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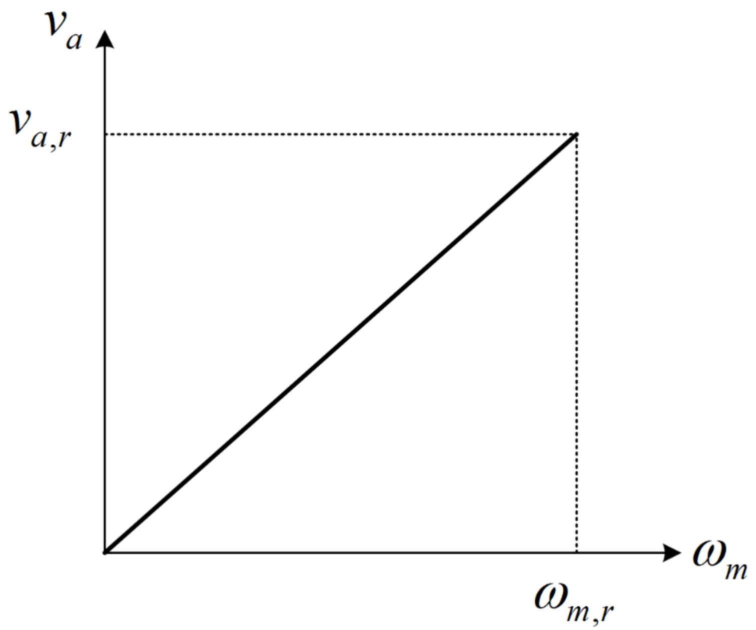
- Principle of DC machine drive

$$v_a = R_a i_a + K\phi_f \omega_m \Rightarrow \omega_m = \frac{v_a - R_a i_a}{K\phi_f}$$

- Armature control: Ideal for speeds lower than motor's rated speed, $\omega_{m,r}$.

$$\phi_f = \phi_{f,r} \Rightarrow \omega_m = \frac{v_a - R_a i_a}{K\phi_{f,r}} \approx \frac{v_a}{K\phi_{f,r}} \Rightarrow \omega_m \; \alpha \; v_a$$



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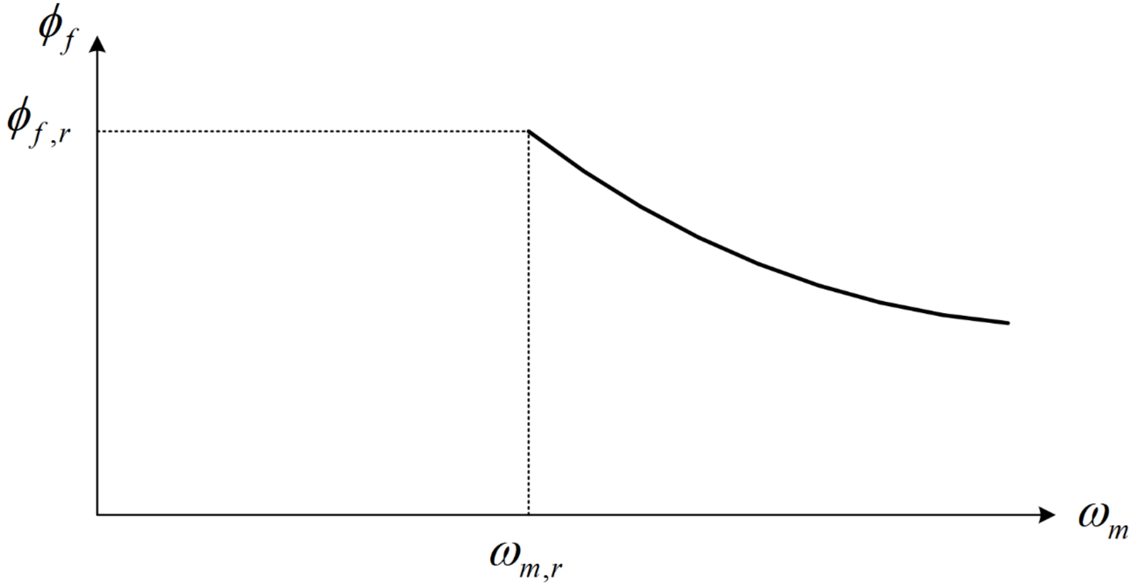
- Field control: Ideal for speeds above than motor’s rated speed, $\omega_{m,r}$.

$$v_a = v_{a,r} \Rightarrow \omega_m \approx \frac{v_{a,r}}{K\phi_f} \Rightarrow \phi_f \; \alpha \; \frac{1}{\omega_m} \Rightarrow \phi_f = \phi_{f,r}\frac{\omega_{m,r}}{\omega_m}$$



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- Armature and Field control: Assume that $i_a = i_{a,r}$.

When $\omega_m \le \omega_{m,r}$

$$\phi_f = \phi_{f,r}$$

$$T_{el} = K\phi_{f,r}\, i_{a,r} = \text{Constant}$$

$$P_a = K\phi_{f,r}\, i_{a,r}\omega_m$$

Constant torque region

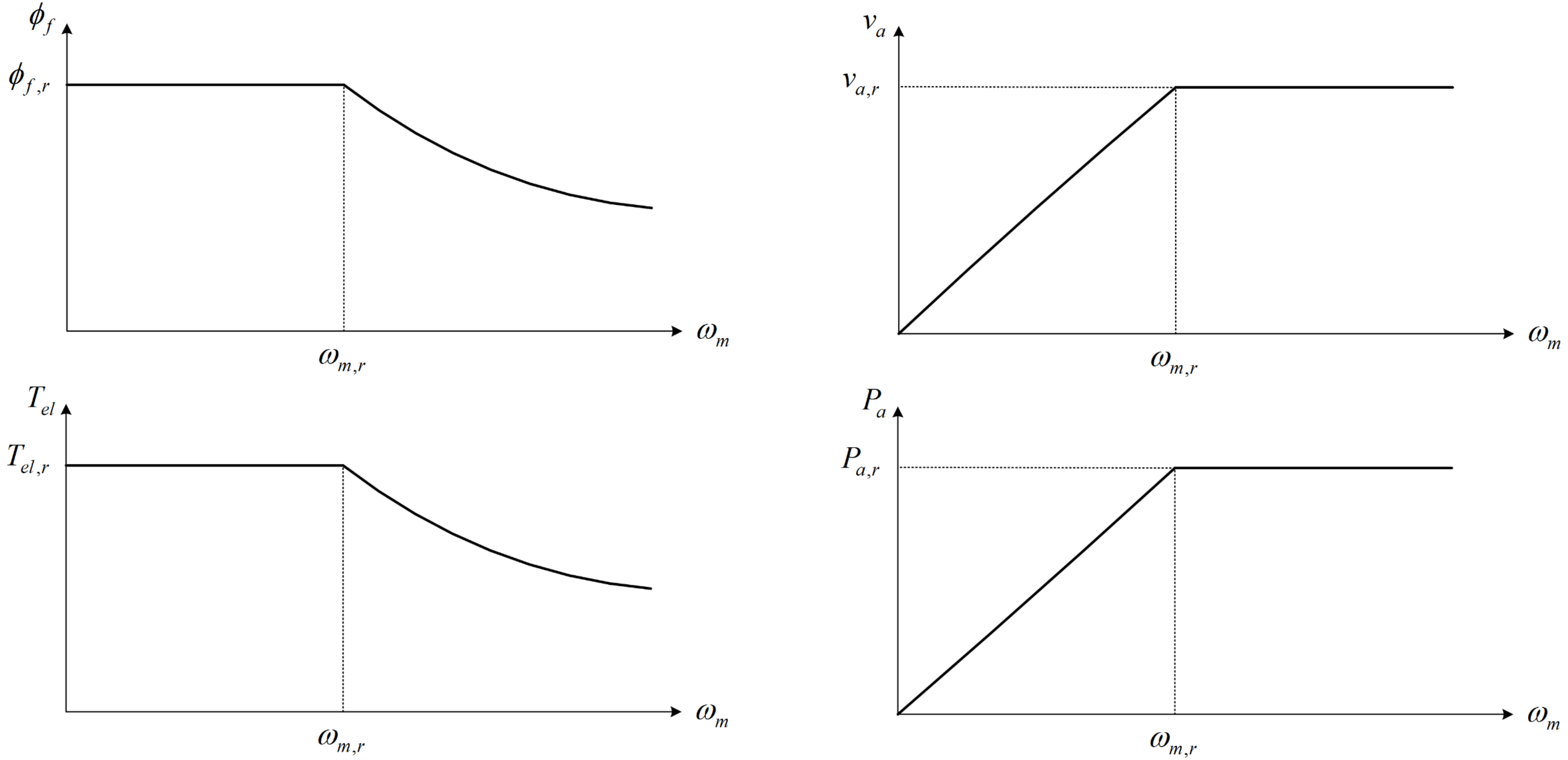
When $\omega_m \ge \omega_{m,r}$

$$\phi_f = \phi_{f,r}\frac{\omega_{m,r}}{\omega_m}$$

$$T_{el} = K\phi_{f,r}\frac{\omega_{m,r}}{\omega_m} i_{a,r}$$

$$P_a = K\phi_{f,r}\, i_{a,r}\omega_{m,r} = \text{Constant}$$

Constant power region


ϕ_f
$\phi_{f,r}$
ω_m
$\omega_{m,r}$
v_a
$v_{a,r}$
ω_m
$\omega_{m,r}$
T_{el}
$T_{el,r}$
ω_m
$\omega_{m,r}$
P_a
$P_{a,r}$
ω_m
$\omega_{m,r}$

- Braking and 4-quadrant operation
  - Braking

The machine is made to work as a generator producing a torque opposite to the motoring torque

$$T_{el} = T_l + J\frac{d\omega_m}{dt}$$

$$\omega_m > 0 \ \& \ \left(T_{el} - T_l\right) > 0 \Rightarrow \text{Forward regeneration}$$

$$T_{el} = T_l + J\frac{d\omega_m}{dt} \Rightarrow \Delta t = J\frac{\Delta\omega_m}{T_{el} - T_l}$$

Δt: stopping time

Why do we need braking?

1. Reducing Δt
2. Achieving quick and smooth stops
3. Achieving accurate stops
4. Holding the speed within safe limit

Braking methods:

1. *Regenerative braking*: generated electrical power is usefully employed
2. *Dynamic braking*: it is an inefficient way of braking
3. *Plugging braking*: it is a highly inefficient way of braking

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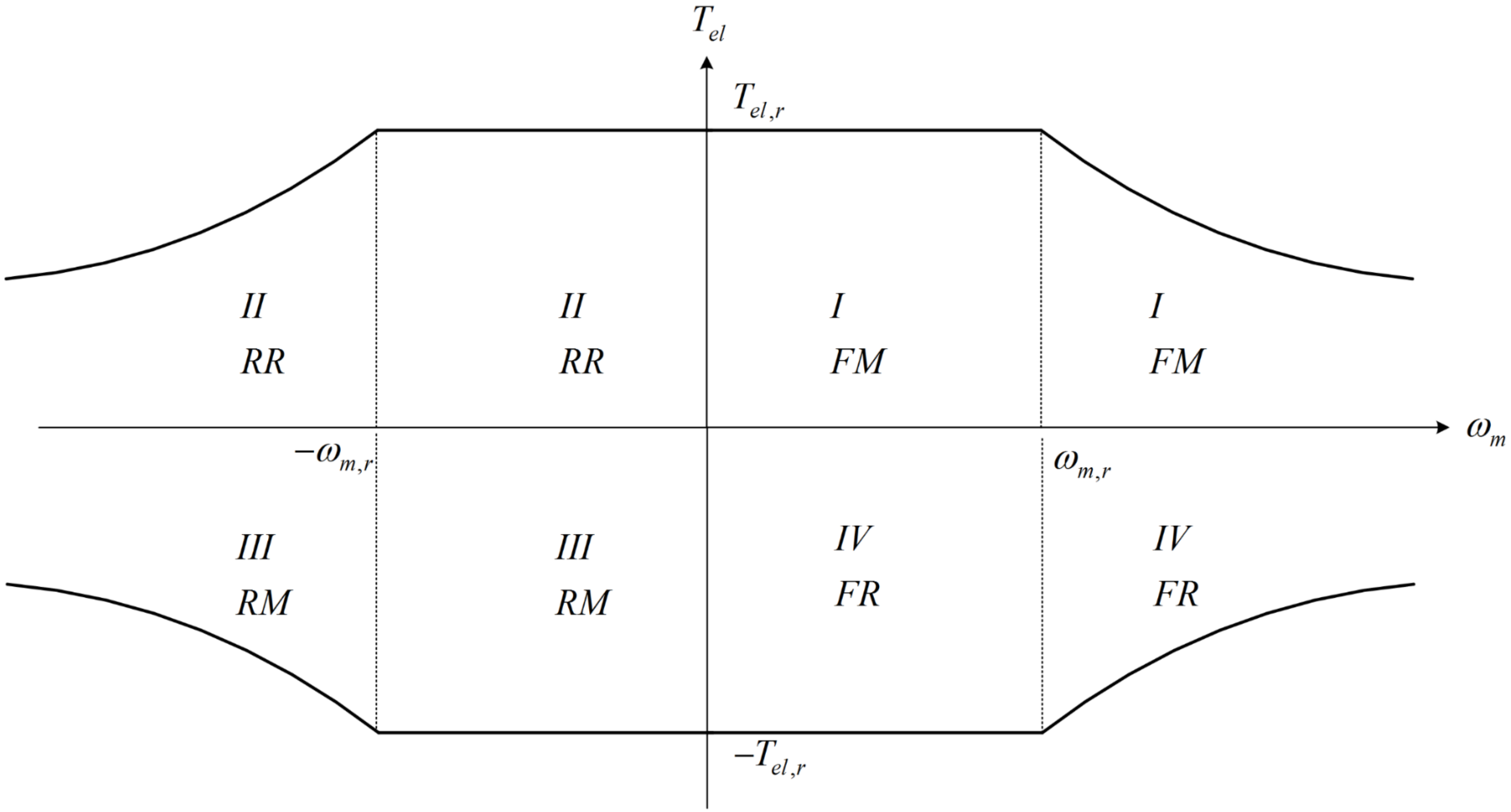
- 4-quadrant operation

  FM: Forward Motoring

  FR: Forward Regeneration

  RM: Reverse Motoring

  RR: Reverse Regeneration



Function	Quadrant	Speed	Torque	Voltage	Current	Power
FM	I	+	+	+	+	+
FR	IV	+	-	+	-	-
RM	III	-	-	-	-	+
RR	II	-	+	-	+	-

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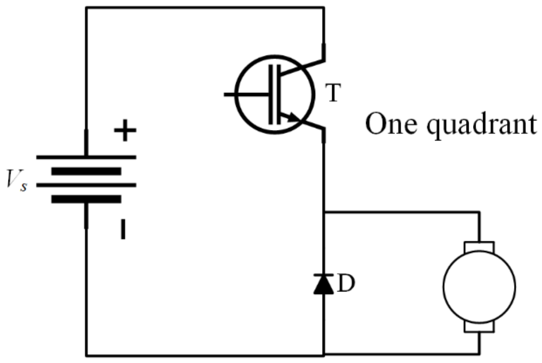
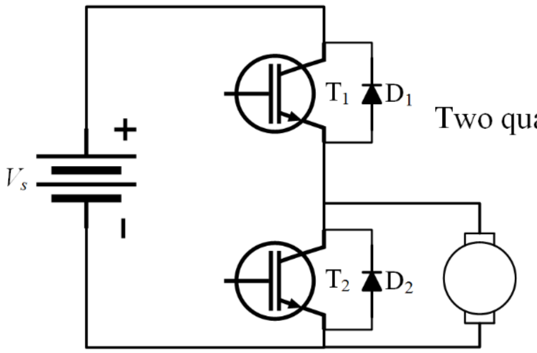
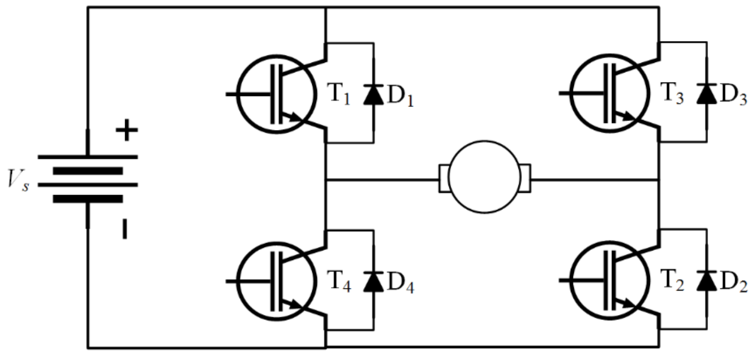
- <u>DC machine drive using chopper circuits</u>



One quadrant chopper circuit
I

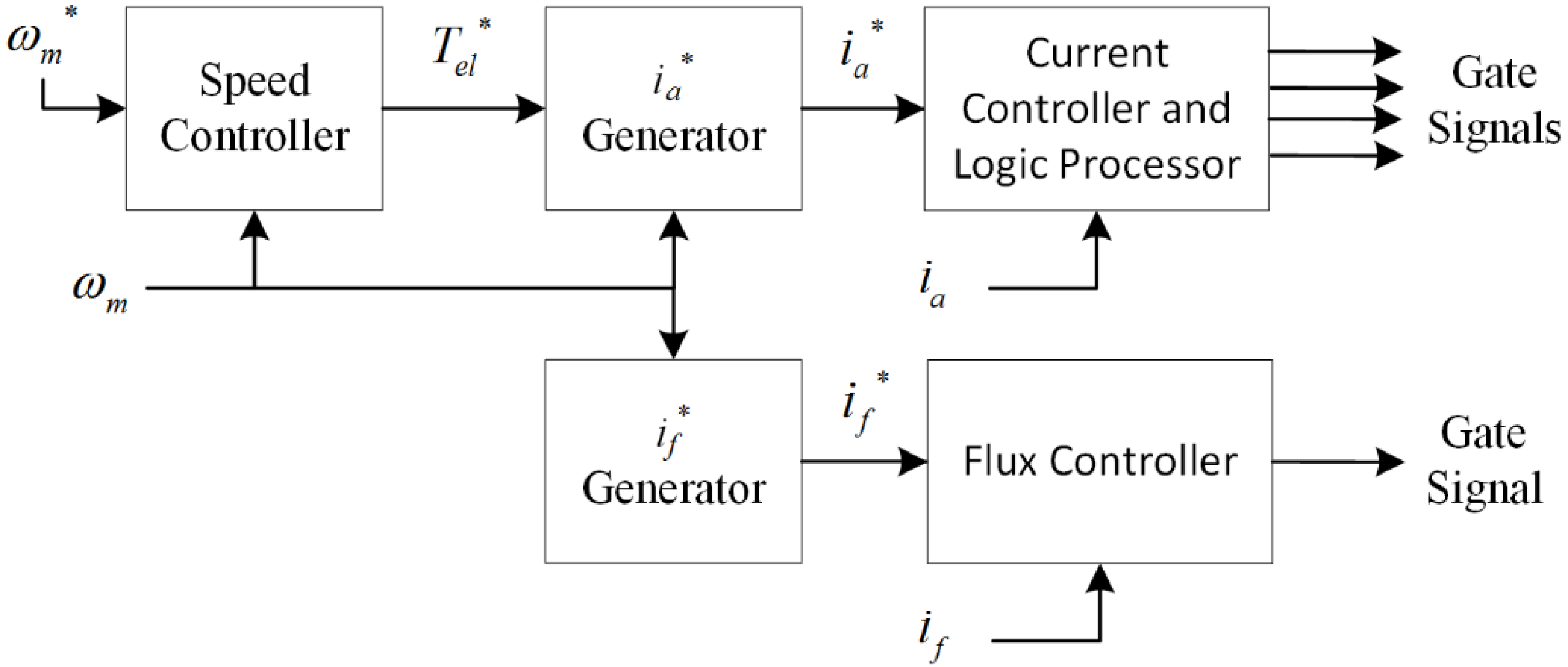


Two quadrant chopper circuit
I and IV



Four quadrant chopper circuit

Block diagram of control system



- i_f^* Generator

$$\omega_m \le \omega_{m,r} \Rightarrow i_f = i_{f,r}$$

$$\omega_m > \omega_{m,r} \Rightarrow i_f = i_{f,r} \frac{\omega_{m,r}}{\omega_m}$$

- i_a^* Generator

$$T_{el} = K\phi_f i_a \Rightarrow i_a^* = \frac{T_{el}^*}{K\phi_f}$$

$$\omega_m \le \omega_{m,r} \Rightarrow \phi_f = \phi_{f,r} \Rightarrow i_a^* = \frac{1}{K\phi_{f,r}} T_{el}^*$$

$$\omega_m > \omega_{m,r} \Rightarrow \phi_f = \phi_{f,r} \frac{\omega_{m,r}}{\omega_m} \Rightarrow i_a^* = \frac{\omega_m}{K\phi_{f,r}\omega_{m,r}} T_{el}^*$$

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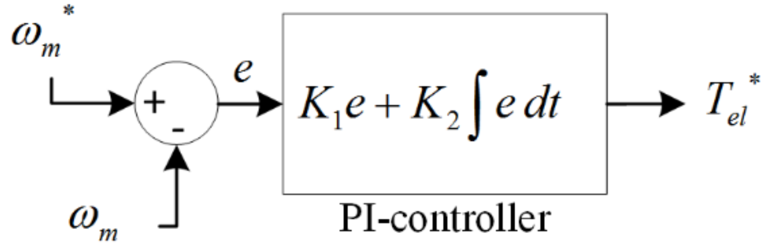
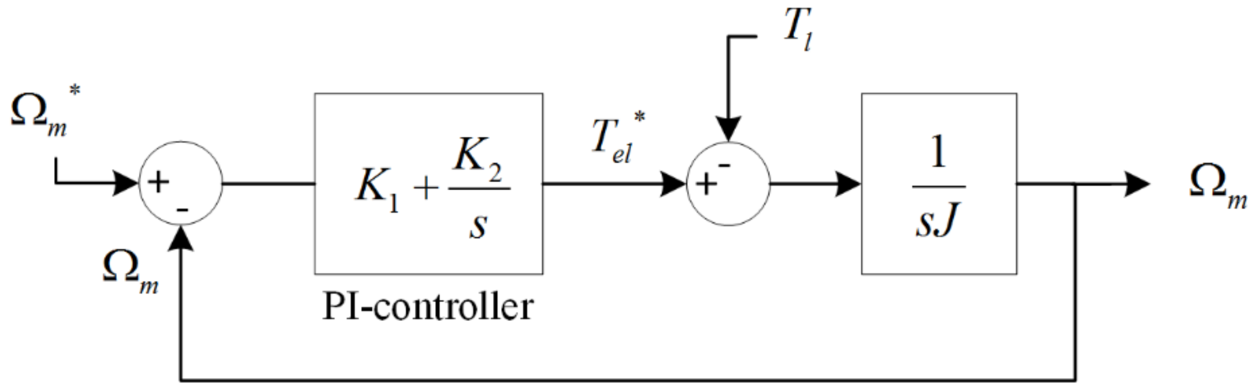
- Speed Controller: It is designed using Newton's 2nd law

$$T_{el} = T_l + J\frac{d\omega_m}{dt} \xrightarrow{Laplace} T_{el} = T_l + Js\Omega_m$$





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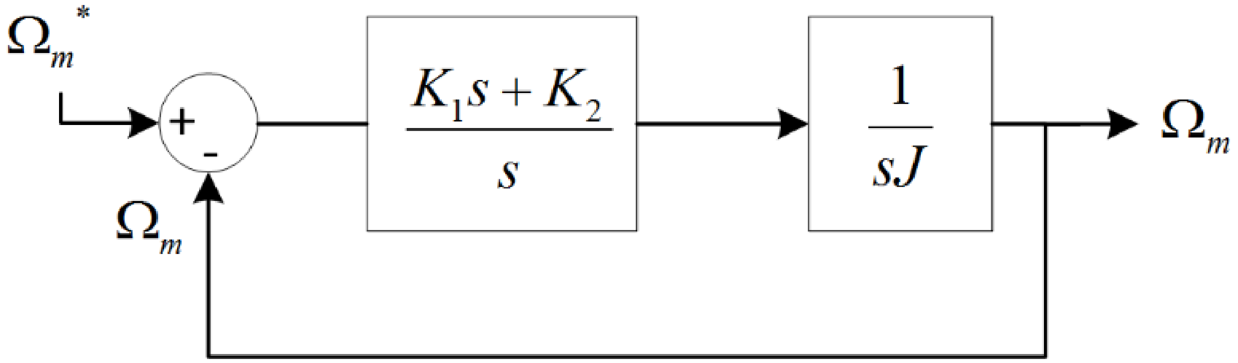
- T_1: $T_l = 0$



$$T_1 = \frac{G_1}{1 + G_1 H_1};$$

$$G_1 = \frac{K_1 s + K_2}{J s^2}; \quad H_1 = 1$$

$$T_1 = \frac{K_1}{J} \frac{s + \frac{K_2}{K_1}}{\underbrace{s^2 + \frac{K_1}{J} s + \frac{K_2}{J}}_{s^2 + 2\xi\omega_n s + \omega_n^2}};$$

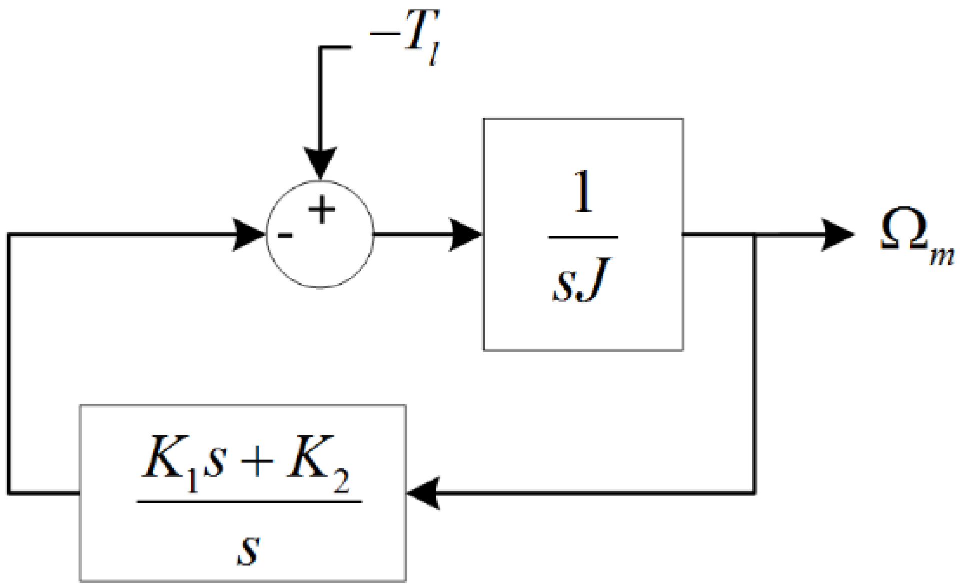
ξ: Damping ratio, ω_n: Natural frequency

$\xi < 1 \rightarrow$ Under-damped

$\xi = 1 \rightarrow$ Critically damped

$\xi > 1 \rightarrow$ Over-damped

- T_2: $\Omega_m{}^* = 0$



$$T_2 = \frac{-G_2}{1 + G_2 H_2};$$

$$G_2 = \frac{1}{Js}; \quad H_2 = \frac{K_1 s + K_2}{s}$$

$$T_2 = -\frac{1}{J} \frac{s}{s^2 + \frac{K_1}{J} s + \frac{K_2}{J}};$$

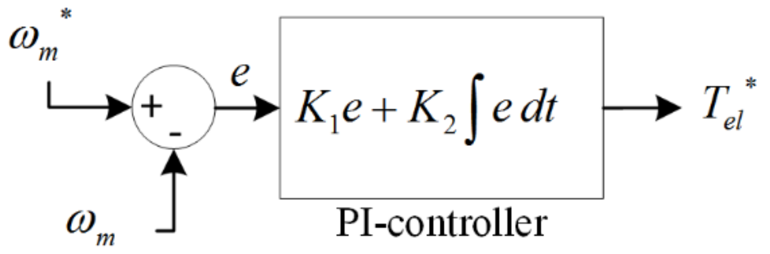
$$\Omega_m = T_1 \Omega_m^* + T_2 T_l$$

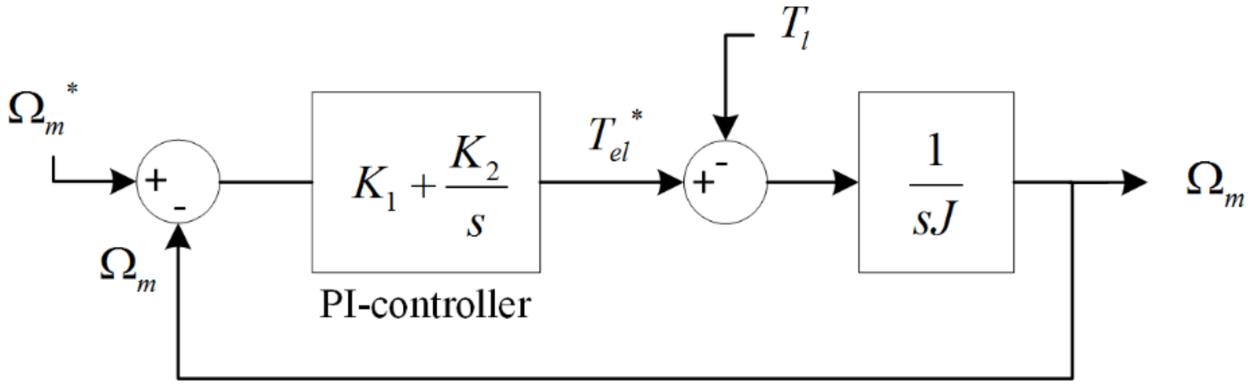
$$\omega_{m,ss} = \lim_{s=0} s\Omega_m = \lim_{s=0} sT_1\Omega_m^* + \lim_{s=0} sT_2T_l$$

Assume $\omega_m^* = Au(t), T_l = Bu(t)$

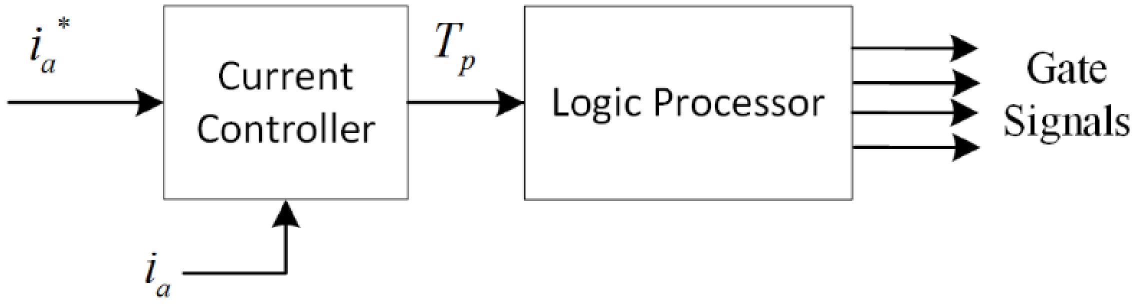
$$\Omega_m^* = \frac{A}{s}, T_l = \frac{B}{s}$$

$$\omega_{m,ss} = A\lim_{s=0} T_1 + B\lim_{s=0} T_2 = A$$





- Current Controller and Logic Processor:
    - PWM current controller
    - Hysteresis current controller



T_p is called the on-time signal

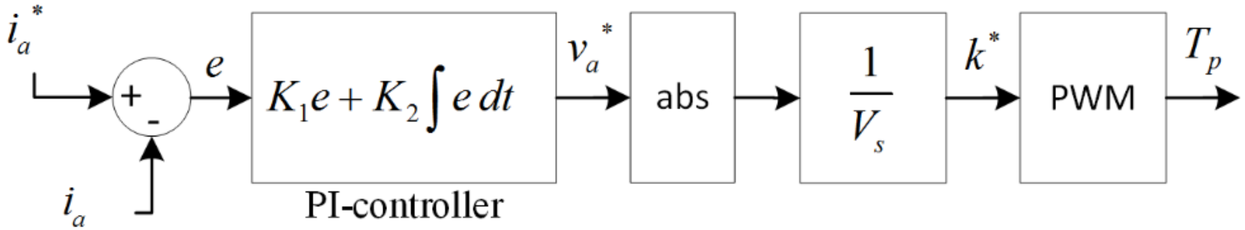
The logic processor determines the quadrant of operation

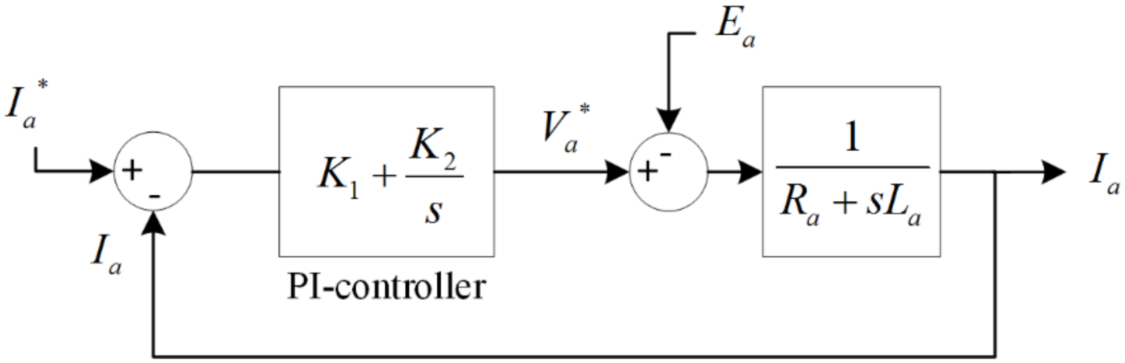
$$T_p = 1 \rightarrow v_a = \pm V_s$$

$$T_p = 0 \rightarrow v_a = 0$$

- PWM current controller

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \xrightarrow{Laplace} V_a = \left(R_a + sL_a\right) I_a + E_a$$





$$I_a = T_1 I_a^* + T_2 E_a$$

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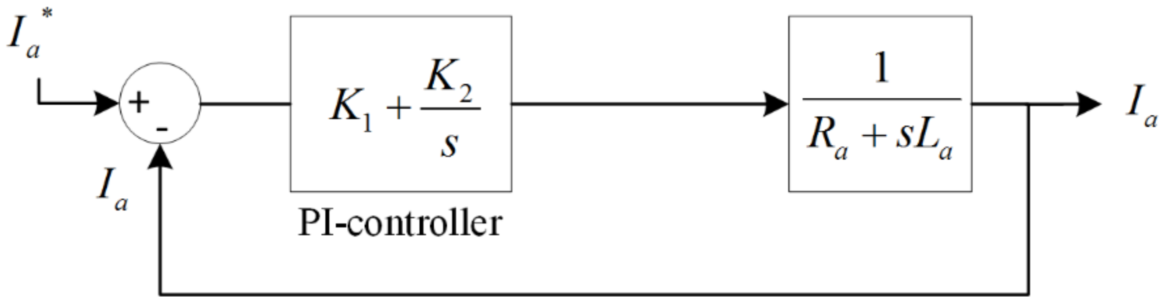
T_1: $E_a = 0$



$$T_1 = \frac{G_1}{1 + G_1 H_1};$$

$$G_1 = \frac{K_1 s + K_2}{(R_a + sL_a)s}; \quad H_1 = 1$$

$$T_1 = \frac{K_1}{L_a} \frac{s + \frac{K_2}{K_1}}{\underbrace{s^2 + \left(\frac{K_1 + R_a}{L_a}\right)s + \frac{K_2}{L_a}}_{s^2 + 2\xi\omega_n s + \omega_n^2}};$$

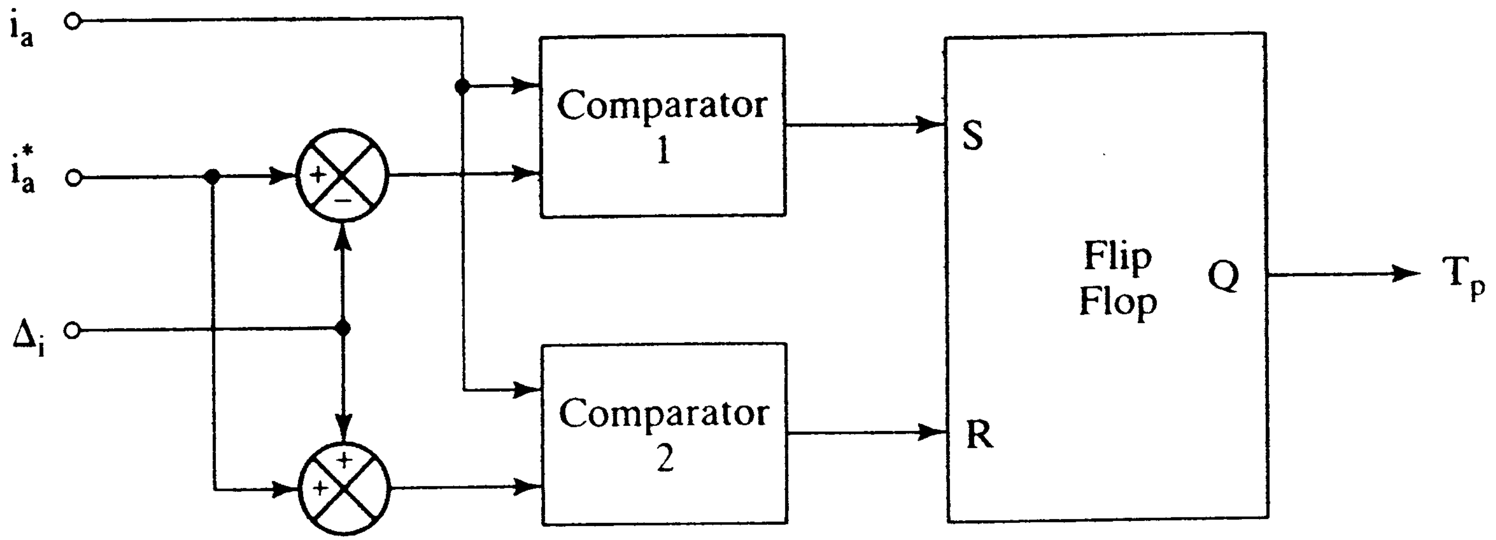
ξ: Damping ratio, ω_n: Natural frequency

$\xi < 1 \rightarrow$ Under-damped

$\xi = 1 \rightarrow$ Critically damped

$\xi > 1 \rightarrow$ Over-damped

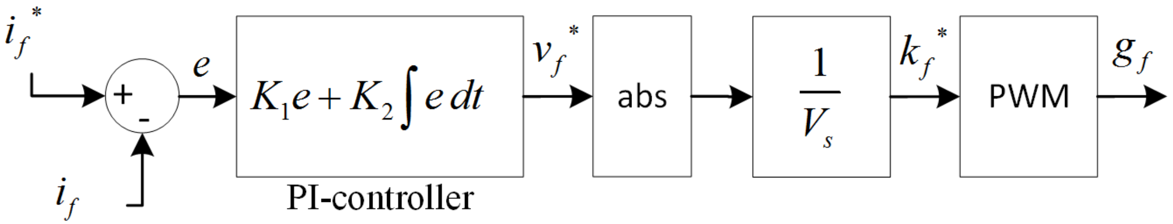
• Hysteresis current controller

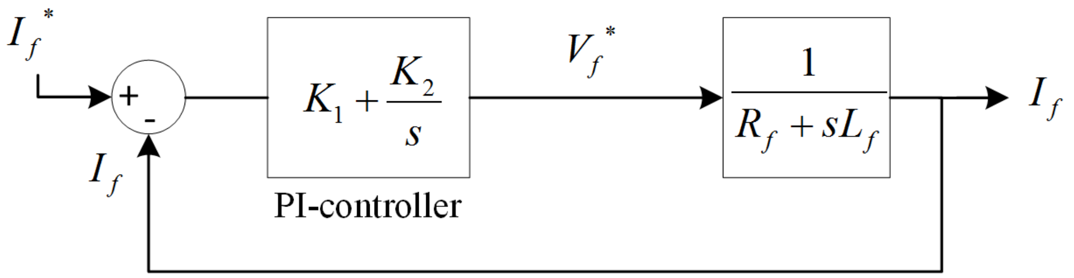


- Flux Controller
  - PWM flux controller
  - Hysteresis flux controller

- PWM flux controller

$$v_f = R_f i_f + L_f \frac{di_f}{dt} \xrightarrow{Laplace} V_f = \left(R_f + sL_f\right) I_f$$





$$T = \frac{G}{1 + GH};$$

$$G = \frac{K_1 s + K_2}{\left(R_f + sL_f\right) s}; \quad H = 1$$

$$T = \frac{K_1}{L_f} \frac{s + \frac{K_2}{K_1}}{\underbrace{s^2 + \left(\frac{K_1 + R_f}{L_f}\right) s + \frac{K_2}{L_f}}_{s^2 + 2\xi\omega_n s + \omega_n^2}};$$