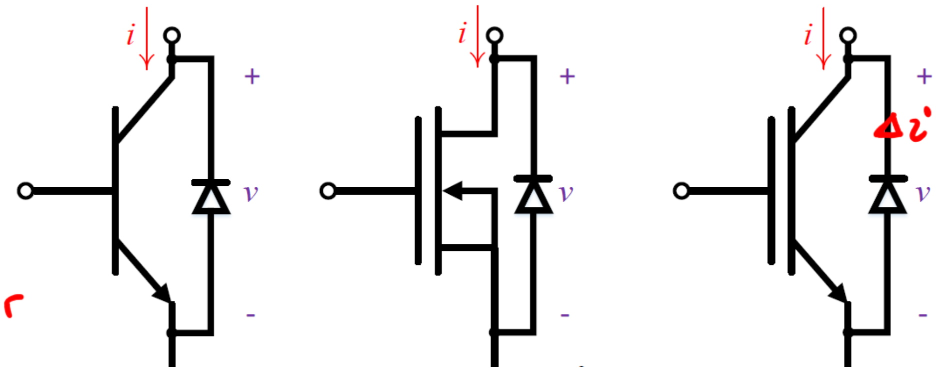
- Switch Cell



Power Semiconductor Devices

- Switch Cell - characteristics





Power Electronic Converters

Converters:

1. **Chopper (DC to DC)**
2. Controlled Rectifier (AC to DC)
3. Inverter (DC to AC)
4. Cycloconverter (AC to AC) – converts a fixed voltage and fixed frequency AC to a variable voltage and variable frequency AC

Power Electronic Converters – DC to DC Converter

- Half Bridge Converter – Two Quadrant Chopper

$-5A \quad 5A$

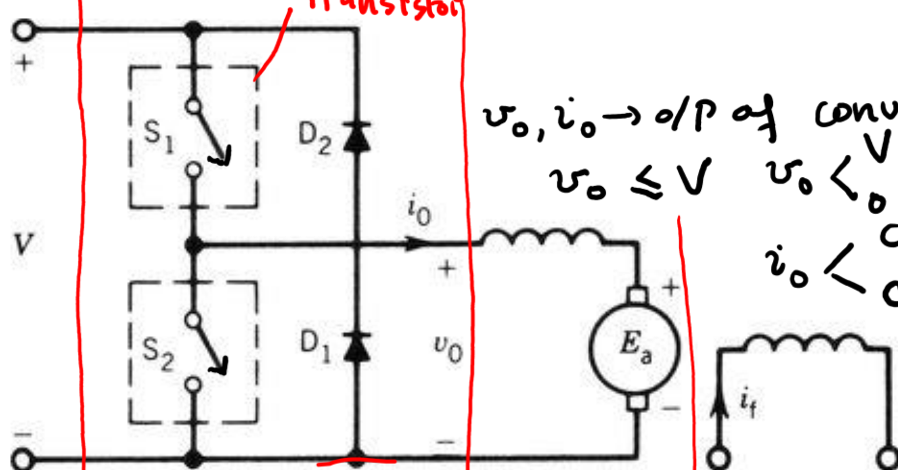
- switch S_1 and S_2 cannot be ON @ the same time

- If switch S_1 and diode D_1 are operating, the DC machine operates as a motor. The output voltage v_0 is either V (when S_1 is ON) or 0 (when S_1 is OFF and D_1 conducts). The average value of the output voltage (v0) is positive and the output current i_0 flows in the positive direction. The Chopper operates in the first quadrant.

- If switch S_2 and diode D_2 are operating, the DC machine operates in the Regenerative braking mode with E_a acting as a source. The output voltage v_0 is either 0 (when S_2 is ON) or V (when S_2 is OFF and D_2 conducts). The average value of the output voltage (v0) is positive but the output current i_0 flows in the negative direction. The Chopper operates in the fourth quadrant.

transistor

100V = V



(a)

fixed DC supply

Half-bridge converter

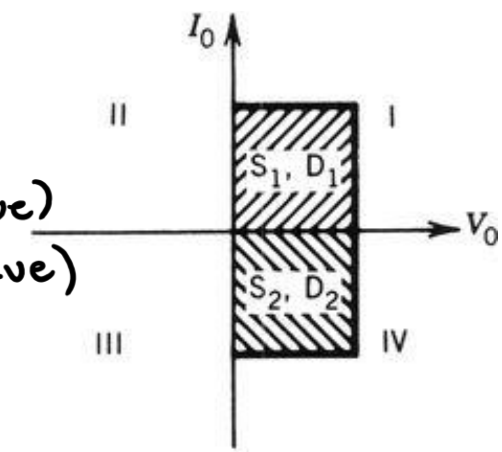
Armature winding of DC motor

↳ Field winding of DC motor

$v_0, i_0 \rightarrow$ o/p of converter

$v_0 \leq V \quad v_0 < V, 0$

$i_0 <$ cw (+ve), ccw (−ve)



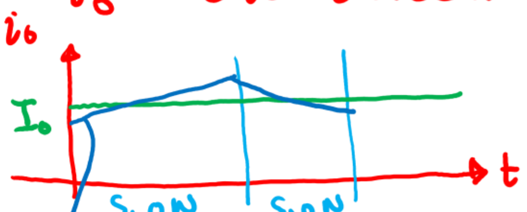
(b)

Power Electronic Converters – DC to DC Converter

- If switch S_1 and diode D_1 are operating, the DC machine operates as a motor. The output voltage v_0 is either V (when S_1 is ON) or 0 (when S_1 is OFF and D_1 conducts). The average value of the output voltage (v0) is positive and the output current i_0 flows in the positive direction. The Chopper operates in the first quadrant.

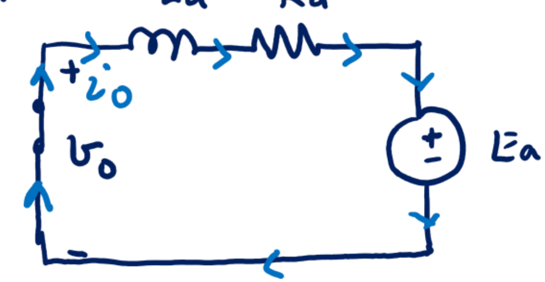
$v_o = V$

$i_o \rightarrow$ cw direction



$i_o \rightarrow$ transient, increasing

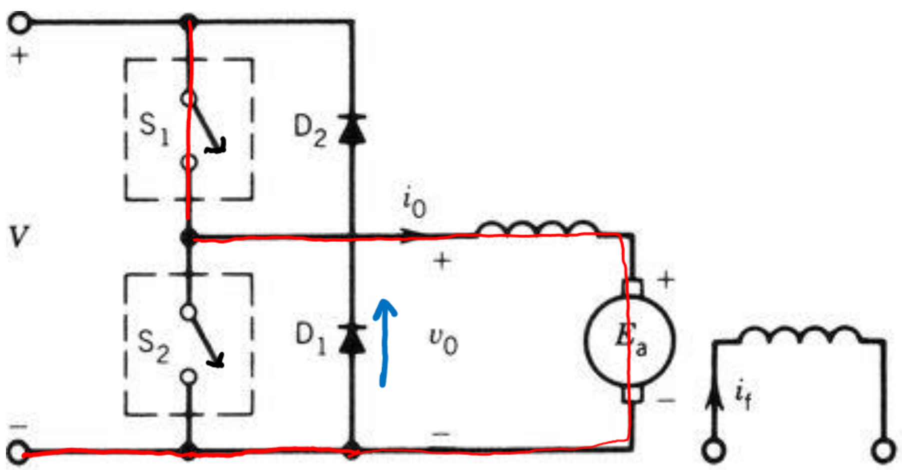
$D_1 \rightarrow$ ON



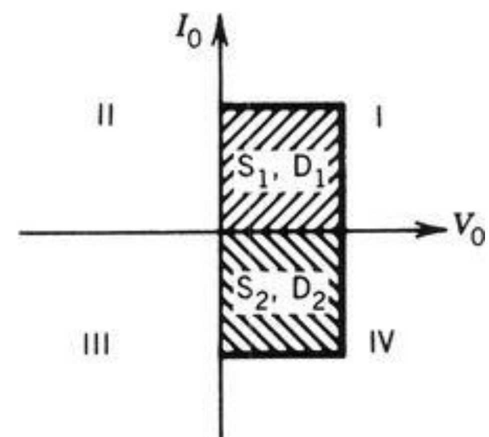
$v_o = 0$

$i_o \rightarrow$ cw direction

$\dot{i}_o \rightarrow$ decaying



(a)



(b)

machine is working as a MOTOR

Power Electronic Converters – DC to DC Converter

- If switch S_2 and diode D_2 are operating, the DC machine operates in the Regenerative braking mode with E_a acting as a source. The output voltage v_0 is either 0 (when S_2 is ON) or V (when S_2 is OFF and D_2 conducts). The average value of the output voltage (v0) is positive but the output current i_0 flows in the negative direction. The Chopper operates in the fourth quadrant.

S_2 - closed

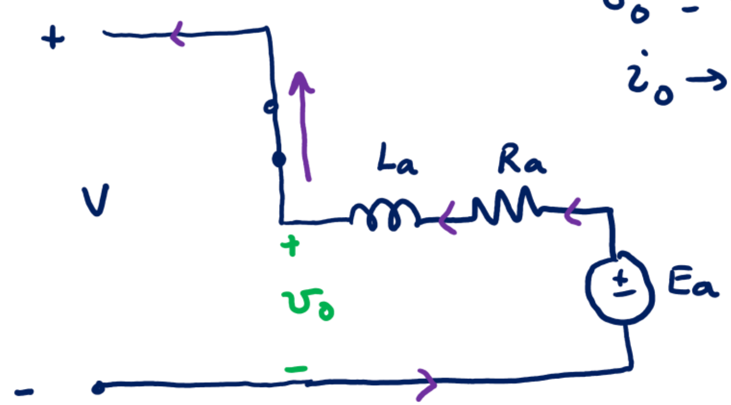
$v_0 = 0$

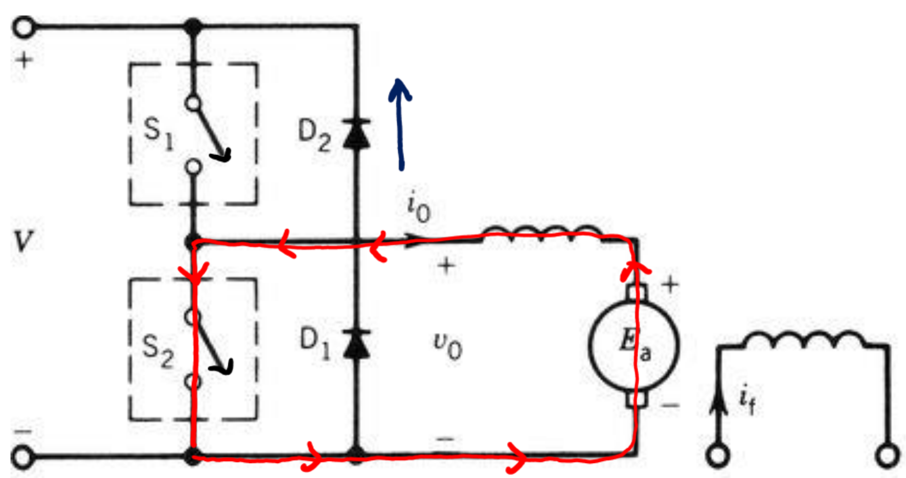
$i_0 \rightarrow$ ccw (-ve)

D_2 - ON

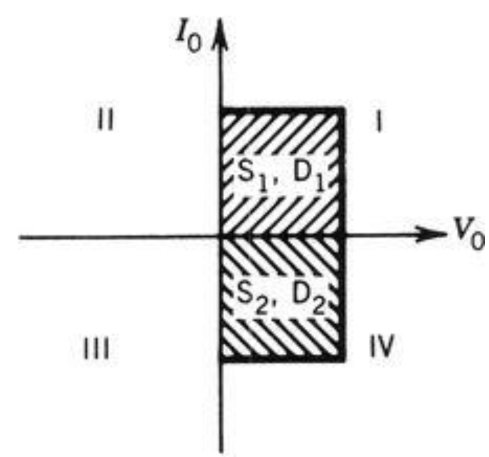
$v_0 = V$

$i_0 \rightarrow$ ccw (-ve)





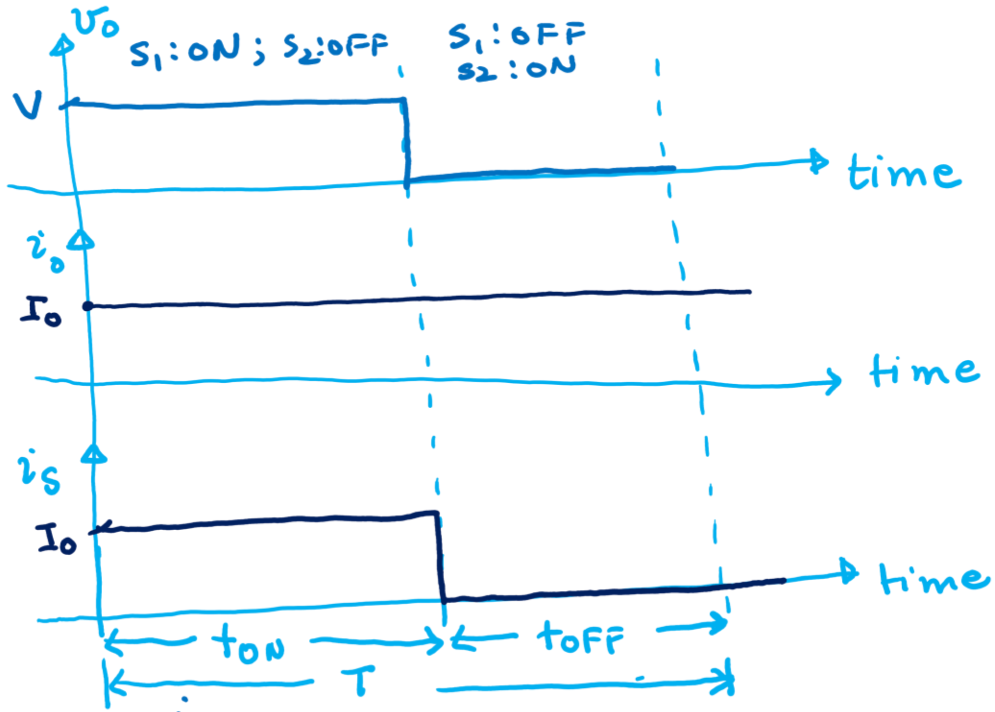
(a)



(b)

Machine is working as a Generator

Power Electronic Converters – DC to DC Converter



$T = \frac{1}{f_{sw}}$

$t_{on} \to$ ON time for S_1

$t_{off} \to$ OFF time for S_1

$T = t_{on} + t_{off}$

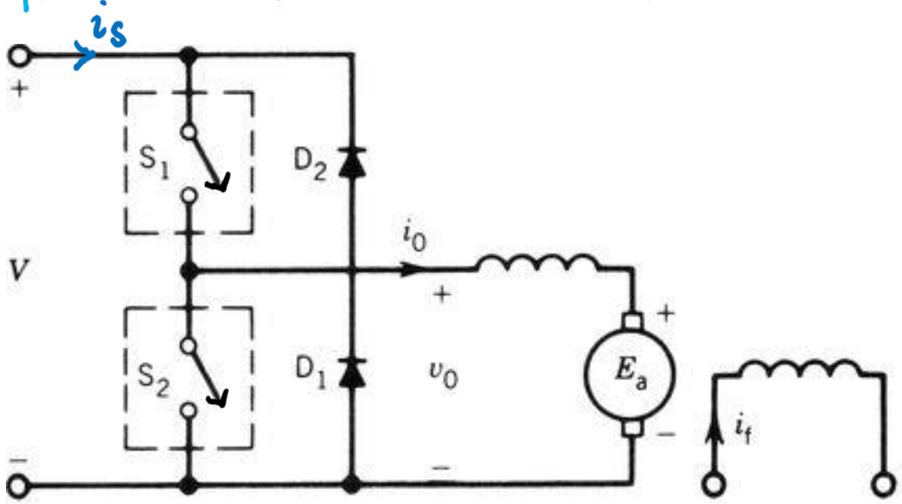
$V_0 \to$ average value of v_0

$$V_0 = \frac{(V \times t_{on}) + (\cancel{0 \times t_{off}}^{\,0})}{T}$$

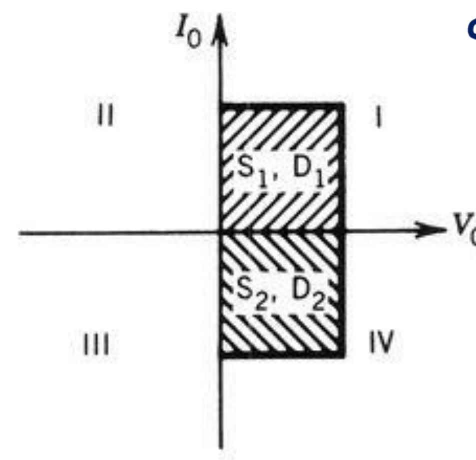
$$V_0 = \frac{t_{on}}{T} V = dV$$

duty cycle (d)

0 — 1



(a)



(b)

Power Electronic Converters – DC to DC Converter

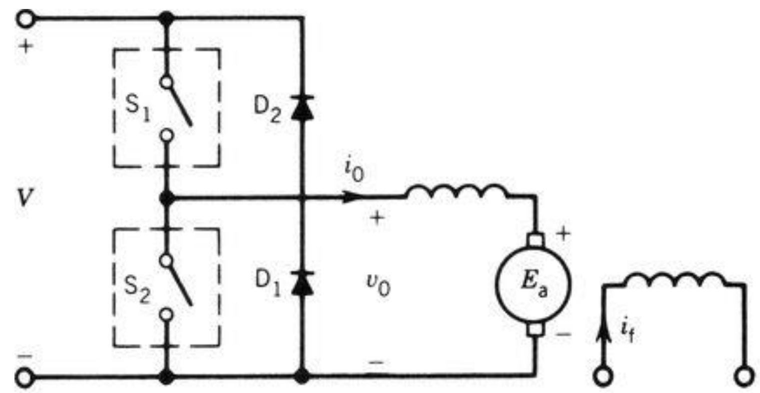
$E_a = K_a \Phi \omega$

$E_a = K_a \Phi N$
V   V/rpm → rpm

- Half Bridge Converter – Two Quadrant Chopper - Example
- A 2-quadrant chopper as shown in the figure below is used to control the speed of the DC motor and is also used for Regenerative braking of the motor. The motor constant $K_a\varphi = 0.1\ \mathrm{V/rpm}$. The chopping frequency is 250 Hz (f_{sw}) and the motor armature resistance is R_a = 0.2 Ω. The inductance L_a is sufficiently large and the motor current i_0 can be assumed ripple free. The supply voltage is 120 V.

v_o V time

- The switch S_1 and diode D_1 are operated to control the speed of the motor. At N = 400 rpm and i_0 = 100 A (constant ripple free)
  - Draw waveforms for v_0, i_0 and i_s
  - Determine the turn ON time (t_{on}) of the switch S_1
  - Determine the power developed by the motor, power absorbed by R_a, and power supplied by the source
- The switch S_2 and diode D_2 are operated for the Regenerative braking of the motor. At N = 350 rpm and i_0 = -100 A (constant ripple free)
  - Draw waveforms for v_0, i_0 and i_s
  - Determine the turn ON time (t_{on}) of the switch S_2
  - Determine the power developed by the motor, power absorbed by R_a, and power to the source



Power Electronic Converters – DC to DC Converter

- A 2-quadrant chopper as shown in the figure below is used to control the speed of the DC motor and is also used for Regenerative braking of the motor. The motor constant $K_a\varphi = 0.1\ \mathrm{V/rpm}$. The chopping frequency is 250 Hz and the motor armature resistance is R_a = 0.2 Ω. The inductance L_a is sufficiently large and the motor current i_0 can be assumed ripple free. The supply voltage is 120 V.

- The switch S_1 and diode D_1 are operated to control the speed of the motor. At N = 400 rpm and i_0 = 100 A (constant ripple free)
  - Draw waveforms for v_0, i_0 and i_s
  - Determine the turn ON time (t_{on}) of the switch S_1
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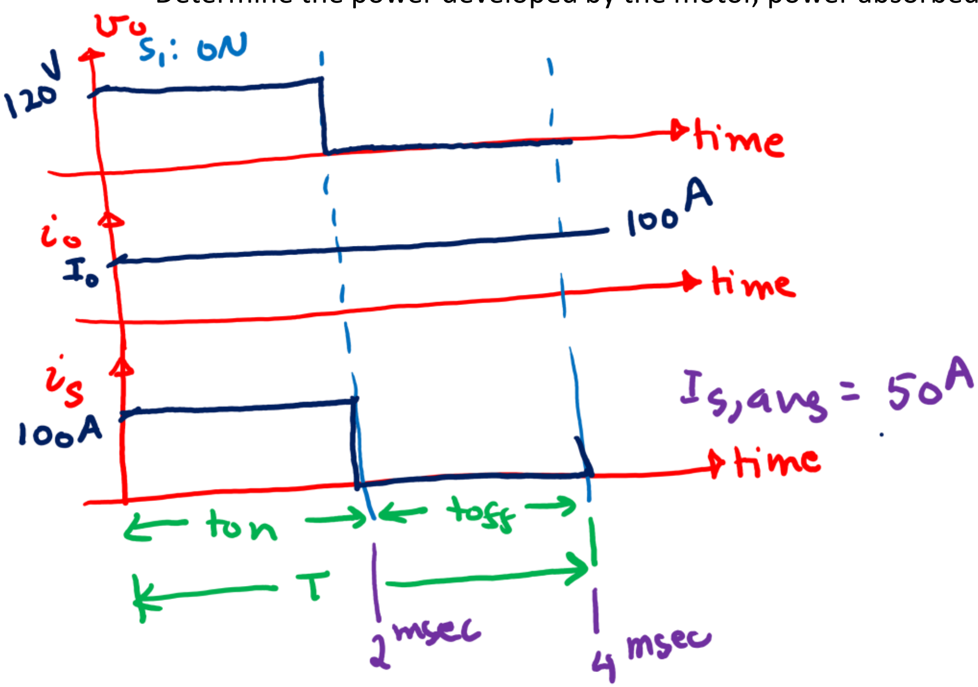

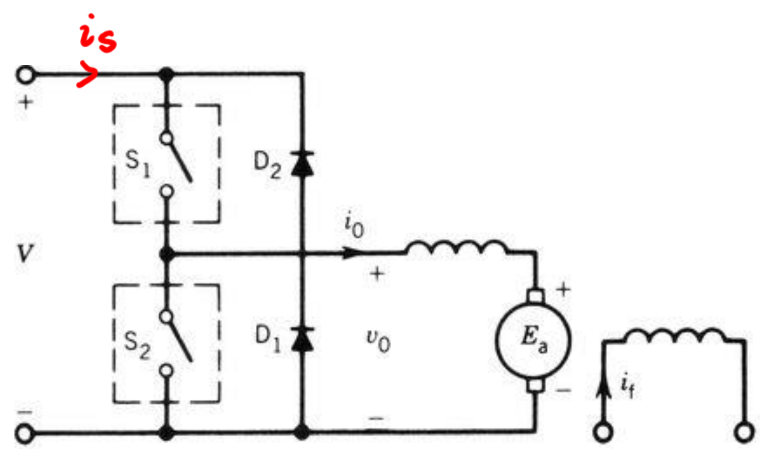

Power Electronic Converters – DC to DC Converter

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  - Determine the power developed by the motor, power absorbed by R_a, and power supplied by the source

$P_{dev} = E_a I_o = 40 \times 100 = 4000$ W

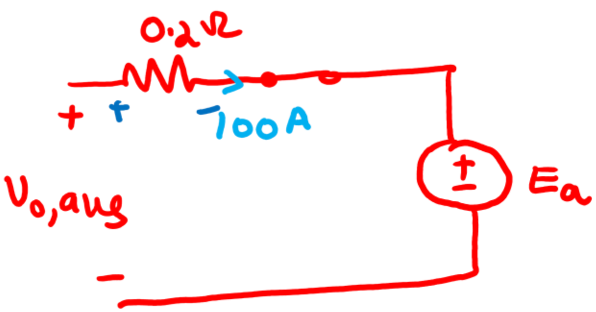
$P_{Ra} = (I_o)^2 R_a = (100)^2 \times 0.2 = 2000$ W

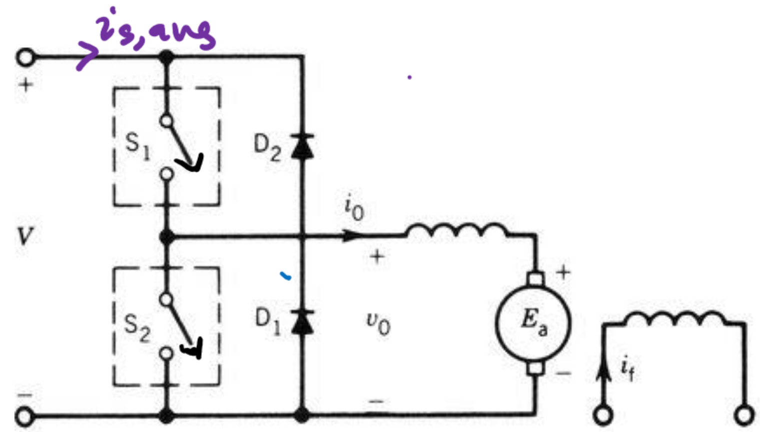
$P_{source} = V\, I_{s,avg} = 120 \times [50] = 6000$ W

$V_{o,avg} = \frac{t_{on}}{T} V$

$T = \frac{1}{250} = 0.004$ sec $= 4$ msec

$60 = \frac{t_{on}}{4}(120) \Rightarrow t_{on} = 2$ msec





$V_{o,avg} = (100 \times 0.2) + E_a$

$E_a = K_a\Phi N = 0.1 \times 400 = 40$ V

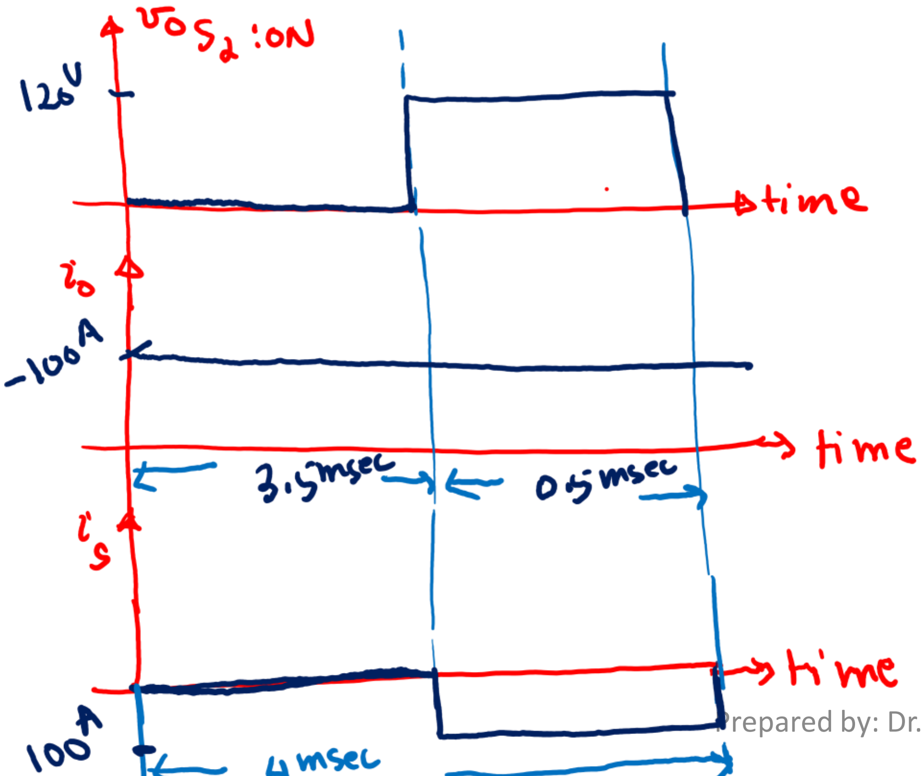
$V_{o,avg} = 20 + 40 = 60$ V

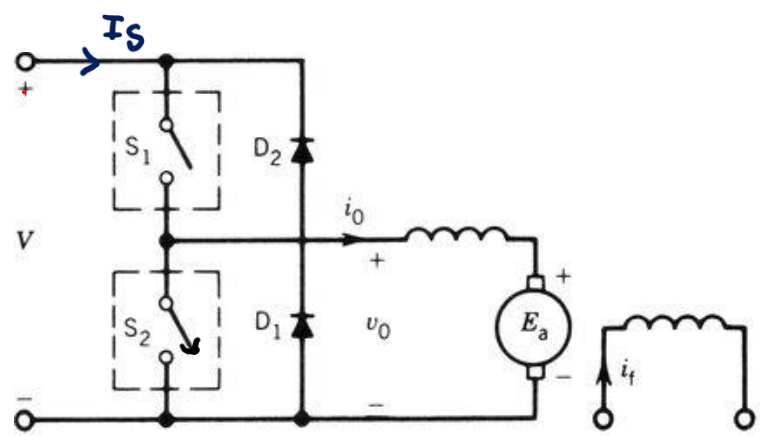
Power Electronic Converters – DC to DC Converter

- A 2-quadrant chopper as shown in the figure below is used to control the speed of the DC motor and is also used for Regenerative braking of the motor. The motor constant $K_a\varphi = 0.1$ V/rpm. The chopping frequency is 250 Hz and the motor armature resistance is R_a = 0.2 Ω. The inductance L_a is sufficiently large and the motor current i_0 can be assumed ripple free. The supply voltage is 120 V.

T= 4 msec

- The switch S_2 and diode D_2 are operated for the Regenerative braking of the motor. At N = 350 rpm and i_0 = -100 A (constant ripple free)
  - Draw waveforms for v_0, i_0 and i_s
  - Determine the turn ON time (t_{on}) of the switch S_2
  - Determine the power developed by the motor, power absorbed by R_a, and power to the source





Power Electronic Converters – DC to DC Converter

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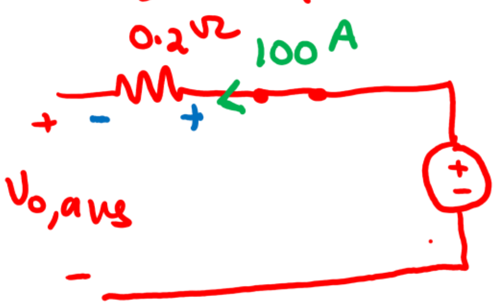
  - Determine the turn ON time (t_{on}) of the switch S_2
  - Determine the power developed by the motor, power absorbed by R_a, and power to the source

$$V_{o,avg} = \frac{t_{on}}{T}(120)$$



$E_a = K_a\varphi N$

$= 0.1 \times 350$

$= 35^V$

$V_{o,avg} + (100 \times 0.2) = 35$

$V_{o,avg} = 35 - 20 = 15^V$

$E_a > V_a$

(Gen).

$15 = \frac{t_{on}}{4}(120) \Rightarrow t_{on} = 3.5^{msec}$

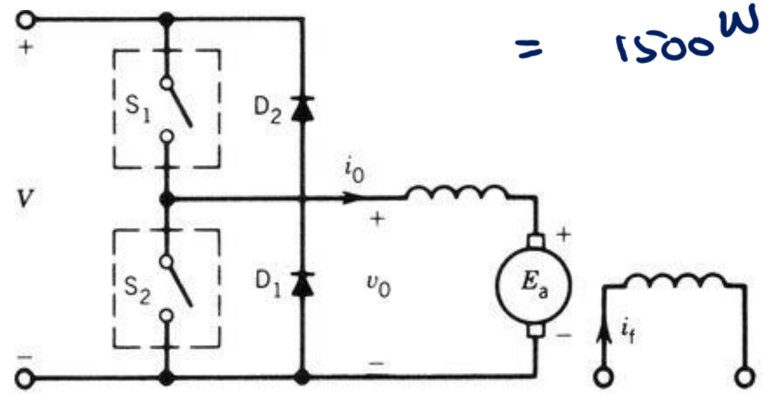
$P_{dev} = E_a I_o = 35 \times (-100) = -3500^W$

Supplied power

$P_{Ra} = (I_o)^2 \times R_a = (-100)^2 \times 0.2 = 2000^W$

$P_s = V I_{s_{avg}} = 120 \times \left(\frac{0.5}{4} \times 100\right)$

$= 1500^W$



Power Electronic Converters – DC to DC Converter

- Full Bridge Converter – Four Quadrant Chopper
- The controlled voltage $v_o = v_{AN} - v_{BN}$ can be controlled by controlling the switch duty cycle and is independent of the magnitude and direction of i_0

$v_0 = v_{AB} = v_A - v_B$

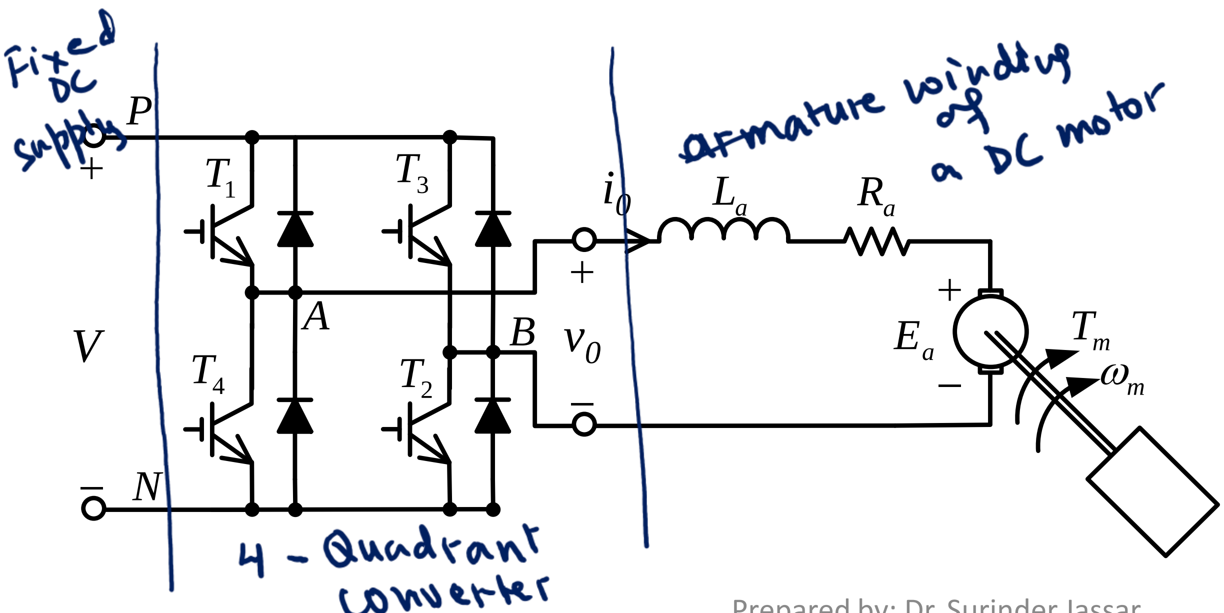
$= v_{AN} - v_{BN}$

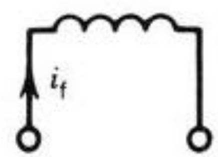
switches $\leftarrow$ T_1, T_2, T_3, T_4

diodes – antiparallel

constraint : T_1 and T_4 → cannot be ON @ the same time

T_2 and T_3 → cannot be ON @ the same time.





Power Electronic Converters – DC to DC Converter

- Full Bridge Converter – Four Quadrant Chopper

T_1 and T_2 : ON $\rightarrow$ ON time of T_1 and $T_2 \rightarrow t_{on}$

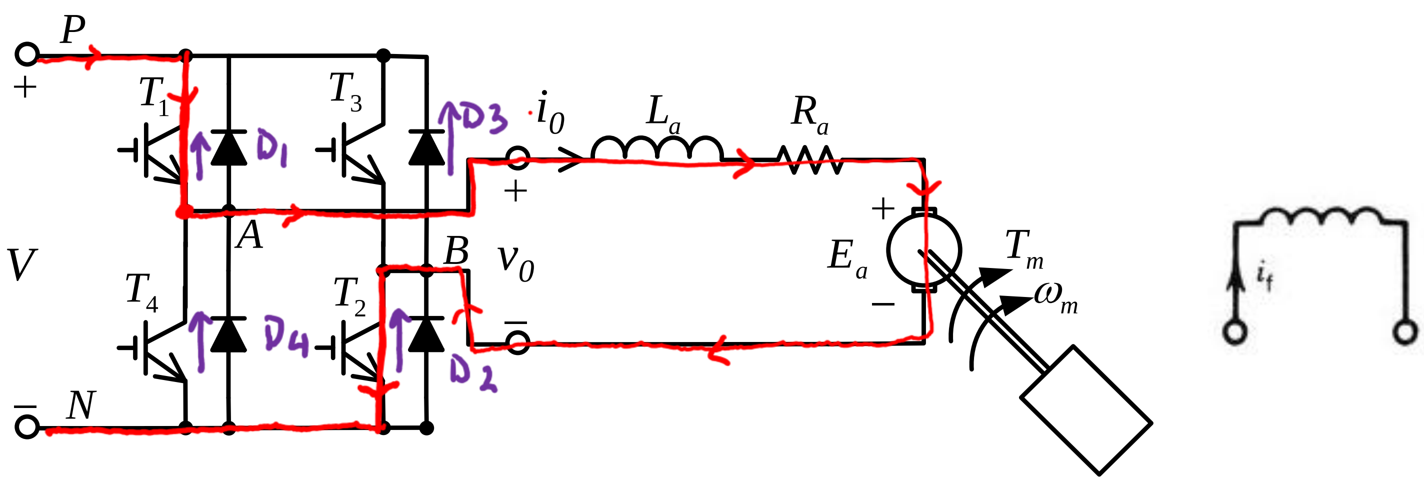
T_3 and T_4 : OFF

$v_0 = V$

$i_0 \rightarrow$ cw (+ve)

$v_0 = v_{AN} - v_{BN} = V - 0 = V$

$i_0 \rightarrow$ cw $\rightarrow$ is also provided by diodes D_3 and D_4.



Power Electronic Converters – DC to DC Converter

- Full Bridge Converter – Four Quadrant Chopper

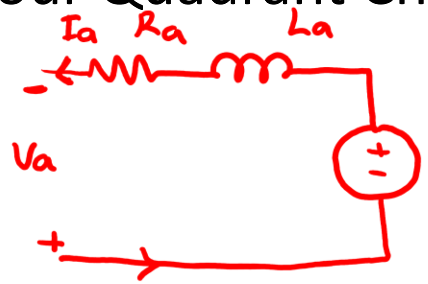
T_3 and T_4 : ON

T_1 and T_2 : OFF

$v_0 = V_{AN} - V_{BN}$

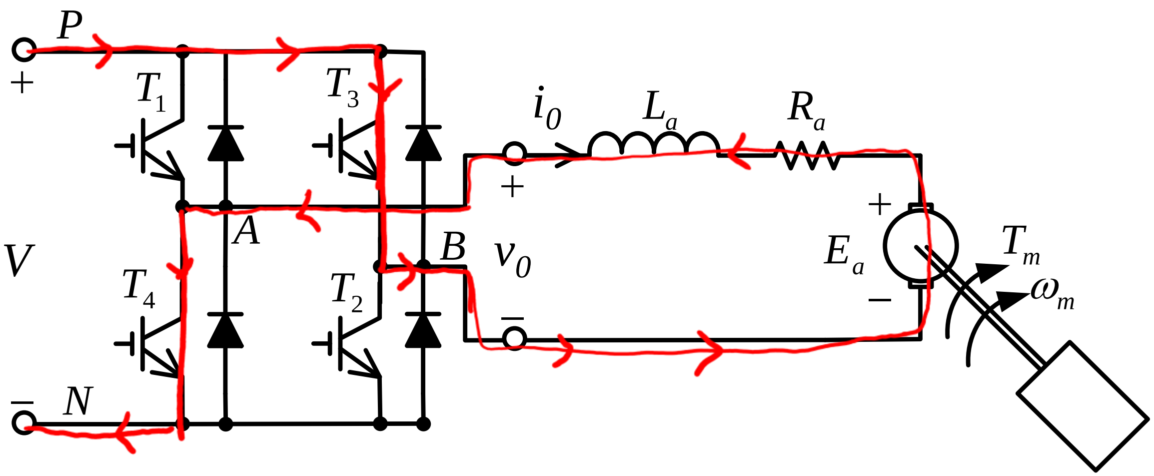
$= 0 - V = -V$

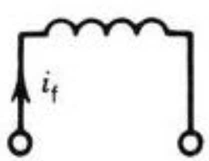
$i_0 \rightarrow$ ccw (-ve)

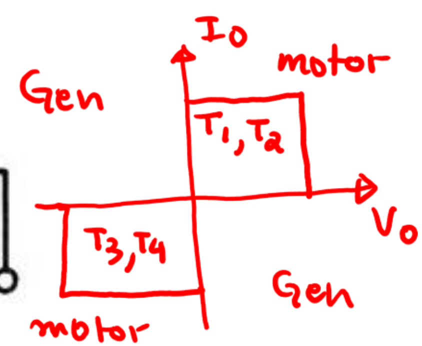


$V_a \rightarrow -ve$, $I_a \rightarrow -ve$

motor

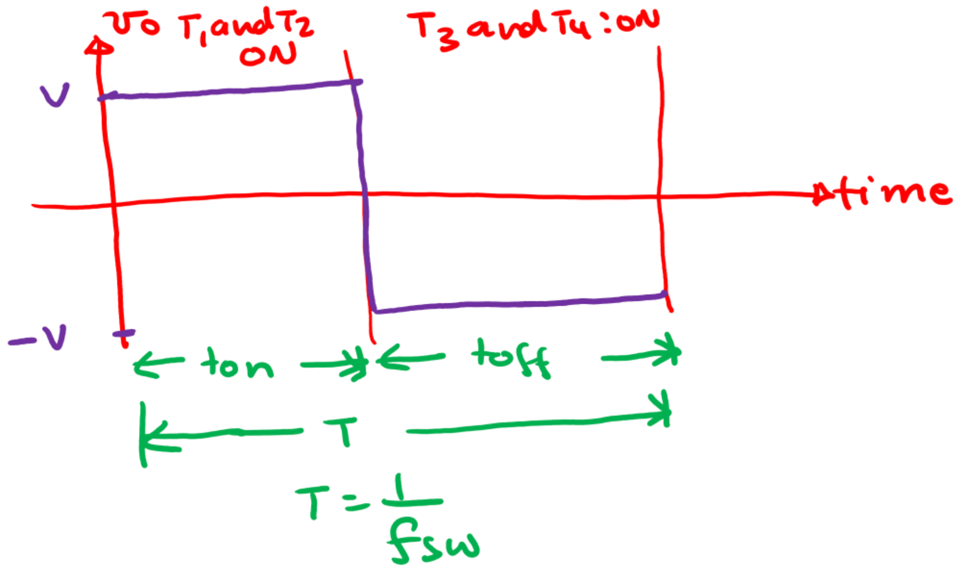






Power Electronic Converters – DC to DC Converter

- Full Bridge Converter – Four Quadrant Chopper



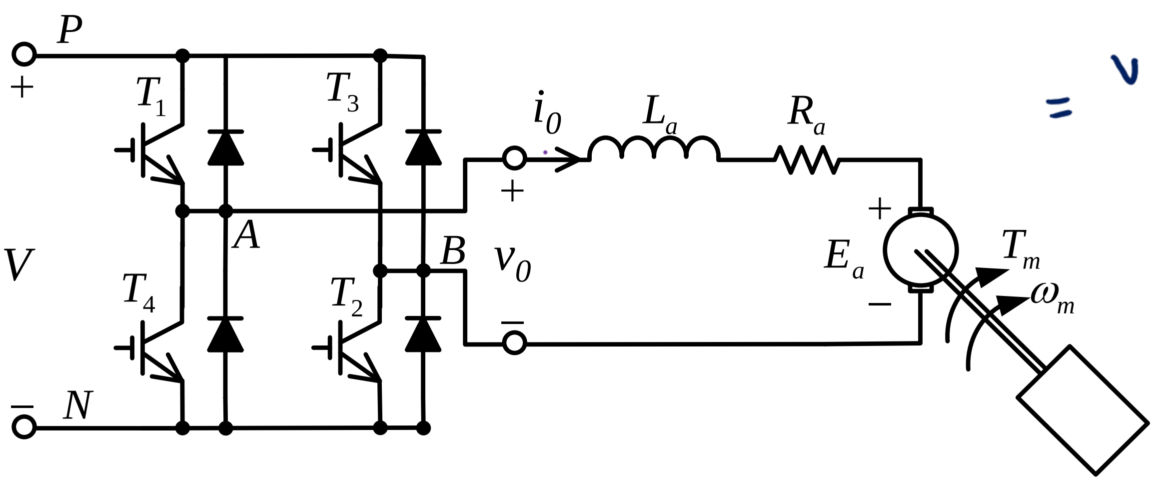
$$V_{o,avg} = \frac{(V \times t_{on}) + (-V \times t_{off})}{T}$$

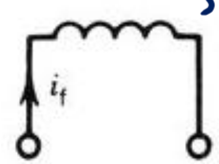
$$= \frac{V[t_{on} - t_{off}]}{T}$$

$$= \frac{V[t_{on} - (T - t_{on})]}{T}$$

$$= V\left[\frac{2t_{on} - T}{T}\right] = V\left[2\frac{t_{on}}{T} - 1\right]$$

$$V_{oavg} = V[2d - 1]$$





Power Electronic Converters

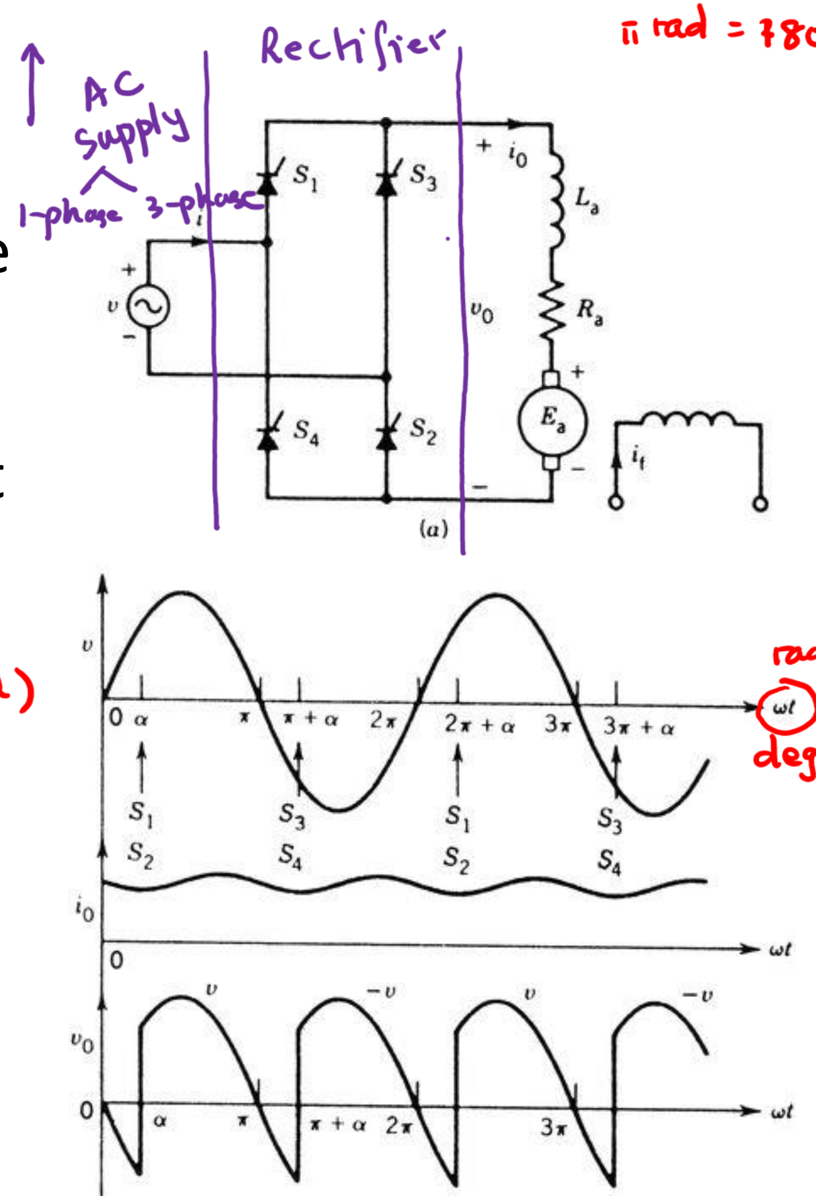
Converters:

1. Chopper (DC to DC)
2. **Controlled Rectifier (AC to DC)**
3. Inverter (DC to AC)
4. Cycloconverter (AC to AC) – converts a fixed voltage and fixed frequency AC to a variable voltage and variable frequency AC

Power Electronic Converters – AC to DC Converter

π rad = 180°

- 1-phase full-bridge controlled rectifier
- Assume that sufficient inductance is present in the DC armature circuit to ensure that motor current is continuous (i.e. present all the time)



thyristor → OFF (Reverse biased)

thyristor → Forward biased → $G = 1$ / $G = 0$

firing angle / delay angle → α

α is same for both S_1 and S_2

S_3 and S_4 → firing angle → $(\pi + \alpha)$

Power Electronic Converters – AC to DC Converter

- 1-phase full-bridge controlled rectifier

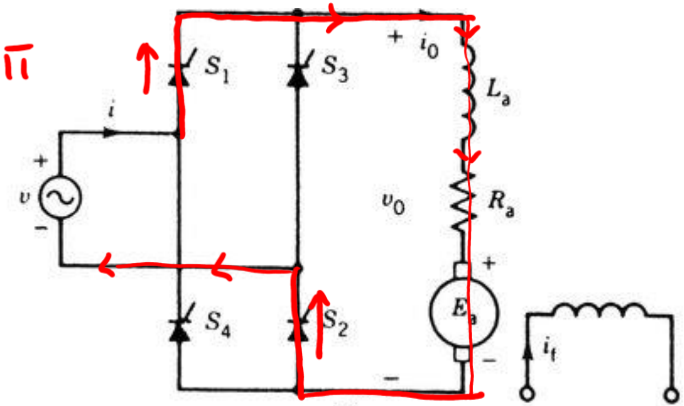
$0 \le \omega t \le 180^\circ$ or $0 \le \omega t \le \pi$

$v \rightarrow +ve$

S_1 and S_2 : FB

S_3 and S_4 : RB

$G=0$ $G=1$



(a)

assume ; $G=1$ @ $\omega t = \alpha = 10^\circ$ (ex.)

0 to $\alpha \rightarrow v_0$ [do not know]

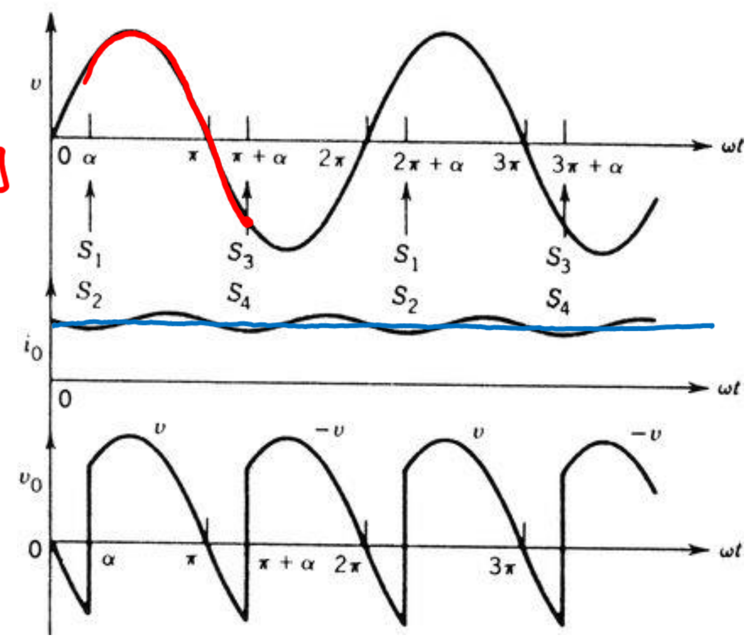
α to $180^\circ \rightarrow S_1$ and $S_2 \rightarrow$ closed
S_3 and $S_4 \rightarrow$ open

$v_0 = v$; $i_0 \rightarrow$ cw (+ve)

180° to $(\pi + \cancel{180^\circ}\ \alpha)$; S_3 and $S_4 \rightarrow$ open (FB)

S_1 and $S_2 \rightarrow$ closed → not by the supply But, by the armature winding (L_a)

$v_0 = v$



Power Electronic Converters – AC to DC Converter

- 1-phase full-bridge controlled rectifier

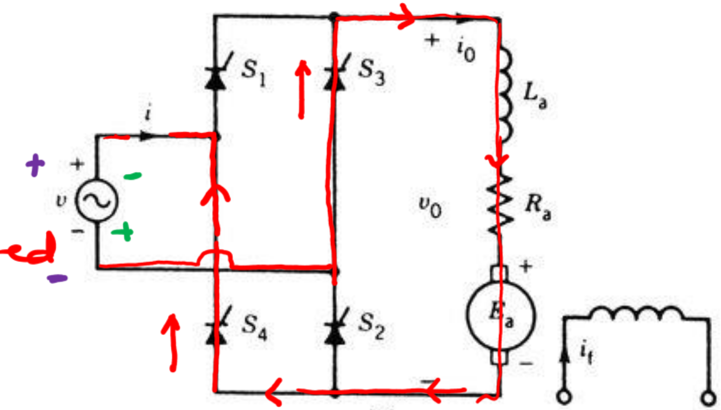
$(\pi + \alpha)$ to 2π < $S_3, S_4 \rightarrow$ FB ; $S_1, S_2 \rightarrow$ RB

@ $(\pi + \alpha)$, gates for S_3 and S_4 are fired

@ $\pi + \alpha$, $S_3, S_4 \rightarrow$ closed

$i_0 \rightarrow$ cw (+ve)

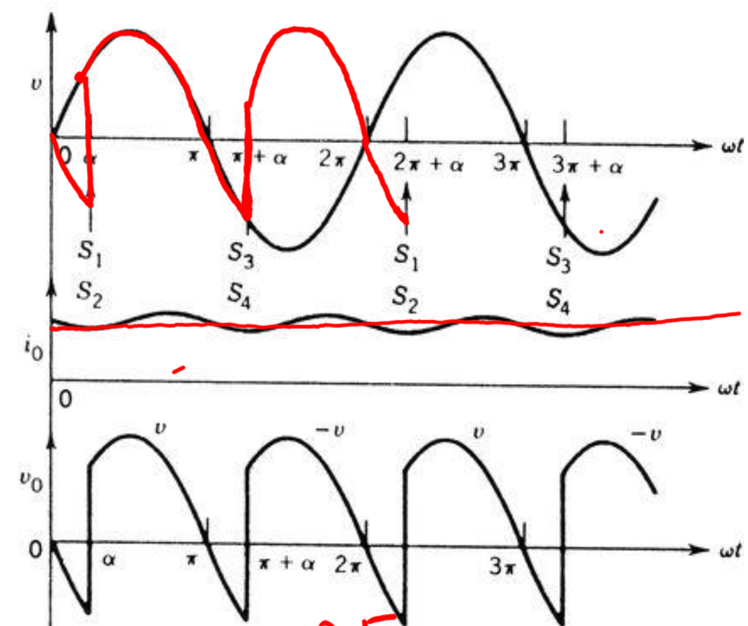
$v_0 = v$ $\mp v$ [+ve values]



(a)

2π to $(2\pi + \alpha)$ < $S_1, S_2 \rightarrow$ FB [OFF] ; $\underbrace{S_3, S_4}_{\text{remain ON due to load } (L_a)} \rightarrow$ Supply RB

[0 to α]



$i_0 \rightarrow$ cw (+ve)

$v_0 = -v$ [$\pm v$ (+ve values)]

$$v_{0,avg} = \frac{2\sqrt{2}}{\pi} V_{rms} \cos\alpha$$

Power Electronic Converters – AC to DC Converter

$V_{o,avg} = \frac{2\sqrt{2}}{\pi} V_{rms} \cos\alpha$

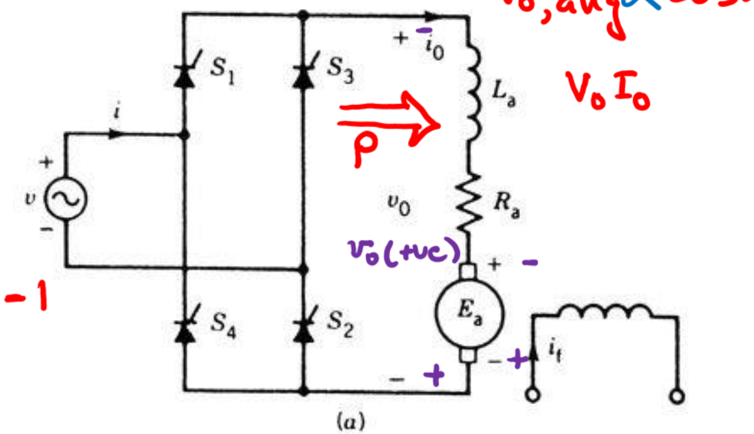
$V_{o,avg} \propto \cos\alpha$

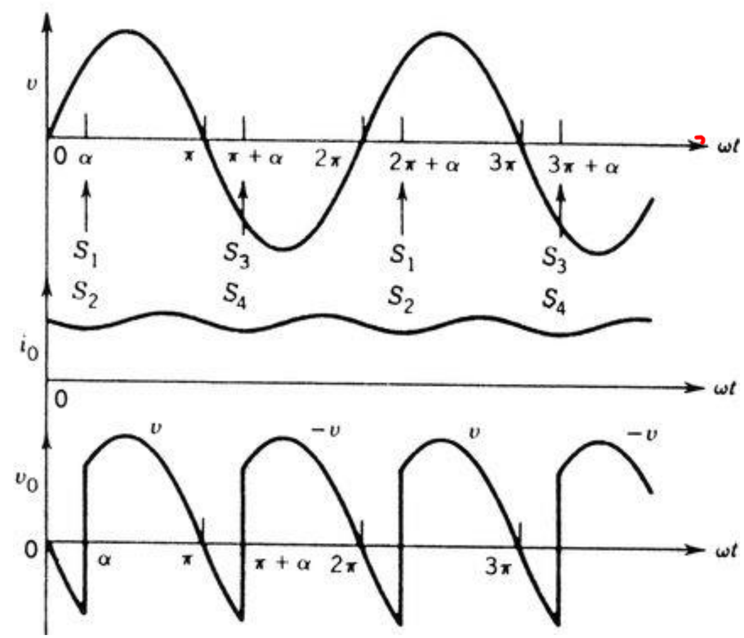
$V_o I_o$

- 1-phase full-bridge controlled rectifier
- The average output voltage is positive for $0^0 < \alpha < 90^0$. The power ($V_0 I_0$) is positive and the power flow is from the input AC supply to the DC machine. The DC machine operates as a motor

$90^\circ \rightarrow \cos\alpha = 0^\circ$ $\quad 180^\circ \rightarrow \cos\alpha = -1$

- The average output voltage is negative for $90^0 < \alpha < 180^0$. The power ($V_0 I_0$) is negative and the power flow is from the DC machine to the AC supply. This is called Inversion operation of the converter. This mode of operation is used for Regenerative braking of the motor. For the inversion operation, the polarity of the motor back emf (E_a) must be negative. It can be reversed by reversing the field current (if) so that the DC machine behaves as a Generator.





$E_a = K_a \phi \omega$

Power Electronic Converters – AC to DC Converter

$E_a = K_a \phi N$

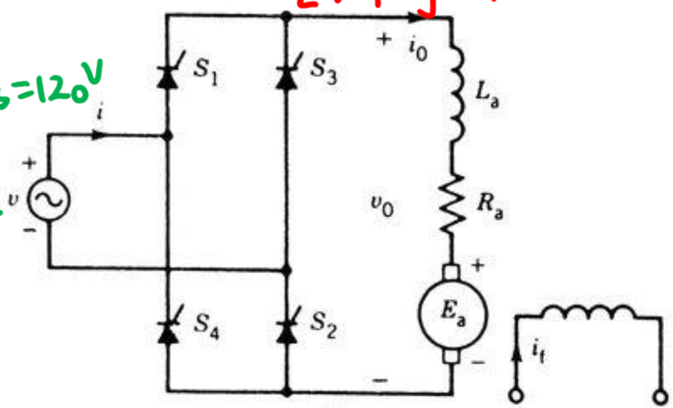
(V) [V/rpm] (rpm)

- 1-phase full-bridge controlled rectifier - Example
- A 1-phase full bridge controlled rectifier is used to control the speed of a 5 hp, 110 V, 1200 rpm, separately excited DC motor. The converter is connected to a 1-phase 120 V, 60 Hz supply. The armature resistance R_a = 0.4 Ω, and armature circuit inductance is L_a = 5 mH. The motor constant $K_a\varphi$ = 0.09 V/rpm.

$V_{rms} = 120^V$

120^V

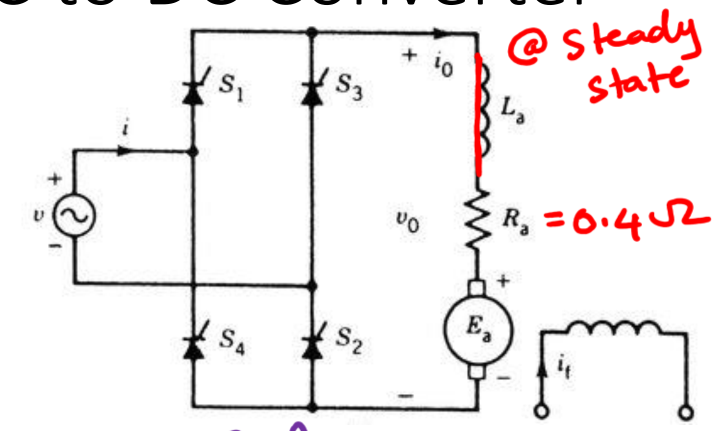
60Hz



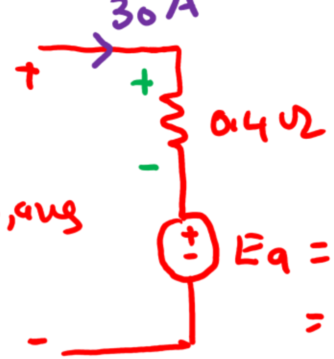
- Rectifier (motoring) operation – The DC machine operates as a motor, runs at 1000 rpm, and carries an armature current of 30 A. Assume that motor current is continuous (ripple free) $\rightarrow I_o$
  - Determine the firing angle
  - Determine the power to the motor
- Inverter (regenerating) operation – The polarity of the motor back emf E_a is reversed, say by reversing the field excitation.
  - Determine the firing angle to keep the motor current at 30 A when the speed is 1000 rpm
  - Determine the power fed back to the supply at 1000 rpm

Power Electronic Converters – AC to DC Converter

- Rectifier (motoring) operation – The DC machine operates as a motor, runs at 1000 rpm, and carries an armature current of 30 A. Assume that motor current is continuous (ripple free)
  - Determine the firing angle
  - Determine the power to the motor



$$V_{o,avg} = \frac{2\sqrt{2}}{\pi} V_{rms} \cos\alpha$$



$$(0.4 \times 30) + 90 = V_{o,avg}$$

$$102\,V$$

$E_a = K_a \phi\, N$

$= 0.09 \times 1000$

$= 90\,V$

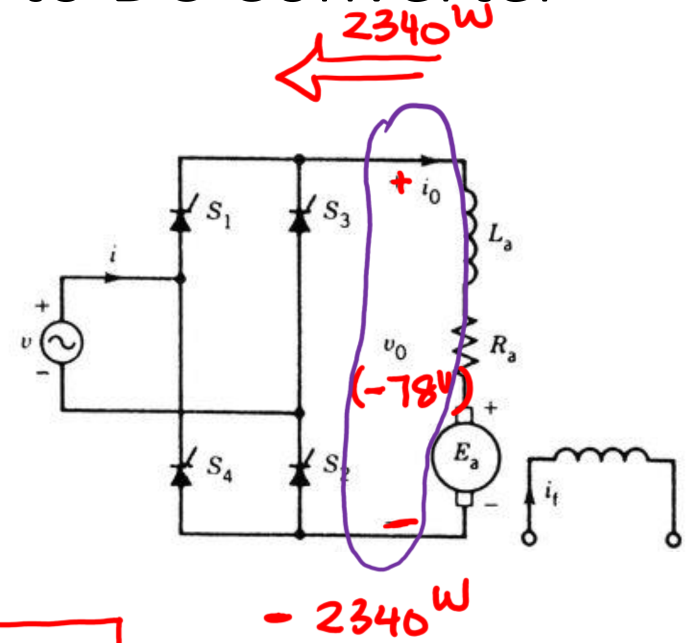
$$102 = \frac{2\sqrt{2}}{\pi} \times 120 \times \cos\alpha$$

$$\alpha = 19.24^\circ$$

$$P \text{ (supplied to the motor]} : V_{o,avg} I_o = 102 \times 30 = 3060\,W$$

Power Electronic Converters – AC to DC Converter

- Inverter (regenerating) operation – The polarity of the motor back emf E_a is reversed, say by reversing the field excitation.
  - Determine the firing angle to keep the motor current at 30 A when the speed is 1000 rpm
  - Determine the power fed back to the supply at 1000 rpm



$E_a = K_a \phi N = 0.09 \times 1000 = 90^V$

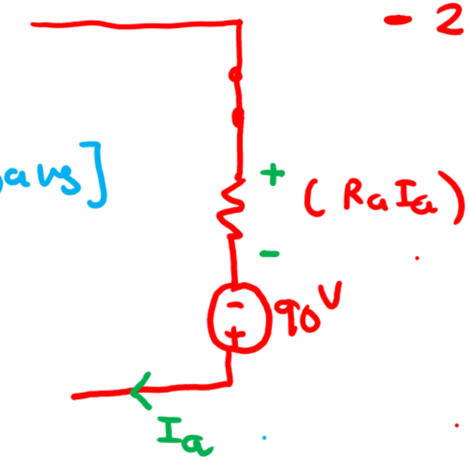
Generator

$v_{o,avg}$ [$-V_{o,avg}$]

$v_{o,avg} + I_a R_a = E_a$

$V_{o,avg} = E_a - I_a R_a$

$= 90 - [30 \times 0.4] = 78^V$



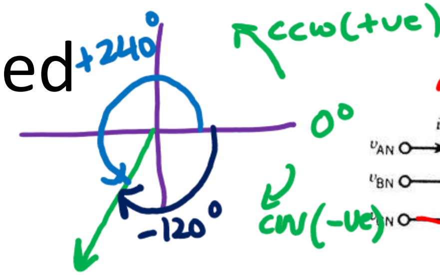
$-78 = \frac{2\sqrt{2}}{\pi} \times 120 \times \cos\alpha_1 \Rightarrow \alpha_1 = 136.2^\circ$

power flow from the machine to the supply

$= V_{o,avg} I_o = 78 \times 30 = 2340^W$

Power Electronic Converters – AC to DC Converter

- 3-phase full-bridge controlled rectifier



$v_{AN} = V_m \sin \omega t$

$v_{BN} = V_m \sin(\omega t - \frac{2\pi}{3}) = V_m \sin(\omega t - 120^\circ)$

$v_{CN} = V_m \sin(\omega t - 240^\circ) = V_m \sin(\omega t - \frac{4\pi}{3})$

$v_{CN} = V_m \sin(\omega t + 120^\circ)$

v_{AN} +ve → S_1 : FB, S_4 : RB
v_{AN} −ve → S_1 : RB, S_4 : FB

v_{BN} +ve → S_3 : FB, S_6 : RB
v_{BN} −ve → S_3 : RB, S_6 : FB

v_{CN}
+ve: S_5 : FB, S_2 : RB
−ve: S_2 : FB, S_5 : RB

S_1 and S_2 : closed

$v_0 = v_{AN} - v_{CN} = v_{AC}$

$\alpha = 30^\circ$

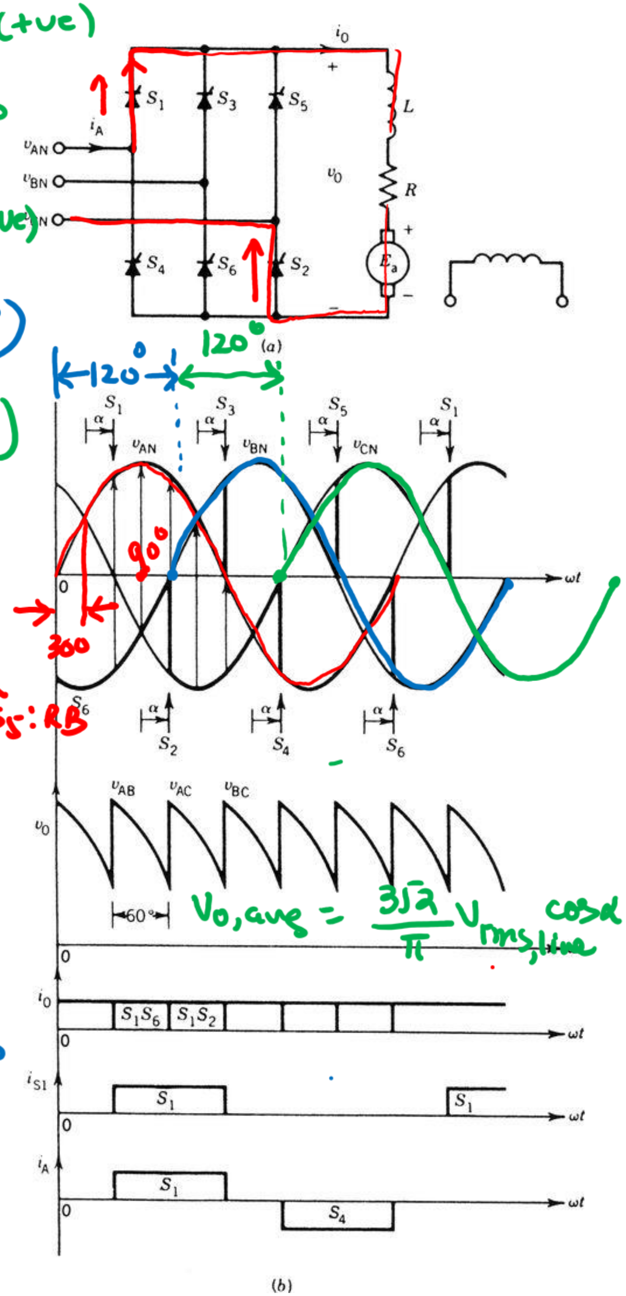
S_1 : ON → 60° to 180°

S_2 : ON → 120° to 240°

$v_{CA} = -v_{AC}$

120° to 180°

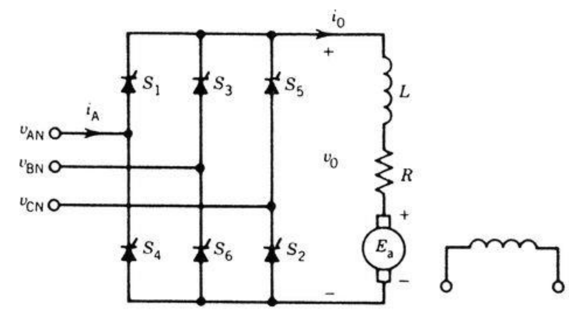
Each switch is ON for a period of 120°



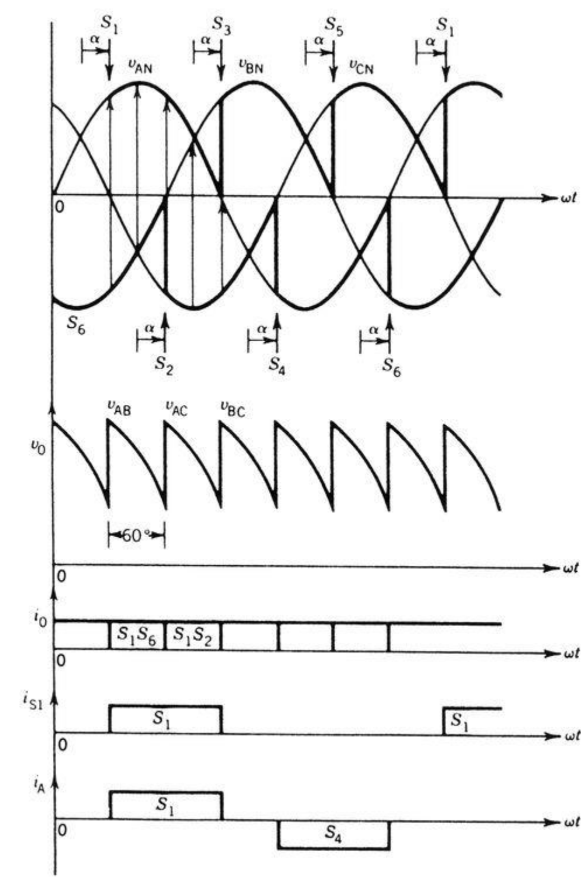
$V_{o,avg} = \frac{3\sqrt{2}}{\pi} V_{rms,line} \cos\alpha$

Power Electronic Converters – AC to DC Converter

- 3-phase full-bridge controlled rectifier
- The average output voltage varies with the firing angle, α
- The output voltage v_0 is positive for $0^0 < \alpha < 90^0$. The power (V_0I_0) is positive and the power flow is from the input AC supply to the DC machine. The DC machine operates as a motor
- The output voltage v_0 is negative for $90^0 < \alpha < 180^0$. The power (V_0I_0) is negative and the power flow is from the DC machine to the AC supply. The converter operates in the Inversion mode. This mode of operation is used for Regenerative braking of the motor.



(a)

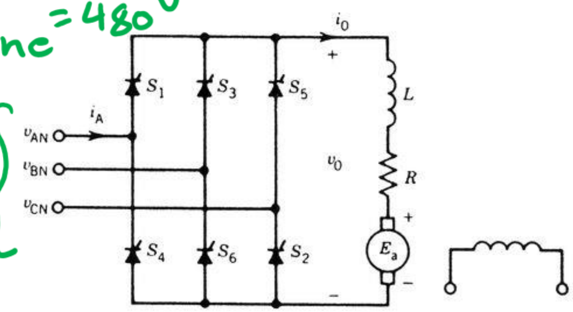


(b)

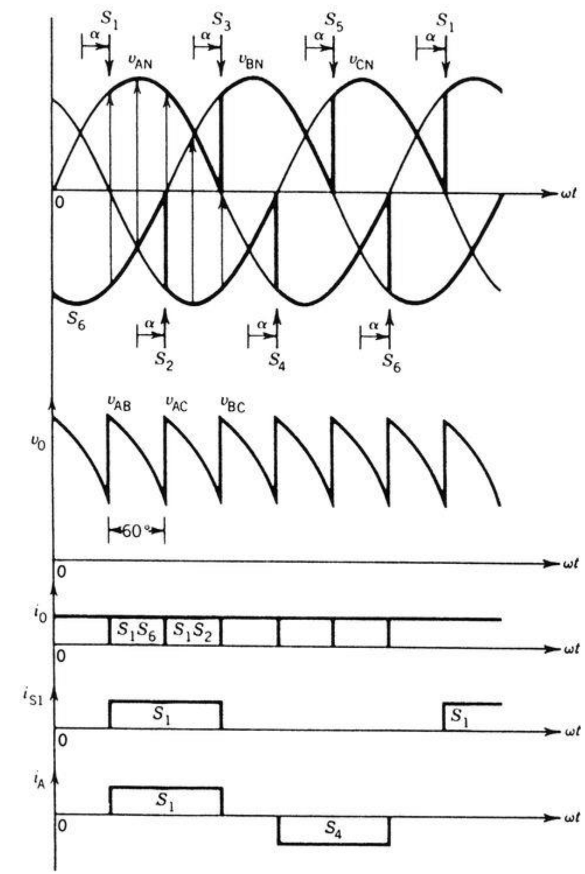
Power Electronic Converters – AC to DC Converter

- 3-phase full-bridge controlled rectifier - Example
- A 3-phase full bridge controlled rectifier is used to control the speed of a 100 hp, 600 V, 1800 rpm, separately excited DC motor. The converter is connected to a 3-phase 480 V, 60 Hz supply. The armature resistance R_a = 0.1 Ω, and armature circuit inductance is L_a = 5 mH. The motor constant $K_a\varphi$ = 0.3 V/rpm. The rated armature current is 130 A.
- Rectifier (motoring) operation – The DC machine operates as a motor, draws rated current, and runs at 1500 rpm. Assume that motor current is continuous (ripple free)
  - Determine the firing angle
  - Determine the power to the motor
- Inverter (regenerating) operation – The DC machine is operated in regenerative braking mode. At 1000 rpm and the rated motor current,
  - Determine the firing angle
  - Determine the power fed back to the supply

$V_{rms,line} = 480V$



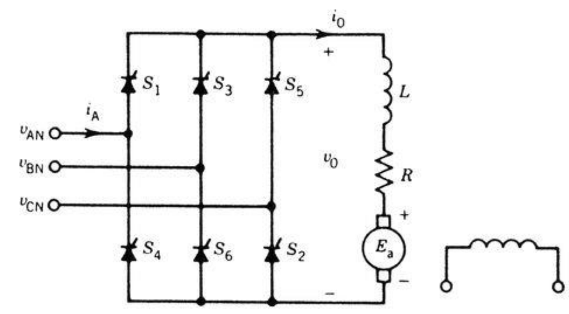
(a)



(b)

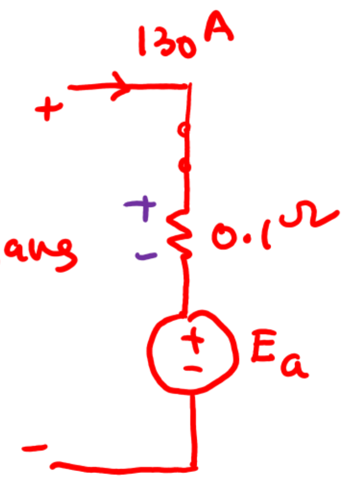
Power Electronic Converters – AC to DC Converter

- Rectifier (motoring) operation – The DC machine operates as a motor, draws rated current, and runs at 1500 rpm. Assume that motor current is continuous (ripple free)
  - Determine the firing angle
  - Determine the power to the motor



(a)

$$V_{o,avg} = \frac{3\sqrt{2}}{\pi} V_{rms,line} \cos\alpha$$



$$V_{o,avg} = R_a I_a + E_a$$

$$E_a = K_a \Phi N = 0.3 \times 1500 = 450^V$$

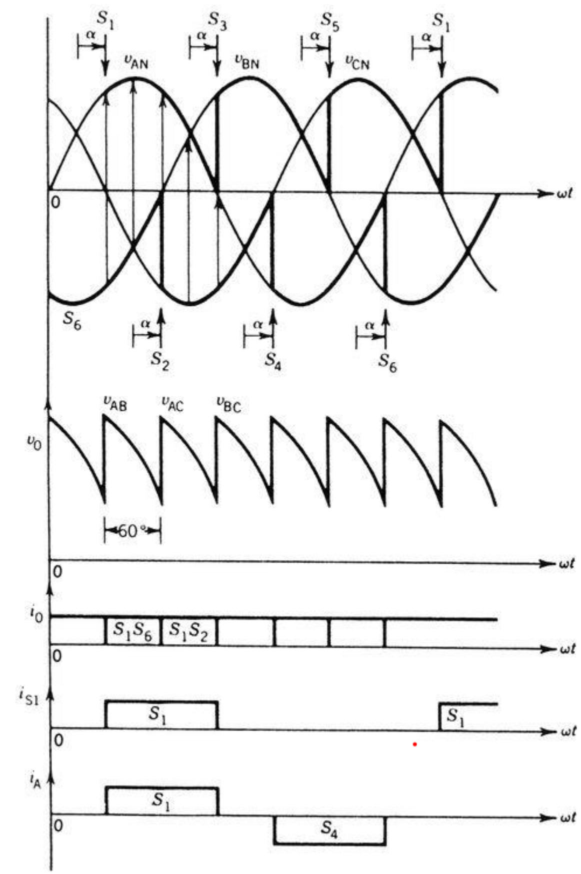
$$V_{o,avg} = (0.1 \times 130) + 450 = 463^V$$

$$463 = \frac{3\sqrt{2}}{\pi} \times 480 \times \cos\alpha \Rightarrow \alpha = 44.42^\circ$$

power supplied to the motor

$$= V_{o,avg} I_o = 463 \times 130$$

$$= 60190^W$$

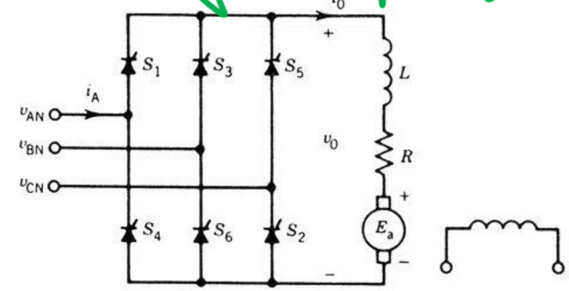


(b)

Power Electronic Converters – AC to DC Converter

$P = 37310\,W$

- Inverter (regenerating) operation – The DC machine is operated in regenerative braking mode. At 1000 rpm and the rated motor current,
  - Determine the firing angle
  - Determine the power fed back to the supply



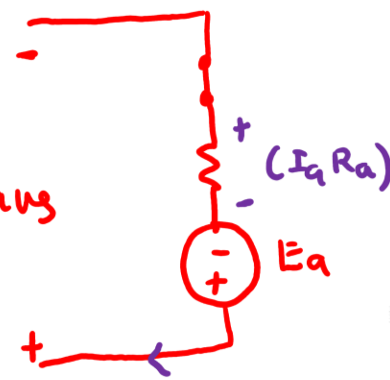
(a)

$$V_{oavg} = \frac{3\sqrt{2}}{\pi} \times 480 \times \cos\alpha$$

$$v_{oavg} = E_a - I_a R_a$$

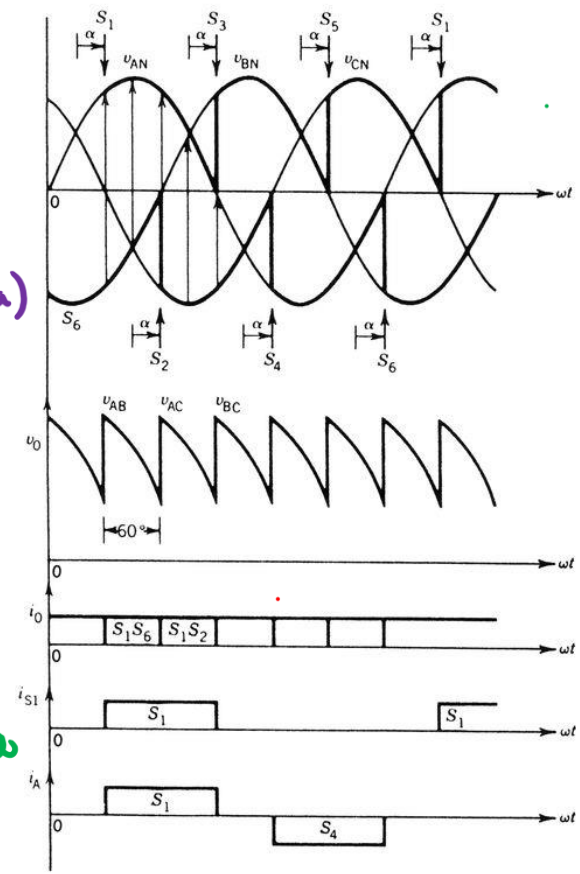
$$= (0.3 \times 1000) - [130 \times 0.1] \quad V_{o,avg}$$

$$V_{o,avg} = 287\,V$$



$$(-287)\,V = \frac{3\sqrt{2}}{\pi} \times 480 \times \cos\alpha \Rightarrow \alpha = 116.3^\circ$$

Power supplied from the machine to the supply $= 287 \times 130 = 37310\,W$



(b)

Power Electronic Converters

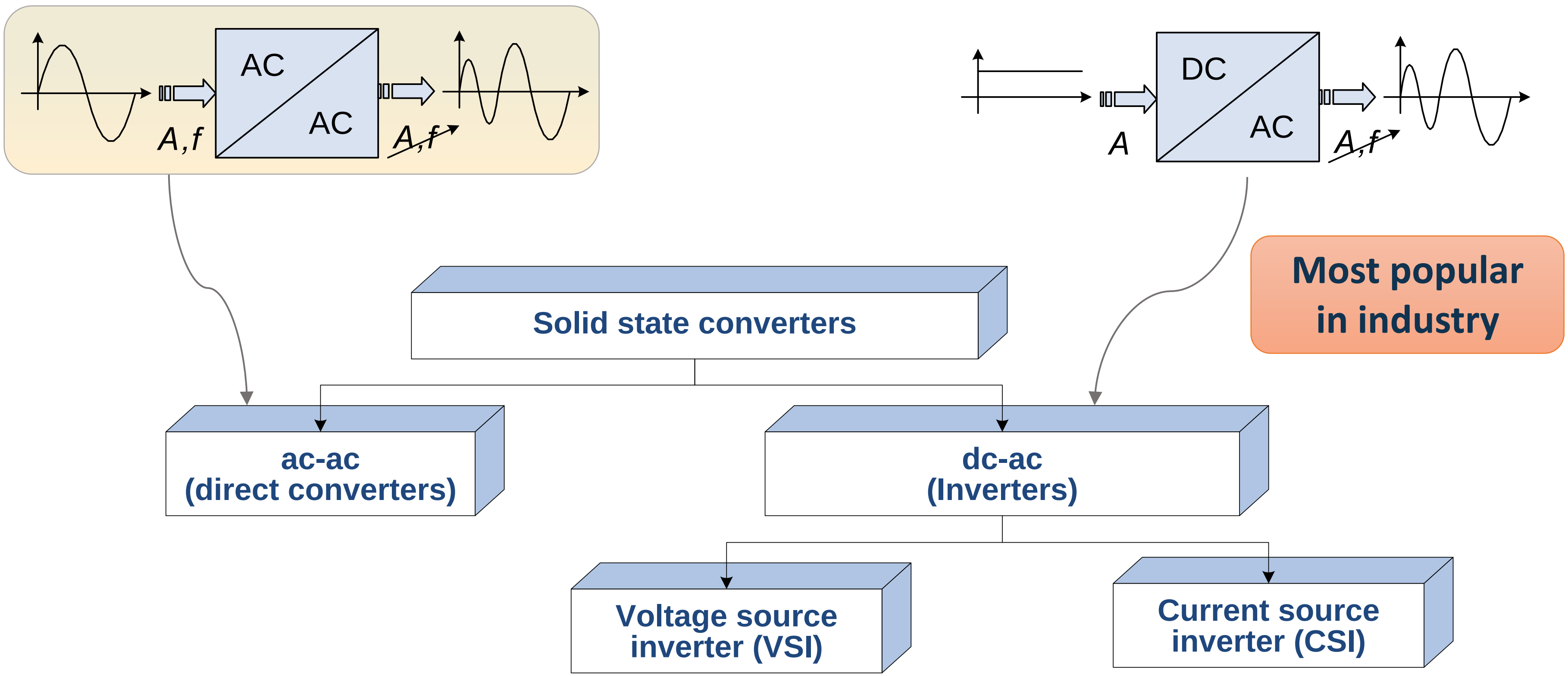
Converters:

1. Chopper (DC to DC)
2. Controlled Rectifier (AC to DC)
3. **Inverter (DC to AC)**
4. Cycloconverter (AC to AC) – converts a fixed voltage and fixed frequency AC to a variable voltage and variable frequency AC

Power Electronics Converters

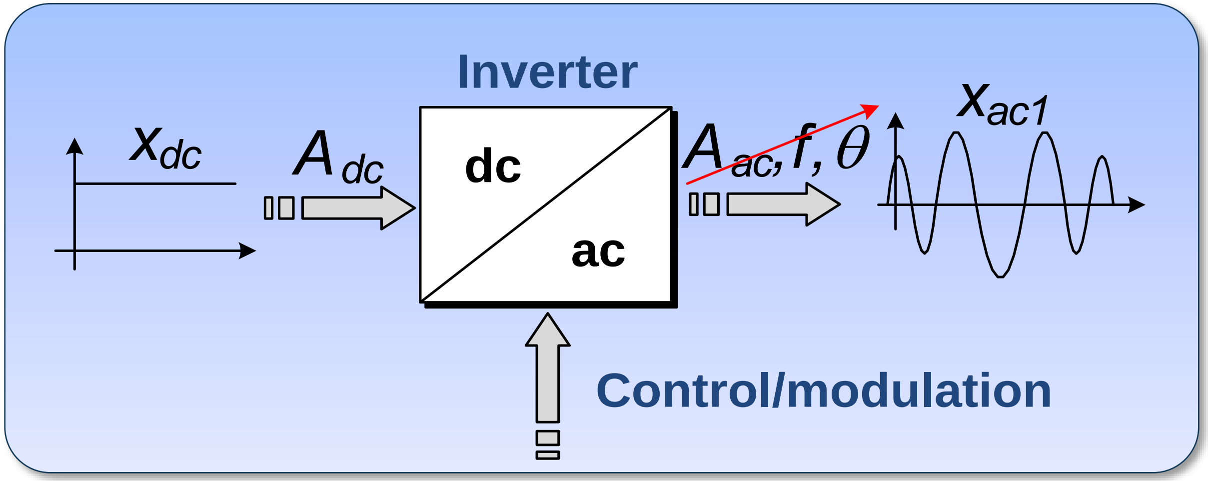
ac-ac and dc-ac converters

- To generate variable ac voltages, a power electronics (solid state) converter is needed



Operating principle of inverters

- Input: dc, fixed
- Output: ac, variable voltage and frequency



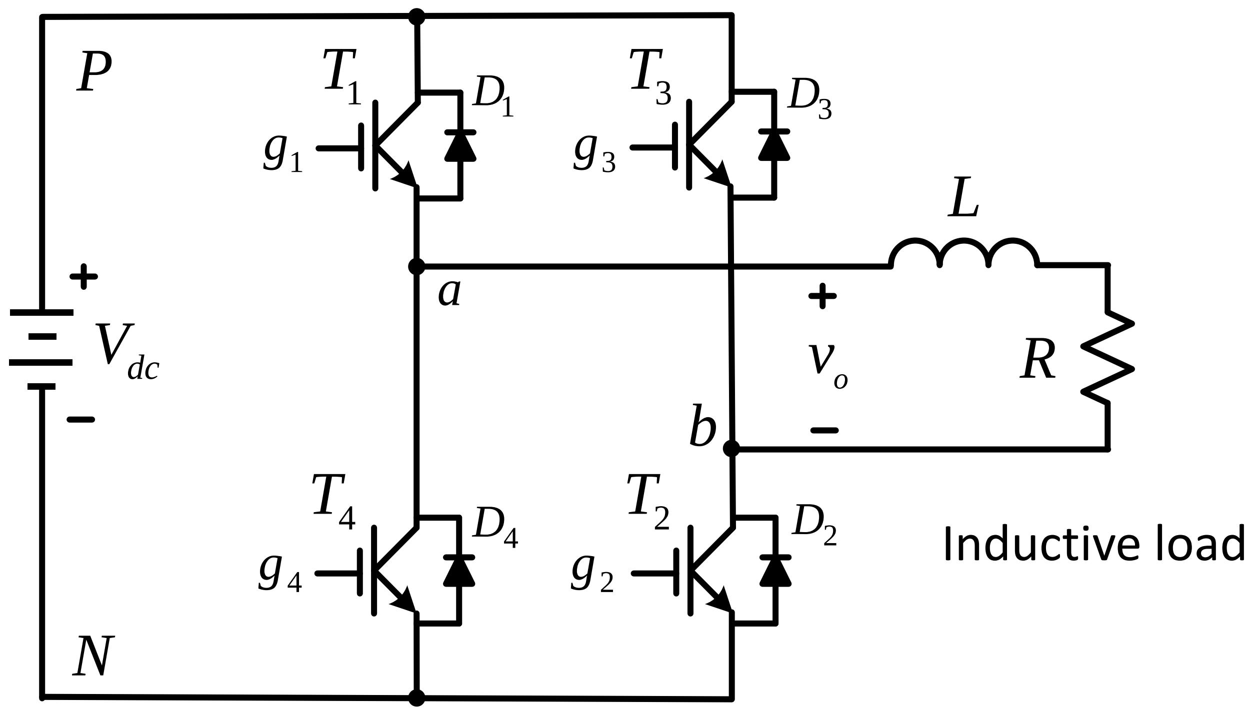
- Inverters are used in Variable Speed AC motor drives

Voltage Source Inverters (VSI)

- In VSI, the inverter converts the input DC voltage into a square wave AC output voltage
- The input can be from a battery or from the output of a controlled rectifier

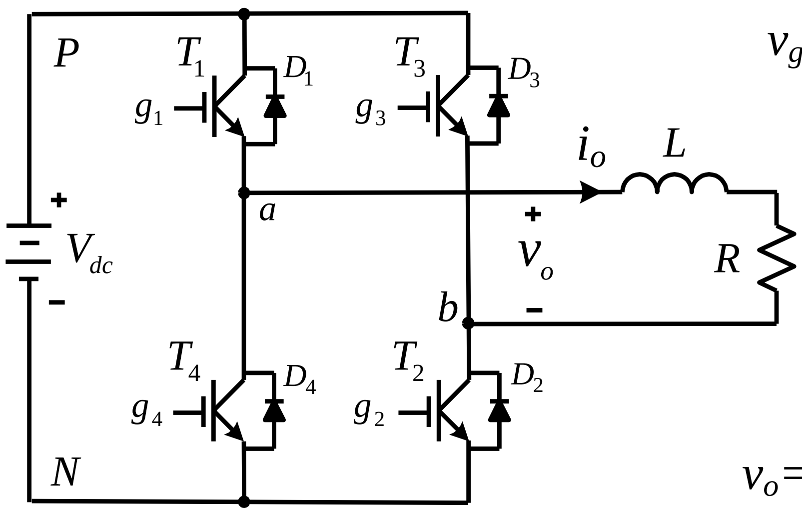
Single-phase full-bridge VSI

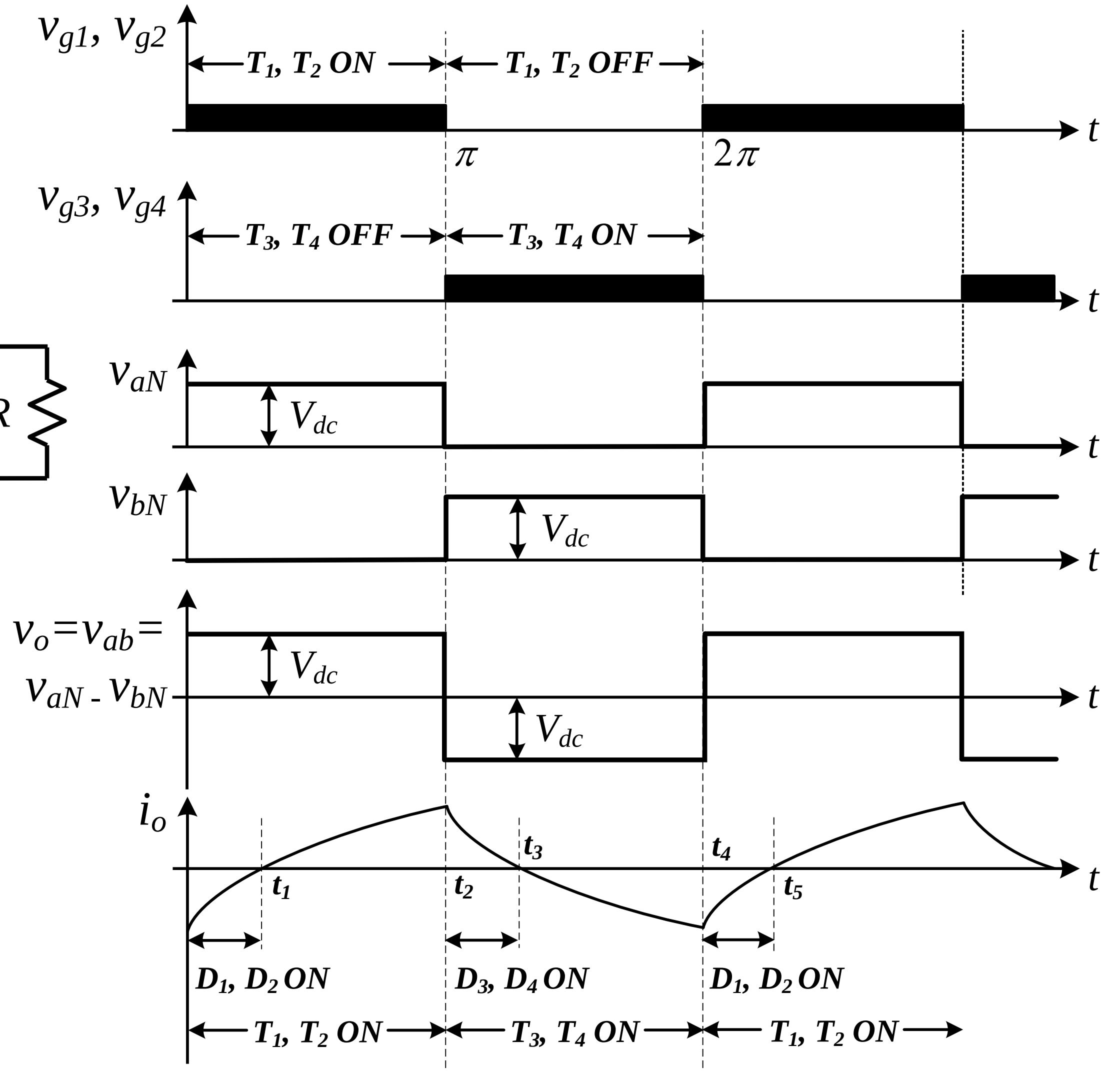
- **T1 ~ T4: Switching devices (IGBTs)**
- **D1 ~ D4: Free wheeling diodes (allow the inductive current to freewheel)**



Power Electronics Converters – Voltage Source Inverter

Single-phase full-bridge VSI

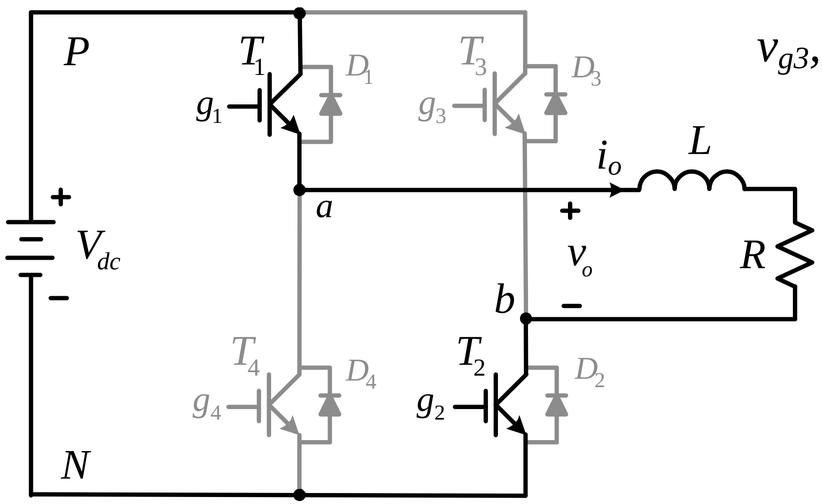


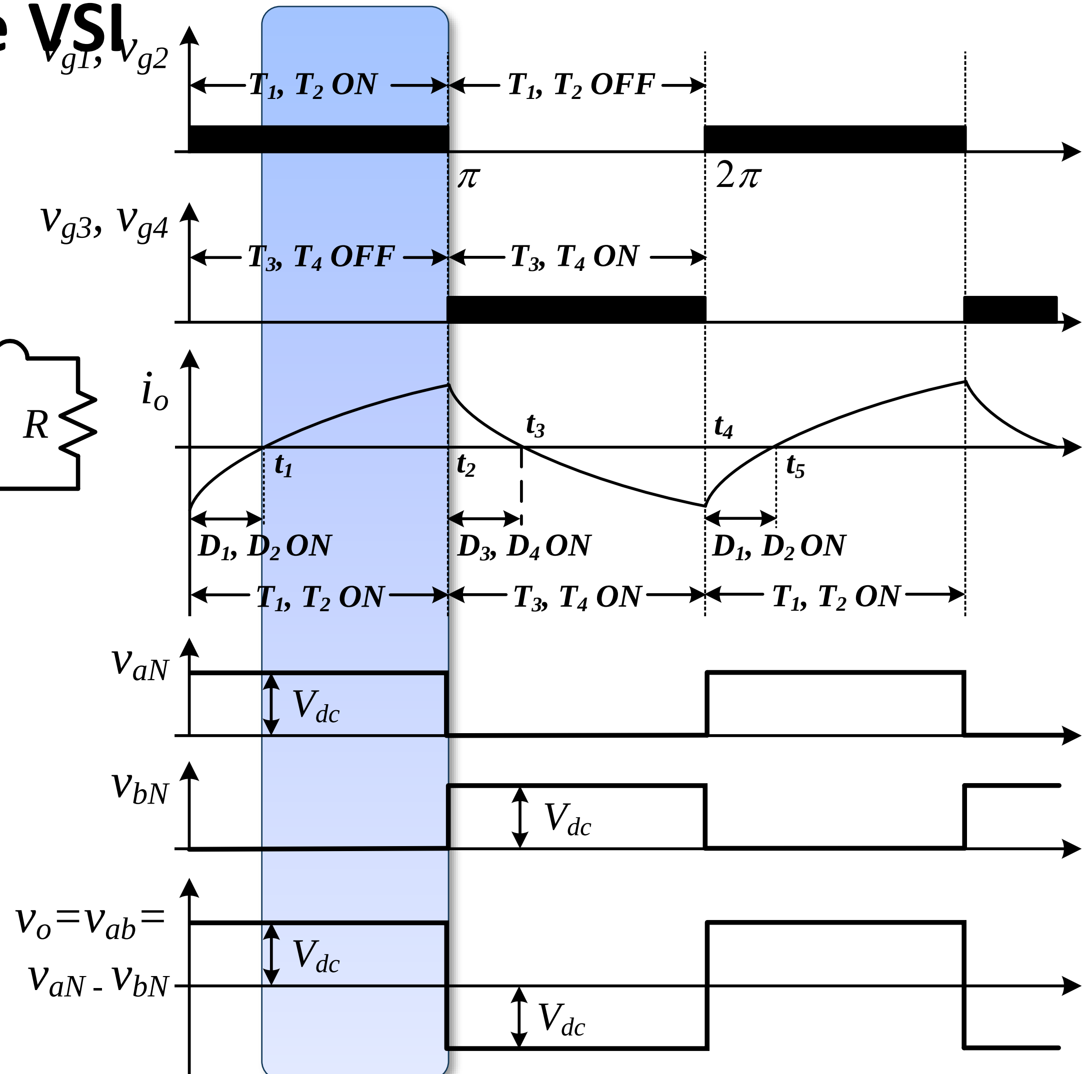


Square wave operation

Power Electronics Converters – Voltage Source Inverter

Single-phase full-bridge VSI





- $t_1 \leq t < t_2$,

  T_1 , T_2 ON, $i_o > 0$,

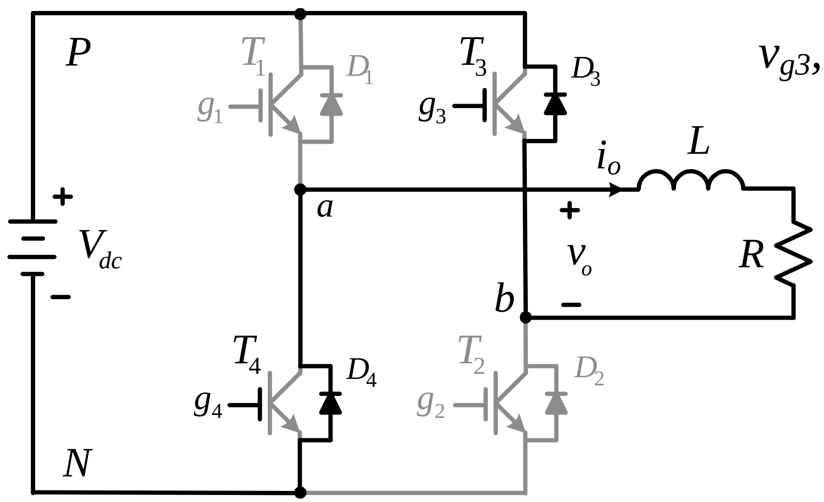
  $V_{dc+} \rightarrow T_1 \rightarrow L \rightarrow R \rightarrow T_2 \rightarrow V_{dc-}$

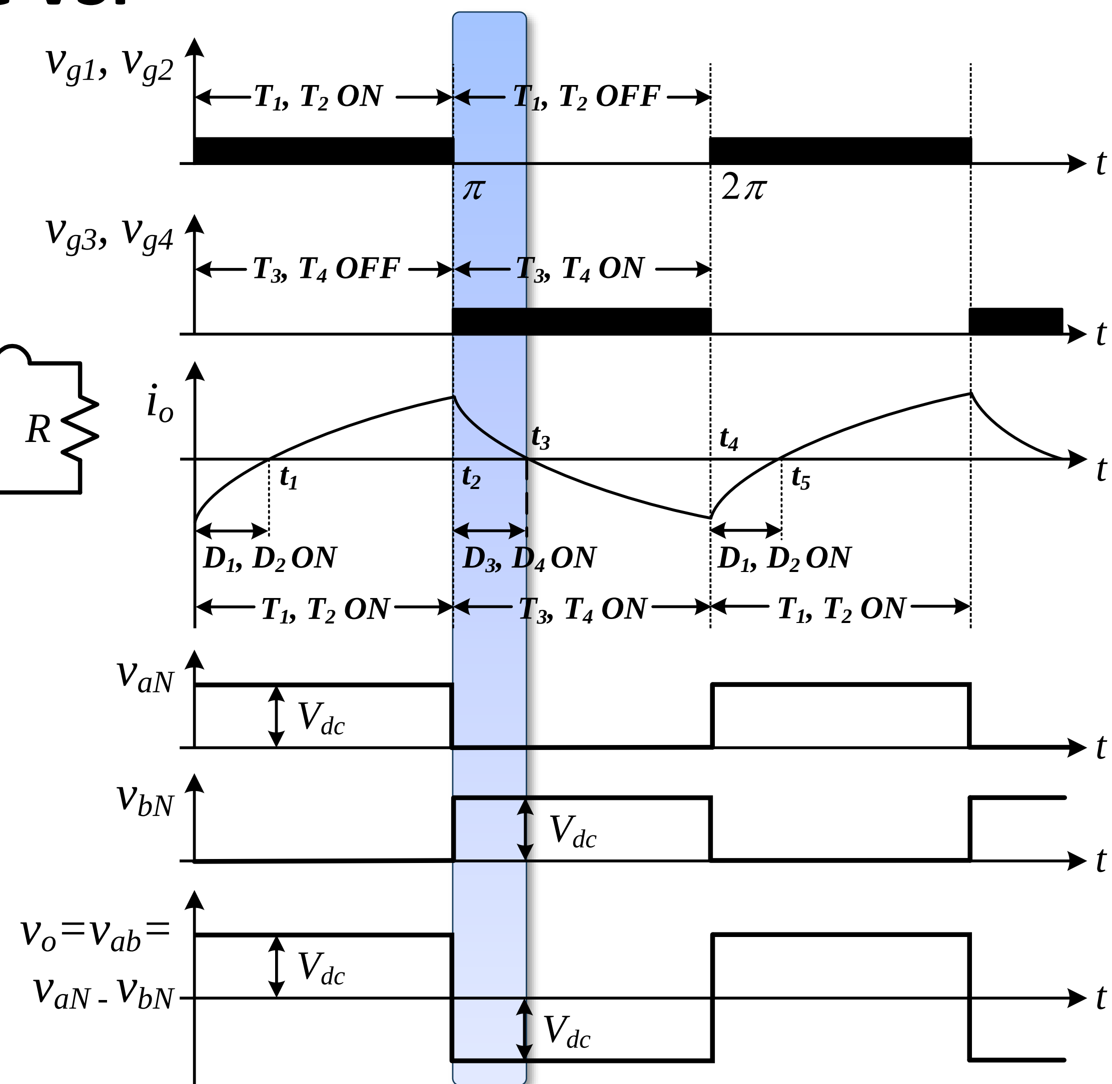
  energy is stored in the inductor L

Square wave operation

Power Electronics Converters – Voltage Source Inverter

Single-phase full-bridge VSI





Square wave operation

- $t_2 \le t < t_3$,

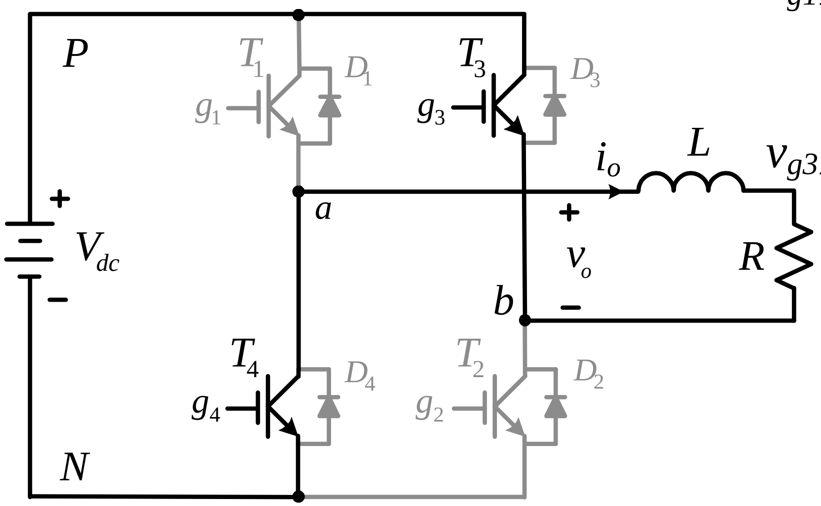
T_1, T_2 OFF, T_3, T_4 ON, $i_o > 0$

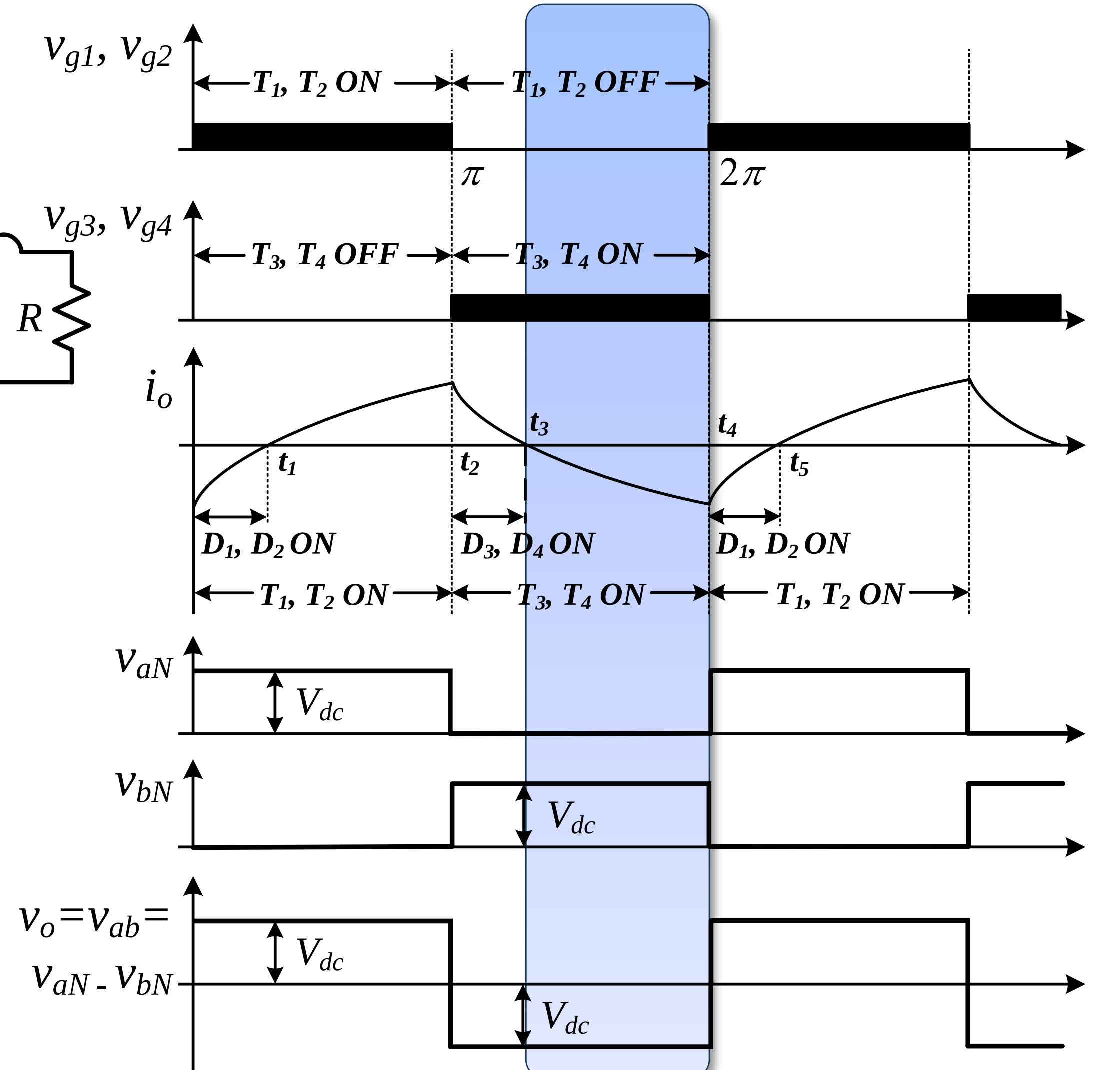
$L \rightarrow R \rightarrow D_3 \rightarrow V_{dc} \rightarrow D_4 \rightarrow L$

stored energy in L released to V_{dc} and R (freewheeling)

Power Electronics Converters – Voltage Source Inverter

Single-phase full-bridge VSI





Square wave operation

- $t_3 \leq t < t_4$,

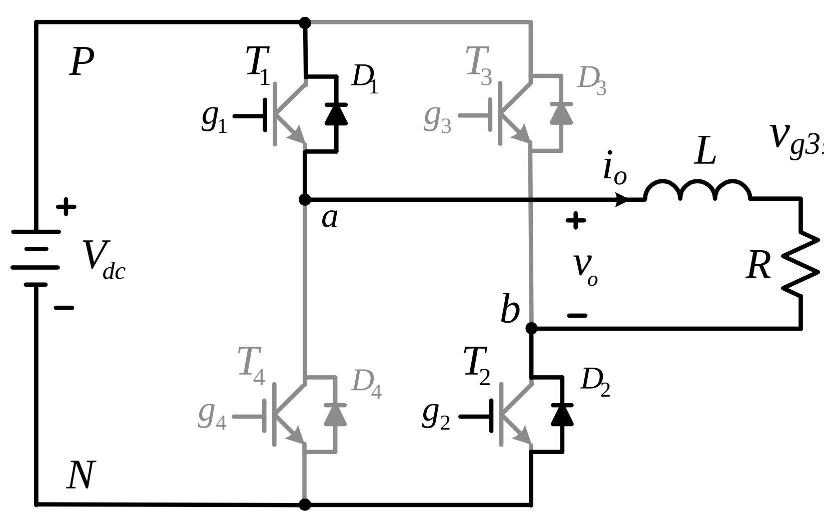
  T_3 , T_4 remain ON, $i_o < 0$

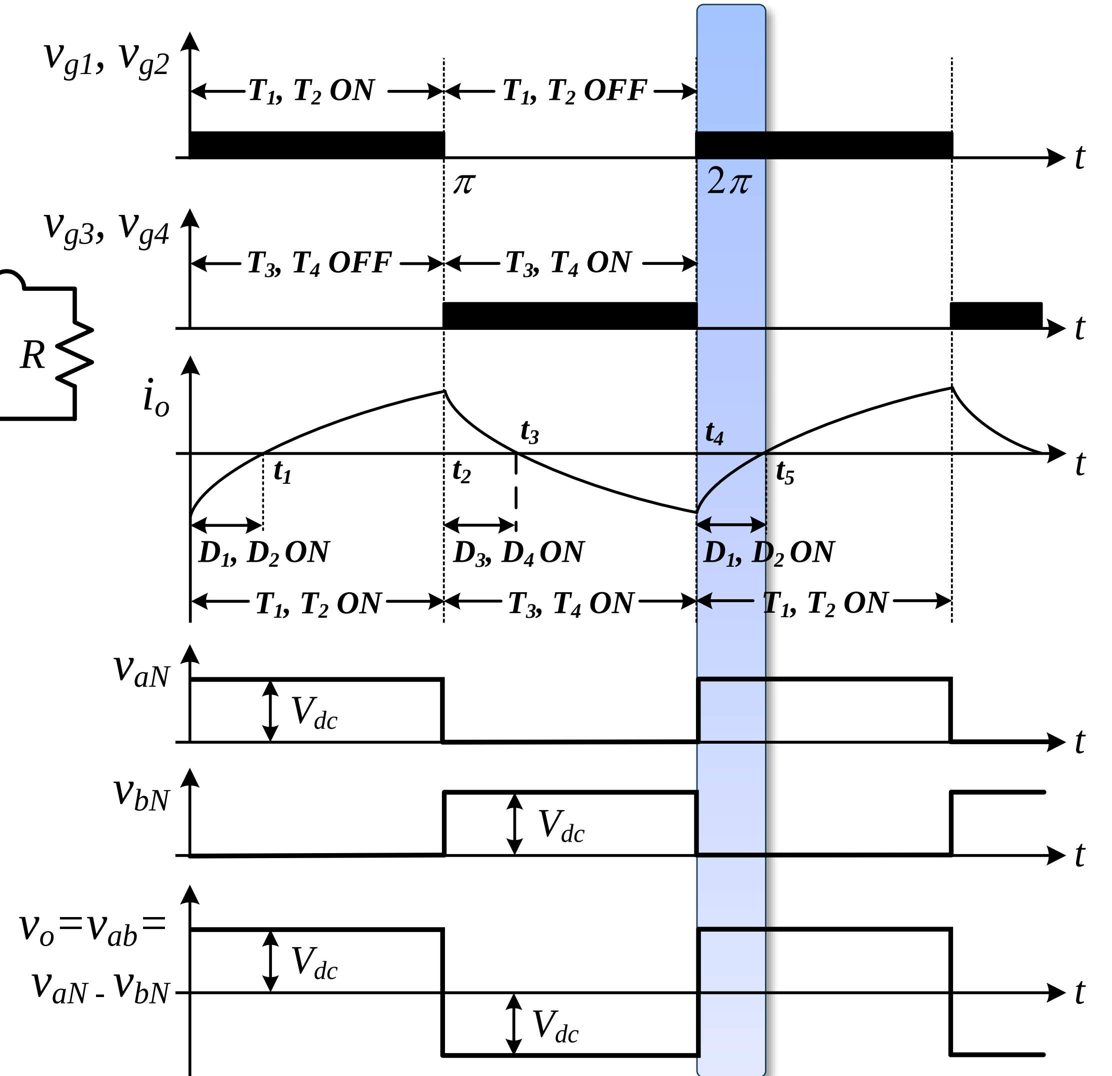
  $V_{dc+} \rightarrow T_3 \rightarrow R \rightarrow L \rightarrow T_4 \rightarrow V_{dc-}$

  D_3, D_4 are OFF

Power Electronics Converters – Voltage Source Inverter

Single-phase full-bridge VSI





Square wave operation

- $t_4 \leq t < t_5$,

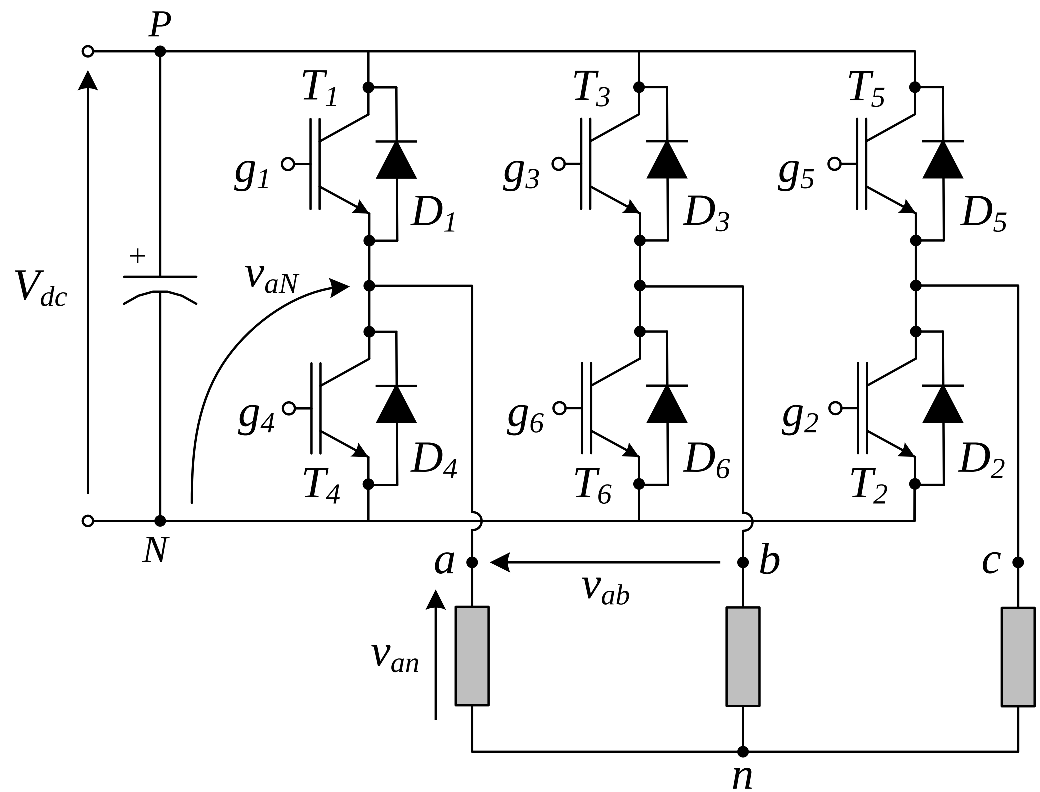
  T_3 , T_4 OFF, T_1 , T_2 ON, $i_o < 0$

  $L \rightarrow D_1 \rightarrow V_{dc} \rightarrow D_2 \rightarrow R \rightarrow L$

  Freewheeling through D_1, D_2

Power Electronics Converters – Voltage Source Inverter

Three-phase two-level VSI

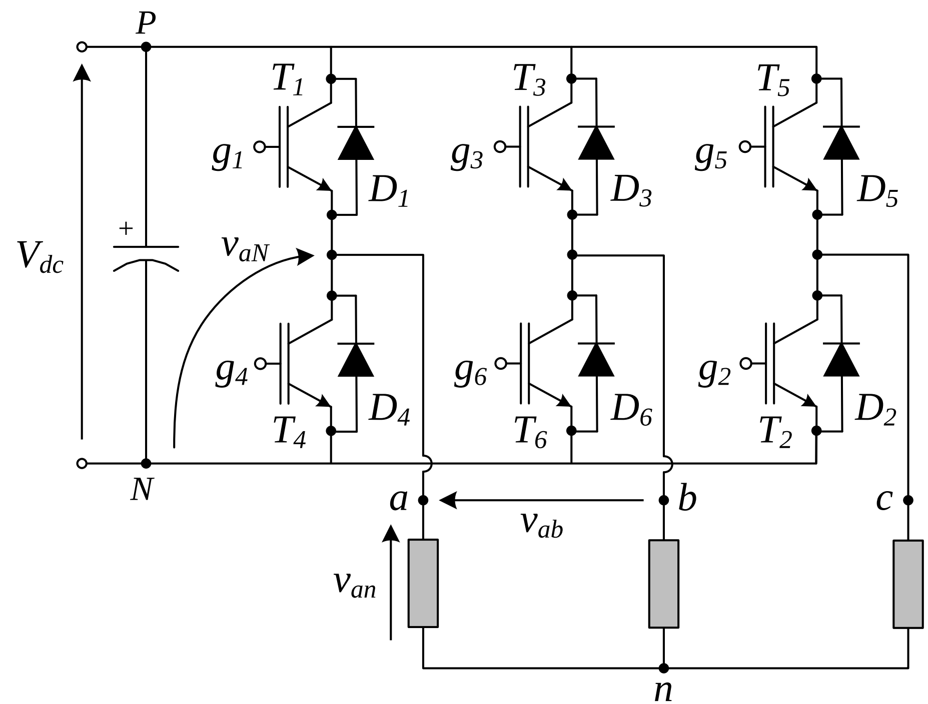


- $T_1 \sim T_6$: Solid state switches; $D_1 \sim D_6$: Free wheeling diodes
- Three phase legs, each connected to an output node: a,b *or* c
- Any two legs can be considered as a single-phase full-bridge VSI (H-bridge)

Power Electronics Converters – Voltage Source Inverter

Three-phase two-level VSI – Switching conditions

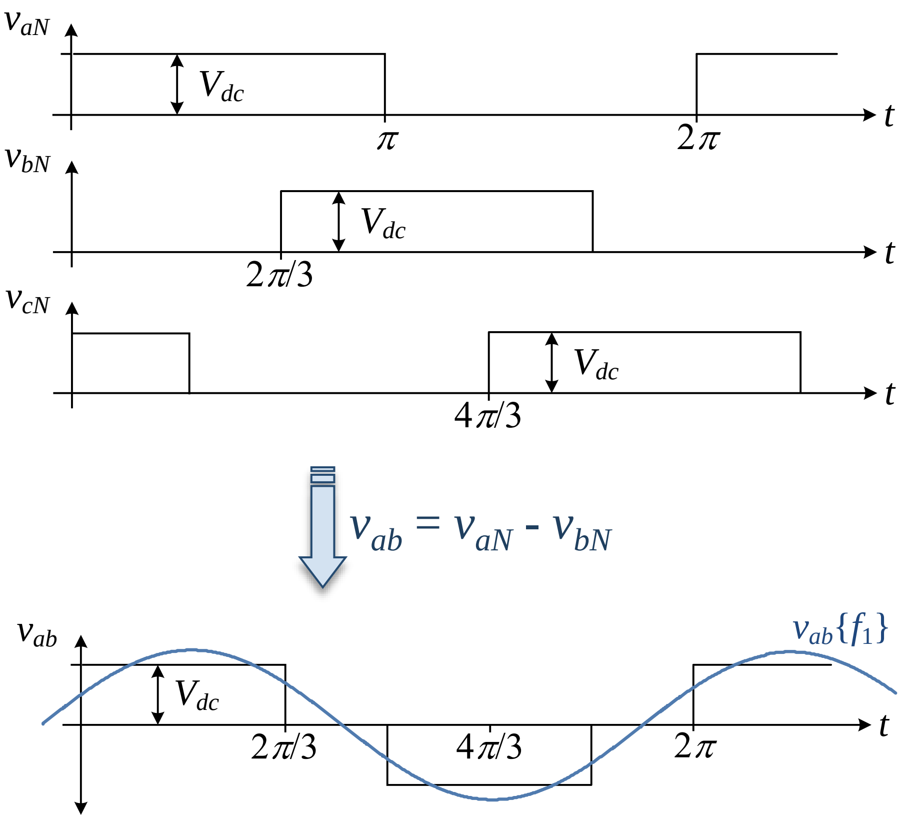
- If both T_1 and T_4 are on
  - → Short circuit
- If both T_1 and T_4 are off
  - → v_{aN} not defined. Not allowed!

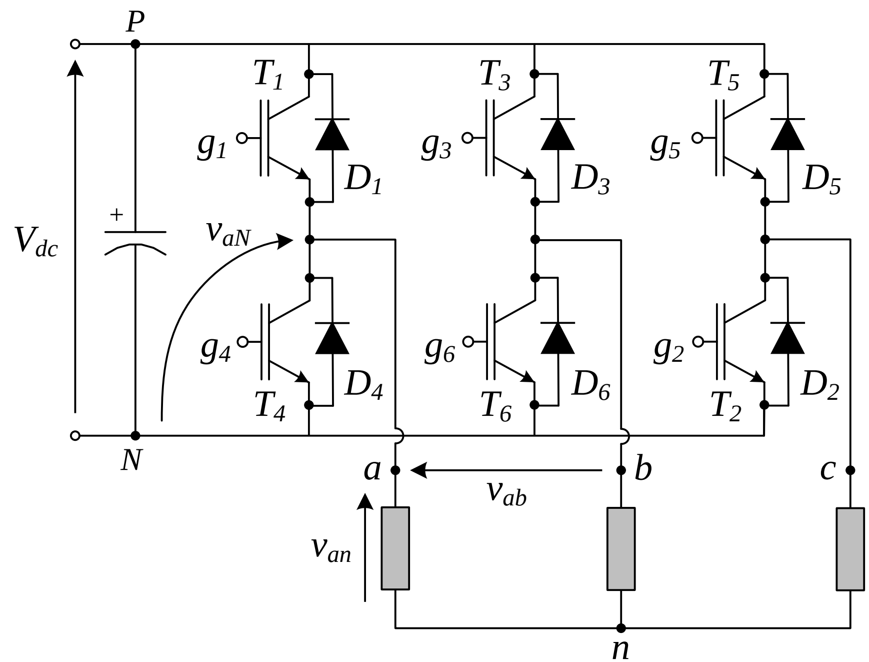


- Summary:
  - Gating signals for T_1 and T_4 are complimentary. When one is on, the other must be off.
  - The same applies to other legs: T_3 and T_6, T_5 and T_2.

Power Electronics Converters – Voltage Source Inverter

Three-phase two-level VSI - Square wave operation

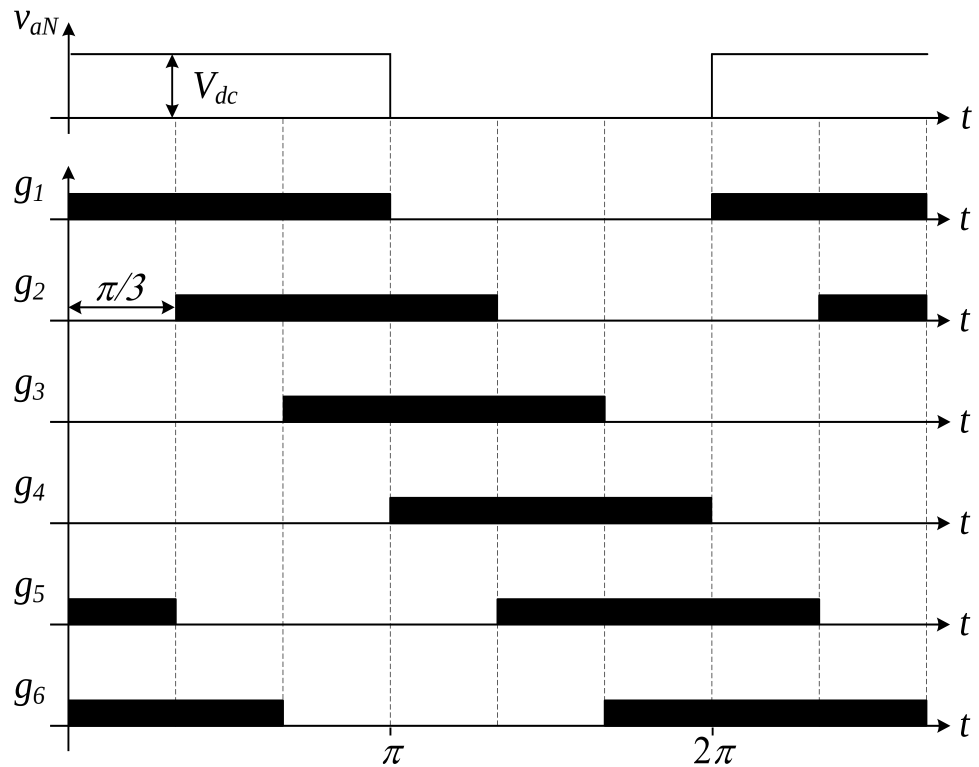


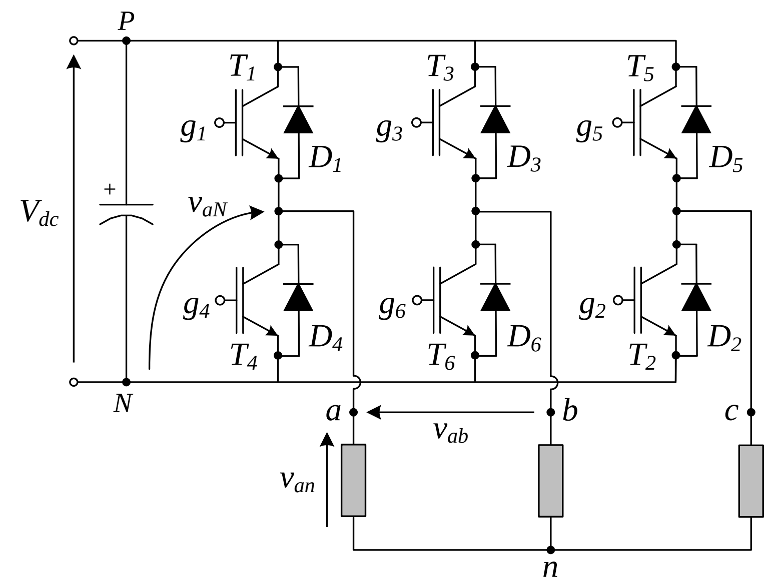


- The phase voltage has two levels (w.r.t N), line-line voltage has three levels

Power Electronics Converters – Voltage Source Inverter

Three-phase two-level VSI - Square wave operation

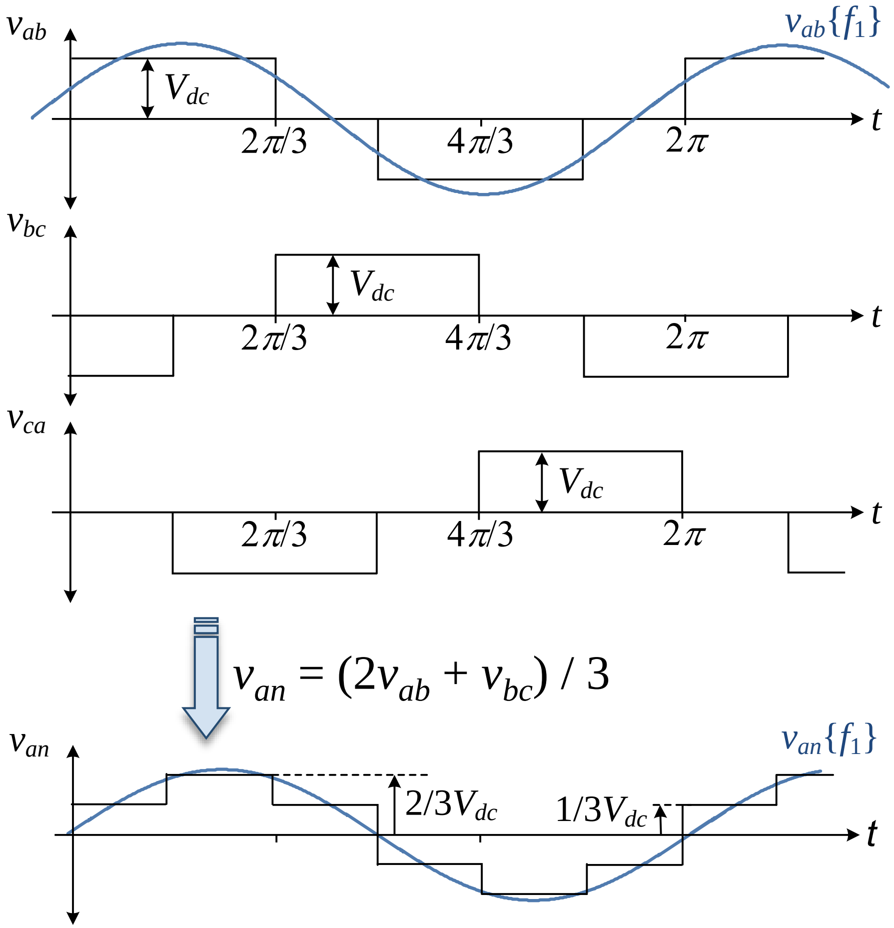


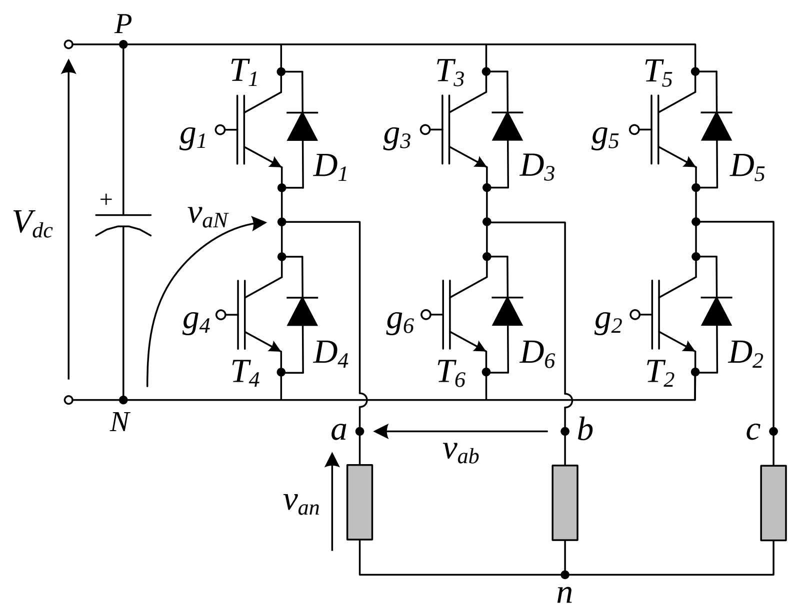


The switching of the six devices occurs every 60°. Each device is on for 180° and then turned off for another 180°

Power Electronics Converters – Voltage Source Inverter

Three-phase two-level VSI - Square wave operation





- The load voltage has 4 levels for square wave operation

Power Electronics Converters – Voltage Source Inverter

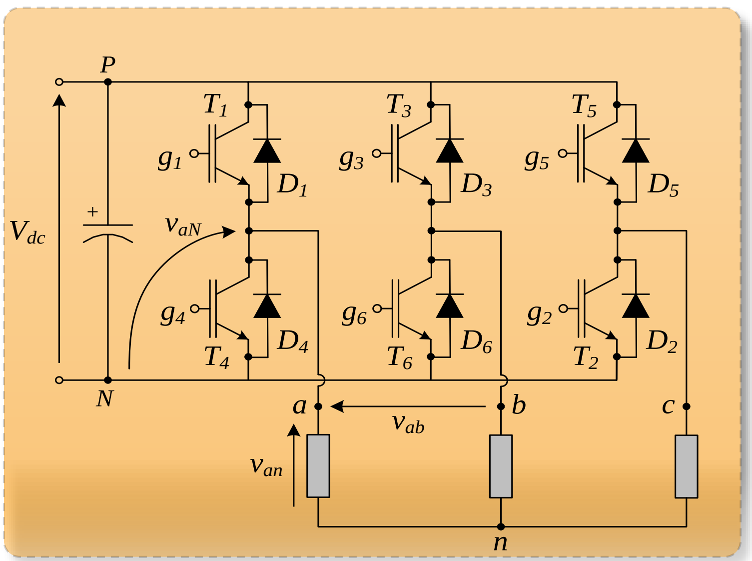
Three-phase two-level VSI - Square wave operation

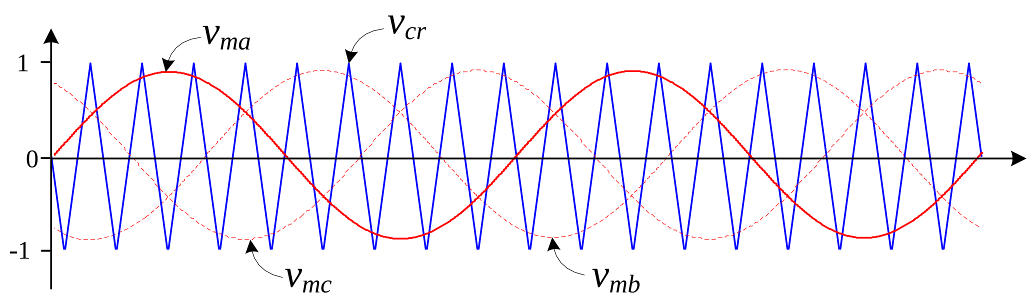
- Inverter output frequency can be changed by changing the frequency of the gating signals.
- Inverter output voltage can be adjusted by:
  - Adjusting the DC voltage V_{dc}
  - Using PWM techniques to adjust DC utilization rate

Power Electronics Converters – Voltage Source Inverter

Three-phase two-level VSI - PWM operation

- **PWM operation for three-phase VSI**
- 3 modulating signals with
  - Same amplitude
  - Same frequency
  - Mutual phase displacement of 120^0

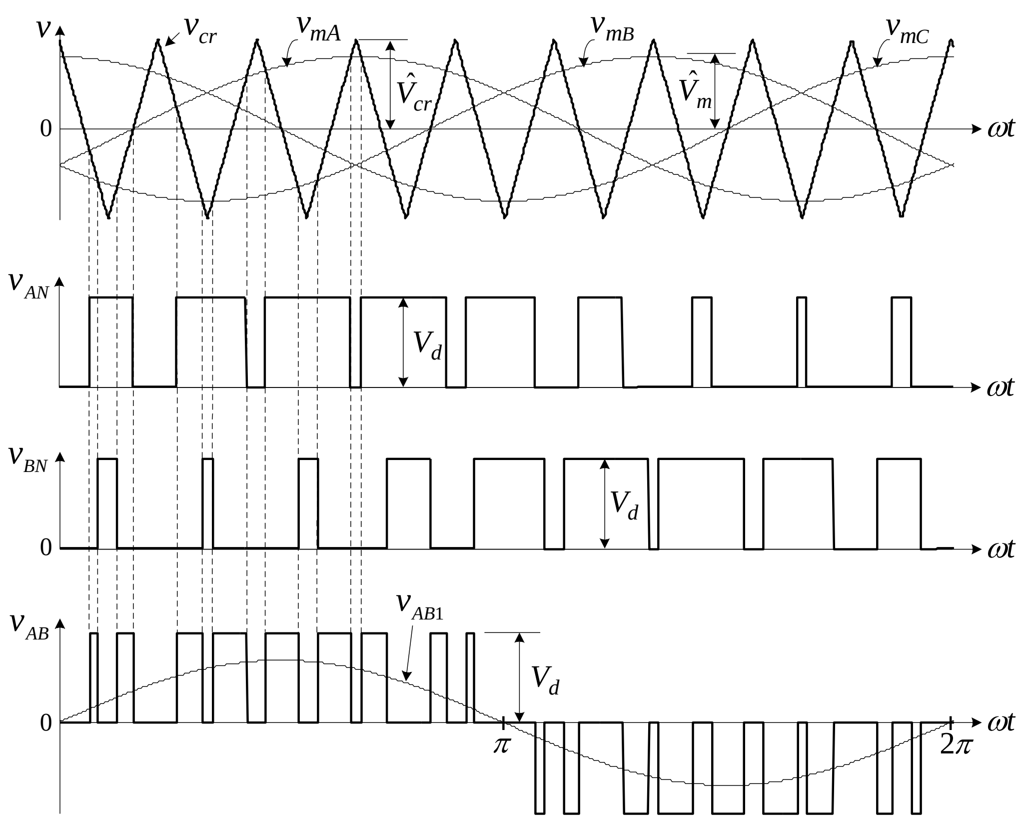


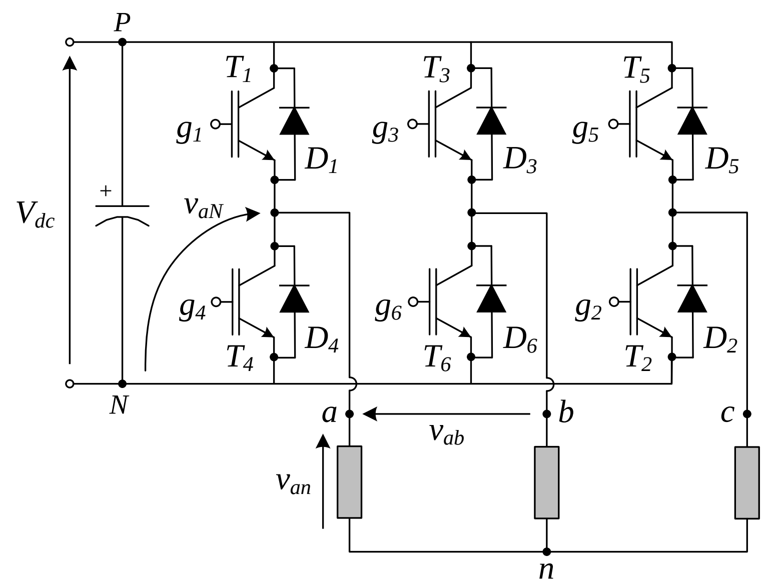


Three-phase modulating waveforms

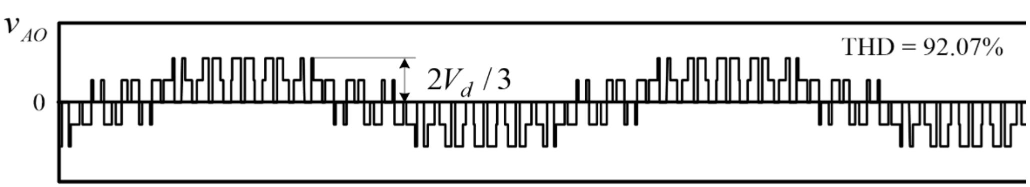
Power Electronics Converters – Voltage Source Inverter

Three-phase two-level VSI - PWM operation - waveforms





Line to line voltage has 3 levels.



Load voltage has 5 levels

Power Electronic Converters

Converters:

1. Chopper (DC to DC)
2. Controlled Rectifier (AC to DC)
3. Inverter (DC to AC)
4. **Cycloconverter (AC to AC) – converts a fixed voltage and fixed frequency AC to a variable voltage and variable frequency AC**

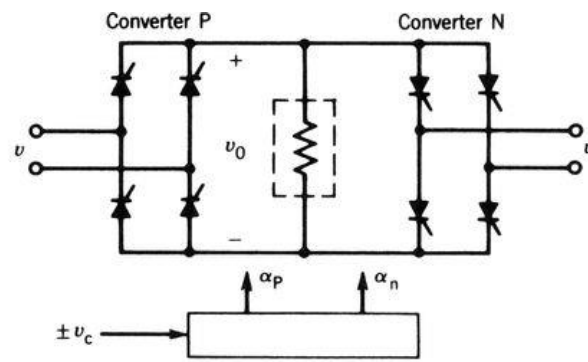
Power Electronics Converters – Cycloconverter

Cycloconverter

- Converts AC input power at one frequency to output power at a different frequency

Single-phase to Single-phase Cycloconverter

- Dual converter with a resistive load.
- Converter P is a positive controlled rectifier – if only converter P is operated, the output voltage is positive
- Converter N is a negative controlled rectifier - if only converter N is operated, the output voltage is negative
- Let the polarity of the control voltage v_c represent the polarity of the output voltage v_0 and the amplitude of v_c represent the desired average output voltage. The frequency of v_c represents the fundamental output frequency of v_0.

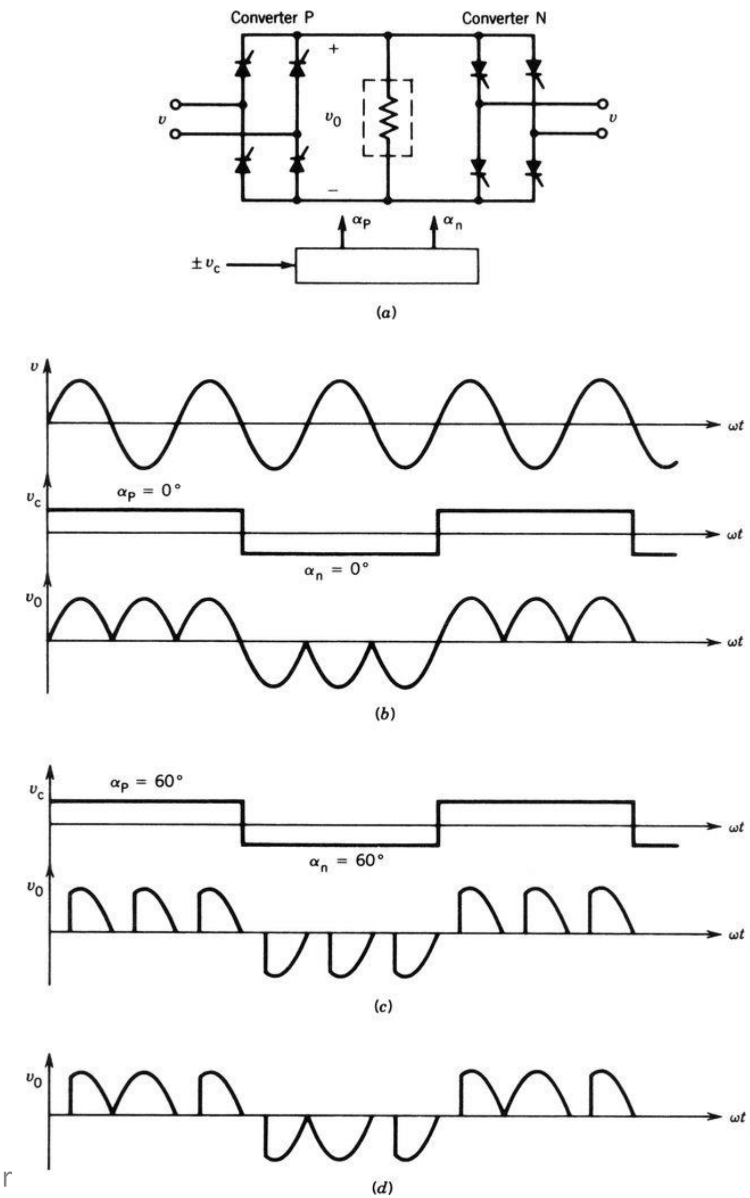


(a)

Power Electronics Converters – Cycloconverter

Single-phase to Single-phase Cycloconverter

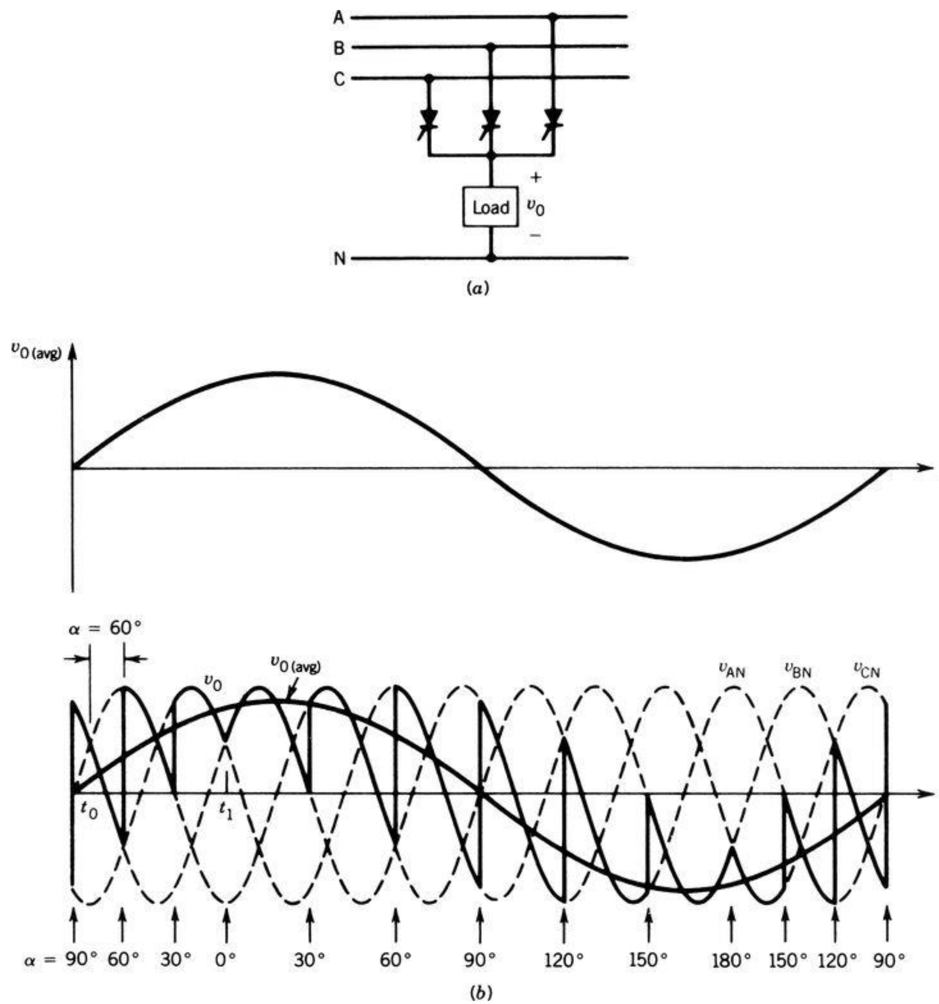
- Fundamental output frequency is one-third of the input frequency
- Not used due to non sinusoidal output voltage



Power Electronics Converters – Cycloconverter

Three-phase Cycloconverter

- Average output voltage of a controlled rectifier:
  - $v_0 = 1.35V_L cos\alpha$
- The successive firing angles can be changed so that the average output voltage changes sinusoidally
- $v_{0(avg)}$ is the sinusoidally varying average voltage
- Zero voltage is required at $t = t_0$, and therefore $\alpha = 90^0$ at this instant
- As $v_{0(avg)}$ increases, the firing angle decreases.

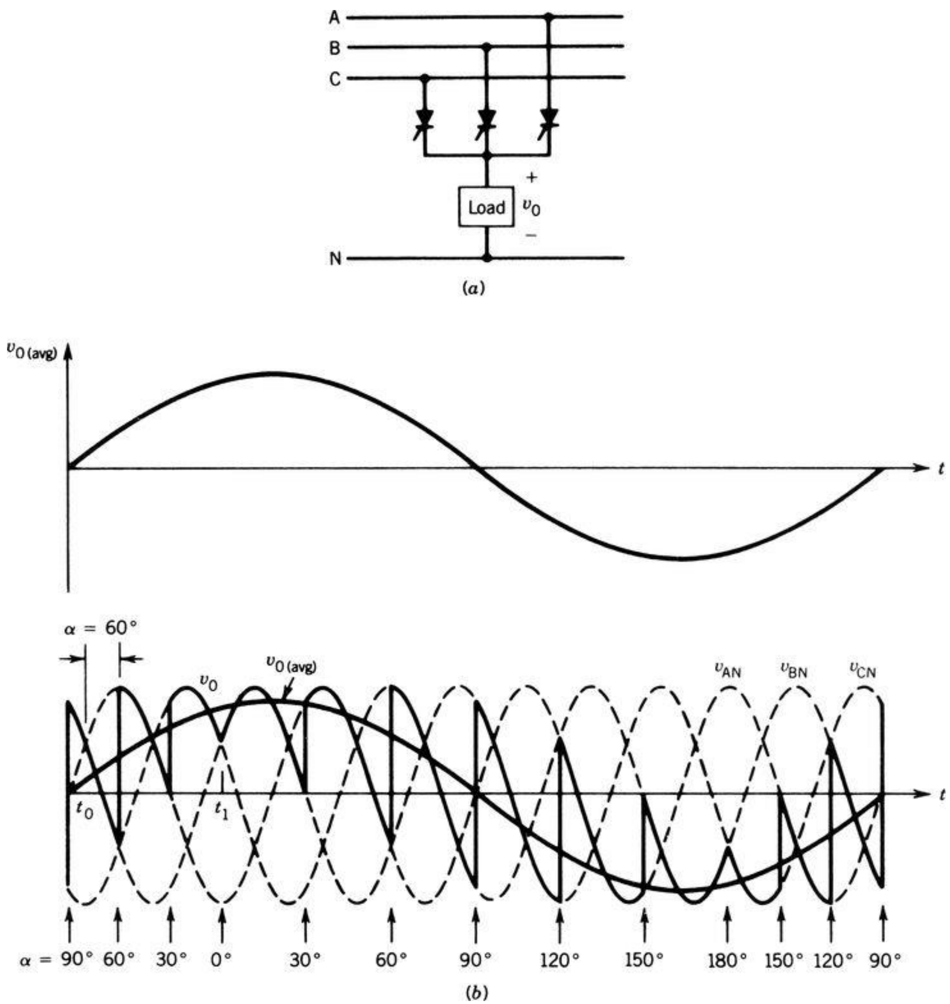


Synthesis of Sinusoidal output voltage

Power Electronics Converters – Cycloconverter

Three-phase Cycloconverter

- At the peak value of $v_{0(avg)}$, the firing angle α is minimum
- The firing angle of the successive pulses is changed from 90^0 to 0^0 and back to 90^0 , and then from 90^0 to 180^0 and then back again to 90^0 , in steps.



Synthesis of Sinusoidal output voltage