

Chapter 2 DC Motor Drives

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Content

- Review of dc motor equivalent circuit
- DC motor speed control
- Converters used in dc motor drives
- Microprocessor control of dc motor drives

2.1 dc motor equivalent circuit

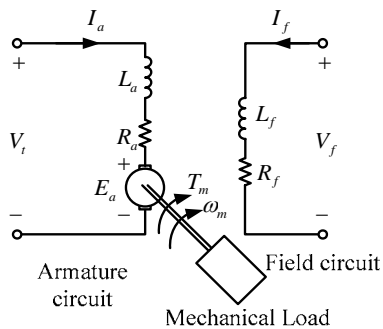
- Review

- DC motor is widely used in industry
- Rating: 0.1W~1000kW
- Applications: train, elevator, steel mill,...etc.
Anywhere a widely adjustable speed is required
- Advantages:
 - Easy to control the motor speed
- Disadvantages:
 - Expensive
 - Commutator needs to be maintained

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2.1 dc motor equivalent circuit

- Equivalent circuit:



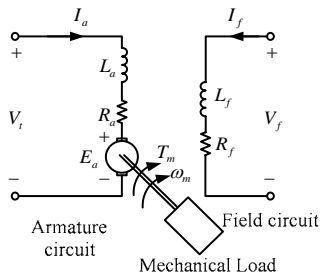
Terminology :

V_f, I_f – field voltage and current, [V]
 V_t, I_a – terminal voltage and armature current, [V]
 R_f, R_a – field winding resistance, [Ω]
 and armature winding resistance
 L_f, L_a – field winding inductance, [H]
 and armature winding inductance
 E_a – Back EMF, where $E_a = K_a \Phi \omega_m$, [V]
 K_a – armature constant
 Φ – flux produced by field current, [Wb]
 ω_m – mechanical speed, [rad/sec]
 T_e – Developed mechanical torque, where $T_e = K_a \Phi I_a$, [Nm]
 T_m – output mechanical torque, where $T_m = T_e - \frac{P_{tot}}{\omega_m}$, [Nm]

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2.1 dc motor equivalent circuit

- Important equations:



Dynamic Equations :

(1) Armature circuit :

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

(2) Field circuit :

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

(3) Motor structure :

$$E_a = K_a \Phi \omega_m$$

$$T_e = K_a \Phi i_a$$

(4) Energy conversion :

$$E_a i_a = T_e \omega_m$$

(5) Mechanical load ($P_{rot} = 0$) :

$$T_e = T_m = T_L + J \frac{d\omega_m}{dt}$$

where J is the moment of inertia, [$\text{kg} \cdot \text{m}^2$]

Steady state Equations :

(1) Armature circuit :

$$V_t = R_a I_a + E_a$$

(2) Field circuit :

$$V_f = R_f I_f$$

(3) Motor structure :

$$E_a = K_a \Phi \omega_m$$

$$T_e = K_a \Phi I_a$$

(4) Energy conversion :

$$E_a I_a = T_e \omega_m$$

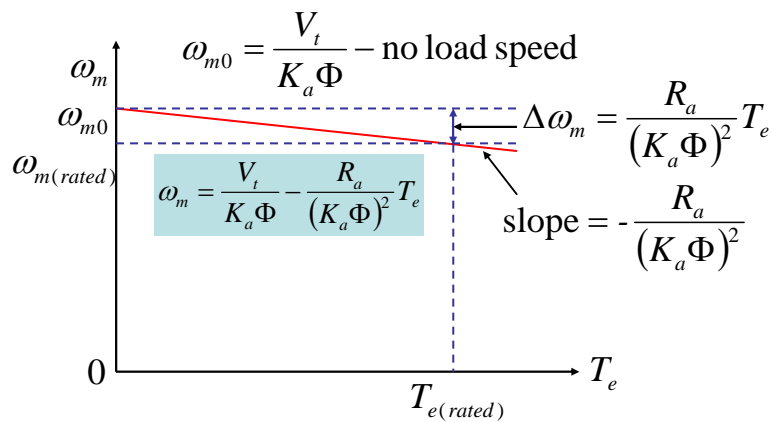
(5) Mechanical load ($P_{rot} = 0$) :

$$T_e = T_m = T_L$$

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2.2 Speed control

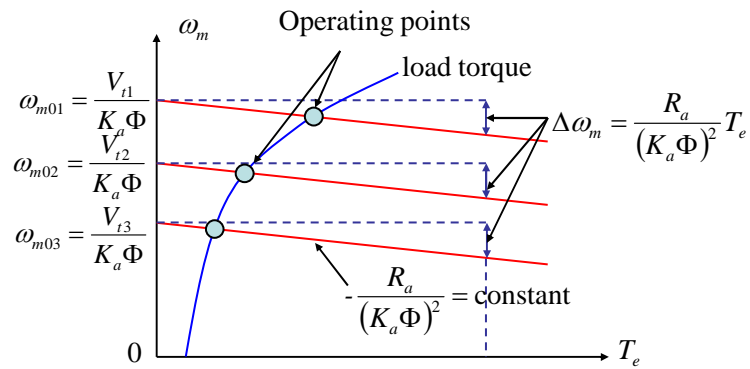
- Speed-torque characteristic:



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2.2 Speed control

- Adjust motor speed:



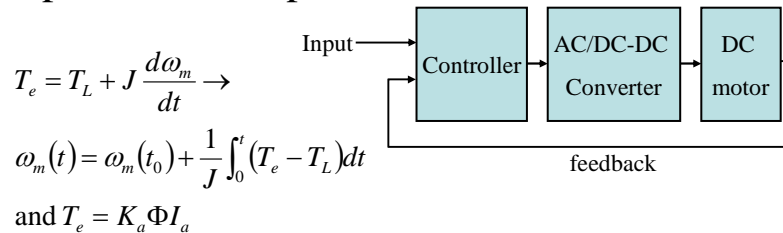
Method : Adjust terminal voltage

usually : $V_t \leq V_{t, \text{rated}}$ (to avoid insulation breakdown) $\rightarrow \omega_m \leq \omega_{m, \text{rated}}$

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2.2 Speed control

- Speed close loop control:



Speed $\uparrow \rightarrow T_e \uparrow \rightarrow I_a \uparrow \rightarrow$ increase V_t

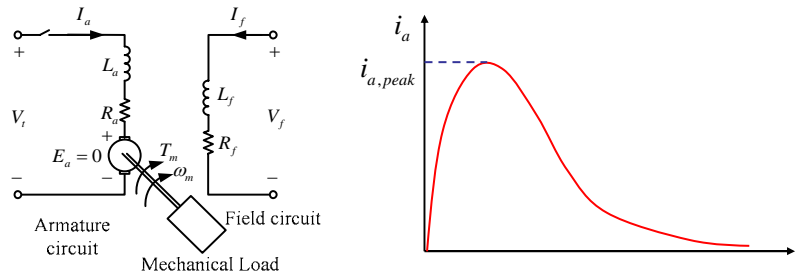
Speed $\downarrow \rightarrow T_e \downarrow \rightarrow I_a \downarrow \rightarrow$ decrease V_t

ω_m can be controlled by controlling I_a

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2.3 Motor starting

- Assumption: $I_f = \text{constant} \rightarrow \Phi = \text{constant}$



(1) At $t = 0$, switch SW is closed, $\omega_m = 0 \rightarrow E_a = K_a \Phi \omega_m = 0$

\rightarrow starting current (without considering L_a) $= \frac{V_t}{R_a}$

(2) with considering L_a , the peak of starting current is still very high.

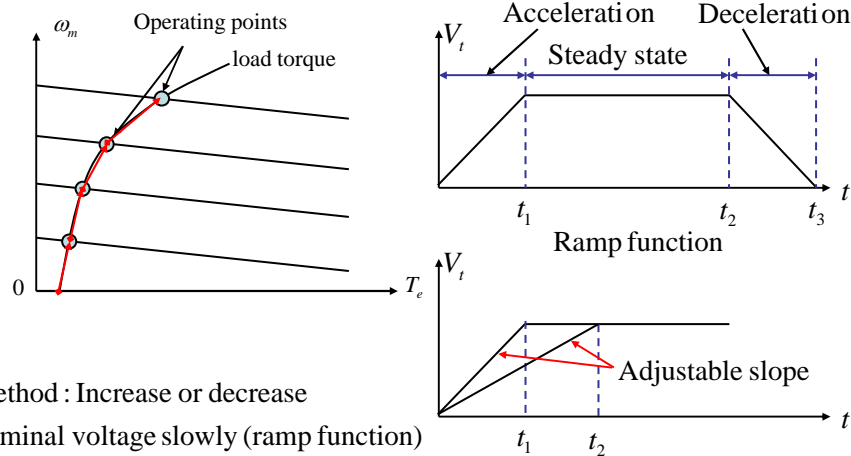
(3) Starting current will be decreased to no load current until the motor

enters steady state : $\omega_m \uparrow \rightarrow E_a = K_a \Phi \omega_m \uparrow \rightarrow I_a = \frac{V_t - E_a}{R_a} \downarrow$

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2.3 Motor starting

- Reduce starting current

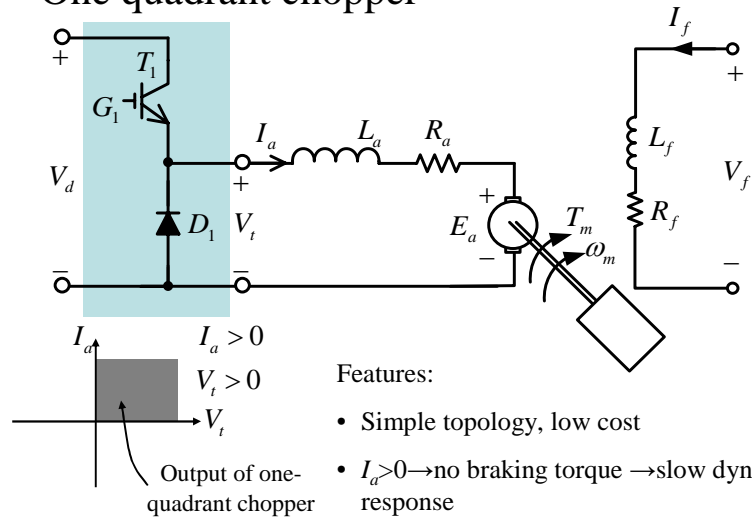


Method : Increase or decrease terminal voltage slowly (ramp function)

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2.4 Converters

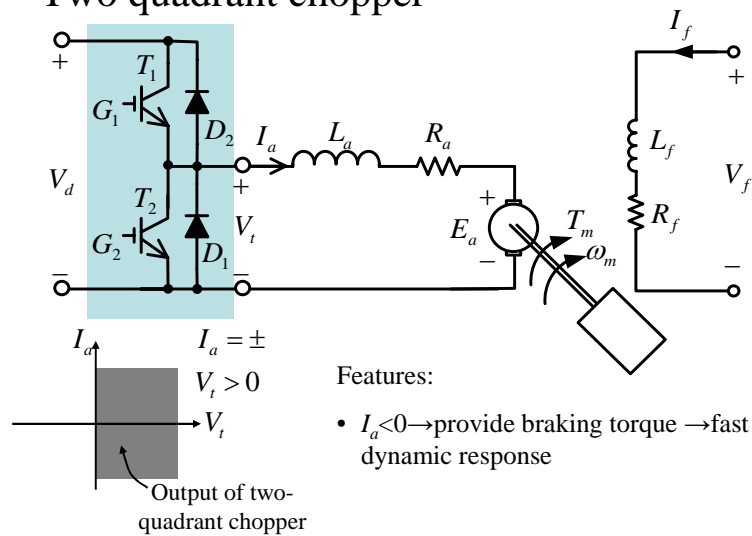
• One quadrant chopper



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2.4 Converters

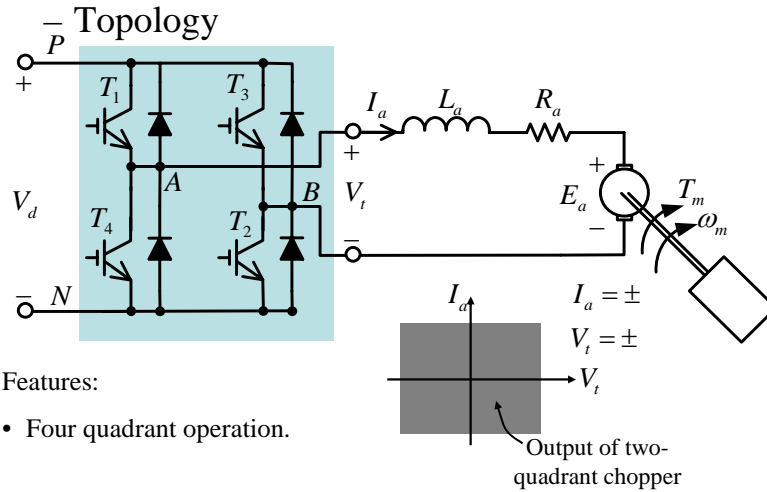
• Two quadrant chopper



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2.4 Converters

- Four quadrant chopper (full bridge)

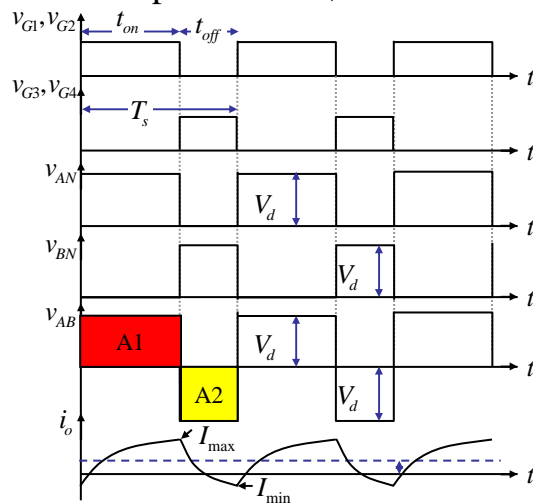


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2.4 Converters

– Bipolar PWM; Waveforms

Note: Textbook: page 188-194



$$V_{o,avg} = \frac{\text{Area A1} - \text{Area A2}}{T_s}$$

$$= \frac{V_d t_{on} - V_d t_{off}}{T_s}$$

$$\therefore V_o = (2D_1 - 1)V_d$$

where $D_1 = \frac{t_{on}}{T_s}$

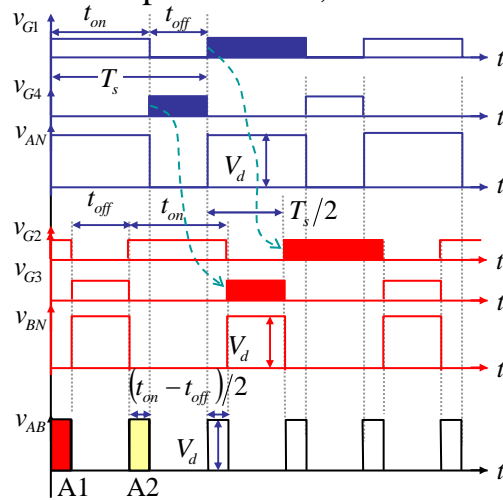
Feature:

Use fast decay modes, large ripple current → large ripple torque → More noisy

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2.4 Converters

– Unipolar PWM; Waveforms



$$V_{o,avg} = \frac{\text{Area A1} + \text{Area A2}}{T_s}$$

$$= \frac{V_d}{T_s} \left(\frac{t_{on} + t_{off}}{2} \right) \times 2$$

$$\therefore V_o = (2D_1 - 1)V_d$$

$$\text{where } D_1 = \frac{t_{on}}{T_s}$$

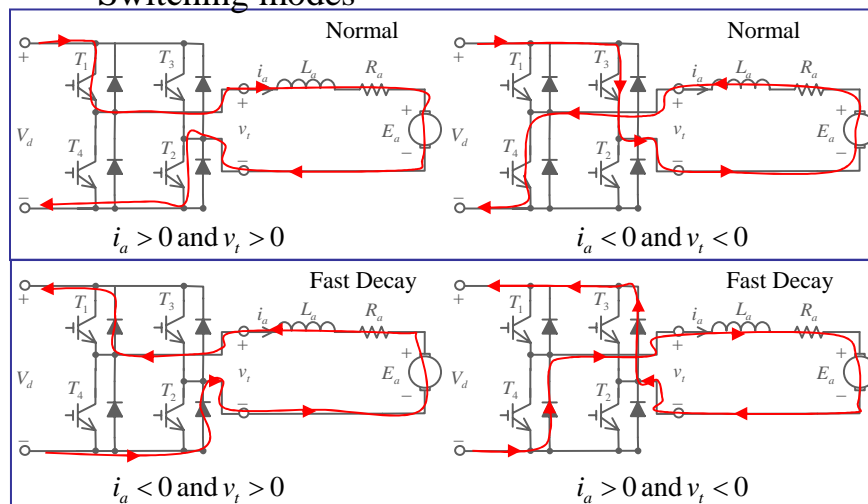
Feature:

- Use slow decay modes, small ripple current → small ripple torque
- Effective switching frequency is doubled.

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2.4 Converters

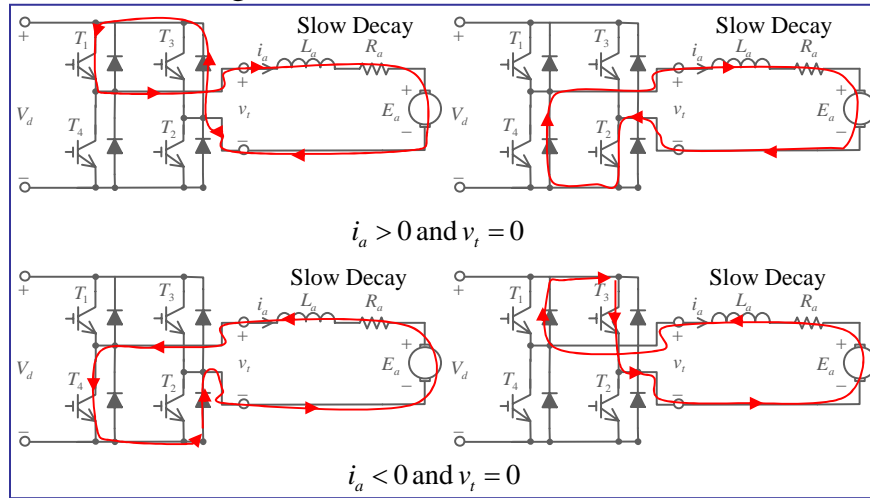
– Switching modes



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2.4 Converters

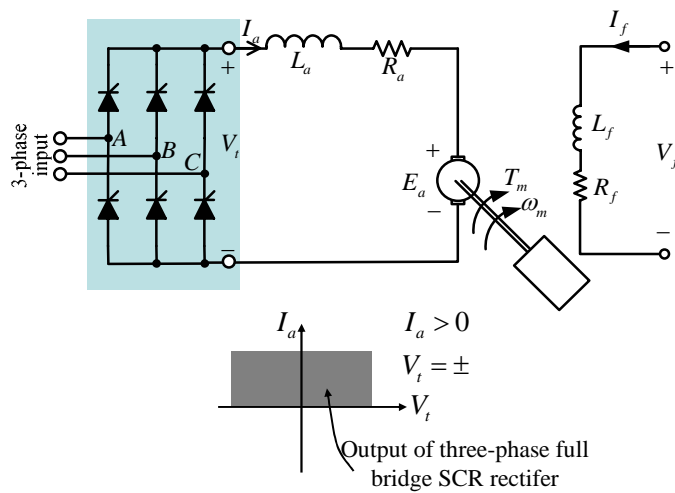
– Switching modes



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2.4 Converters

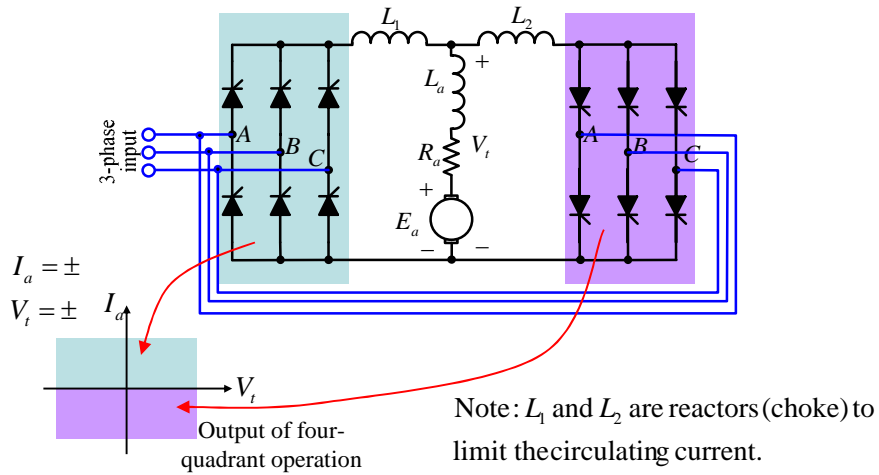
- SCR rectifier



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2.4 Converters

- Four quadrant operation using SCR rectifier



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Example

- Given: $V_d=150\text{V}$, $L_a=0.16\text{mH}$, $R_a=0.8\Omega$, $K_a\Phi=0.9\text{V}\cdot\text{sec}/\text{rad}$, $f_{sw}=1\text{KHz}$. The motor is coupled to a mechanical load. Duty cycle = 40%, speed $n=650\text{rpm}$
- Find :
 - (1) I_{\max} and I_{\min}
 - (2) $T_{e,(avg)}$
 - (3) Sketch to scale the waveforms of v_t , i_a and T_e

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Example

Solution (1) :

step 1 \Rightarrow Assume continuous current mode

$$\text{step 2} \Rightarrow \tau = \frac{L_a}{R_a} = \frac{0.16 \times 10^{-3}}{0.8} = 0.2 \text{ms}$$

$$\text{step 3} \Rightarrow T_s = \frac{1}{f_{sw}} = \frac{1}{1000} = 1 \text{ms}$$

$$\text{step 4} \Rightarrow t_{on} = DT_s = 0.4 \times 1 = 0.4 \text{ms}$$

$$\text{step 5} \Rightarrow E_a = K_a \Phi \omega_m = 0.9 \times \frac{650 \times 2\pi}{60} = 61.3 \text{V}$$

$$\text{step 6} \Rightarrow I_{\min} = \frac{V_d e^{t_{on}/\tau} - 1}{R_a e^{T_s/\tau} - 1} \frac{E}{R} = \frac{150 e^{0.4/0.2} - 1}{0.8 e^{1/0.2} - 1} \frac{61.3}{0.8} = -68.5 \text{A}$$

step 7 $\Rightarrow I_{\min} < 0 \rightarrow$ discontinuous current mode

$$\text{step 8} \Rightarrow I_{\max} = \frac{V_d - E_a}{R_a} \left(1 - e^{-\frac{t_{on}}{\tau}}\right) = \frac{150 - 61.3}{0.8} \left(1 - e^{-0.4/0.2}\right) = 95.9 \text{A}$$

$$\text{and } I_{\min} = 0 \text{A}$$

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Example

Solution (2) :

$$\begin{aligned} \text{step1} \Rightarrow t_x &= \tau \ln \left\{ e^{t_{on}/\tau} \left[1 + \frac{V_d - E}{E} \left(1 - e^{-t_{on}/\tau} \right) \right] \right\} \\ &= 0.2 \times 10^{-3} \left\{ e^{0.4/0.2} \left[1 + \frac{150 - 61.3}{61.3} \left(1 - e^{-0.4/0.2} \right) \right] \right\} = 0.562 \text{ms} \end{aligned}$$

$$\text{step2} \Rightarrow V_{o,avg} = \frac{t_{on}}{T_s} V_d + \frac{T_s - t_x}{T_s} E = \frac{0.4}{1} \times 150 + \frac{1 - 0.562}{1} \times 61.3 = 86.8 \text{V}$$

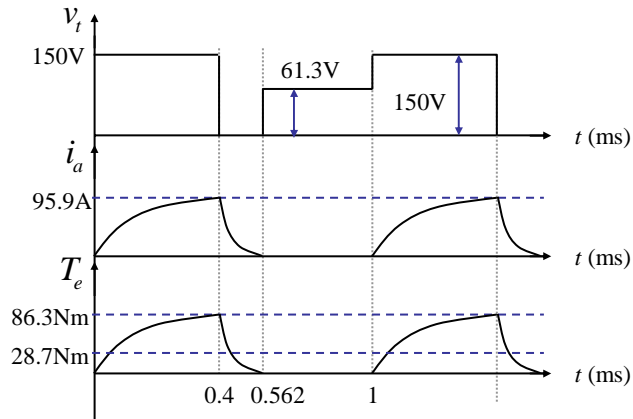
$$\text{step3} \Rightarrow I_{o,avg} = \frac{V_{o,avg} - E}{R} = \frac{86.8 - 61.3}{0.8} = 31.9 \text{A}$$

$$\text{step4} \Rightarrow T_{e,avg} = K_a \Phi I_{o,avg} = 0.9 \times 31.9 = 28.7 \text{Nm}$$

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Example

Solution (3):



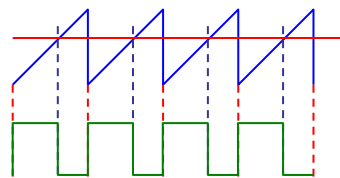
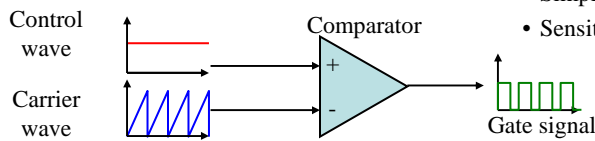
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2.5 Generate gating signals

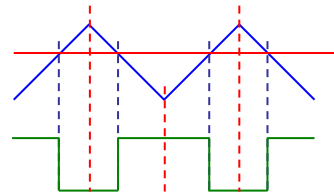
• Analog circuit

Features:

- Simple circuit and low cost
- Sensitive to the noise



Edge aligned



Center aligned

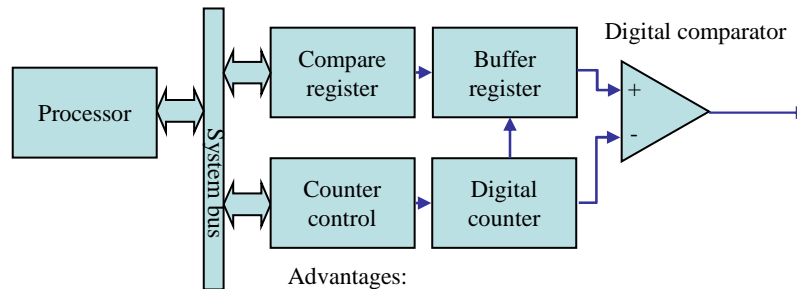
For: switch mode power supply, 1Q or 2Q choppers, flyback or forward converters

For: three-phase applications, full-bridge dc-dc converter.

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2.5 Generate gating signals

- Digital circuit



Advantages:

- Stable, very robust to the noise
- Easy to be controlled by CPU/DSP
- Reduce the load of CPU/DSP

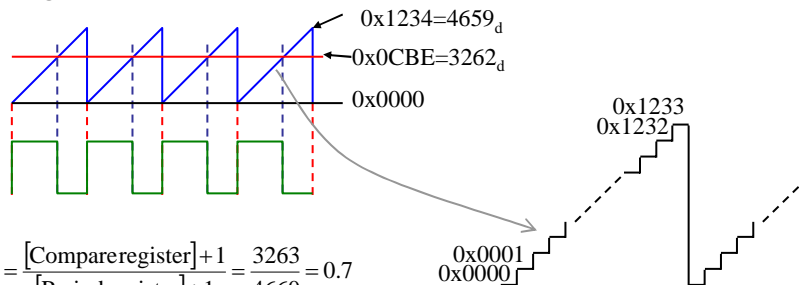
Disadvantages:

- Expensive hardware
- High frequency counter

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2.5 Generate gating signals

- Digital circuit



$$D = \frac{[\text{Compare register}] + 1}{[\text{Period register}] + 1} = \frac{3263}{4660} = 0.7$$

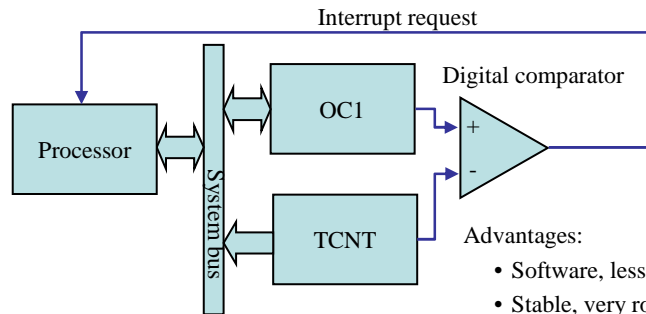
switching frequency

$$f_{sw} = \frac{f_{counter}}{[\text{Period register}] + 1} = \frac{10\text{MHz}}{4660} = 2.146\text{KHz}$$

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2.5 Generate gating signals

- Software



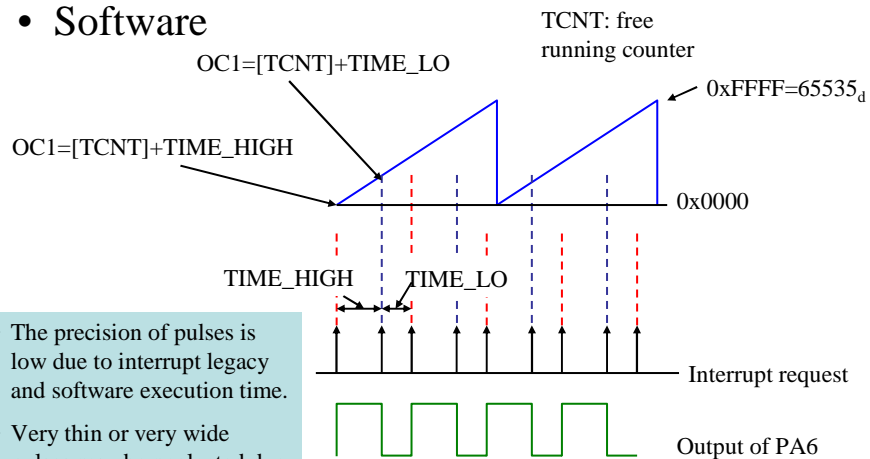
- Advantages:
- Software, less hardware
 - Stable, very robust to the noise
 - Easy to be controlled by CPU/DSP
- Disadvantages:
- Increase the calculation load of CPU/DSP

TCNT: Free running counter
 OC1: output compare register #1

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2.5 Generate gating signals

- Software

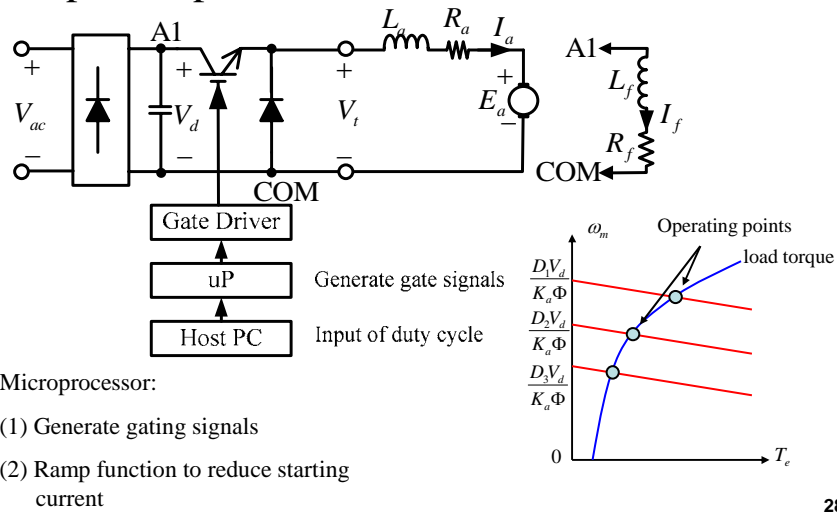


- The precision of pulses is low due to interrupt legacy and software execution time.
- Very thin or very wide pulses may be neglected due to interrupt legacy and software execution time

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2.6 uP control of DC motor drives

- Open loop control

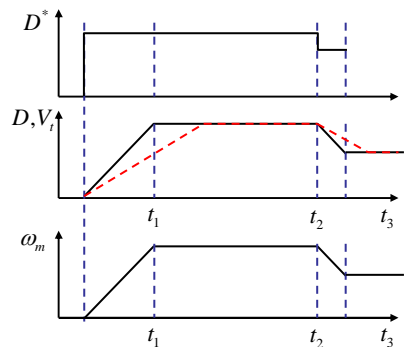


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2.6 uP control of DC motor drives

- Ramp function

D^* is reference duty cycle from Host PC
 D is the real duty cycle generated by uP



Q1 : How to adjust the slope?

A1 : Adjust delay time, which is 50ms in project 1

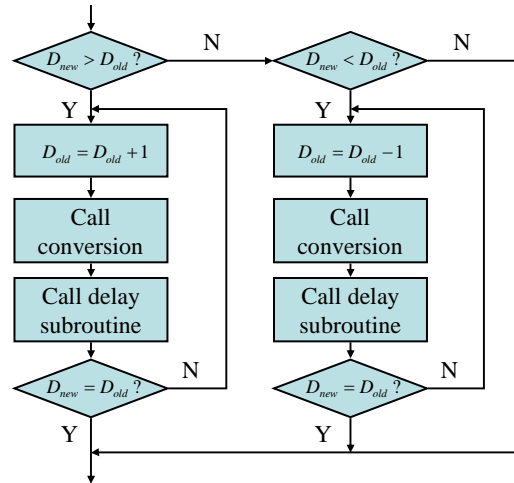
Q2 : How to trace the reference D^* ?

A2 : Get reference D^* from host PC in the loop of ramp function

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2.6 uP control of DC motor drives

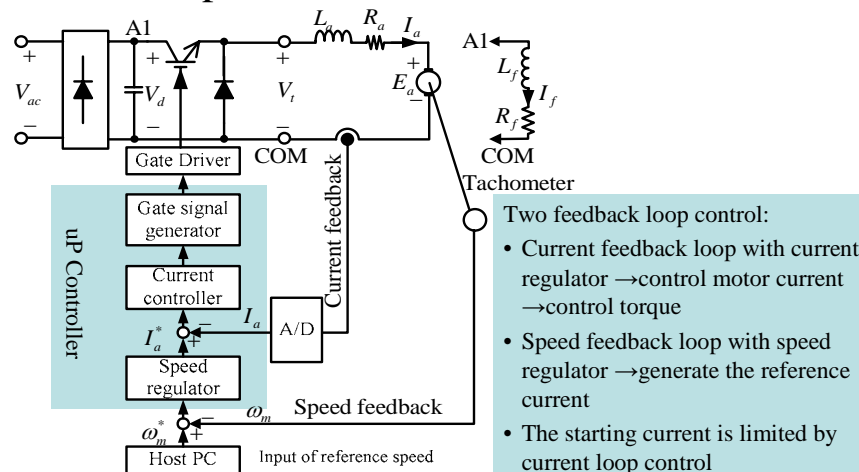
- Generate ramp function



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2.6 uP control of DC motor drives

- Close loop control



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Summary

- Dynamic and steady state equivalent circuits of dc motor
- DC motor speed control, motor starting
- Power converters used for dc motor drives
- Full-bridge (H-bridge) dc-dc converters
- Gate signal generator
- uP control of dc motor drives