# DC MOTOR DRIVES
# (MEP 1422)

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# Contents

# INTRODUCTION

- DC DRIVES: Electric drives that use DC motors as the prime movers
- DC motor: industry workhorse for decades
- Dominates variable speed applications <u>before</u> PE converters were introduced

- Will AC drive replaces DC drive ?
  - Predicted 30 years ago
  - DC strong presence – easy control – huge numbers
  - AC will eventually replace DC – at a slow rate

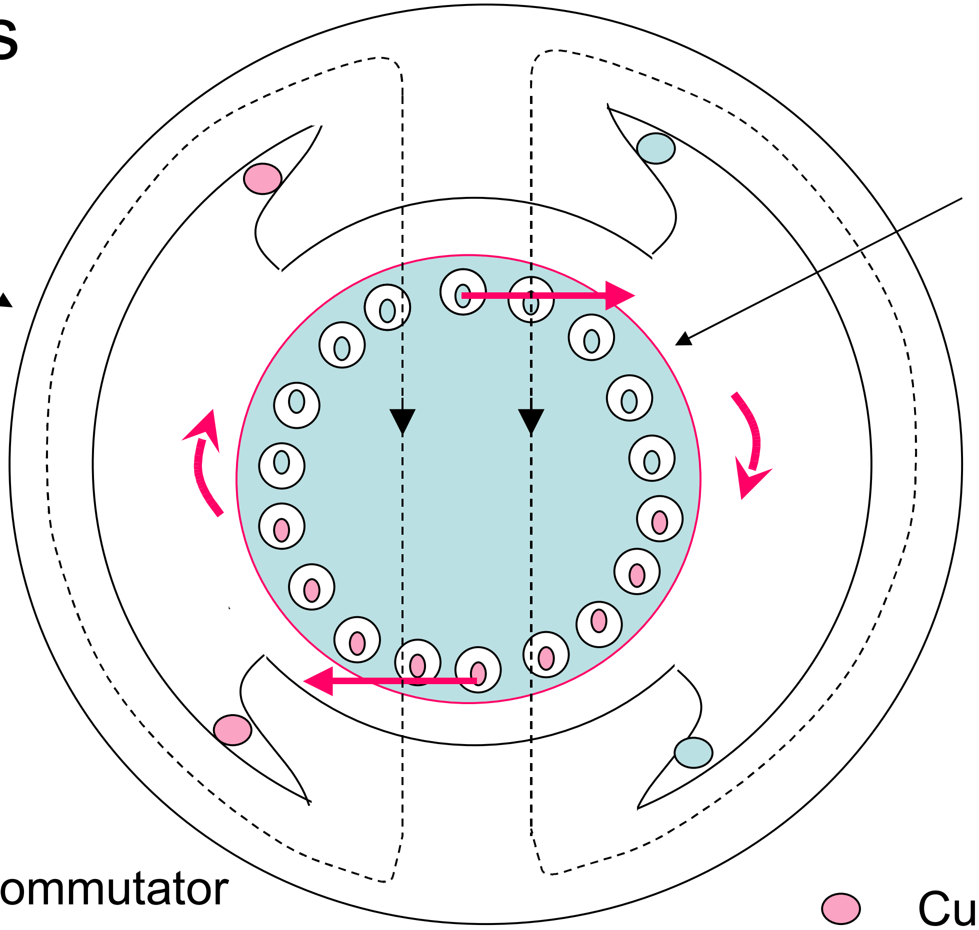
## Introduction

### DC Motors

- Advantage: Precise torque and speed control without sophisticated electronics
- Several limitations:
  - Regular Maintenance
  - Heavy
  - Sparking
  - Expensive
  - Speed limitations

# Introduction

## DC Motors



Stator: field windings

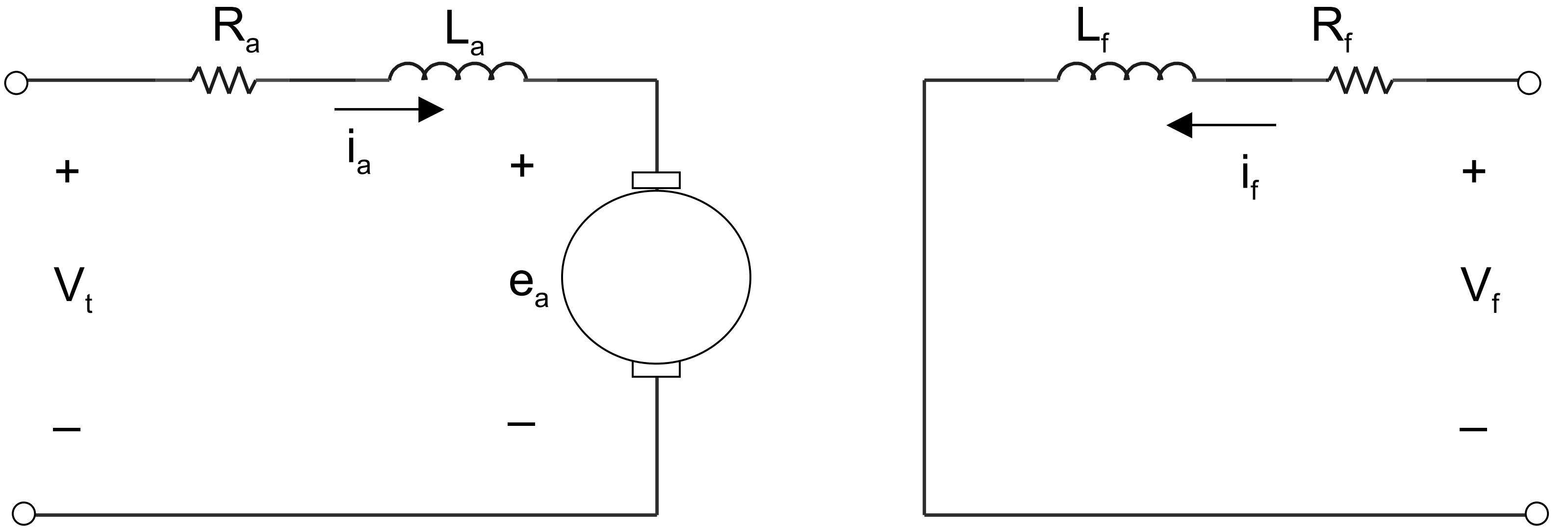
Rotor: armature windings

- Mechanical commutator
- Large machine employs compensation windings

🟥 Current in

🟦 Current out

# Introduction



$$v_t = R_a i_a + L\frac{di_a}{dt} + e_a$$

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

$$Te = k_t \phi i_a$$ Electric torque

$$e_a = k_E \phi \omega$$ Armature back e.m.f.

# Introduction

Armature circuit:

$$V_t = R_a i_a + L\frac{di_a}{dt} + e_a$$

In steady state,

$$V_t = R_a I_a + E_a$$

Therefore speed is given by,

$$\omega = \frac{V_t}{k_T\phi} - \frac{R_a T_e}{\left(k_T\phi\right)^2}$$

Three possible methods of speed control:

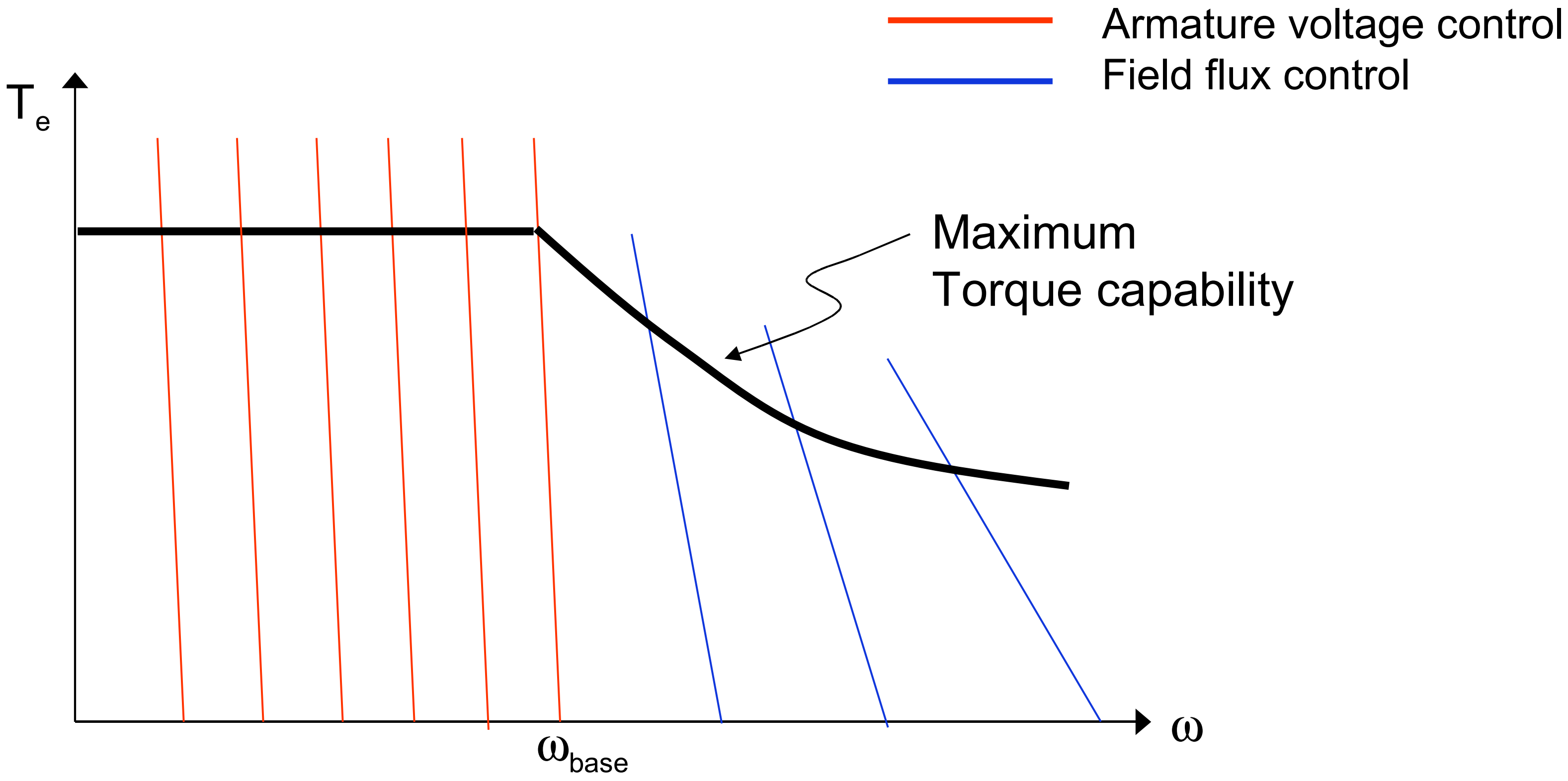
Field flux
Armature voltage $V_t$
Armature resistance Ra

## Introduction

Armature voltage control : retain maximum torque capability

Field flux control (i.e. flux reduced) : reduce maximum torque capability

For wide range of speed control
0 to $\omega_{base} \rightarrow$ armature voltage, above $\omega_{base} \rightarrow$ field flux reduction



# MODELING OF CONVERTERS AND DC MOTOR

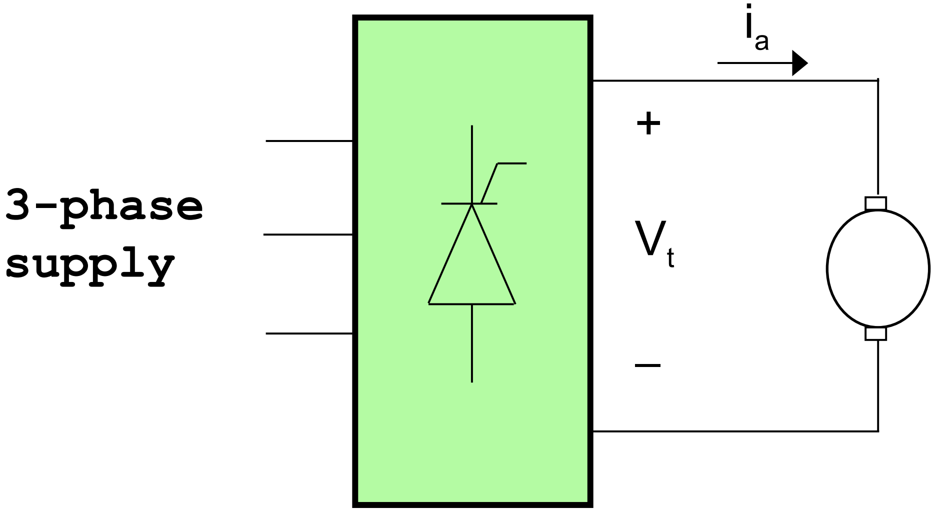
## POWER ELECTRONICS CONVERTERS

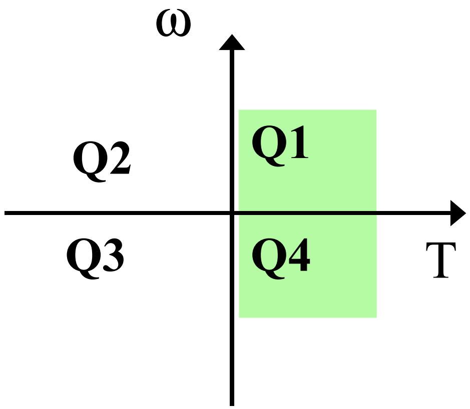
Used to obtain variable armature voltage

- Efficient
  Ideal : lossless
- Phase-controlled rectifiers (AC $\rightarrow$ DC)
- DC-DC switch-mode converters(DC $\rightarrow$ DC)

# Modeling of Converters and DC motor

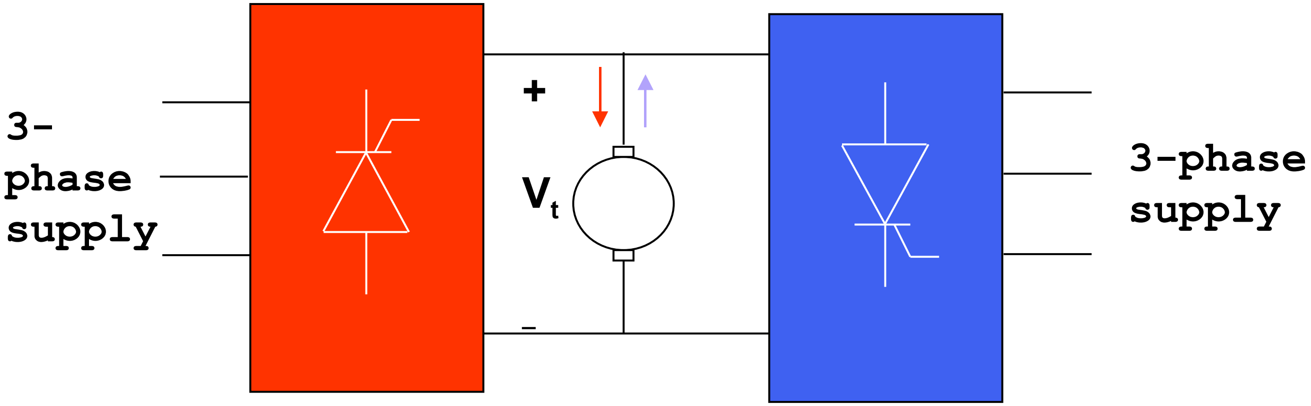
## Phase-controlled rectifier (AC–DC)

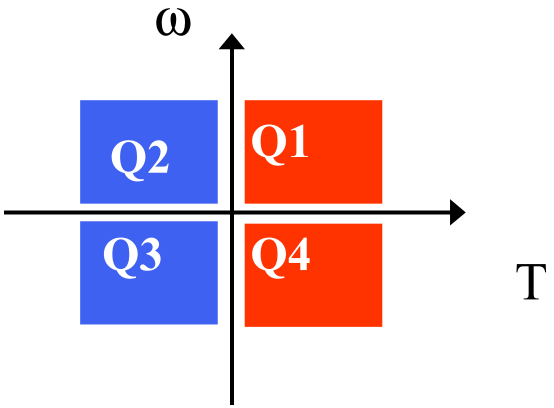




# Modeling of Converters and DC motor

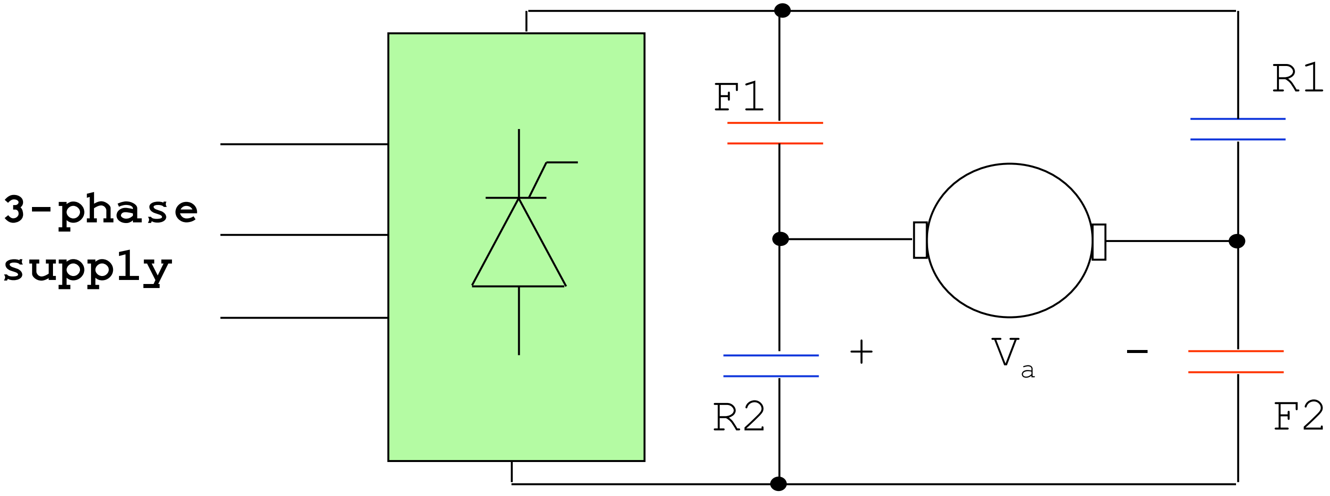
## Phase-controlled rectifier

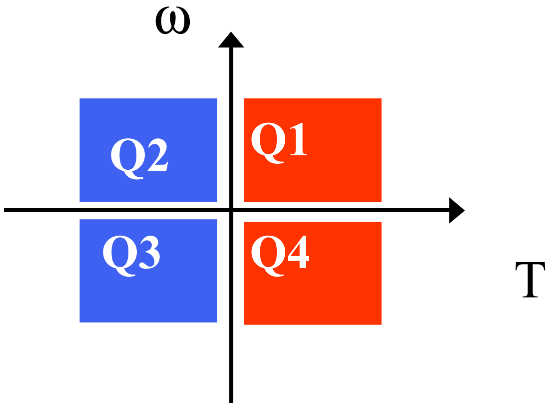




# Modeling of Converters and DC motor

## Phase-controlled rectifier



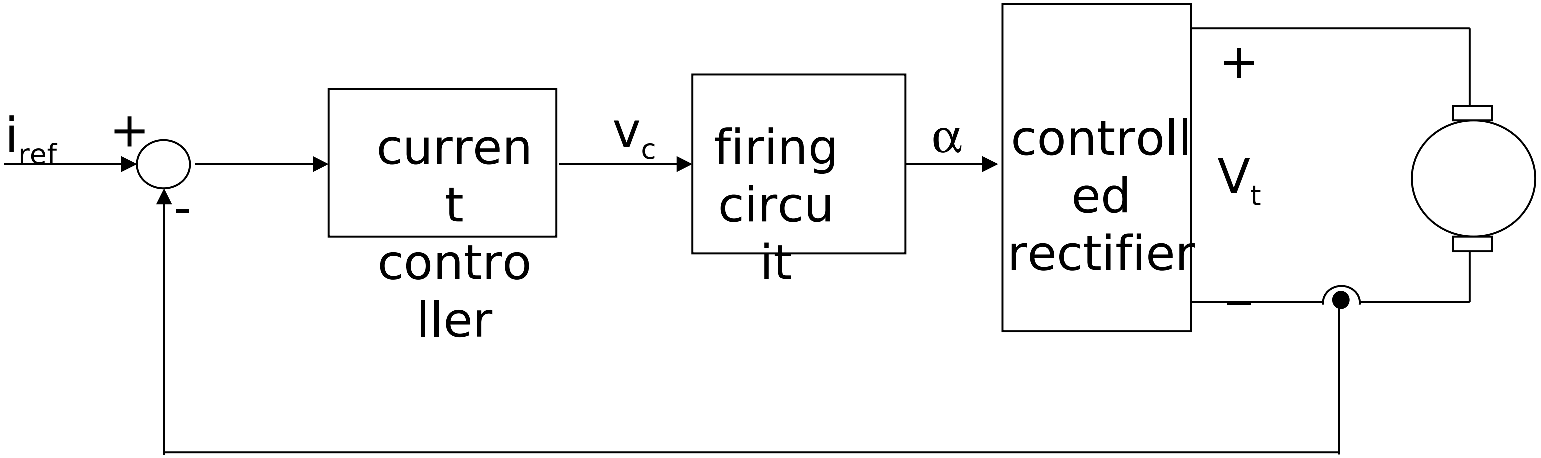


## Modeling of Converters and DC motor

Phase-controlled rectifier (continuous current)

- Firing circuit –firing angle control

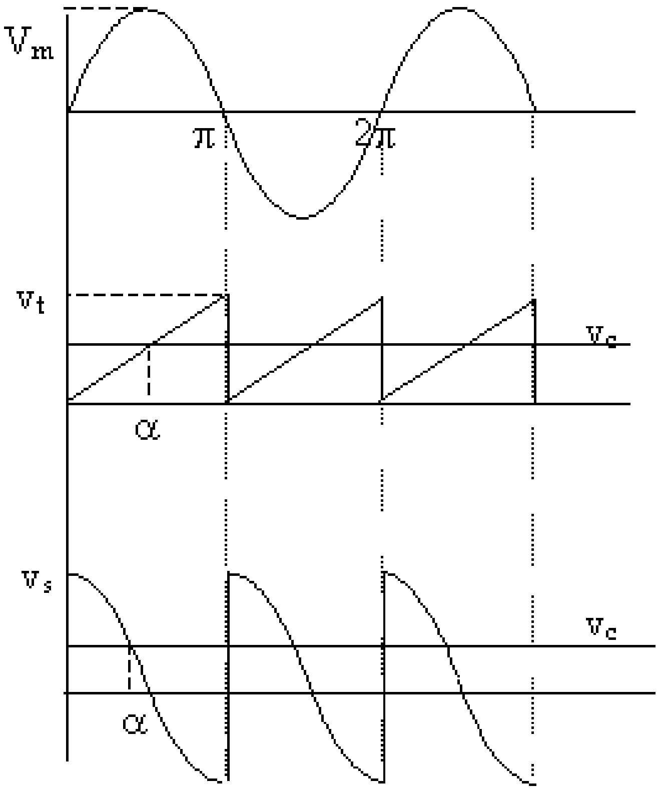
  $\rightarrow$ Establish relation between $v_c$ and $V_t$



## Modeling of Converters and DC motor

### Phase-controlled rectifier (continuous current)

- Firing angle control



linear firing angle control

$$\frac{v_t}{180} = \frac{v_c}{\alpha} \qquad \alpha = \frac{v_c}{v_t} 180$$

$$\boxed{V_a = \frac{V_m}{\pi} \cos\left( \frac{v_c}{v_t} 180 \right)}$$

Cosine-wave crossing control

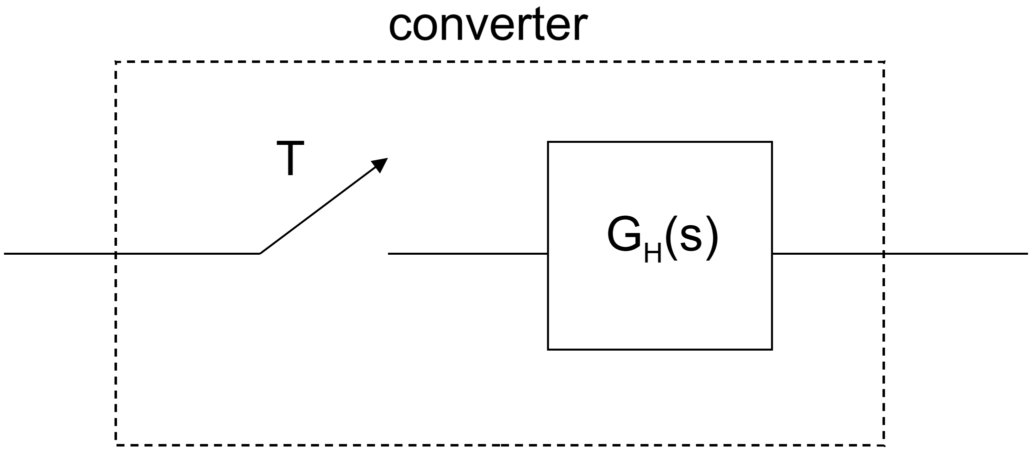
$$v_c = v_s \cos \alpha$$

$$\boxed{V_a = \frac{V_m}{\pi} \frac{v_c}{v_s}}$$

**Modeling of Converters and DC motor**

## Phase-controlled rectifier (continuous current)

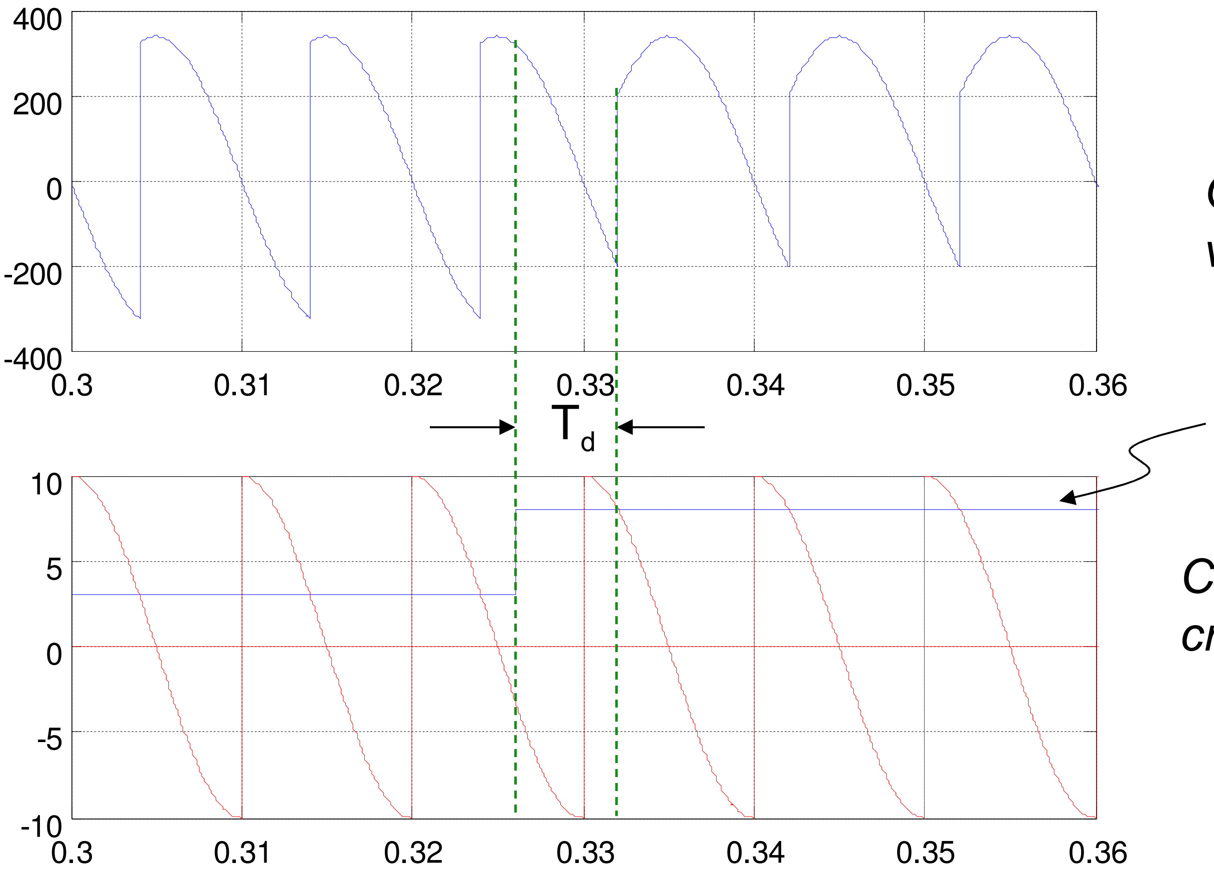
- Steady state: linear gain amplifier
  - Cosine wave–crossing method
- Transient: sampler with zero order hold



T – 10 ms for 1-phase 50 Hz system
– 3.33 ms for 3-phase 50 Hz system

# Modeling of Converters and DC motor

## Phase-controlled rectifier (continuous current)



*Output voltage*

*Control signal*

*Cosine-wave crossing*

$T_d$ – Delay in <u>average</u> output voltage generation

0 – 10 ms for 50 Hz single phase system

## Modeling of Converters and DC motor

### Phase-controlled rectifier (continuous current)

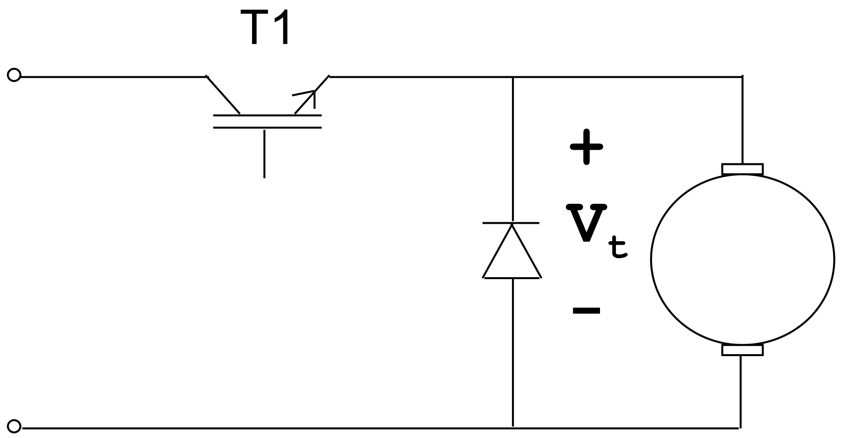
- Model simplified to linear gain if bandwidth (e.g. current loop) much lower than sampling frequency

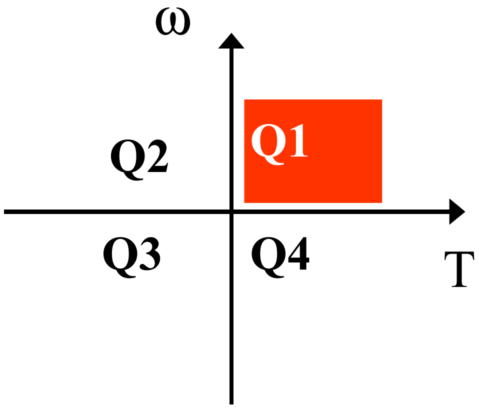
  ⇒ Low bandwidth – limited applications

- Low frequency voltage ripple → high current ripple → undesirable

## Modeling of Converters and DC motor

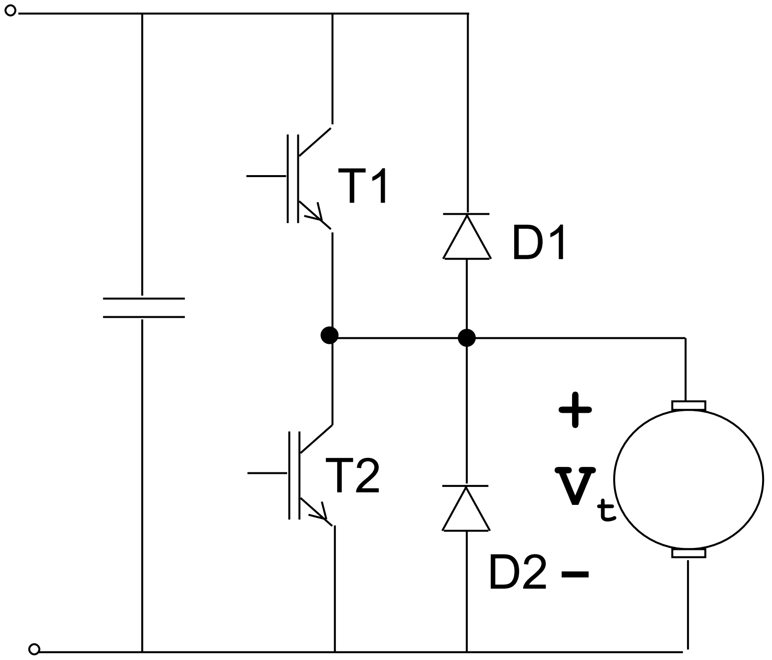
### Switch–mode converters

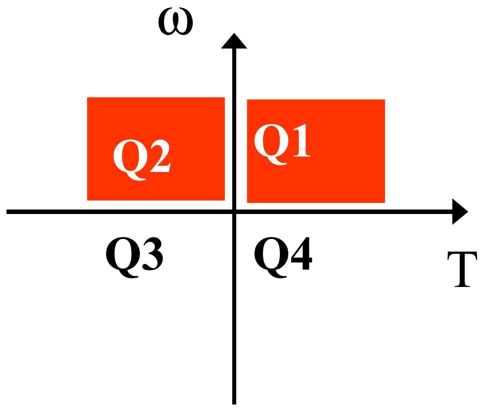




# Modeling of Converters and DC motor

## Switch–mode converters



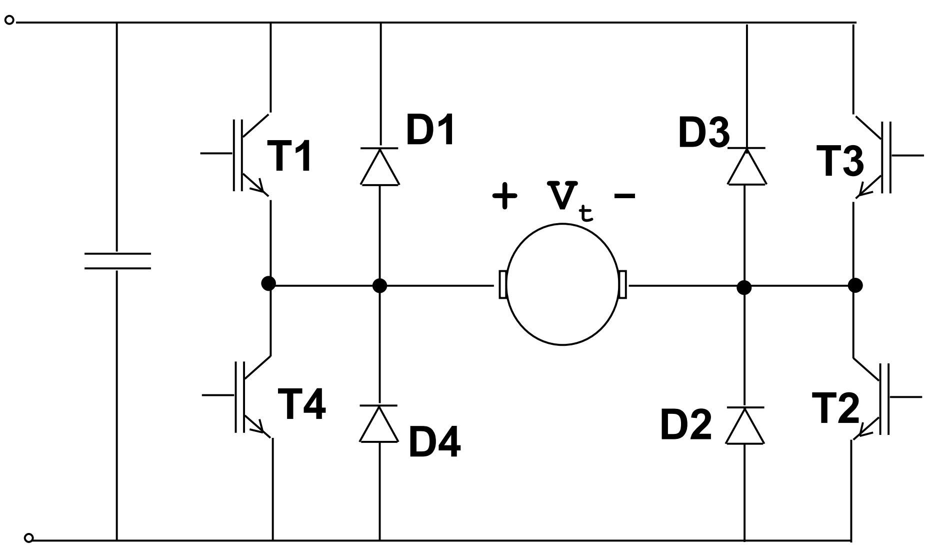


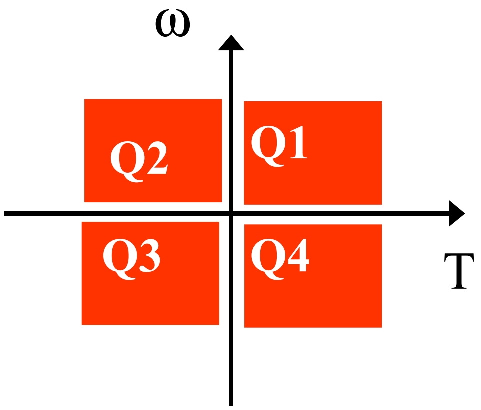
Q1 → T1 and D2

Q2 → D1 and T2

# Modeling of Converters and DC motor

## Switch–mode converters





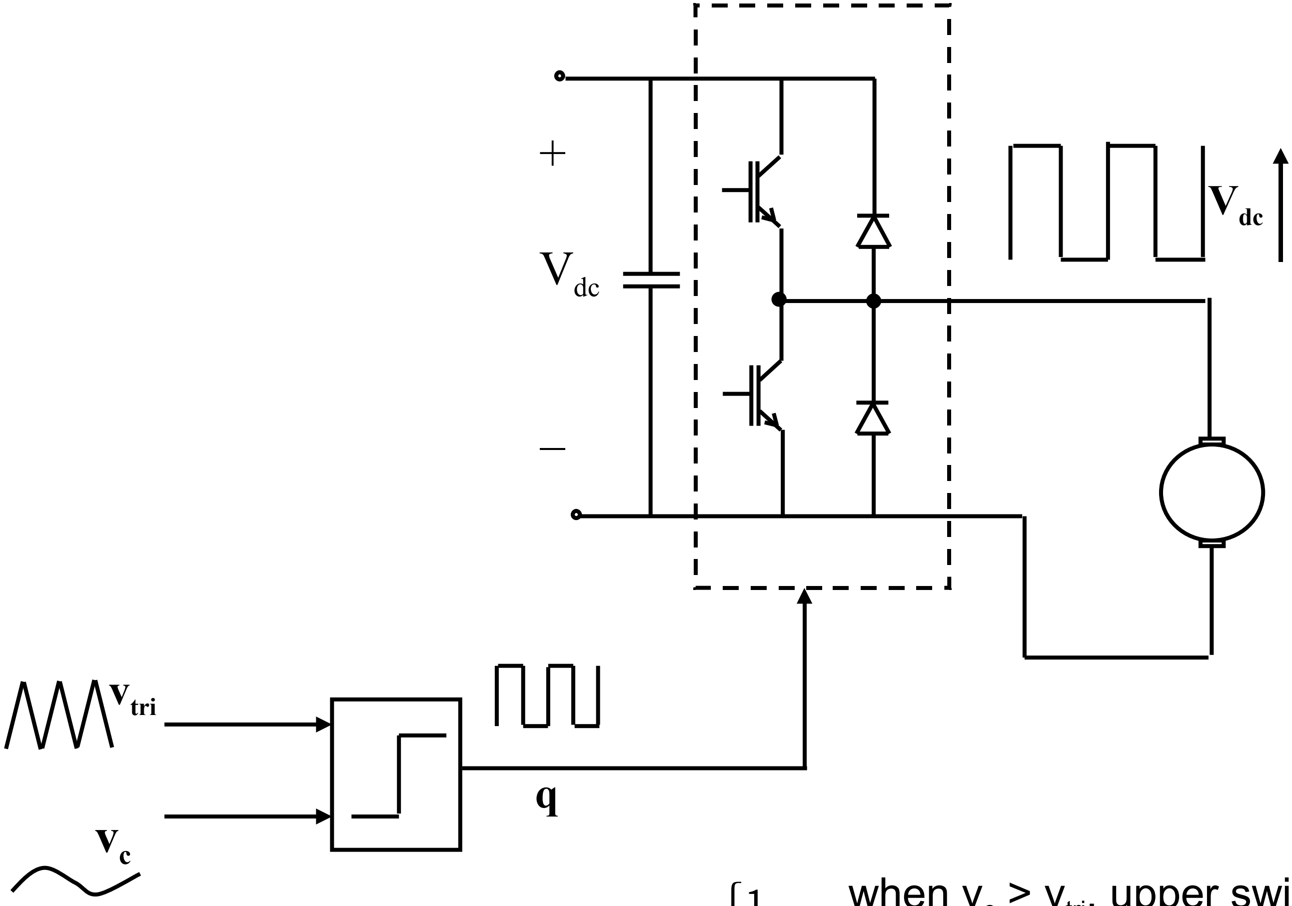
## Modeling of Converters and DC motor

### Switch–mode converters

- Switching at high frequency
  - → Reduces current ripple
  - → Increases control bandwidth
- Suitable for high performance applications

## Modeling of Converters and DC motor

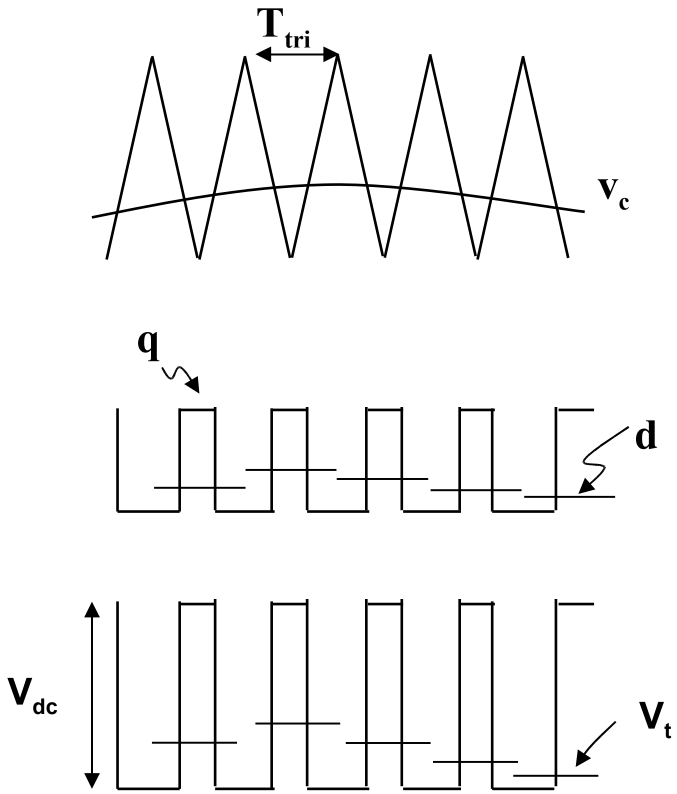
### Switch–mode converters - modeling



$$q = \begin{cases} 1 & \text{when } v_c > v_{tri}\text{, upper switch ON} \\ 0 & \text{when } v_c < v_{tri}\text{, lower switch ON} \end{cases}$$

**Modeling of Converters and DC motor**

# Switch–mode converters – averaged model

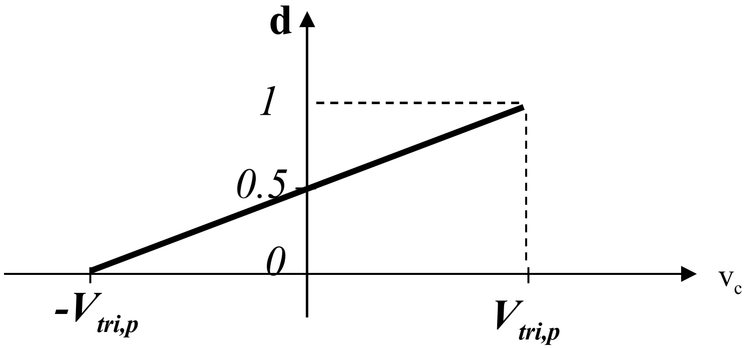


$$d = \frac{1}{T_{tri}} \int_{t}^{t+T_{tri}} q\,dt = \frac{t_{on}}{T_{tri}}$$

$$V_t = \frac{1}{T_{tri}} \int_{0}^{dT_{tri}} V_{dc}\,dt = dV_{dc}$$

**Modeling of Converters and DC motor**

# Switch–mode converters – averaged model



$$d = 0.5 + \frac{v_c}{2V_{tri,p}}$$

$$\boxed{V_t = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri,p}} v_c}$$

# Modeling of Converters and DC motor

## DC motor – small signal model

$$v_t = i_a R_a + L_a \frac{di_a}{dt} + e_a \qquad T_e = T_l + J \frac{d\omega_m}{dt}$$

$$T_e = k_t \; i_a \qquad e_e = k_t \; \omega$$

Extract the dc and ac components by introducing small perturbations in $V_t$, $i_a$, $e_{a,}$ $T_e$, $T_L$ and $\omega_m$

| ac components | dc components |
|---|---|
| $\tilde{v}_t = \tilde{i}_a R_a + L_a \frac{d\tilde{i}_a}{dt} + \tilde{e}_a$ | $V_t = I_a R_a + E_a$ |
| $\tilde{T}_e = k_E(\tilde{i}_a)$ | $T_e = k_E I_a$ |
| $\tilde{e}_e = k_E(\tilde{\omega})$ | $E_e = k_E \omega$ |
| $\tilde{T}_e = \tilde{T}_L + B\tilde{\omega} + J \frac{d(\tilde{\omega})}{dt}$ | $T_e = T_L + B(\omega)$ |

# Modeling of Converters and DC motor

## DC motor – small signal model

Perform Laplace Transformation on ac components

$$\tilde{v}_t = \tilde{i}_a R_a + L_a \frac{d\tilde{i}_a}{dt} + \tilde{e}_a \quad \Longrightarrow \quad V_t(s) = I_a(s)R_a + L_a sIa + E_a(s)$$

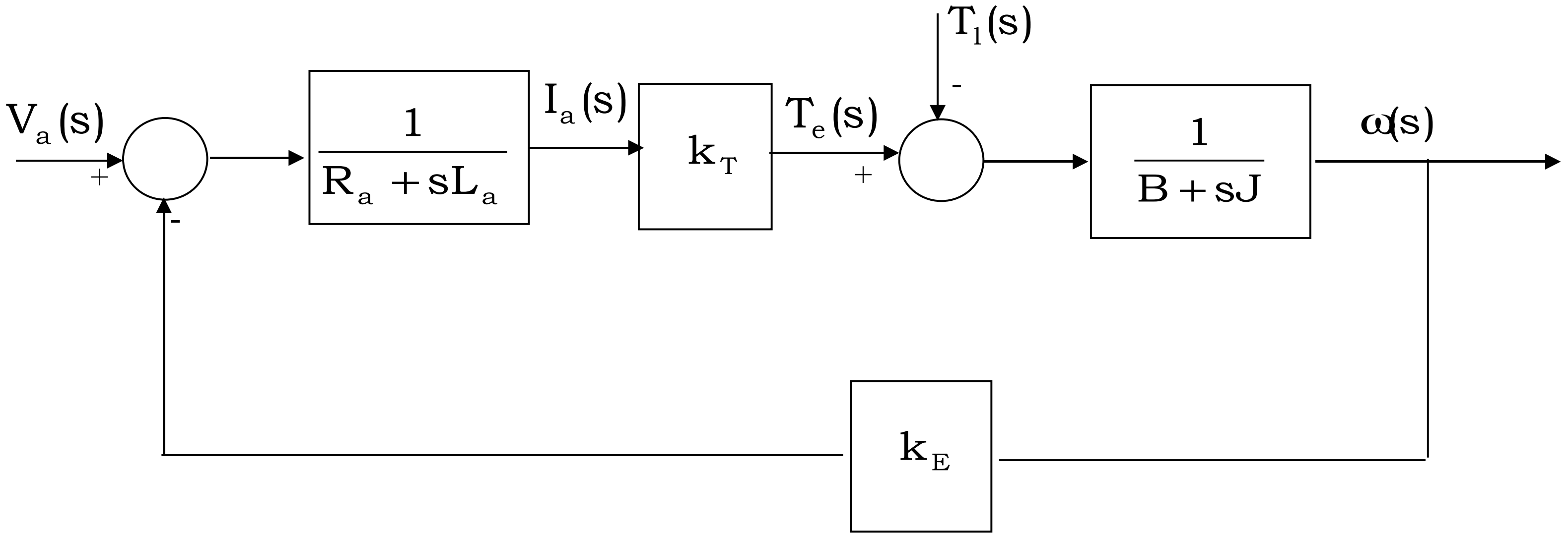
$$\tilde{T}_e = k_E(\tilde{i}_a) \quad \Longrightarrow \quad T_e(s) = k_E I_a(s)$$

$$\tilde{e}_e = k_E(\tilde{\omega}) \quad \Longrightarrow \quad E_a(s) = k_E \omega(s)$$

$$\tilde{T}_e = \tilde{T}_L + B\tilde{\omega} + J\frac{d(\tilde{\omega})}{dt} \quad \Longrightarrow \quad T_e(s) = T_L(s) + B\omega(s) + sJ\omega(s)$$

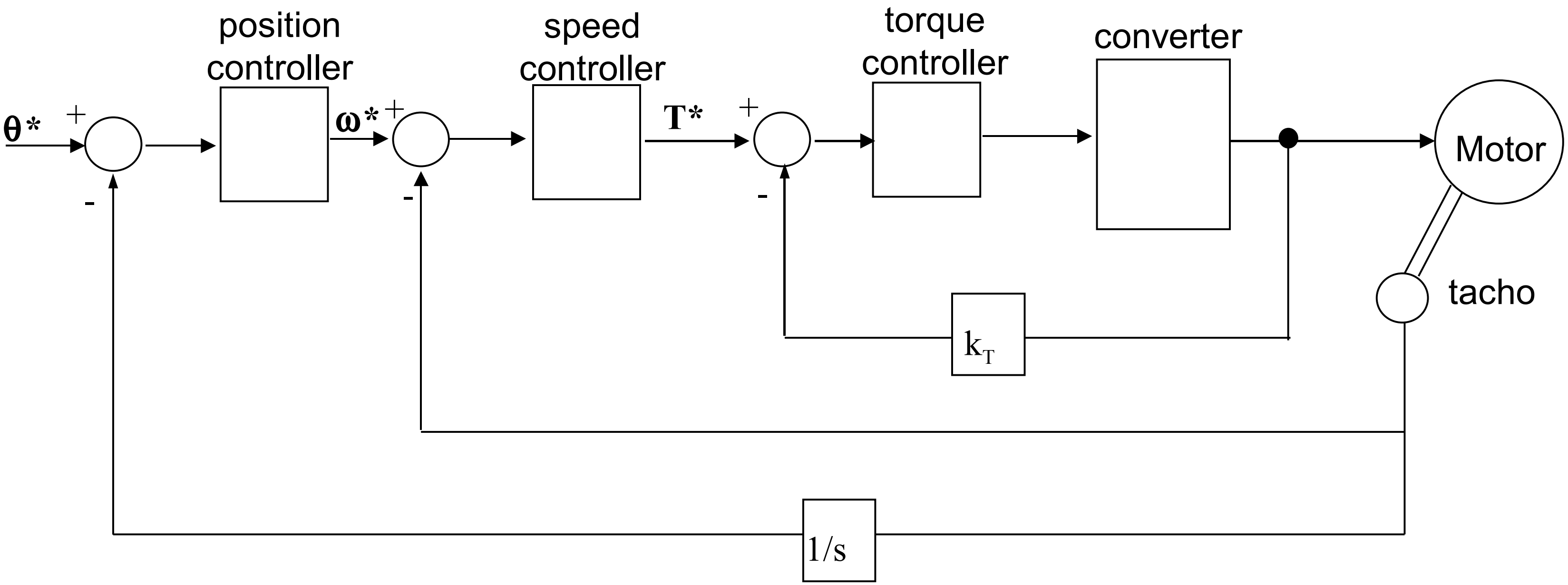
# Modeling of Converters and DC motor

## DC motor – small signal model



# CLOSED-LOOP SPEED CONTROL

## Cascade control structure



- The control variable of inner loop (e.g. torque) can be limited by limiting its reference value
- It is flexible – outer loop can be readily added or removed depending on the control requirements

# Design procedure in cascade control structure

- Inner loop (current or torque loop) the fastest – largest bandwidth
- The outer most loop (position loop) the slowest – smallest bandwidth
- Design starts from torque loop proceed towards outer loops

# Closed-loop speed control – an example

OBJECTIVES:

- Fast response – large bandwidth
- Minimum overshoot
  good phase margin ($>65^{o}$)
- Zero steady state error – very large DC gain

BODE PLOTS

METHOD

- Obtain linear small signal model
- Design controllers based on linear small signal model
- Perform large signal simulation for controllers verification

# Closed-loop speed control – an example

Permanent magnet motor's parameters

Ra = 2 Ω La = 5.2 mH

B = $1 \times 10^{-4}$ kg.m$^2$/sec J = $152 \times 10^{-6}$ kg.m$^2$

$k_e$ = 0.1 V/(rad/s) $k_t$ = 0.1 Nm/A

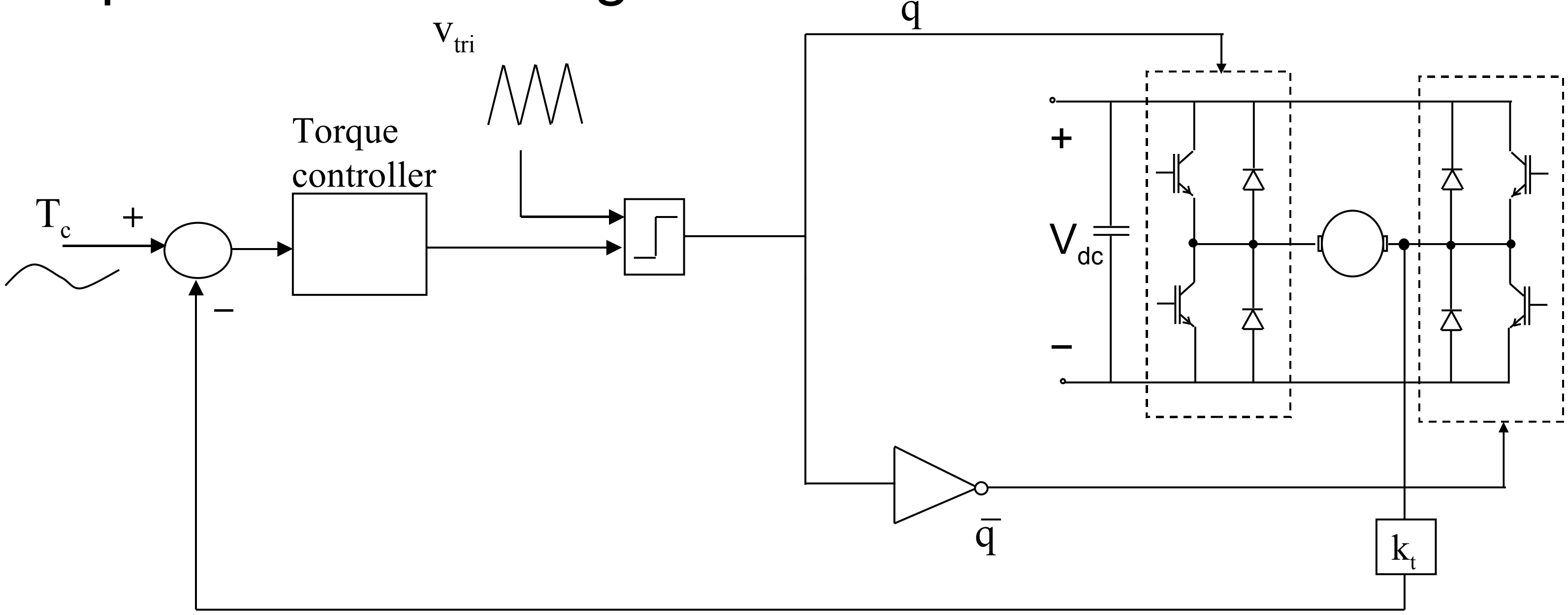
$V_d$ = 60 V $V_{tri}$ = 5 V

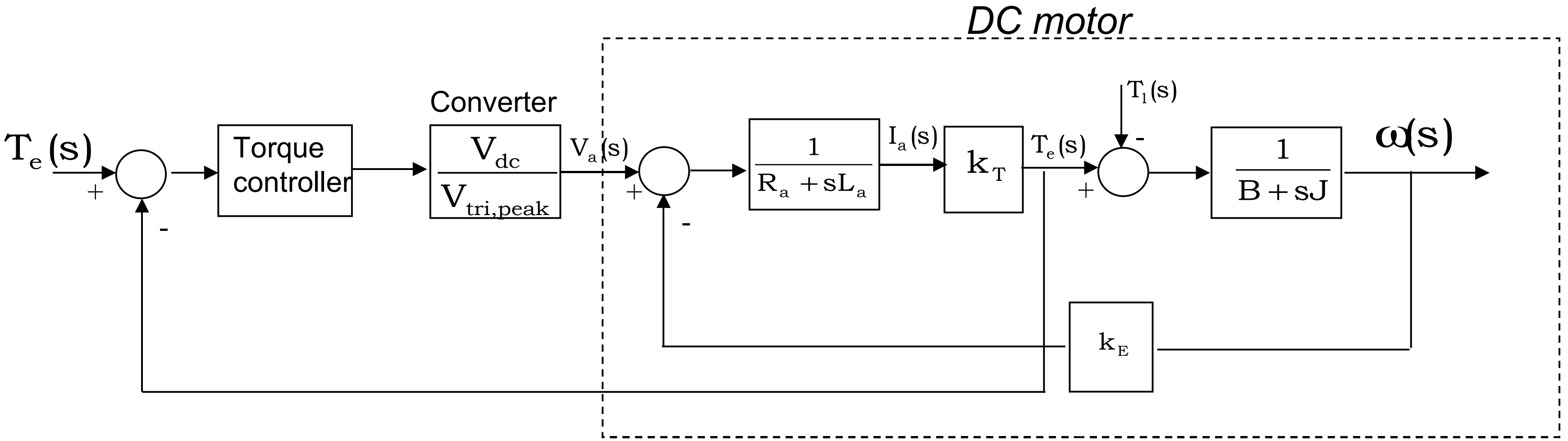
$f_s$ = 33 kHz

- PI controllers
- Switching signals from comparison of $v_c$ and triangular waveform

**CLOSED-LOOP SPEED CONTROL**

# Torque controller design

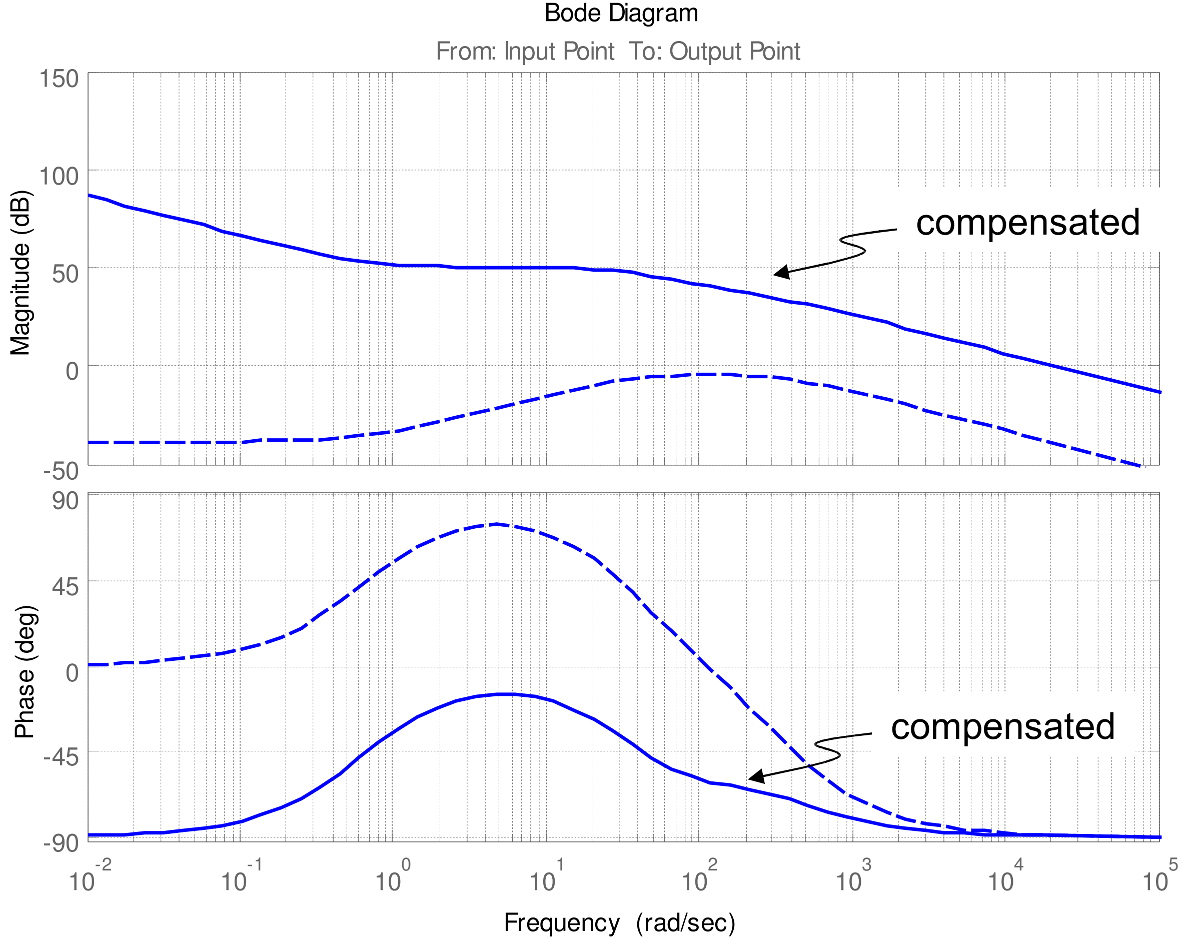




**CLOSED-LOOP SPEED CONTROL**

# Torque controller design

*Open-loop gain*



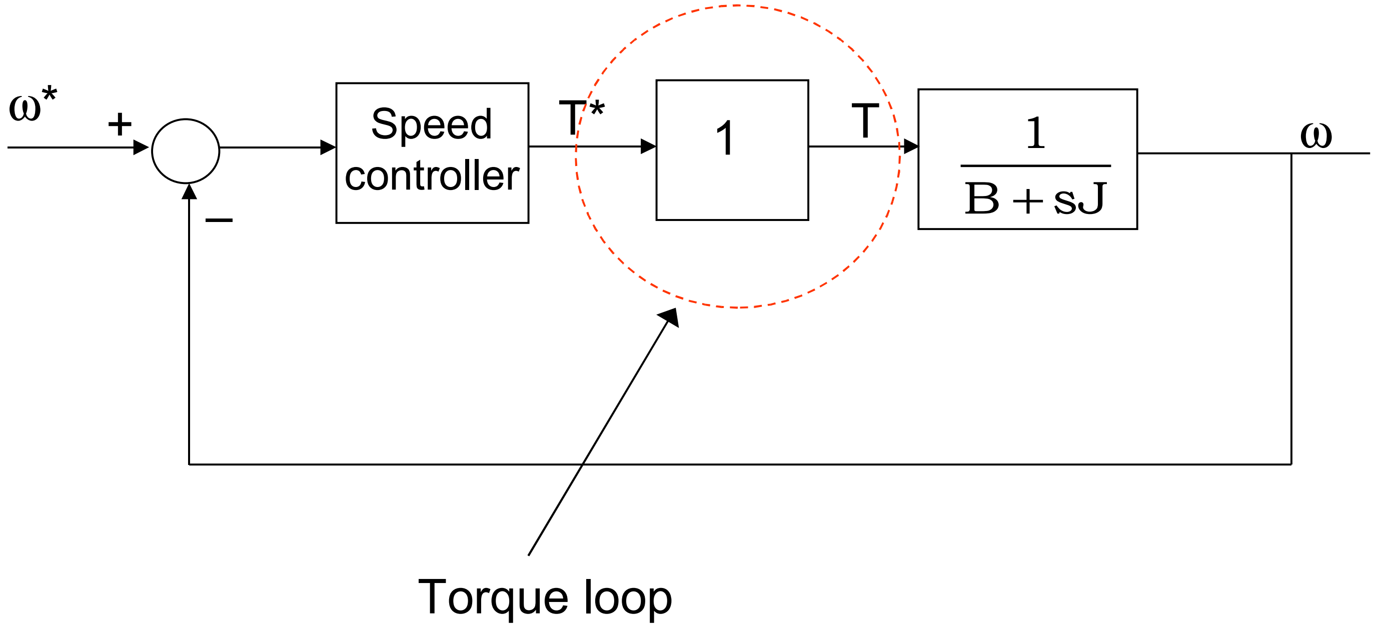
$k_{pT}= 90$

$k_{iT}= 18000$

# CLOSED-LOOP SPEED CONTROL

## Speed controller design

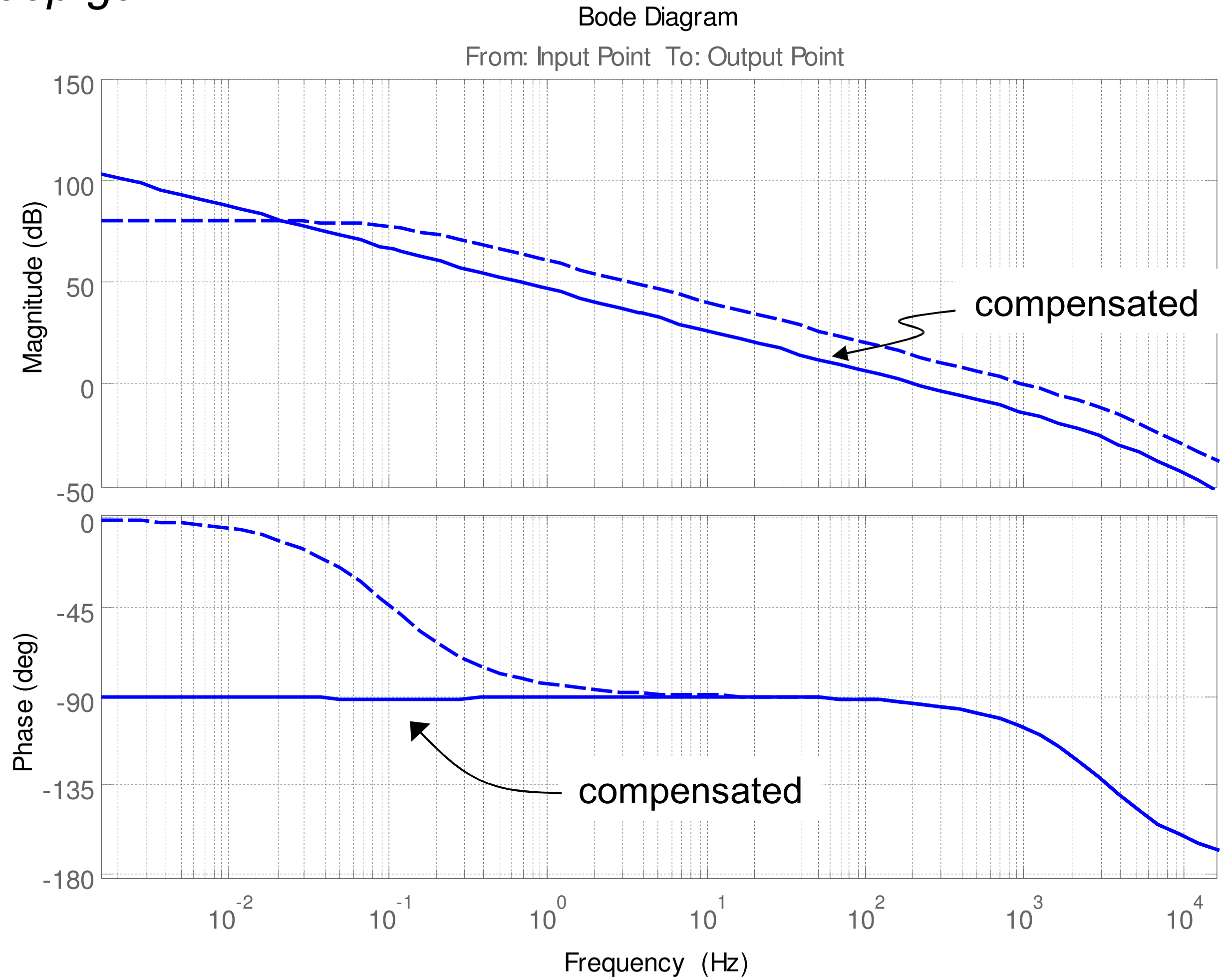
Assume torque loop unity gain for speed bandwidth << Torque bandwidth



**CLOSED-LOOP SPEED CONTROL**

# Speed controller

*Open-loop gain*



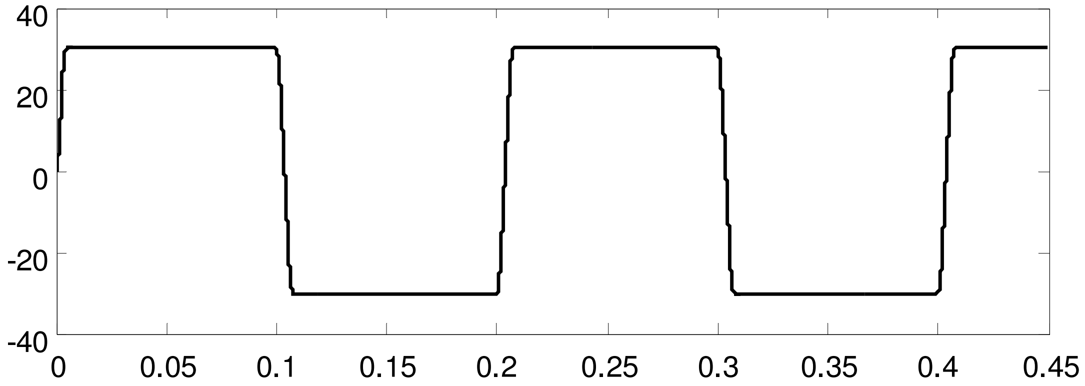
$k_{ps}= 0.2$

$k_{is}= 0.14$

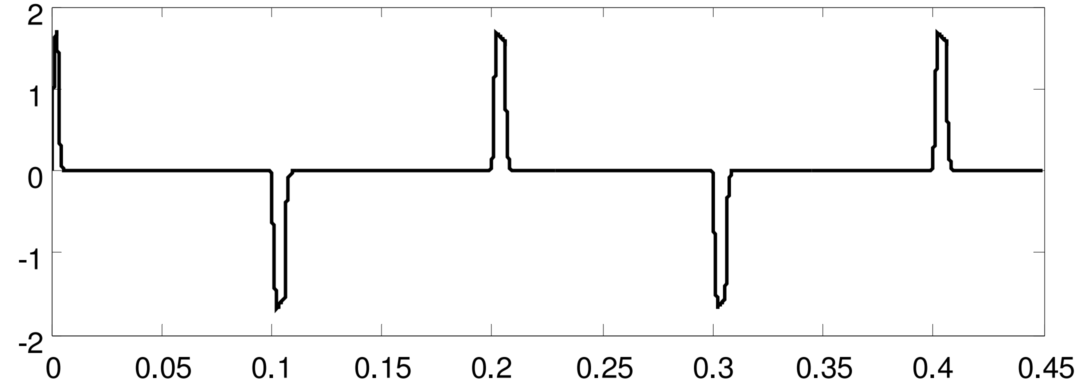
**CLOSED-LOOP SPEED CONTROL**

## Large Signal Simulation results

Speed



Torque



# SUMMARY

Speed control by: armature voltage ($0 \rightarrow \omega_b$) and field flux ($\omega_b \uparrow$)

Power electronics converters – to obtain variable armature voltage

- Phase controlled rectifier – small bandwidth – large ripple
- Switch-mode DC-DC converter – large bandwidth – small ripple

Controller design based on linear small signal model

- Power converters - averaged model
- DC motor – separately excited or permanent magnet

Closed-loop speed control design based on Bode plots

- Verify with large signal simulation