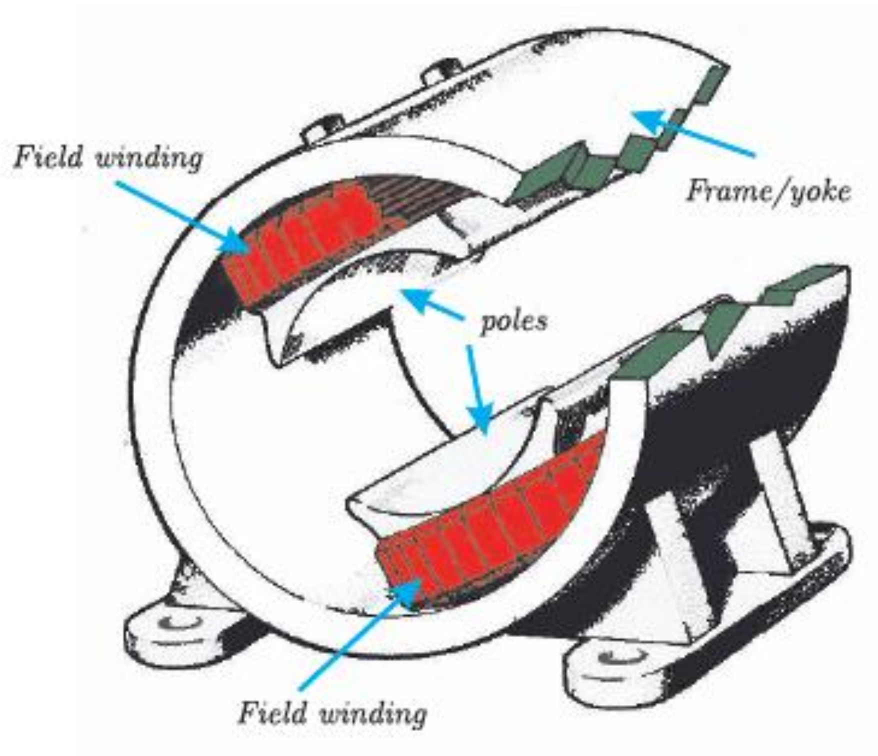
Chapter 2

Modeling and Control of DC Machines

$\phi = M i_f$, $T = k\phi i_a$, $E_a = k\phi w$, $V_t = R_a i_a + E_a$

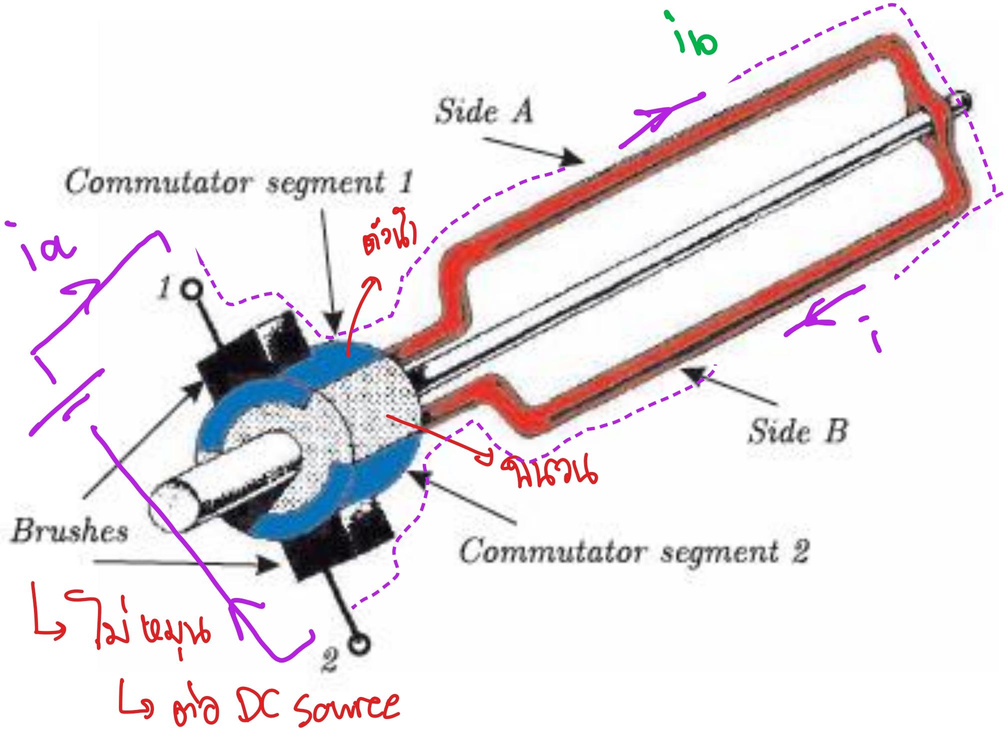
$T = J\frac{dw}{dt} + T_{Load}$

2.1 Machine Structure



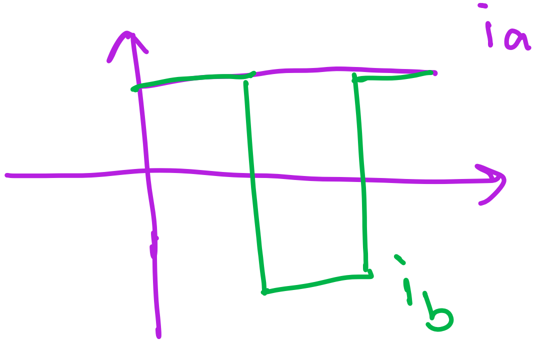
2-Pole DC Machine - Stator

- The field winding consists of N turn concentrated winding of which each half is wrapped around a pole.
- The frame is the yoke-part of the magnetic flux path.
- The use of a field winding gives us the ability to control the magnetic flux.
- Permanent magnets are often used to replace the field winding which leads to a more compact and efficient machine.
- However, we loose the control of flux magnitude and the potential of operating the machine on an AC source (universal machines)



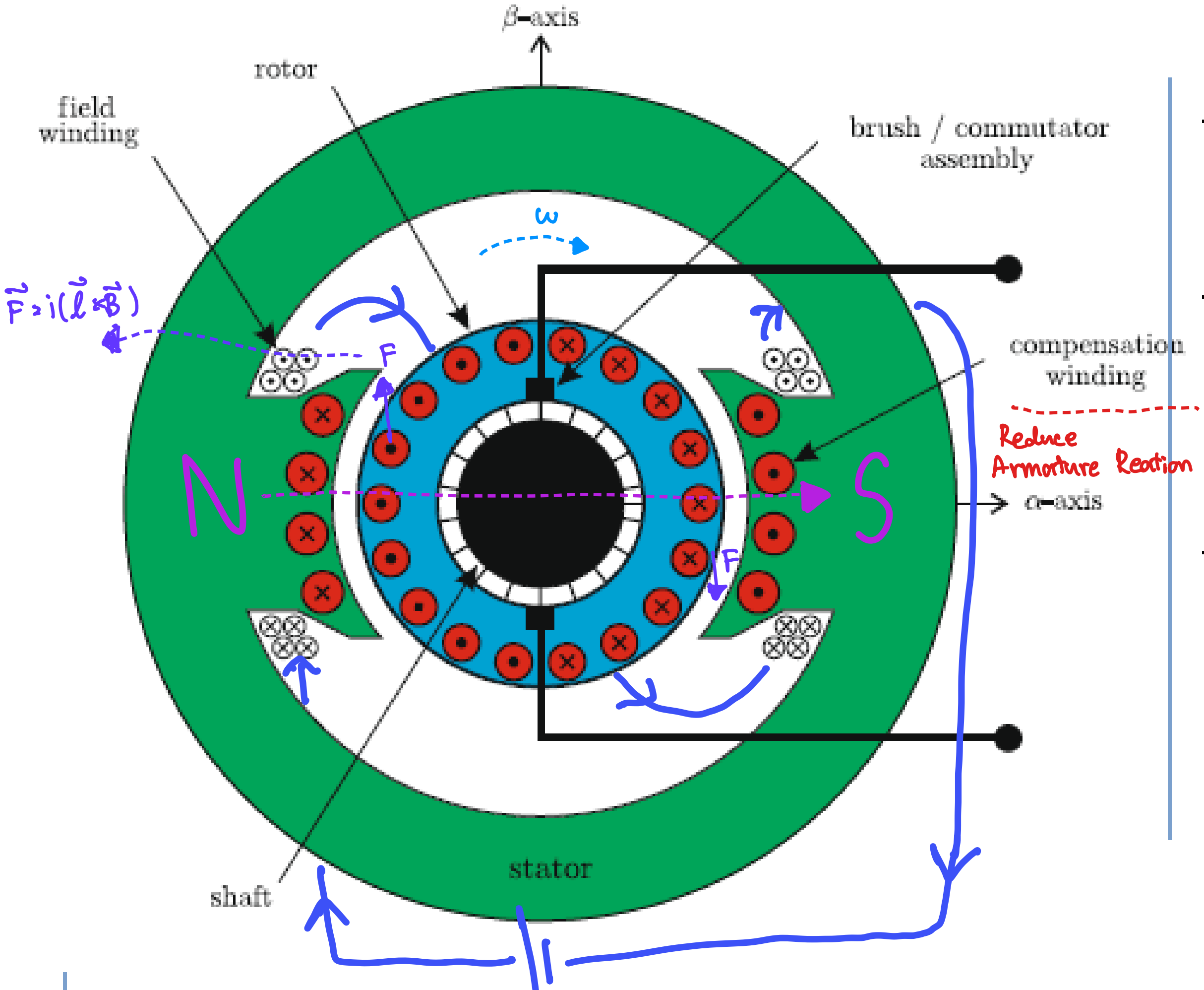
DC Machine - Rotor

- A very simple example of A DC rotor shows the same single turn winding introduced for the synchronous machine.
- The slip ring/brush combination is replaced by a so-called commutator.



Separately Excited DC Machine

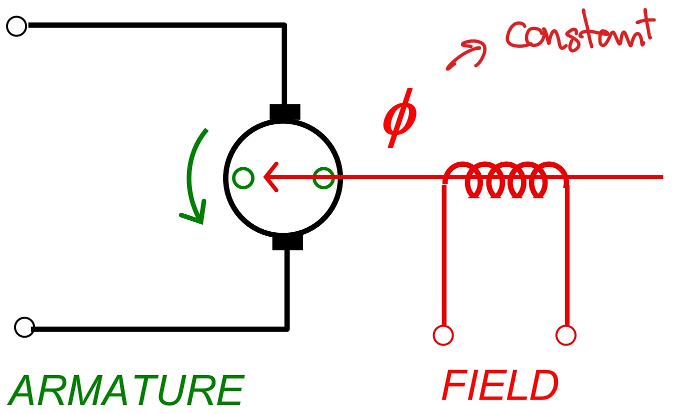
rotor → armature
stator → field winding



- Field winding : stator based excitation winding.
- With regard to the compensation winding, the magnetizing flux will remain oriented along the α- axis.
- In addition to the magnetizing flux, other component will appear due to the leakage inductance of the armature winding.

Cross-sectional view of a separately excited DC machine

2.2 Model of Separately-Excited DC Machine

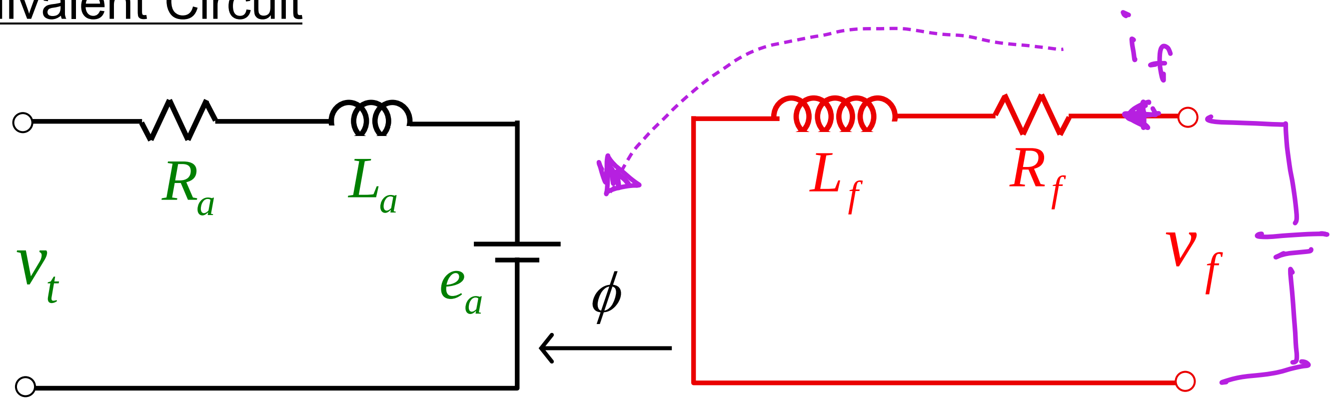


Basic Equation

$$e_a = k\phi\omega$$
$$T = k\phi i_a$$

k : Armature Constant

Equivalent Circuit



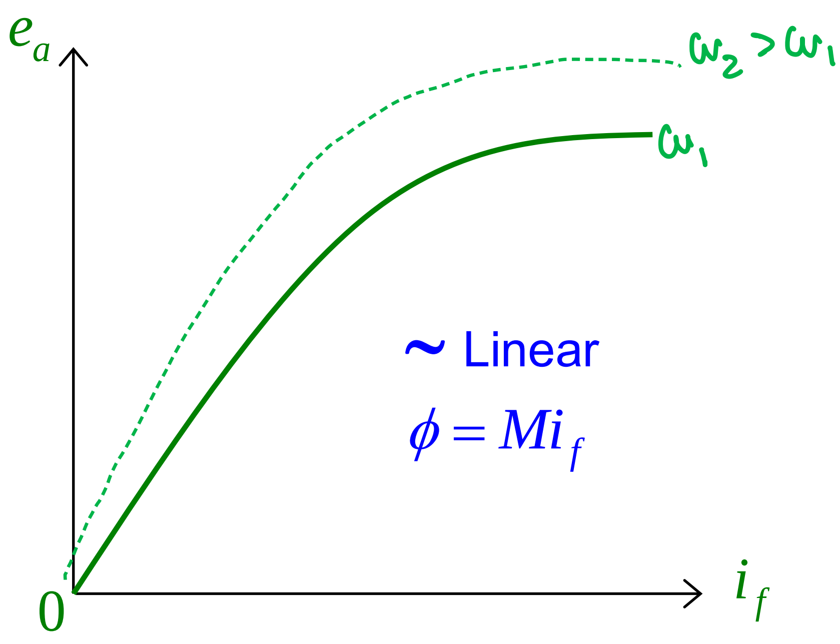
Electrical Equation

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

armature $$v_t = R_a i_a + L_a \frac{di_a}{dt} + \underbrace{k\phi\omega}_{e_a}$$

Mechanical Equation

$$T = k\phi i_a = J\frac{d\omega}{dt} + T_{Load}$$



MAGNETIZATION CURVE

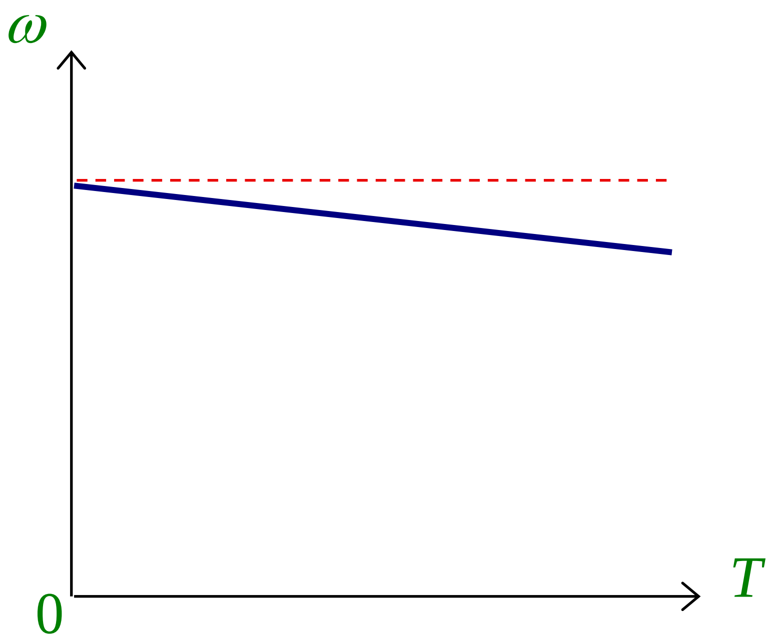
ที่ STEADY STATE

$$\begin{cases} v_f = R_f i_f \\ v_t = R_a i_a + k\phi\omega \\ T = T_{LOAD} = k\phi i_a \end{cases}$$

2.3 SPEED CONTROL

ที่ STEADY STATE

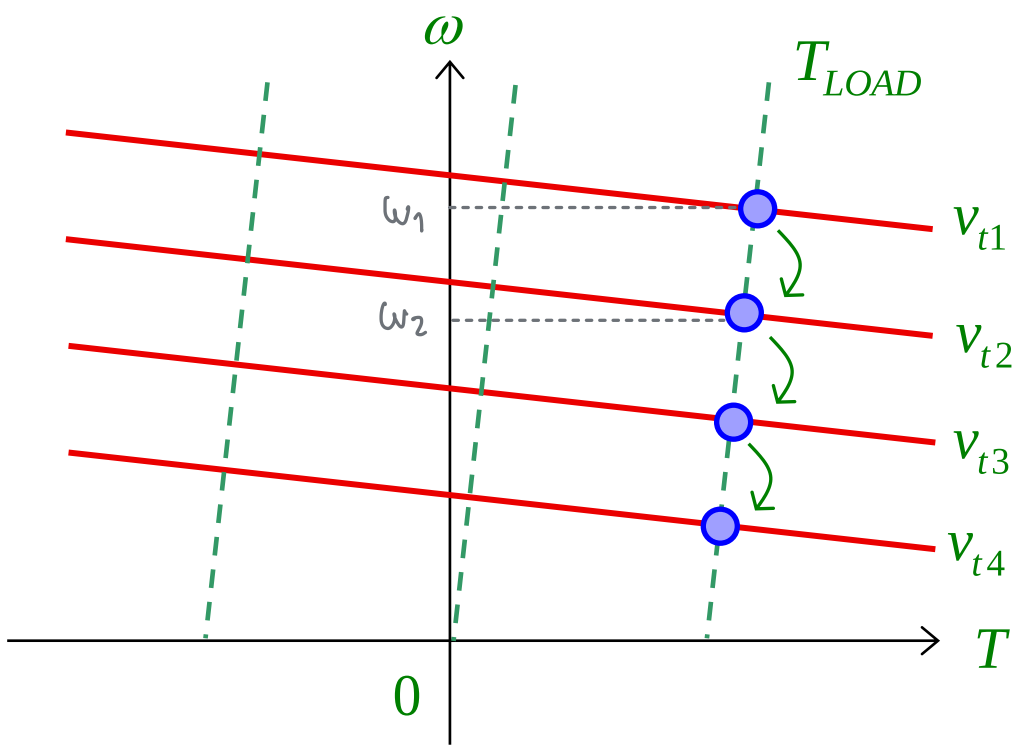
$$\boxed{\omega = \frac{v_t}{k\phi} - \frac{R_a}{(k\phi)^2} \cdot T} \qquad (T = T_{LOAD})$$



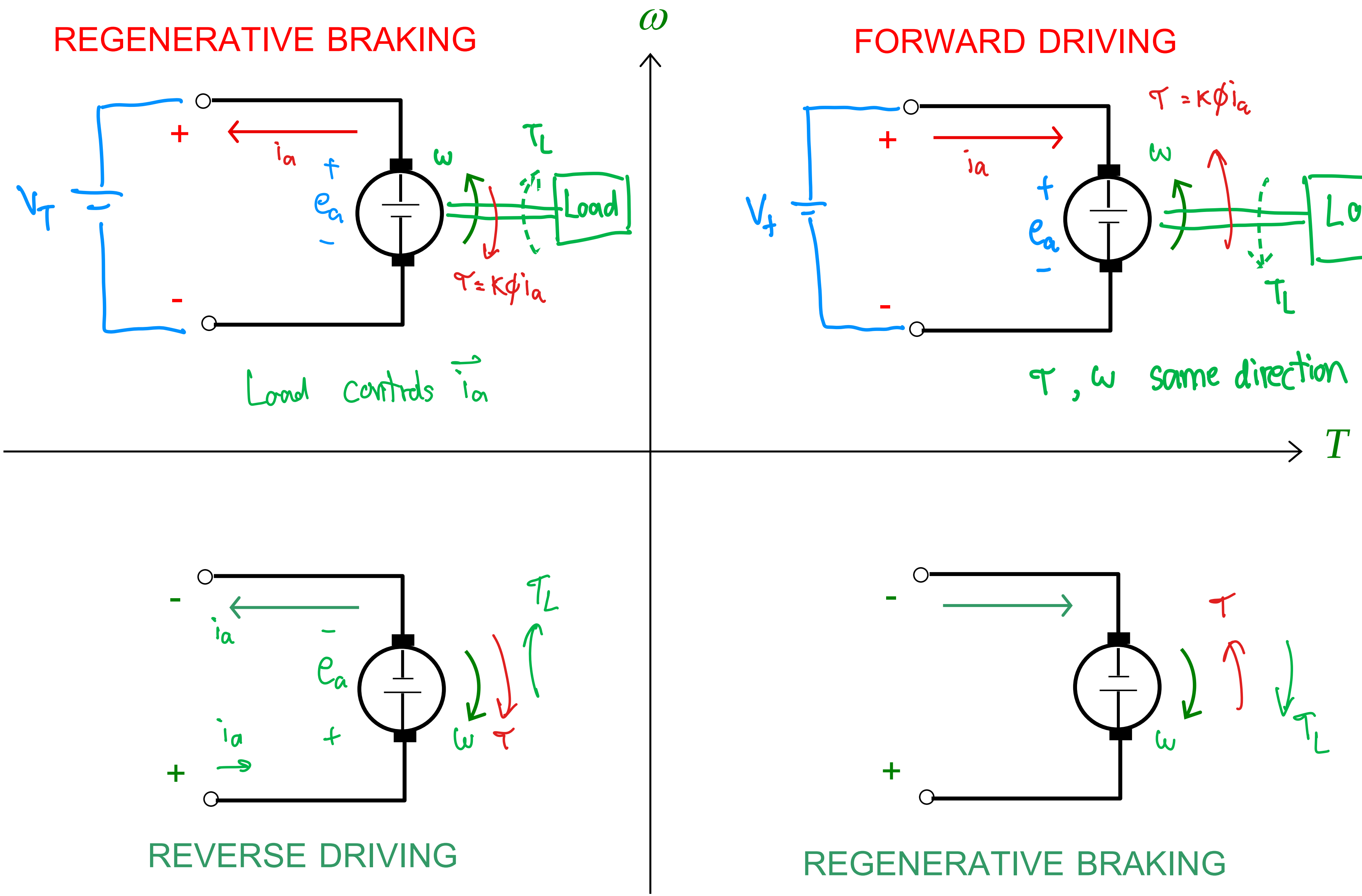
จากสมการข้างต้น ω สำหรับ T_{LOAD} ค่าหนึ่ง สามารถปรับเปลี่ยนได้ โดย

v_t, $(k\phi)$, R_a

- SPEED CONTROL BY v_t

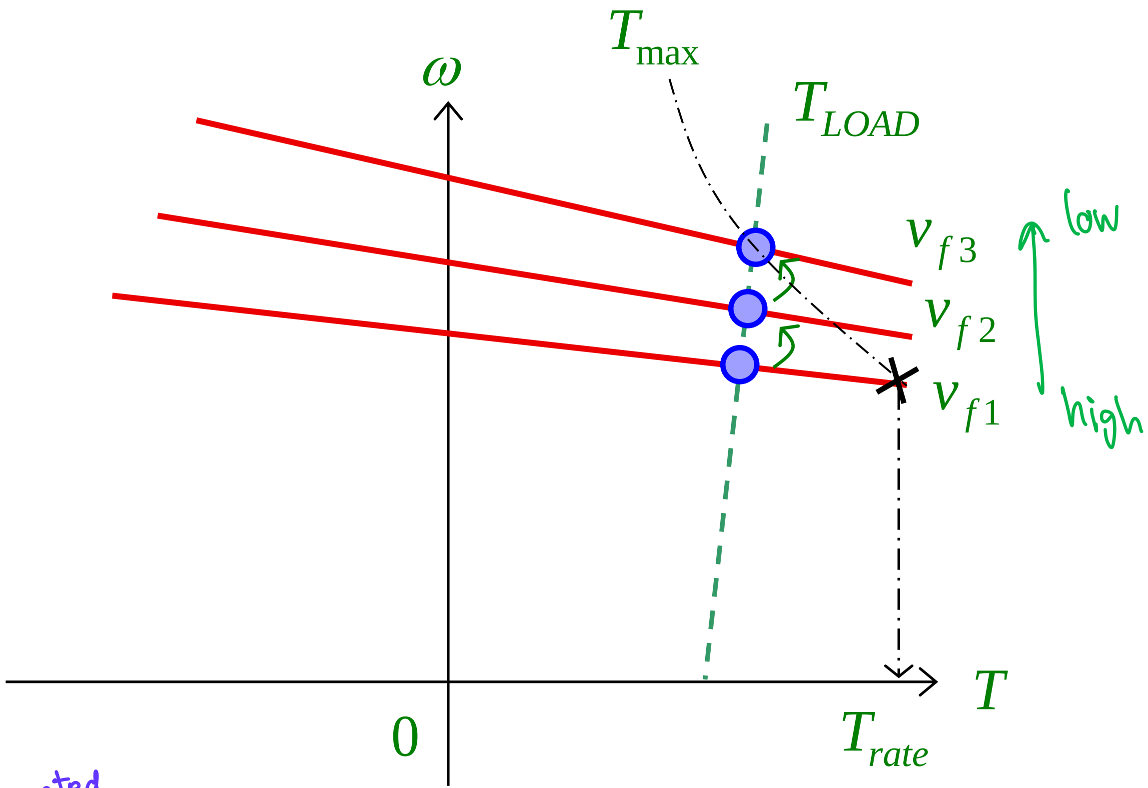


- Field ไม่เปลี่ยน
- $-v_{rate} < v_t < v_{rate}$
- $\omega < \omega_{base}$
- $i_a < i_{\max}$ (พิกัด)



REGENERATIVE BRAKING
FORWARD DRIVING
REVERSE DRIVING
REGENERATIVE BRAKING
ω
T
V_T
i_a
e_a
ω
T_L
Load
τ = Kφi_a
Load controls $\vec{i_a}$
V_t
e_a
τ , ω same direction

● SPEED CONTROL BY FIELD WEAKENING



- v_t คงที่ (v_{rate})
- $v_{f1} > v_{f2} > v_{f3}....$

  $\phi_1 > \phi_2 > \phi_3....$

  (rate)

  $I_{f1} > I_{f2} > I_{f3} \ldots$
- $\omega > \omega_{base}$
- $i_a < i_{max}$ (พิกัด)

  $T_{max} \left(= k\phi i_{max}\right) \propto 1/\omega$

  $P_{max} = Const.$

rated

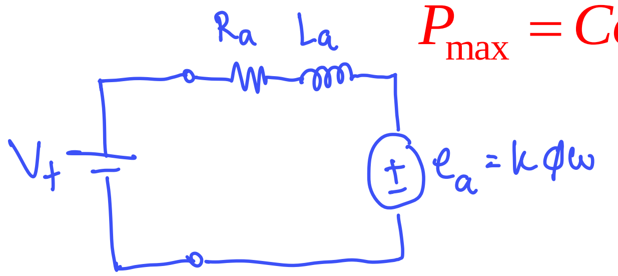
(น้อย)

$$v_t = R_a i_a + k\phi\omega = \text{คงที่}$$

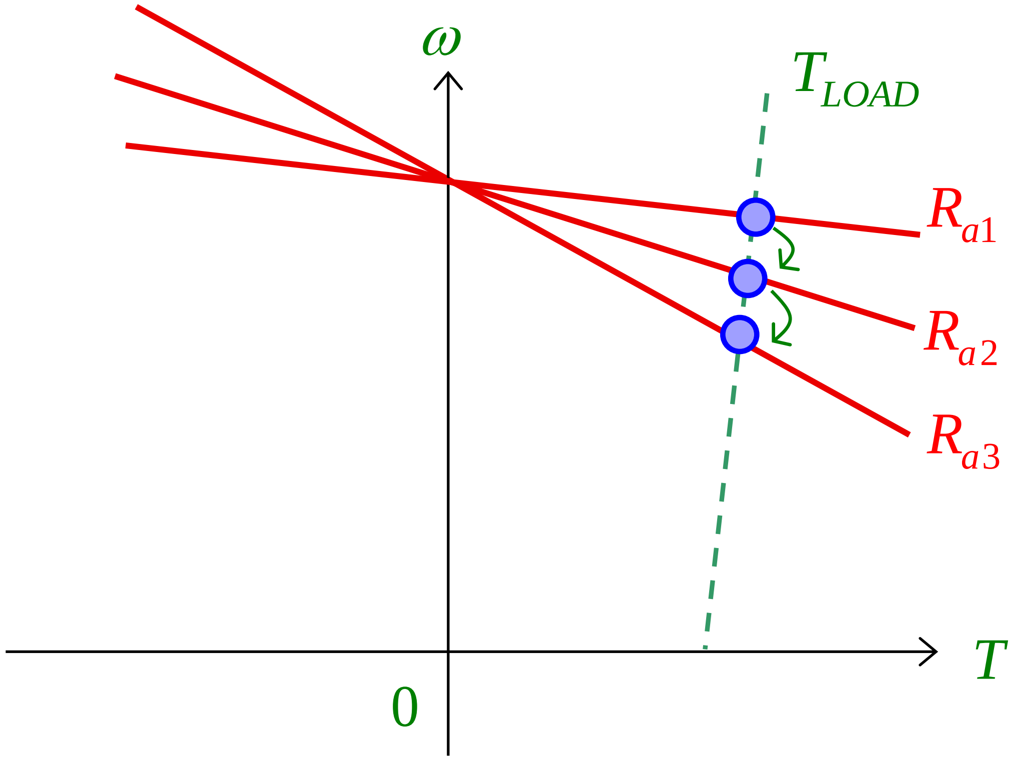
$$\approx k\phi\omega$$

rated base

$\phi \downarrow \Rightarrow \omega \uparrow$



- SPEED CONTROL BY R_a



- เพิ่ม Loss
- SPEED REGULATION เพิ่ม
- ω เปลี่ยนแปลงน้อยในช่วงโหลดต่ำ
- $i_a < i_{\max}$ (พิกัด)

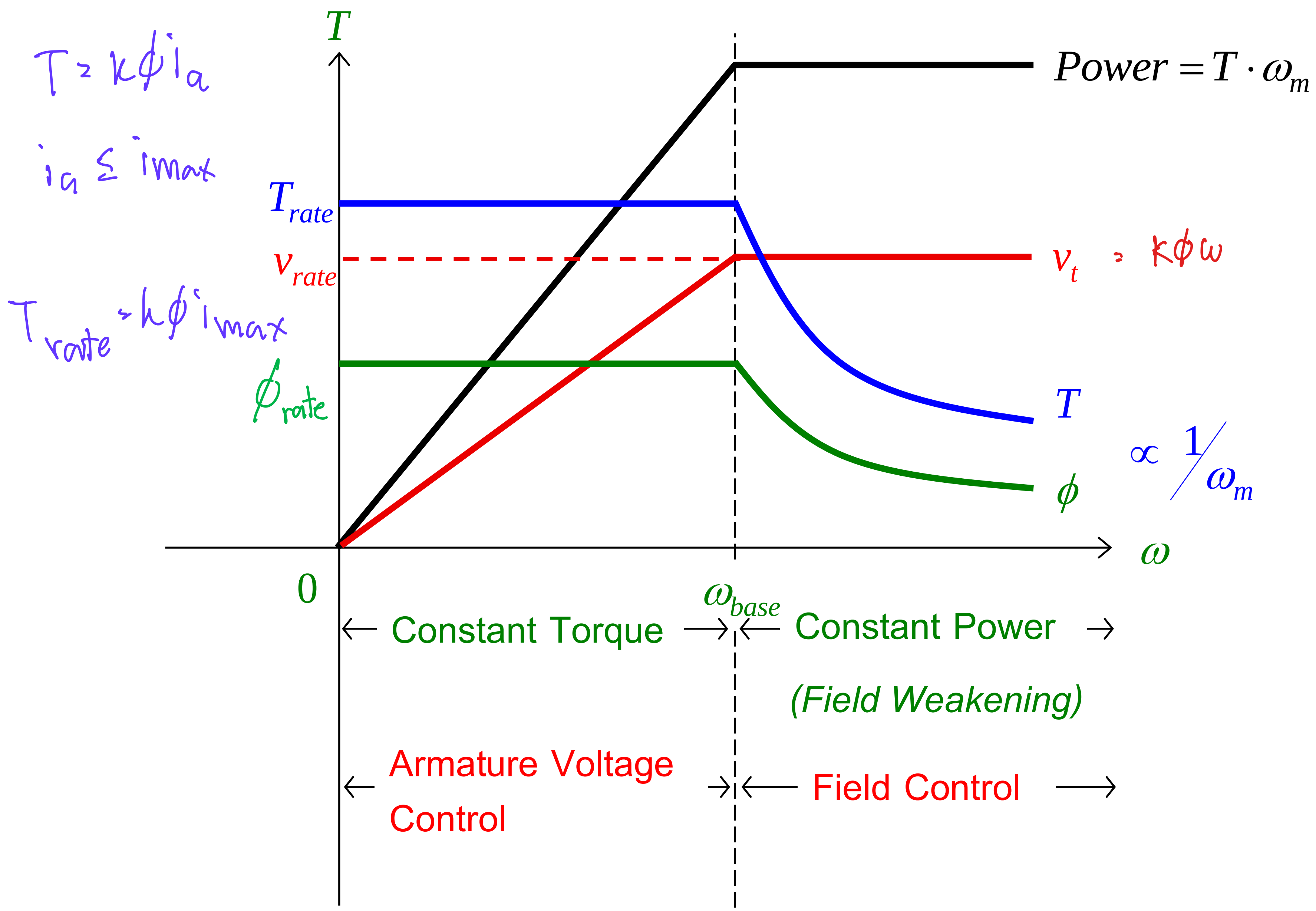
LIMIT

$$|v_t| \leq v_{rate} = v_{\max}$$

$$|i_a| \leq i_{rate} = i_{\max}$$

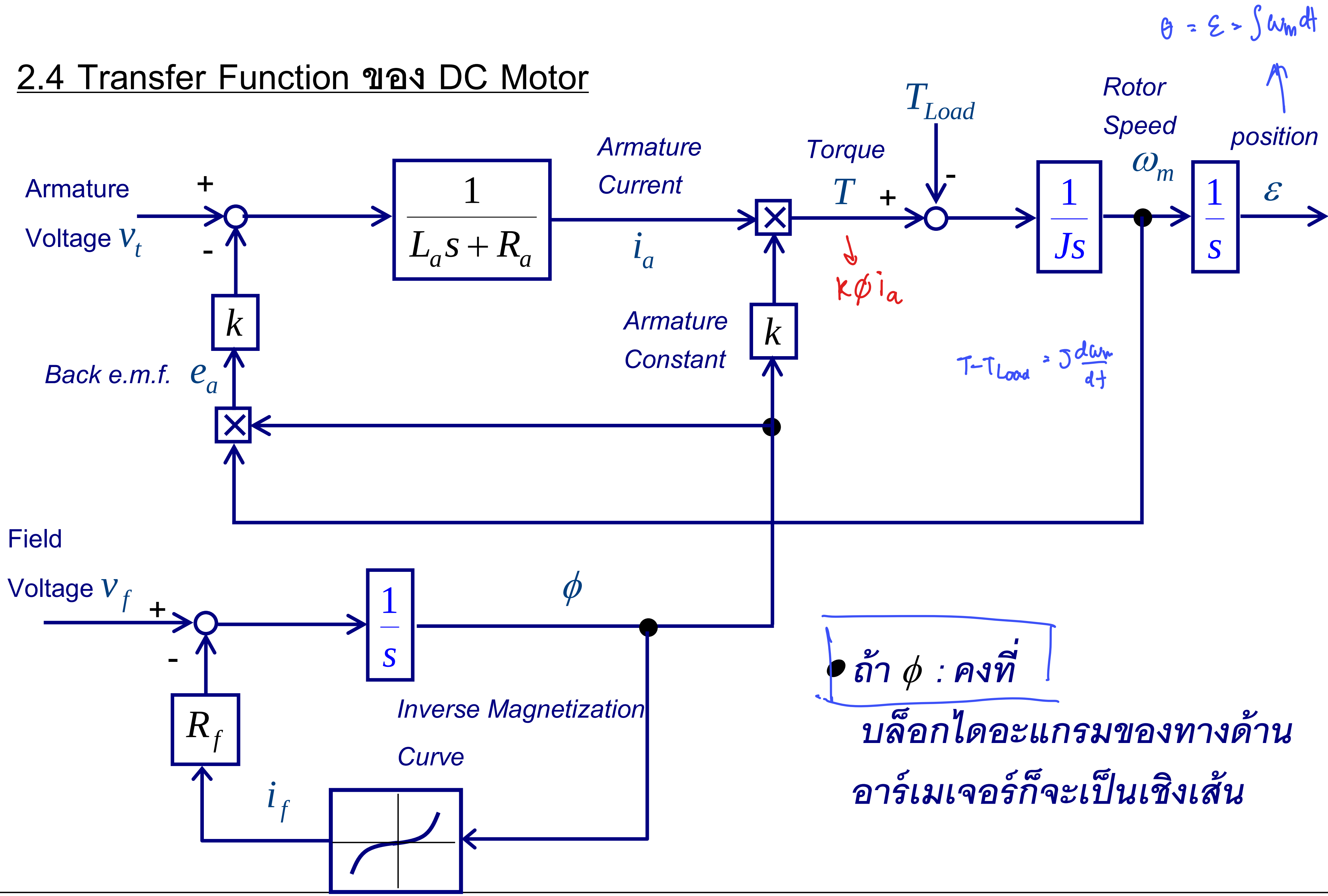
$$\omega \leq \omega_{\max} \quad \text{(อาจสูงกว่า } \omega_{base}\text{)}$$

$$|i_f| \leq i_{frate}$$



T
$Power = T \cdot \omega_m$
$T = k\phi i_a$
$i_a \le i_{max}$
T_{rate}
v_{rate}
$v_t = k\phi\omega$
$T_{rate} = k\phi i_{max}$
ϕ_{rate}
T
$\propto 1/\omega_m$
ϕ
ω
0
ω_{base}
Constant Torque
Constant Power
(Field Weakening)
Armature Voltage Control
Field Control

2.4 Transfer Function ของ DC Motor



- ถ้า ϕ : คงที่

บล็อกไดอะแกรมของทางด้านอาร์เมเจอร์ก็จะเป็นเชิงเส้น

$$V_t = R_a i_a + L_a \frac{d}{dt} i_a + K\phi\omega$$

↓ Laplace transform

$$V_t = R_a i_a + L_a s i_a + K\phi\omega$$

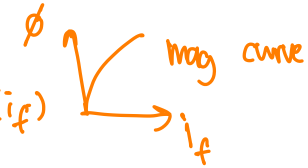
$$V_t - K\phi\omega = (R_a + L_a s) i_a$$

$$\frac{i_a}{V_t - K\phi\omega} = \frac{1}{L_a s + R_a}$$

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

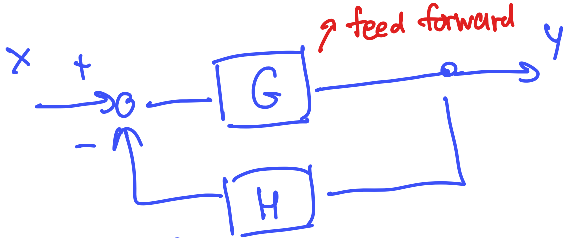
$$= R_f i_f + \frac{d}{dt}(L_f i_f)$$

$\phi = L_f i_f = f(i_f)$



$$V_f - R_f i_f = s\phi$$

$$\frac{\phi}{V_f - R_f i_f} = \frac{1}{s}$$



$$\frac{Y}{X} = \frac{G}{1+\underbrace{GH}_{\text{loop gain}}}$$

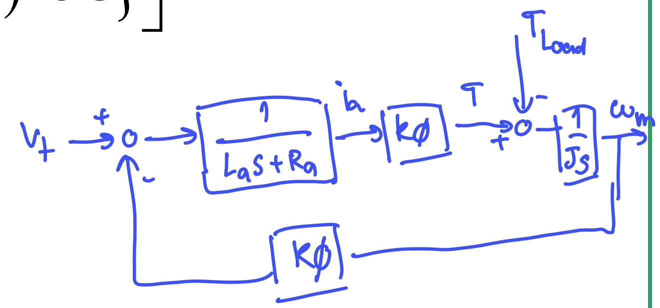
Dynamic Behavior ของ DC Motor ที่ Const. Flux

⊗
$$\omega_m = F_1(s)\cdot v_t + F_2(s)\cdot T_{Load}$$

Superposition

$$F_1(s) = \left.\frac{k\phi}{(L_a s + R_a)\cdot Js}\right/\left[1 + \left.(k\phi)^2\right/\{(L_a s + R_a)\cdot Js\}\right]$$

$$= \frac{k\phi}{Js(L_a s + R_a) + (k\phi)^2}$$



$$F_2(s) = \left.\frac{-1}{Js}\right/\left[1 + \left.(k\phi)^2\right/\{(L_a s + R_a)\cdot Js\}\right]$$

$$= \frac{-(L_a s + R_a)}{Js(L_a s + R_a) + (k\phi)^2}$$

⊗

$$i_a = F_3(s)\cdot v_t + F_4(s)\cdot T_{Load}$$

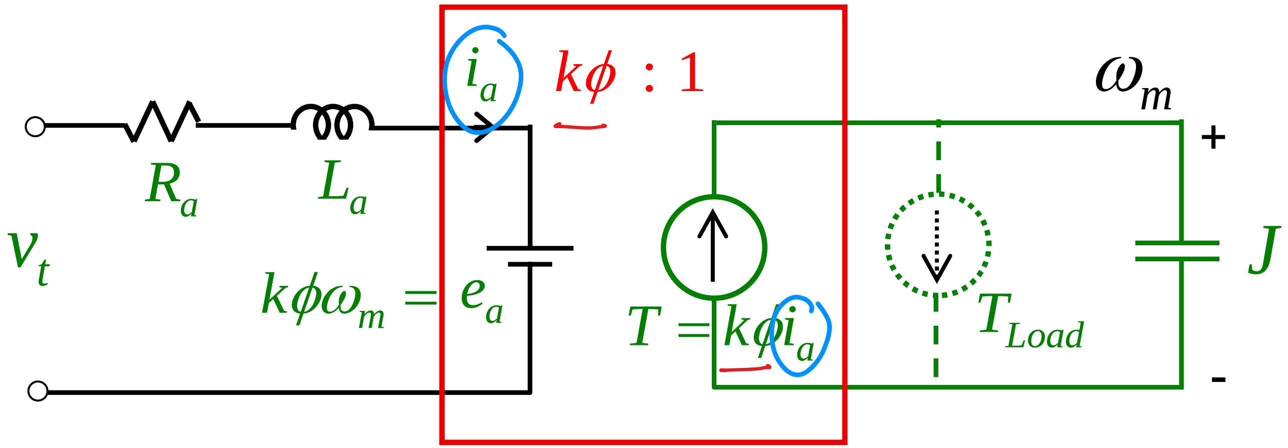
$$F_3(s) = \frac{1}{(L_a s + R_a)} \Bigg/ \left[1 + {(k\phi)^2} \Big/ {\{(L_a s + R_a)\cdot J s\}}\right]$$

$$= \frac{J s}{J s(L_a s + R_a) + (k\phi)^2} \qquad = \frac{\frac{J}{(k\phi)^2}\cdot s}{\frac{J}{(k\phi)^2}\cdot s(L_a s + R_a) + 1}$$

$$F_4(s) = \frac{k\phi}{Js(L_a s + R_a)} \Bigg/ \left[1 + {(k\phi)^2} \Big/ {\{(L_a s + R_a)\cdot J s\}}\right]$$

$$= \frac{k\phi}{J s(L_a s + R_a) + (k\phi)^2} \qquad = F_1(s)$$

⊗



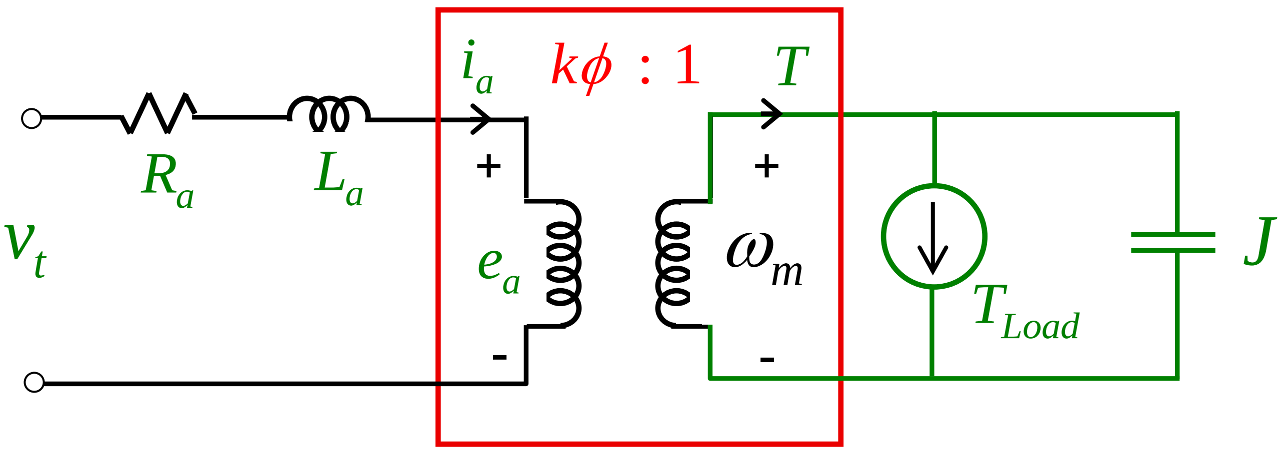
$$J\frac{d\omega}{dt} = T - T_{Load}$$

$$\Updownarrow$$

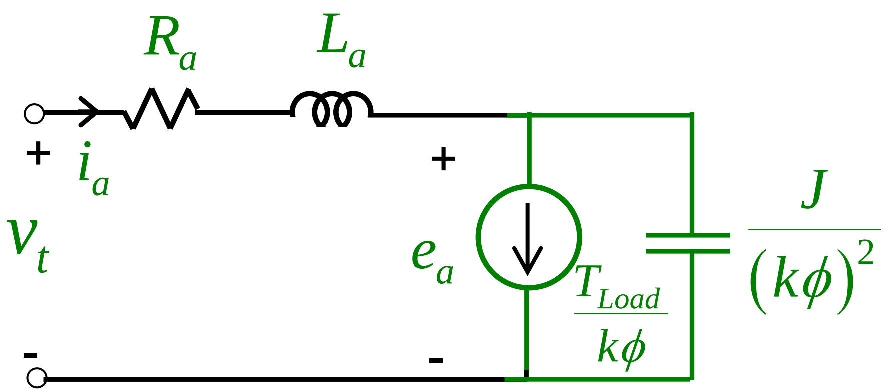
$$c\frac{dv}{dt} = i$$

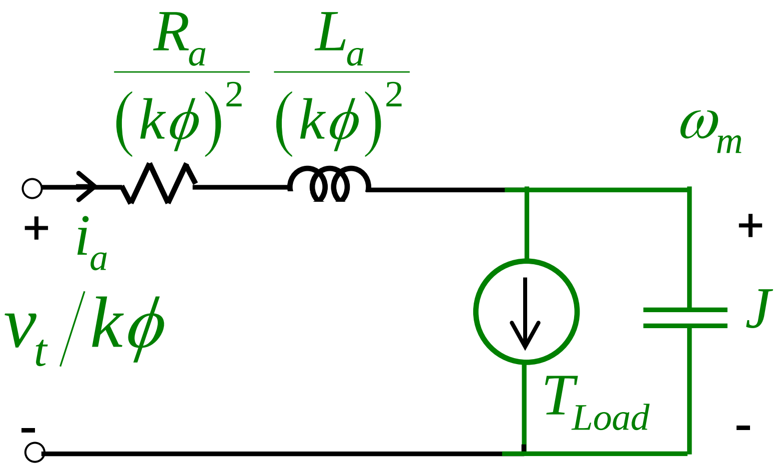
ทางด้านอาร์เมเจอร์

ทางด้านกล



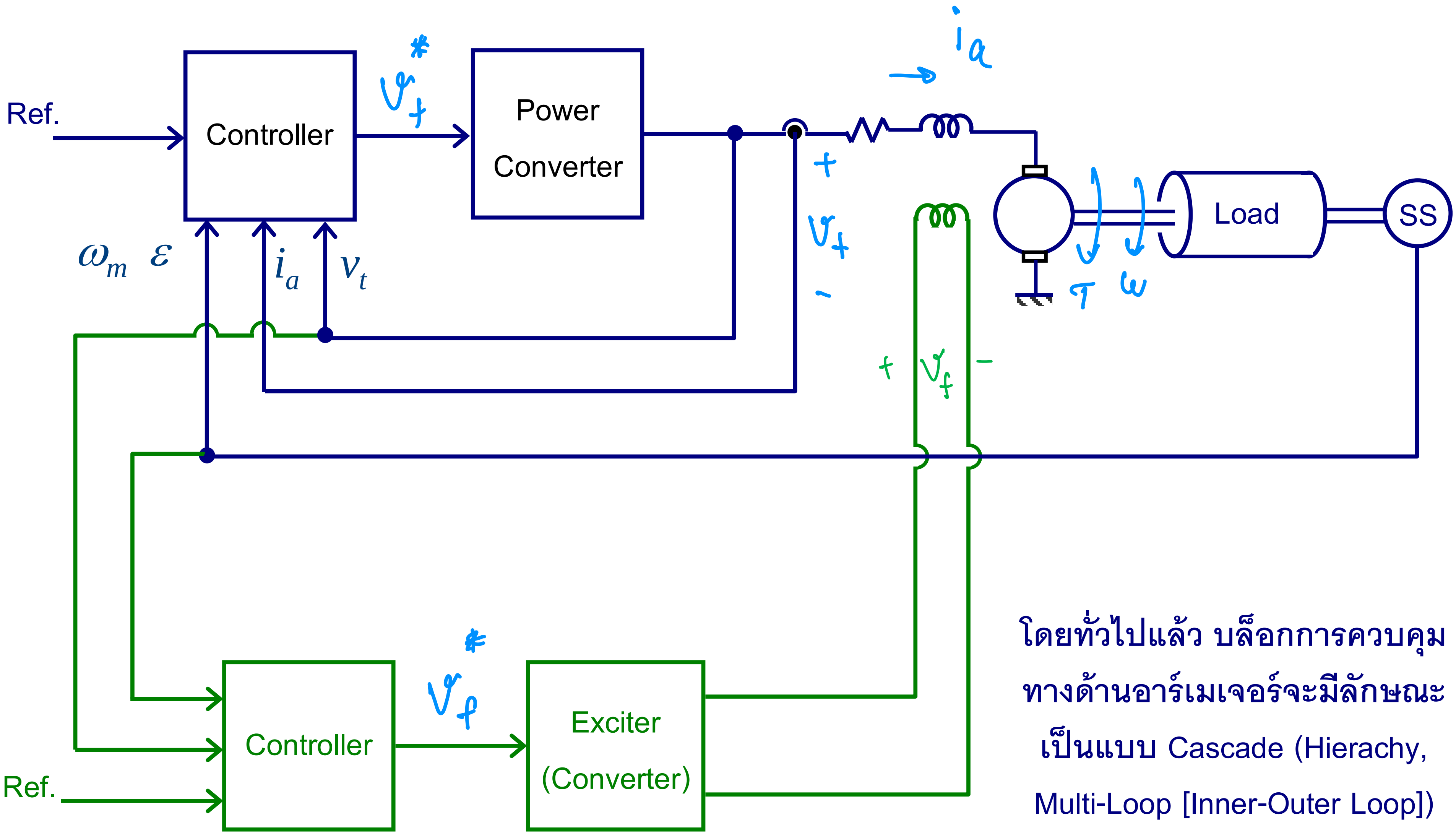
Ideal Transformer





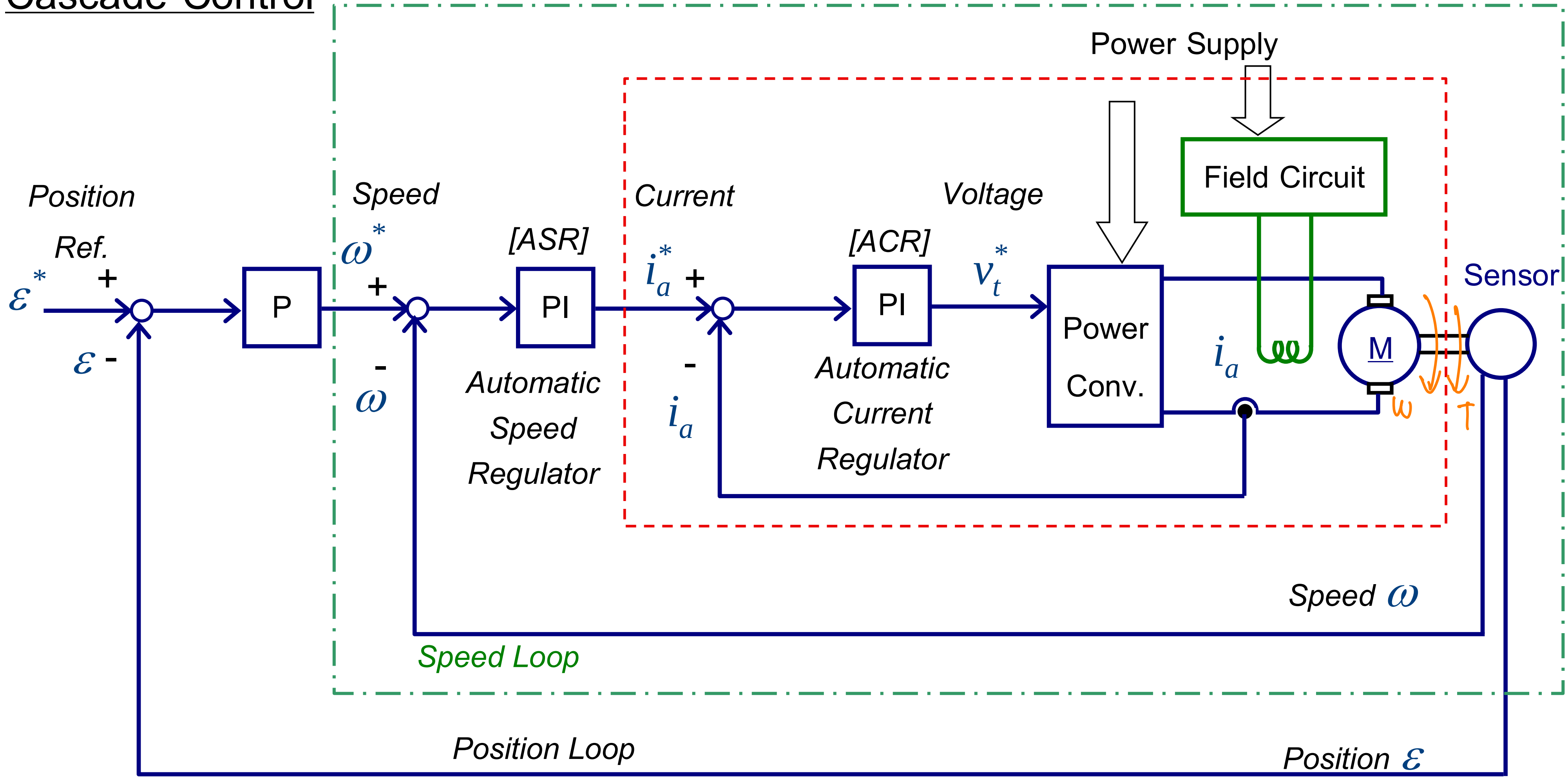
พลังงานที่สะสมใน $J = \frac{1}{2}J\omega_m^2$

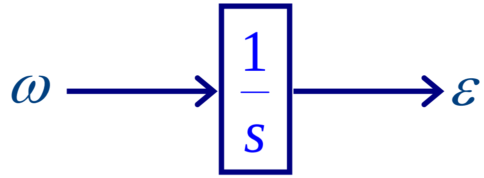
Control of Separately Excited DC Motor



โดยทั่วไปแล้ว บล็อกการควบคุม
ทางด้านอาร์เมเจอร์จะมีลักษณะ
เป็นแบบ Cascade (Hierachy,
Multi-Loop [Inner-Outer Loop])

Cascade Control





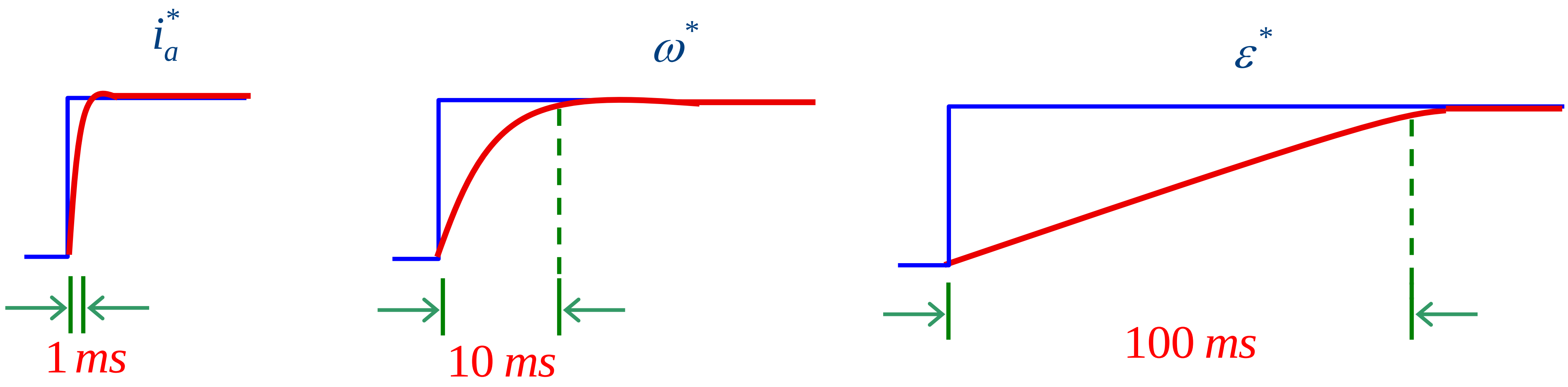
- การออกแบบระบบจะง่าย **(อิสระต่อกัน)** ถ้า

Response ของ Loop ใน >> Response ของ Loop นอก

(Inner Loop) เร็วกว่า (Outer Loop)

Bandwidth เร็วกว่า 10 เท่า โดยทั่วไป

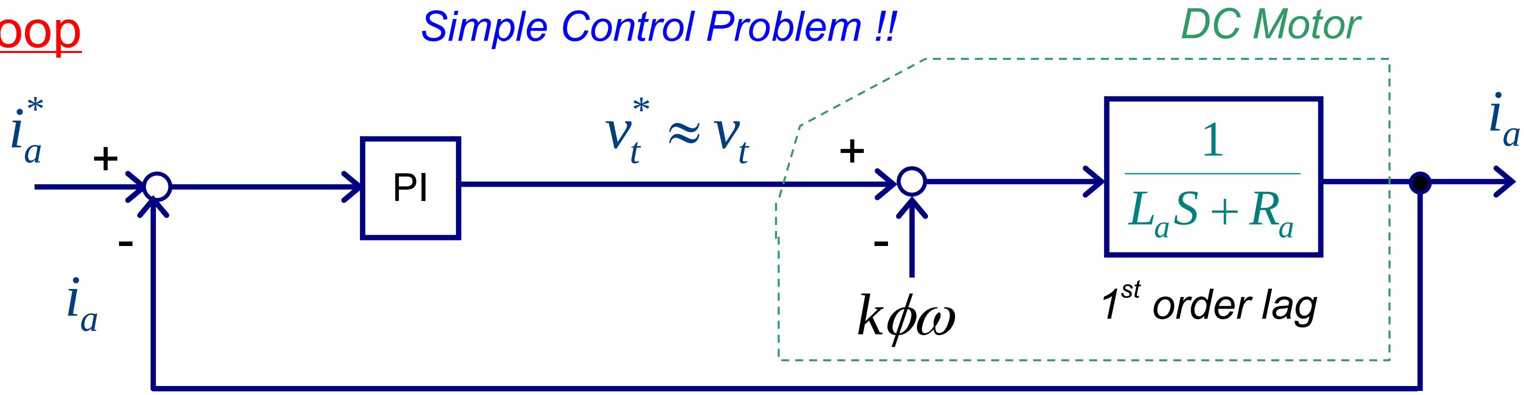
consider loop ใน โดยที่ loop นอกยังไม่เปลี่ยนไป



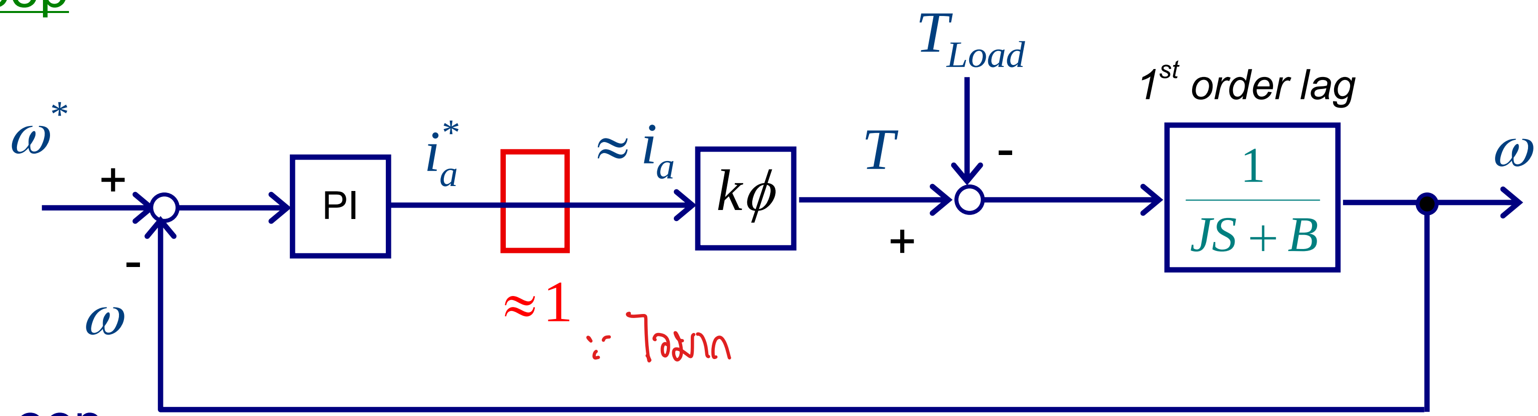
$\tau = \frac{L_a}{R_a}$ (time const.)

Current Loop

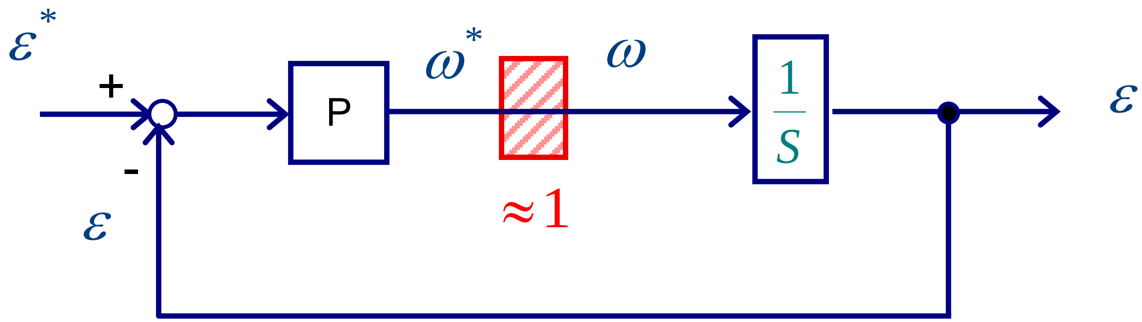
Simple Control Problem !!



Speed Loop

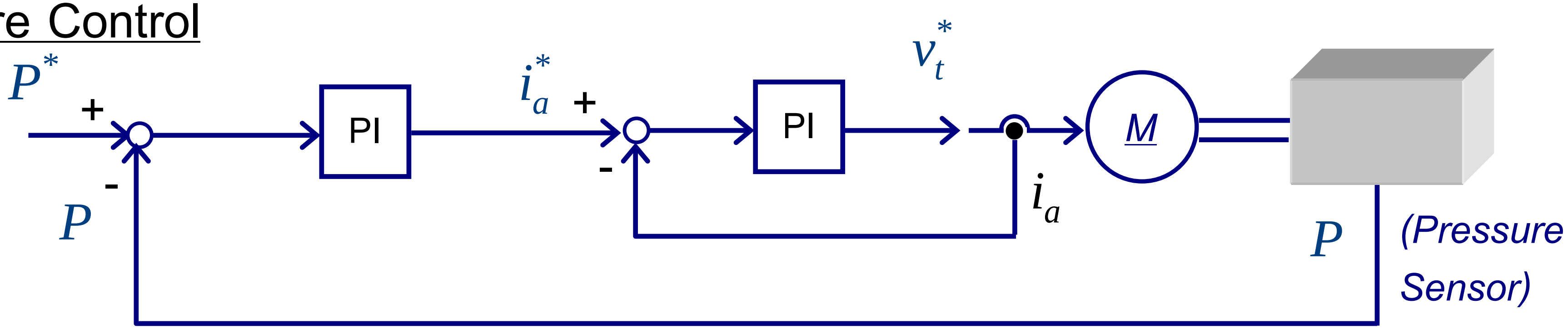


Position Loop

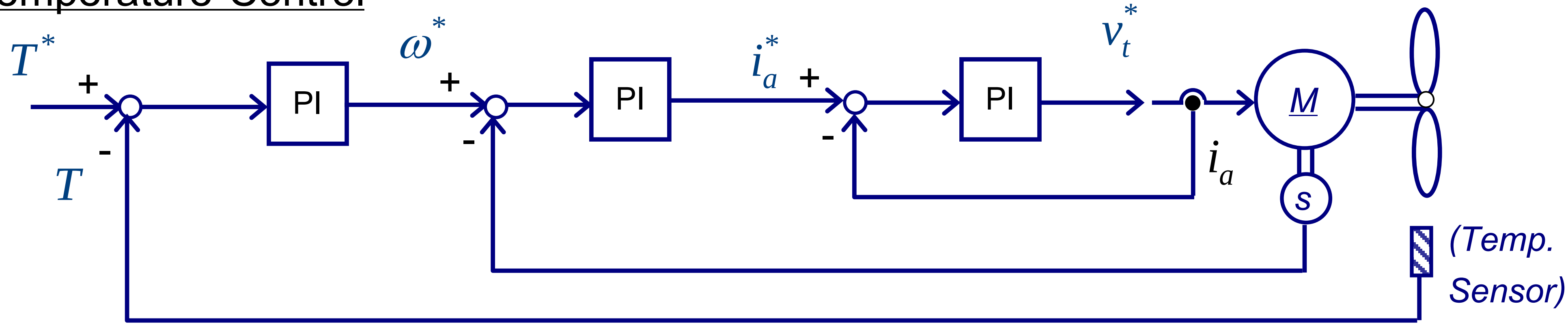


$$\frac{P/S}{1 + P/S} \qquad \frac{P}{S+P}$$

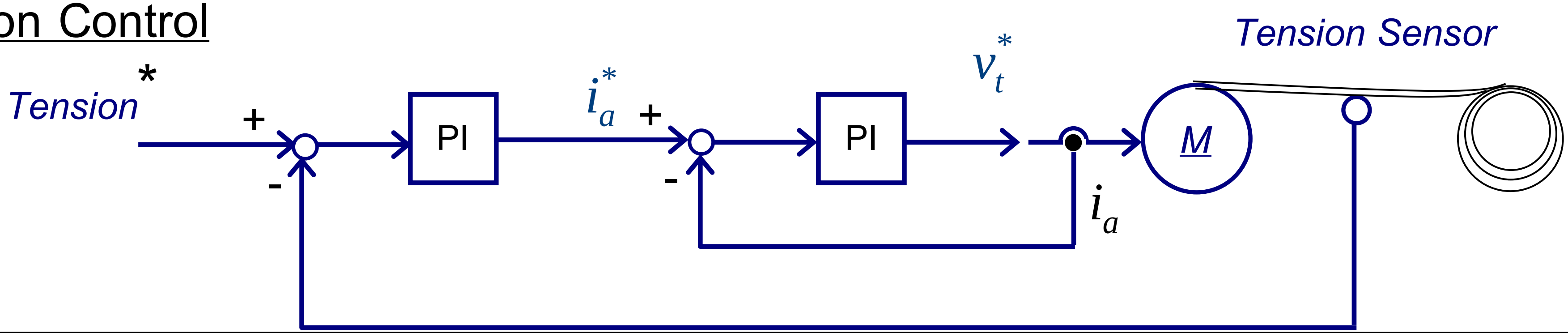
Pressure Control



Temperature Control



Tension Control



Basic Drive Circuit

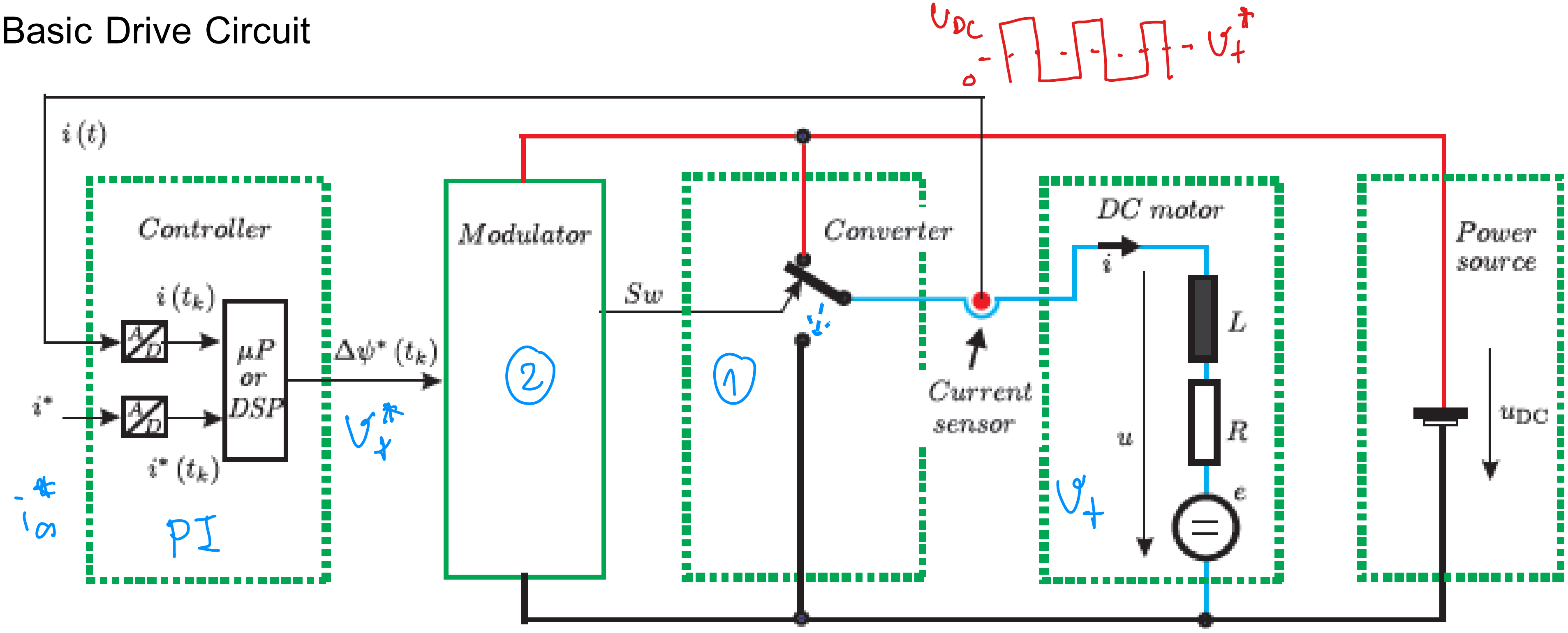


Figure 11.1. Basic electrical drive

The aim of this drive circuit is to control the current in the motor in such a way that the reference current value matches the actual load current under all circumstances, i.e. transient as well as in steady-state.

Power Electronic Converters

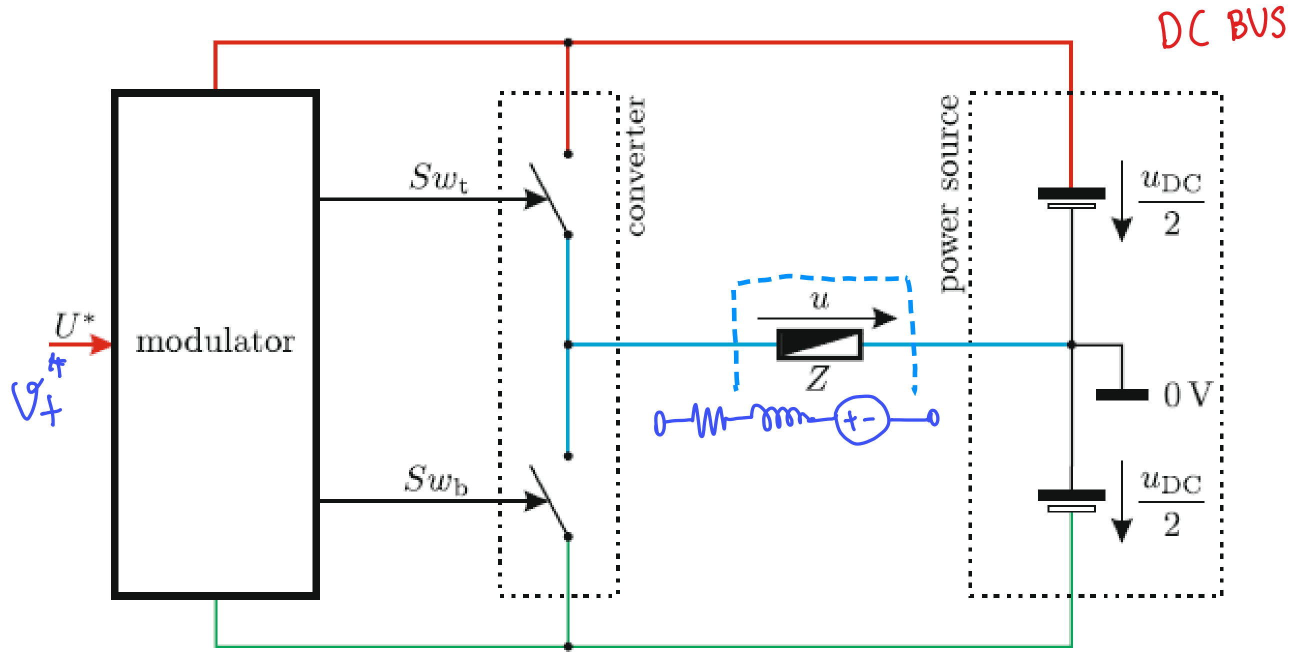


Fig. 2.1 Two switch *half-bridge* converter with power source and mo

Single-Phase Half-Bridge Converter:

- Consists of 2 switches.
- The average output voltage can be varied between $+\frac{u_{DC}}{2}$ and $-\frac{u_{DC}}{2}$.
- Output waveform is bipolar.

Table 2.1 Half-bridge switching states

Sw_t	Sw_b	Voltage u	Comment
0	0	–	Idle mode
0	1	$-\frac{u_{DC}}{2}$	Active mode
1	0	$\frac{u_{DC}}{2}$	Active mode
1	1	–	Shoot-through mode

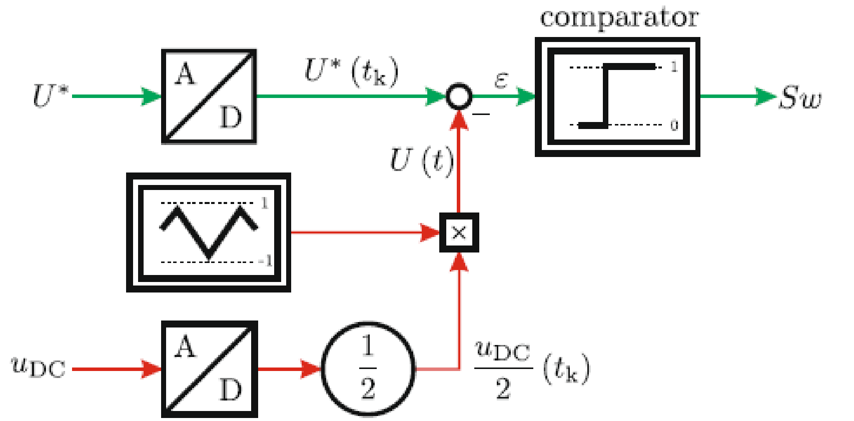
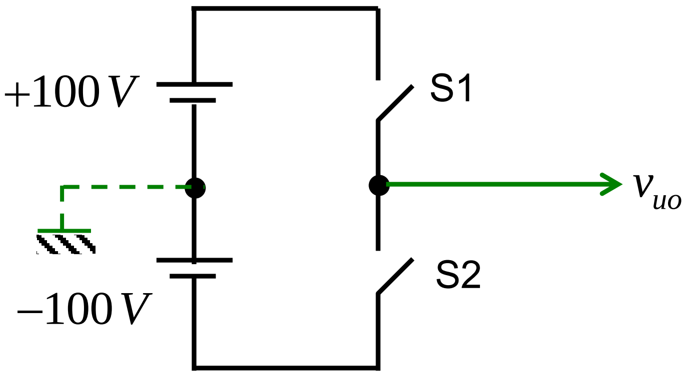


Fig. 2.4 Generic model of double edged PWM based half-bridge modulator

Pulse Width-Modulation Converter

- ลด Harmonics ที่ความถี่ต่ำของ Six-Step Inverter
- ใช้การปรับ duty cycle (อัตราส่วน $\dfrac{\text{Ton ของ S1}}{\text{Ton+Toff ของ S1}}$)

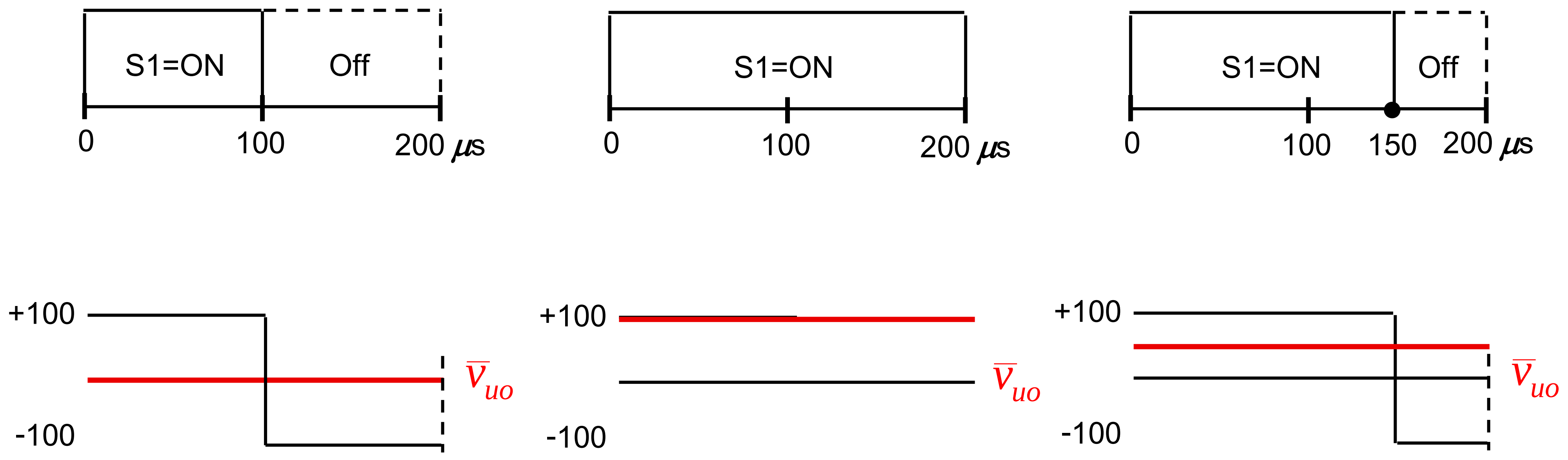


ให้ค่าเฉลี่ยแรงดันมีค่าตามต้องการ

Ex $E_d = 200\,V;\ T = 200\,\mu s$

$$\therefore v_{uo} = \begin{cases} +100\,V \\ -100\,V \end{cases}$$

$U^* = 0$ $U^* = 100\ V$ $U^* = 50\ V$

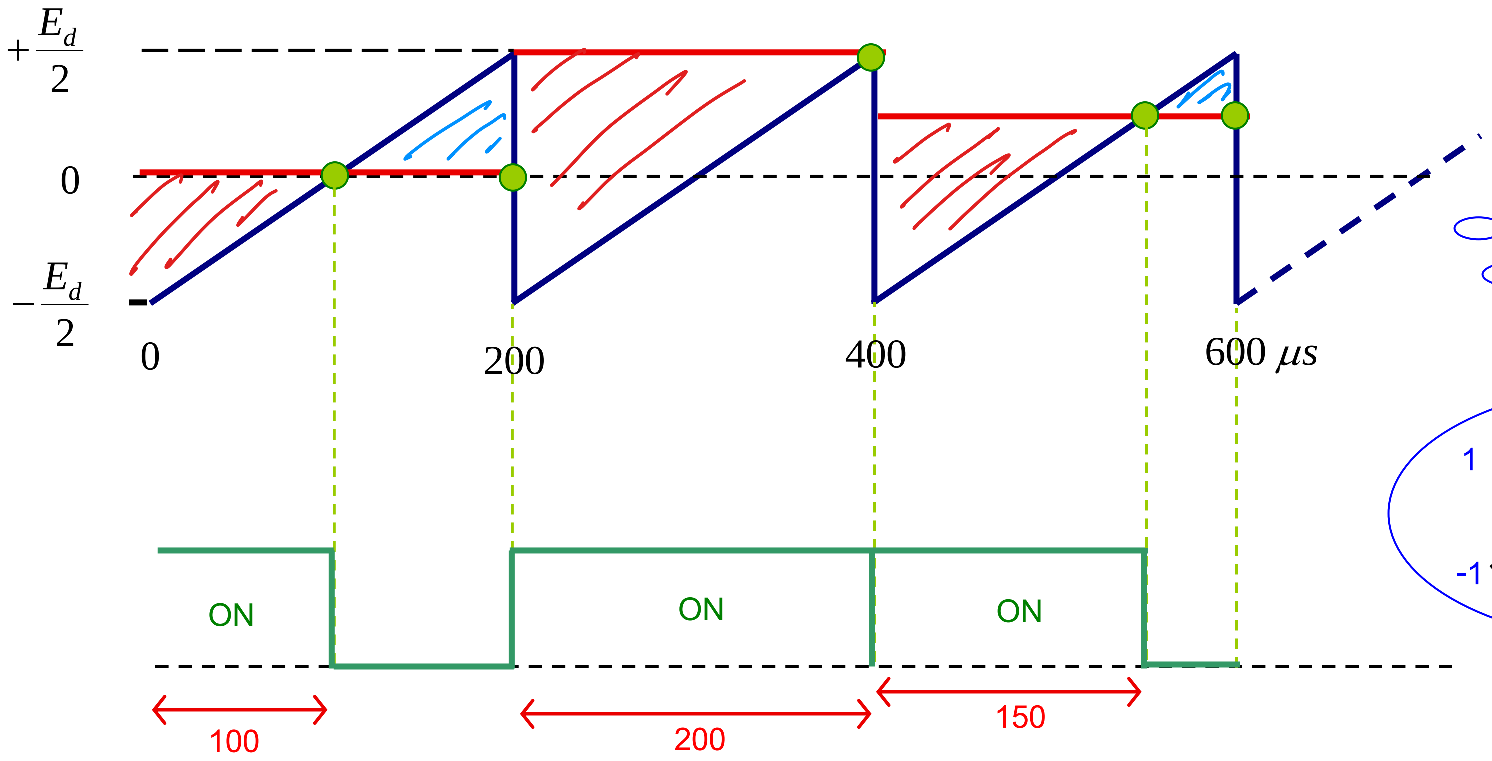


$\bar{v}_{uo} = 0\,V$ $\bar{v}_{uo} = +100\,V$ $\bar{v}_{uo} = +50\,V$

เราสามารถปรับค่าเฉลี่ยของแรงดันได้อย่างต่อเนื่องระหว่างค่า

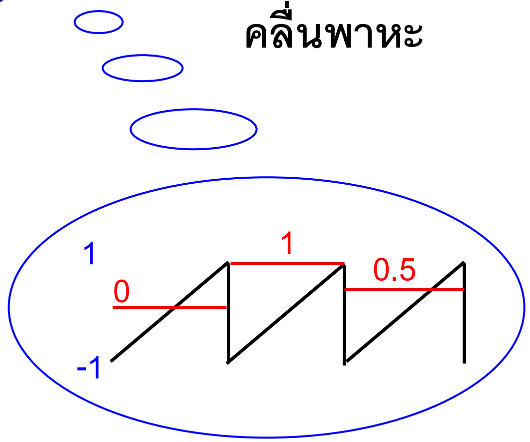
$$+\frac{E_d}{2}\ ,\ -\frac{E_d}{2}\quad (+100V\ , -100V)$$

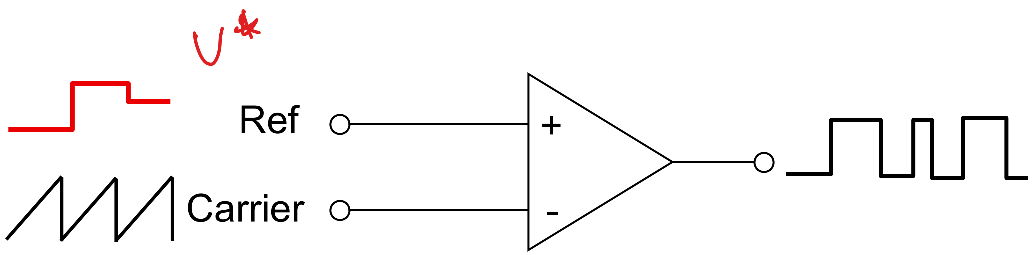
วิธีการหาตำแหน่งเวลาการสวิตช์



Carrier Wave

คลื่นพาหะ





Single-Phase Full-Bridge Converter

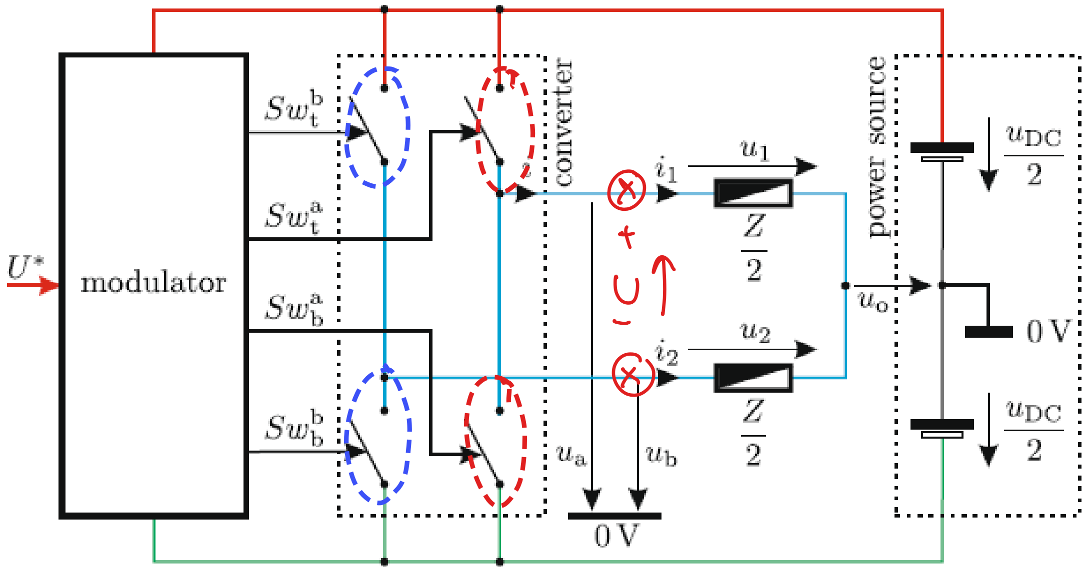
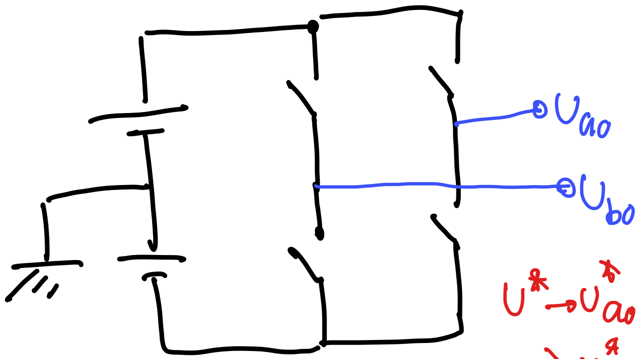


Fig. 2.5 H-bridge converter

Single-Phase Full-Bridge Converter:

- Consists of 4 switches.
- The average output voltage can be varied between $+u_{DC}$ and $-u_{DC}$.
- Output waveform is unipolar.



$U = U_{ao} - U_{bo}$

$U^* \rightarrow U^*_{ao} = \frac{1}{2}U^*$

$U^*_{bo} = -\frac{1}{2}U^*$

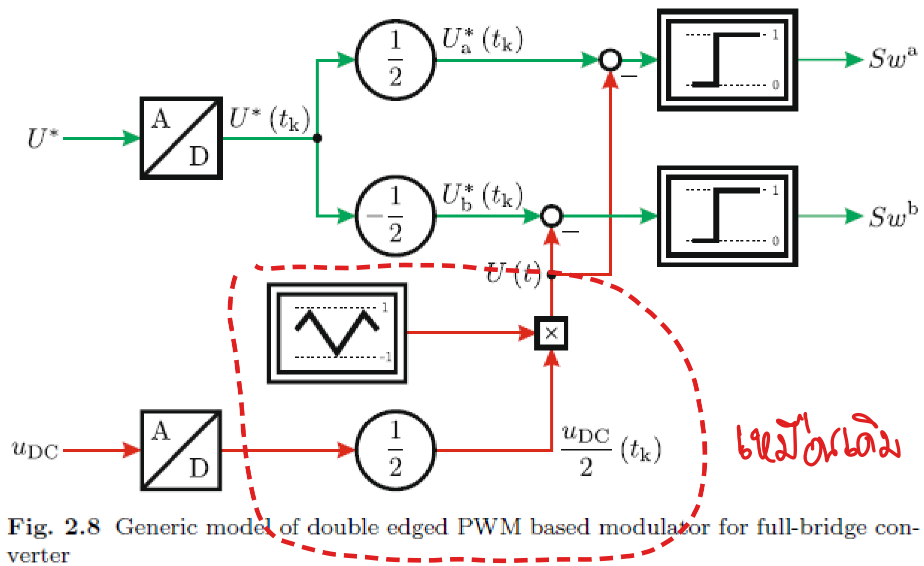
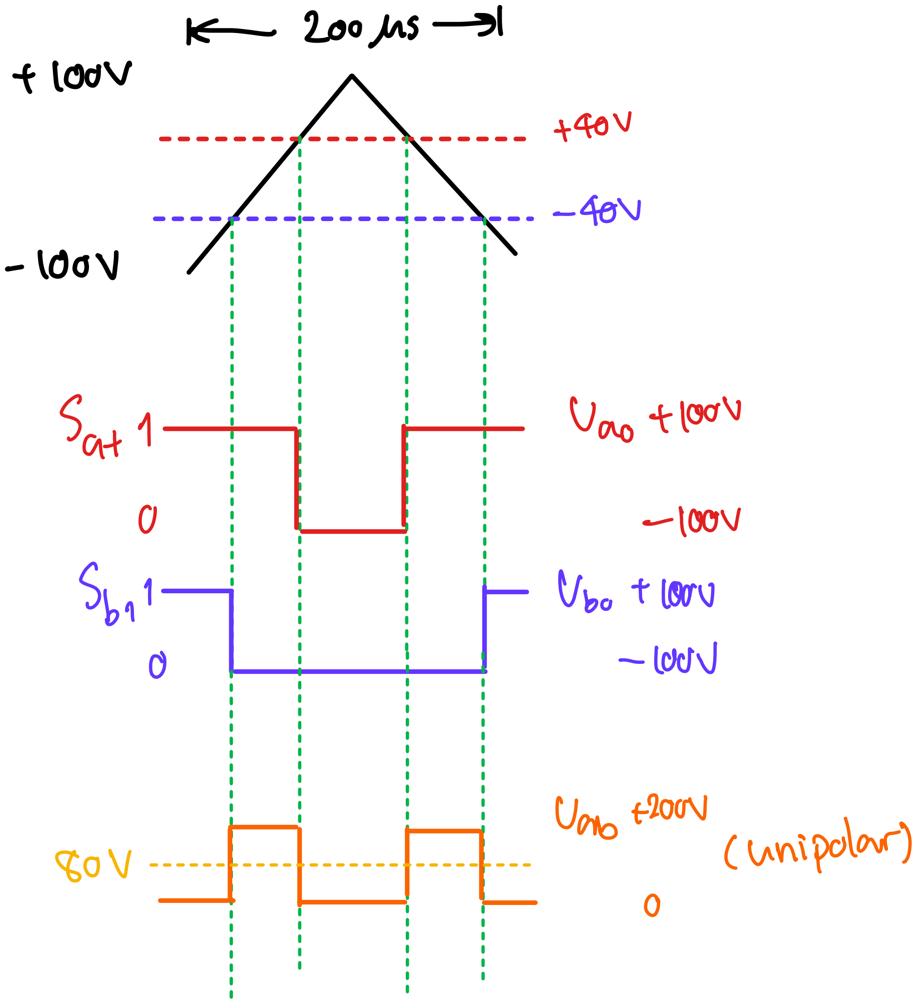


Fig. 2.8 Generic model of double edged PWM based modulator for full-bridge converter

$V^* = +80V$, $T_s = 200\,\mu s$, $u_{DC} = 200V$

$\downarrow$

$V_{ao}^* = 40V$, $V_{bo}^* = -40V$



Current Control of Single-Phase Load

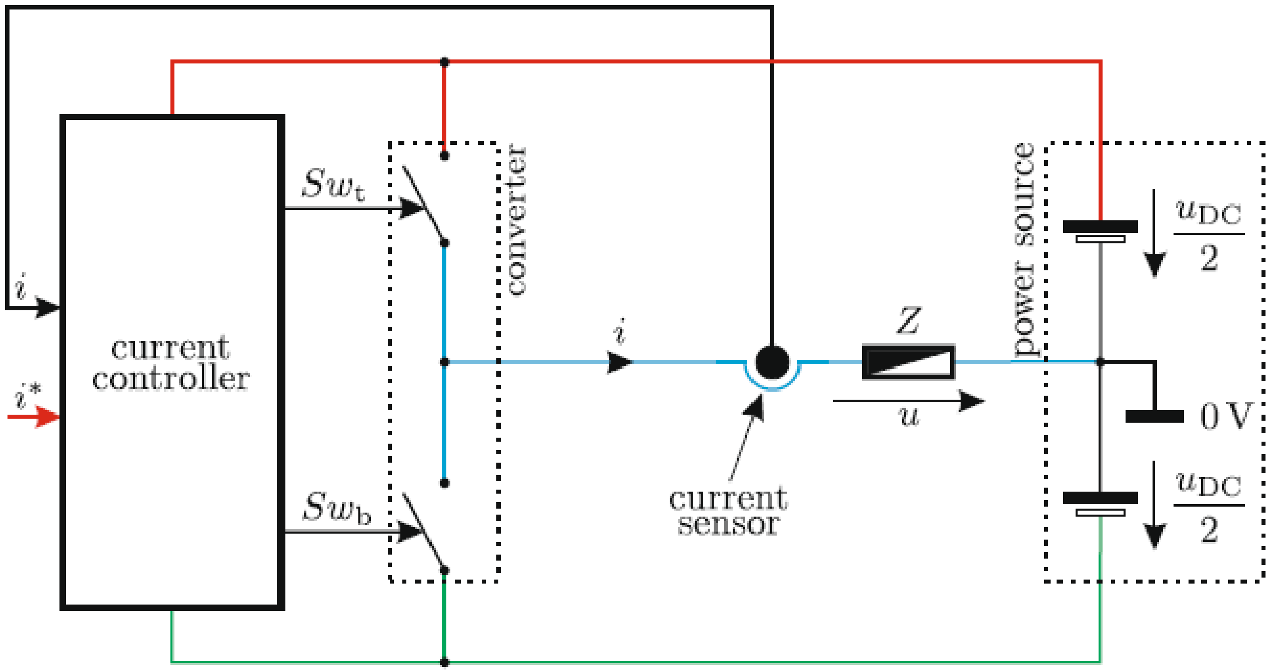
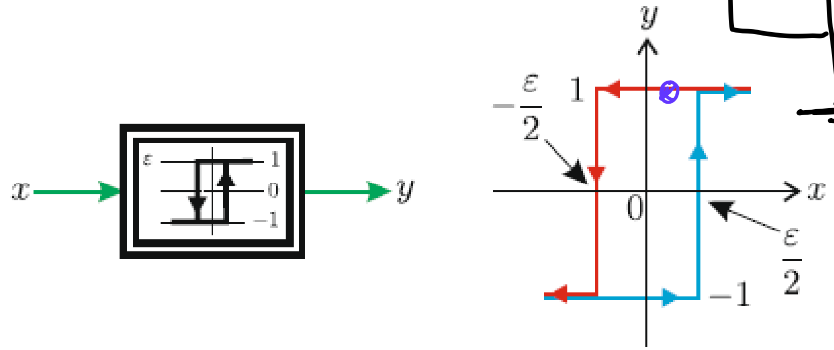


Fig. 3.2 Single-phase converter with hysteresis current controller

1) Hysteresis Current Control

2) PI (+ Feedforward) Current Control

1) Hysteresis Current Control



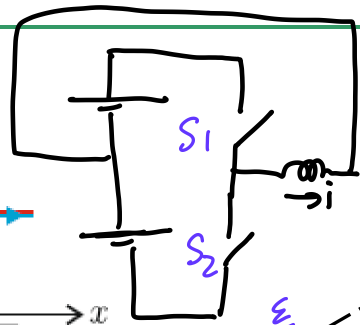


Fig. 3.1 Generic hysteresis module and transfer function

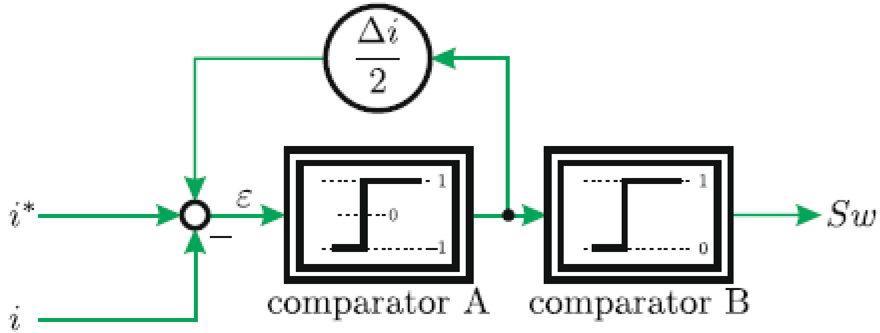
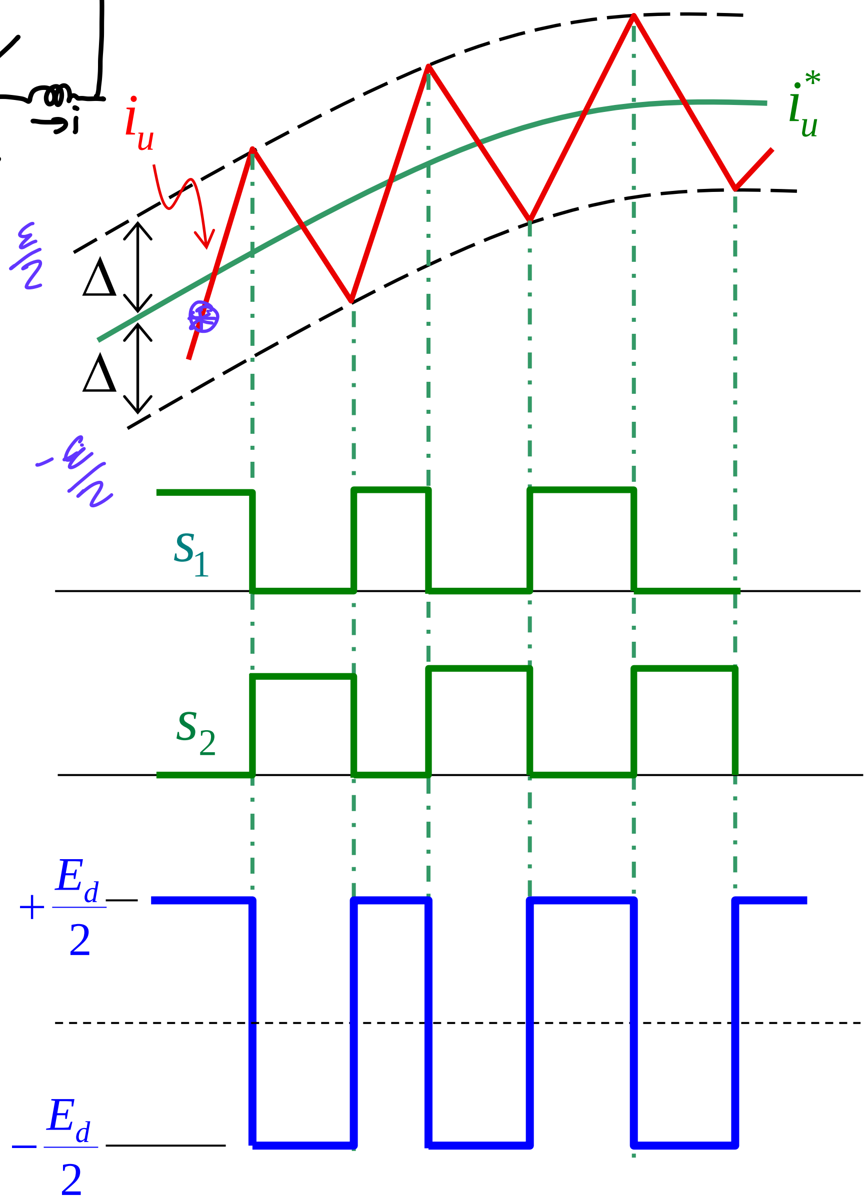
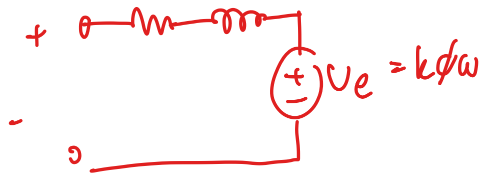


Fig. 3.3 Generic structure of hysteresis current controller



- ไม่มีการทำ PWM
- สัญญาณออกของ Hysteresis Comparator เป็น Switching Signal โดยตรง
- ไม่มี Carrier Frequency…… Switching Frequency ไม่คงที่
- เหมาะกับ Analog มากกว่า Digital
- Response เร็ว



2) PI (+ Feedforward) Current Control

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

$\tilde{U} + \cancel{U_e} = R_a i_a + L_a \frac{di_a}{dt} + \cancel{U_e}$

$V_e = k\phi\omega$

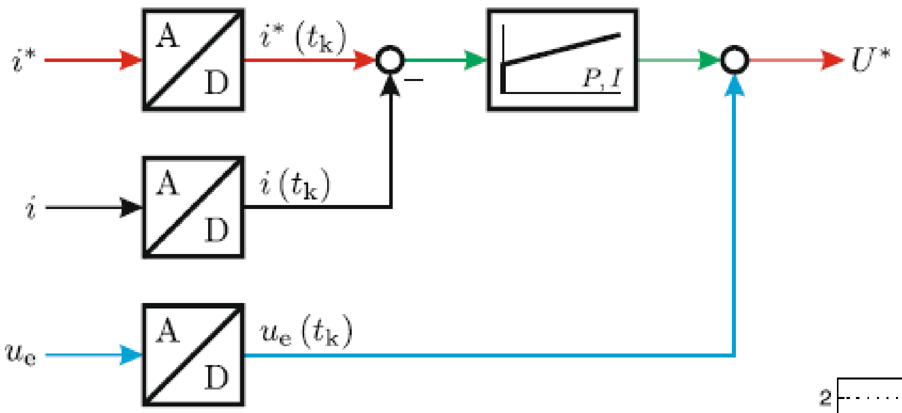


Fig. 3.7 Model based current controller structure

- มีการทำ PWM
- สัญญาณออกของตัวควบคุมเป็นคำสั่งแรงดัน
- มี Carrier Frequency…… มี Switching Frequency ตามที่กำหนด
- เหมาะทั้ง Analog และ Digital
- Feedforward Control ช่วยให้ Response เร็วขึ้น

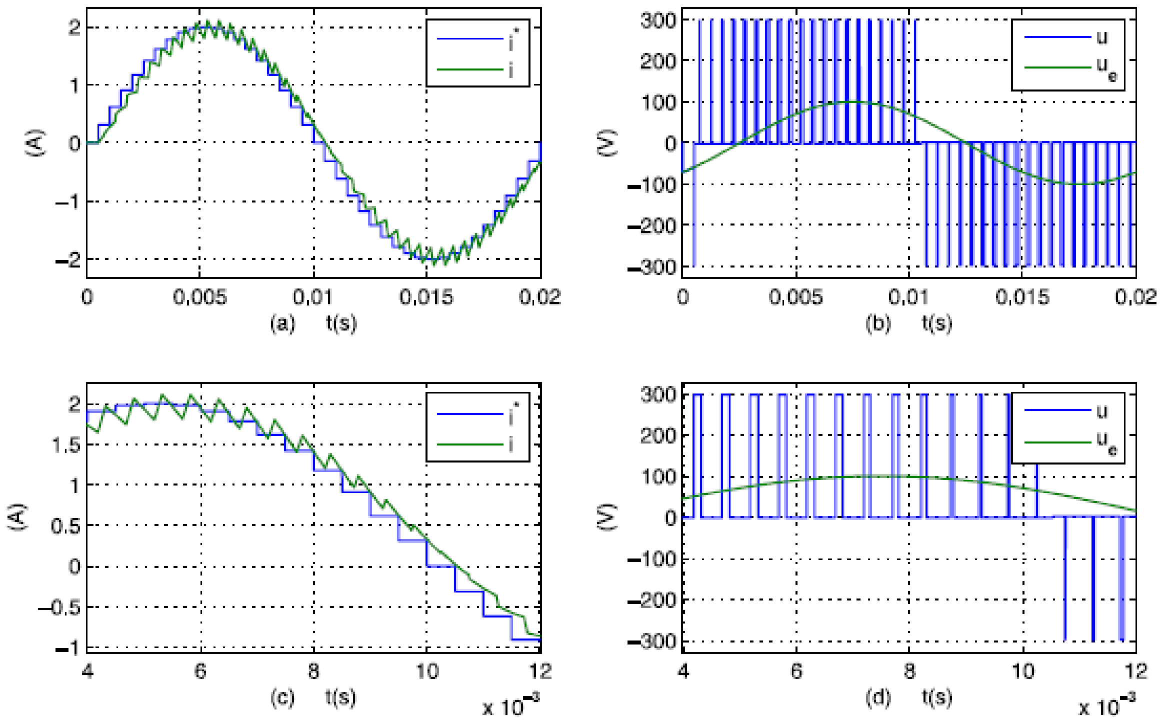


Fig. 3.8 Single-phase model based current control example

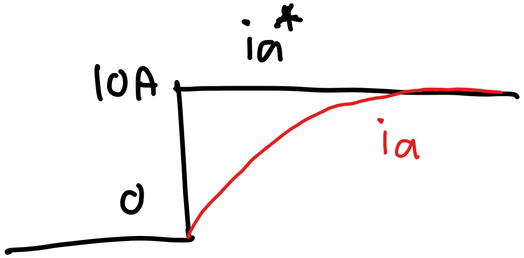
$R_a = 1\,\Omega$, $L_a = 10\,mH$, $i_a^* = 10\,A$, $V_e = 50V$

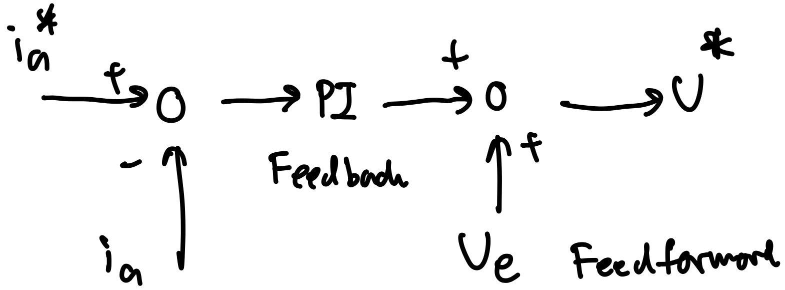
$$u = \tilde{u} + \cancel{50} = R_a i_a + L_a \frac{di_a}{dt} + \cancel{50}$$

$$\Downarrow$$

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

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





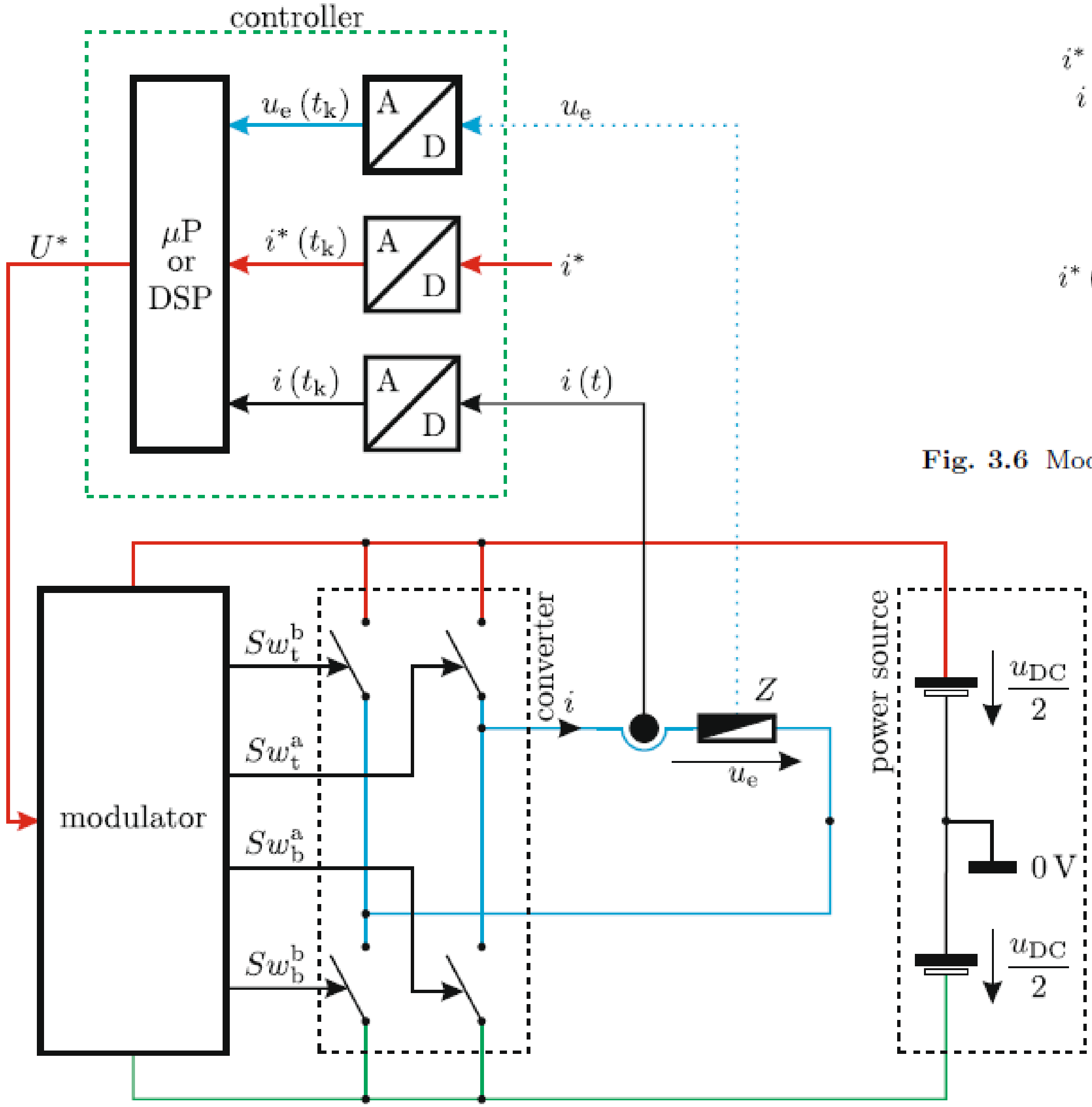


Fig. 3.5 Single-phase model based current control

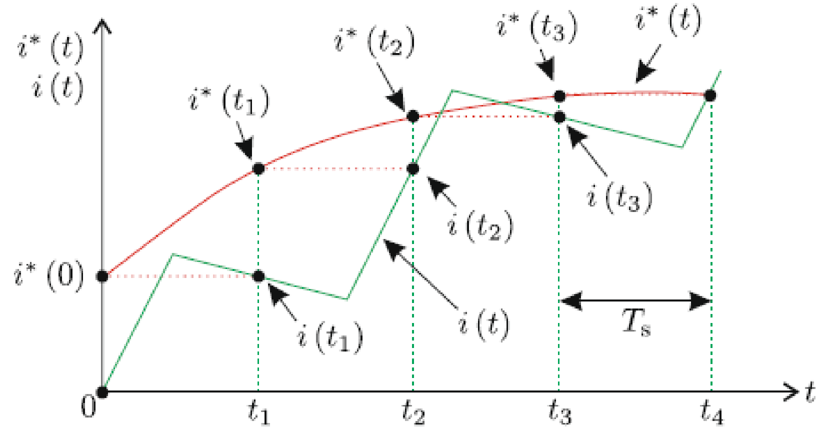


Fig. 3.6 Model based current control