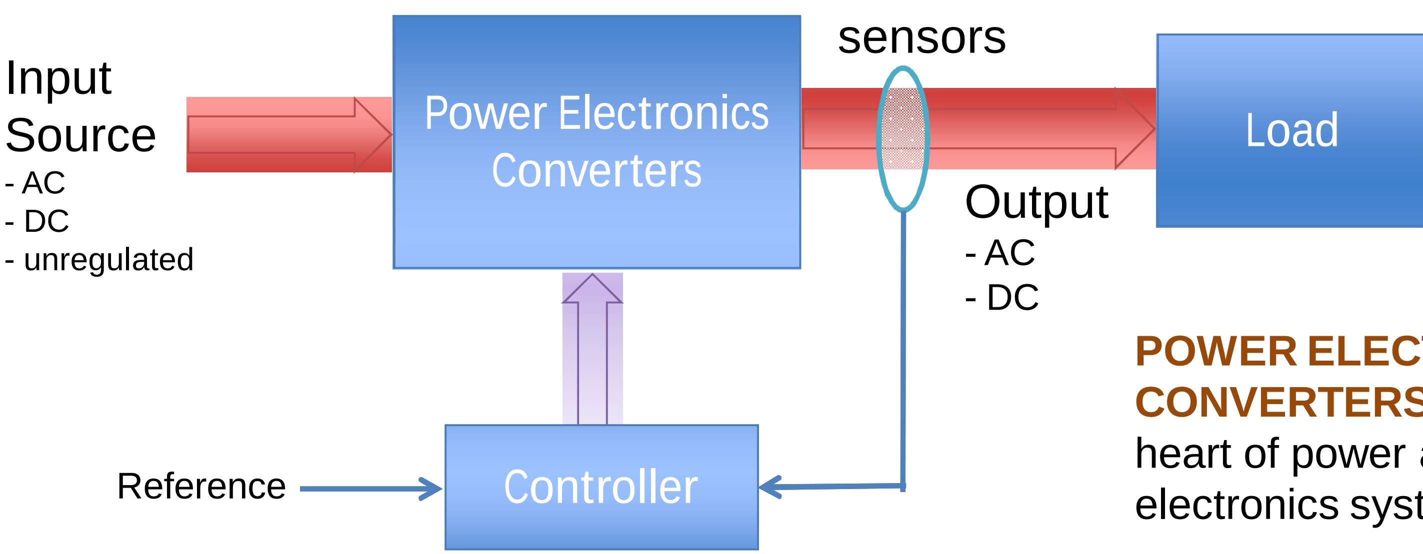
ELECTRICAL DRIVES

Power Electronic Systems

What is Power Electronics ?

A field of Electrical Engineering that deals with the application of power semiconductor devices for the control and conversion of electric power



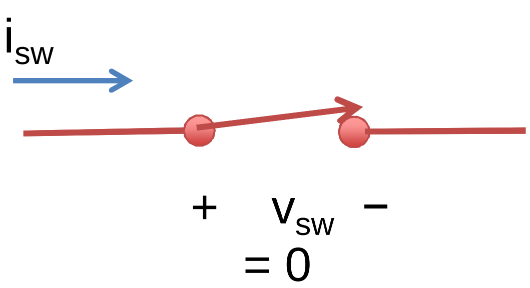
POWER ELECTRONIC CONVERTERS – the heart of power a power electronics system

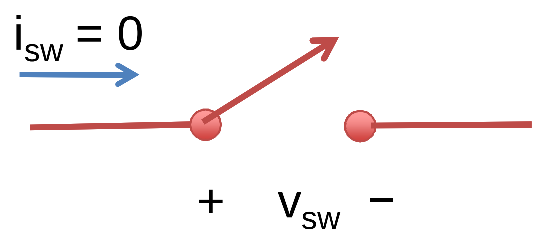
Power Electronic Systems

Why Power Electronics ?

Power semiconductor devices ⟷ ***Power switches***

ON or OFF





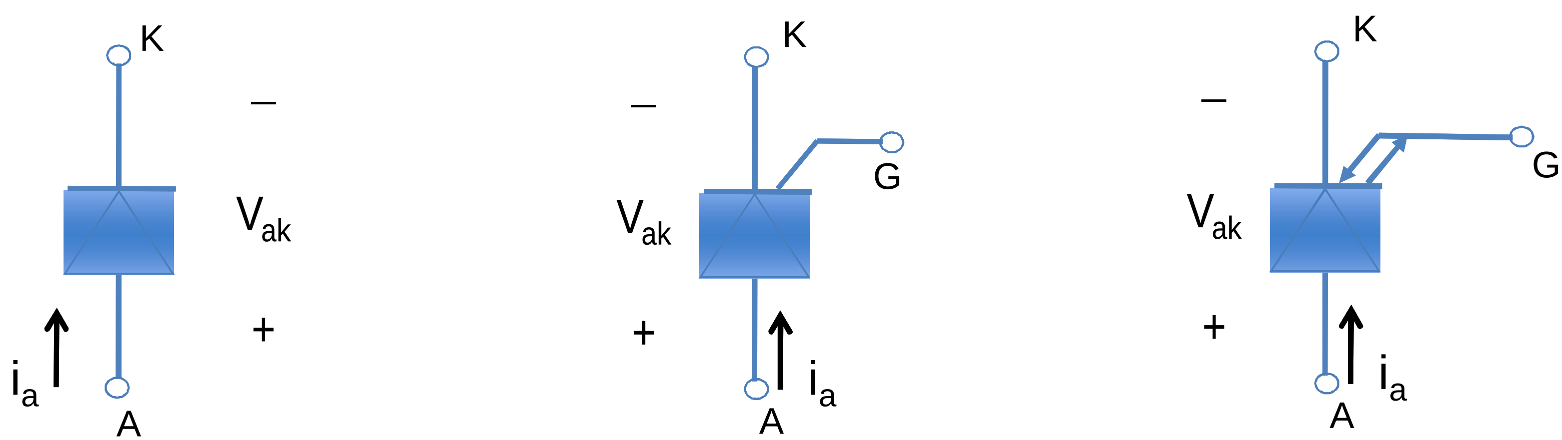
$$P_{loss} = v_{sw} \times i_{sw} = 0$$

Losses ideally ZERO !

Power Electronic Systems

Why Power Electronics ?

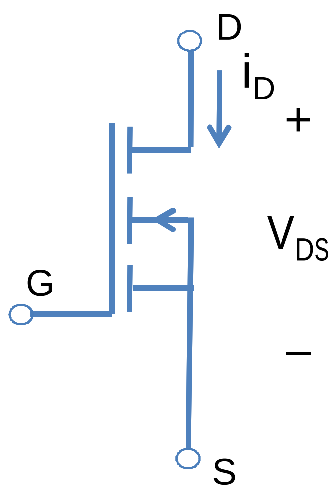
Power semiconductor devices ⟺ ***Power switches***

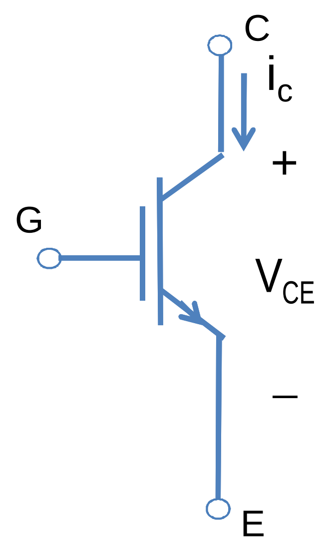


Power Electronic Systems

Why Power Electronics ?

Power semiconductor devices ⟺ ***Power switches***

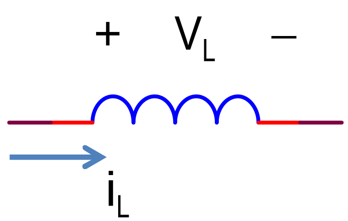




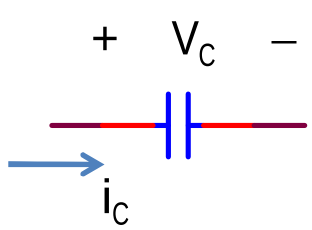
Power Electronic Systems

Why Power Electronics ?

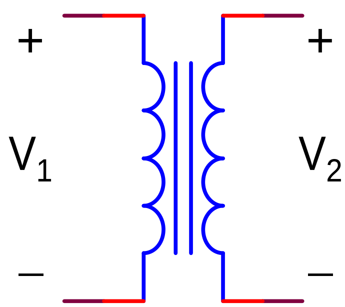
Passive elements



Inductor

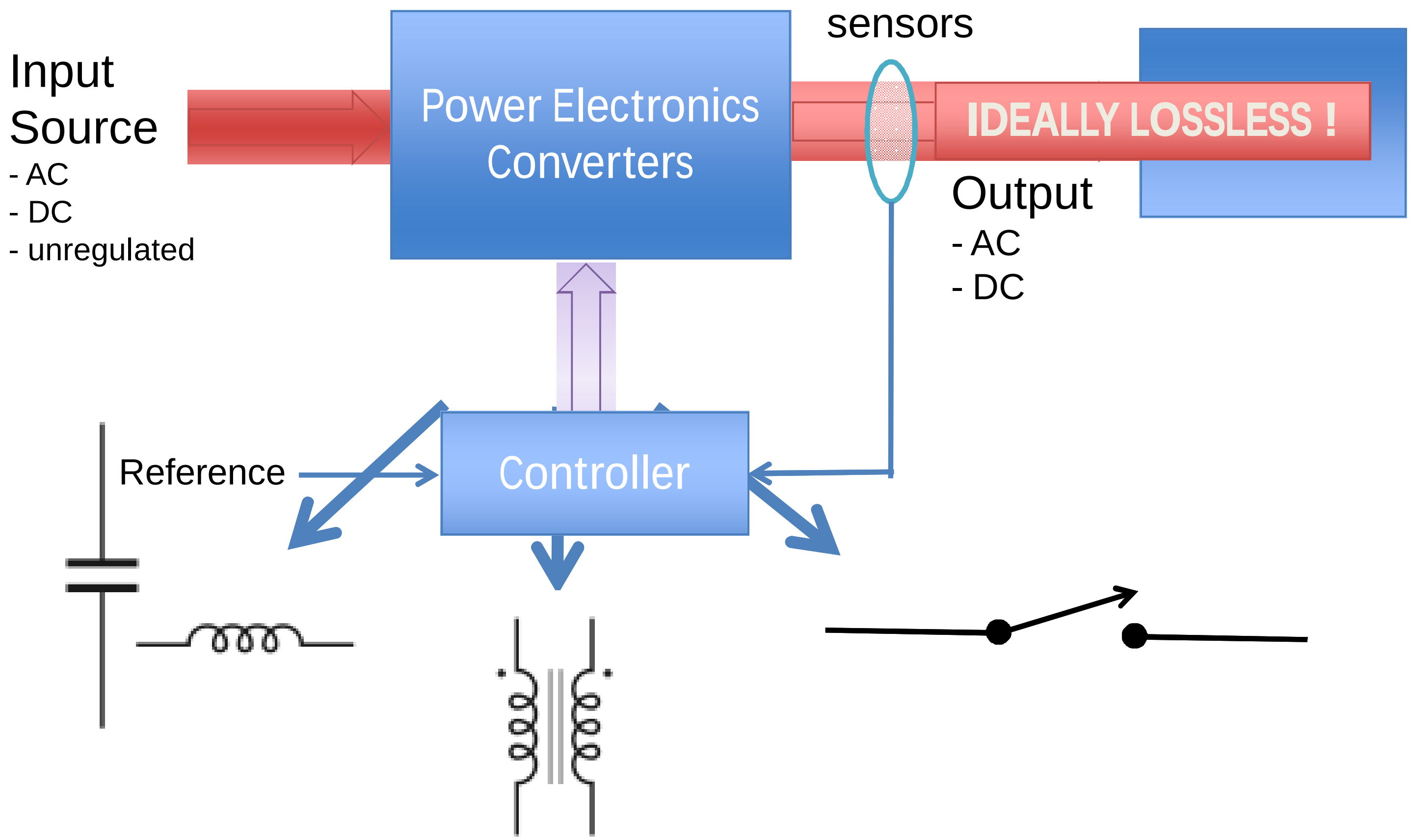


High frequency transformer



Power Electronic Systems

Why Power Electronics ?



Power Electronic Systems

Why Power Electronics ?

Other factors:

- Improvements in power semiconductors fabrication
    - Power Integrated Module (PIM), Intelligent Power Modules (IPM)
- Decline cost in power semiconductor
- Advancement in semiconductor fabrication
    - ASICs
    - FPGA
    - DSPs
    - Faster and cheaper to implement complex algorithm

Power Electronic Systems

Some Applications of Power Electronics :

Typically used in systems requiring efficient control and conversion of electric energy:

- Domestic and Commercial Applications
- Industrial Applications
- Telecommunications
- Transportation
- Generation, Transmission and Distribution of electrical energy

Power rating of < 1 W (portable equipment)

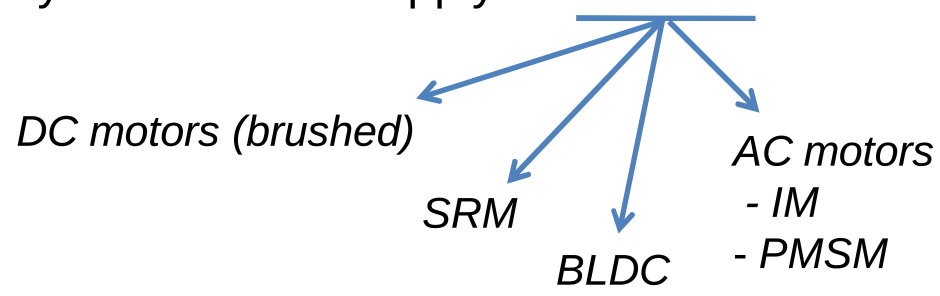
Tens or hundreds Watts (Power supplies for computers /office equipment)

kW to MW : drives

Hundreds of MW in DC transmission system (HVDC)

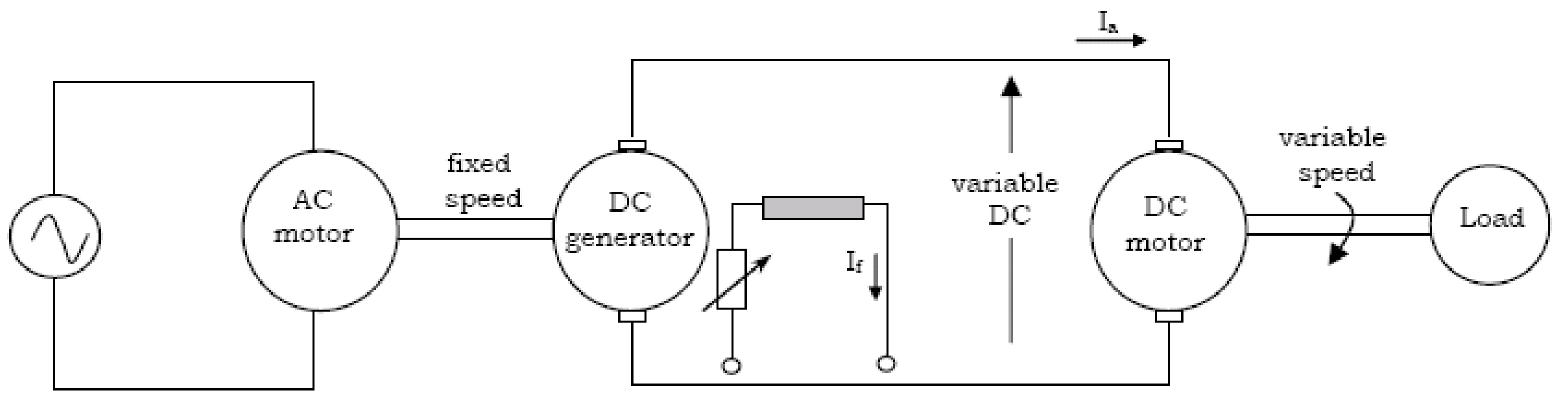
Modern Electrical Drive Systems

- About 50% of electrical energy used for drives
- Can be either used for fixed speed or variable speed
  - 75% - constant speed, 25% variable speed (expanding)
- Variable speed drives typically used PEC to supply the motors



Modern Electrical Drive Systems

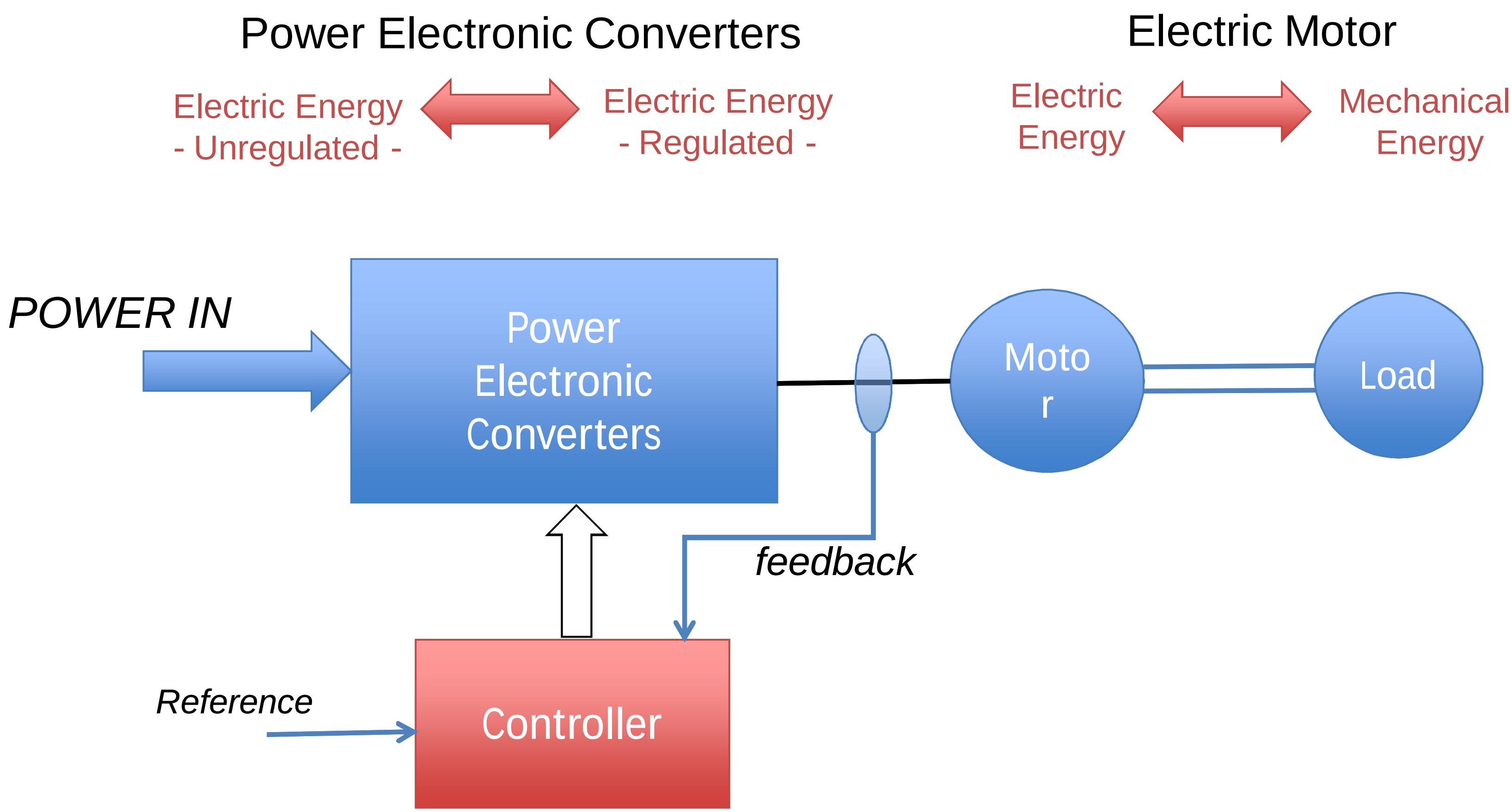
Classic Electrical Drive for Variable Speed Application :



- Bulky
- Inefficient
- inflexible

Modern Electrical Drive Systems

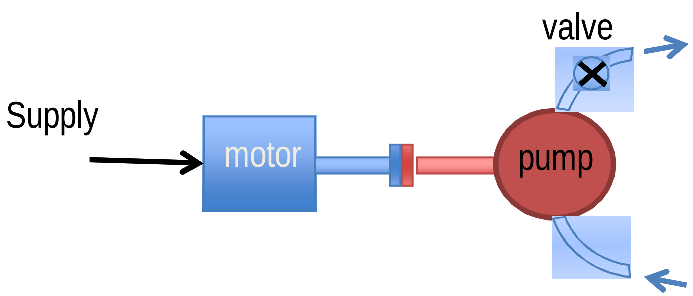
Typical Modern Electric Drive Systems



Modern Electrical Drive Systems

Example on VSD application

<u>Constant speed</u>

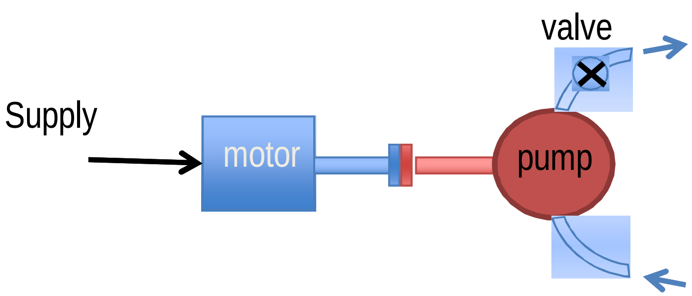


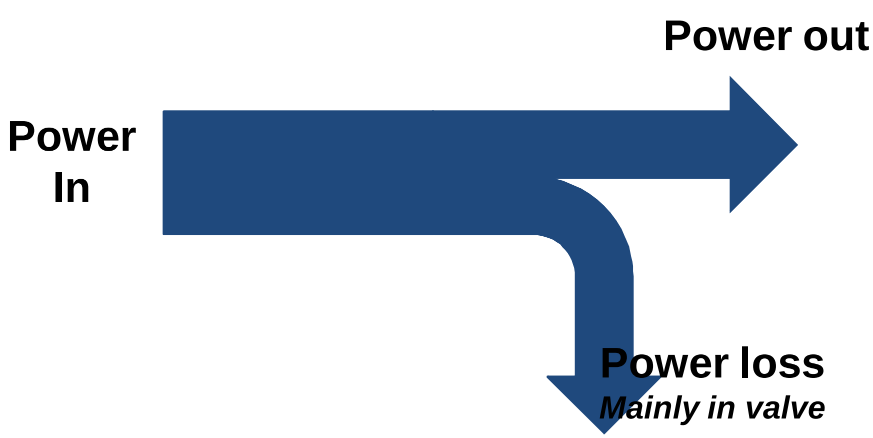
<u>Variable Speed Drives</u>

Modern Electrical Drive Systems

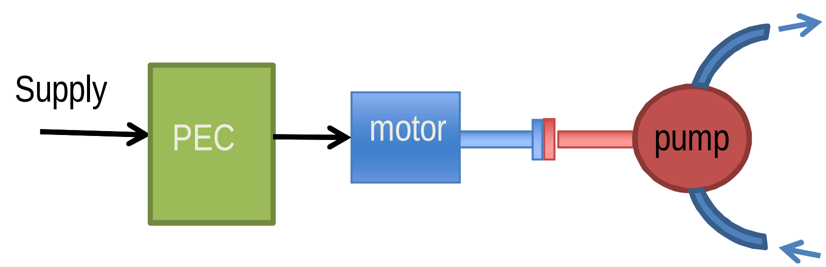
Example on VSD application

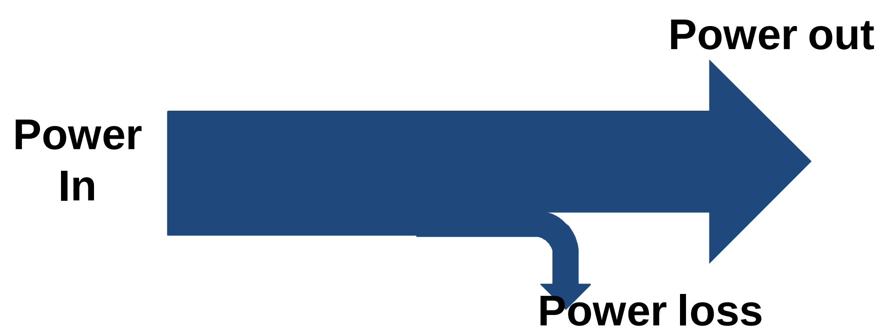
Constant speed





Variable Speed Drives

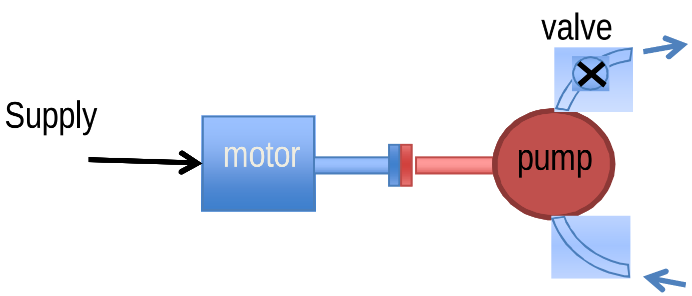


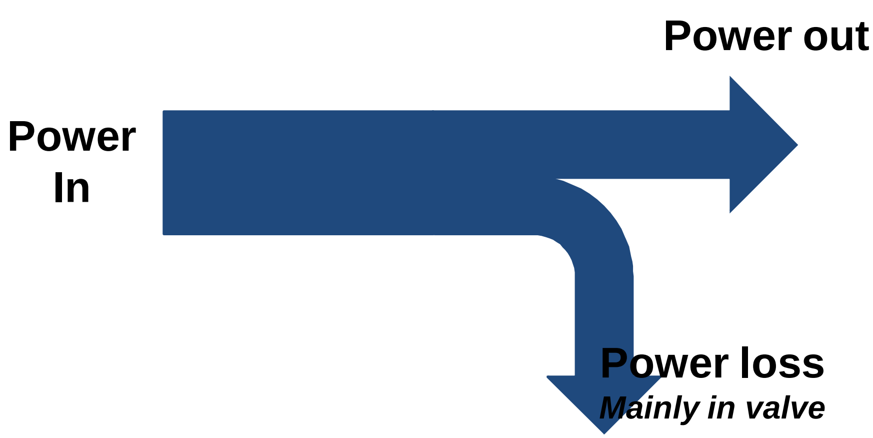


Modern Electrical Drive Systems

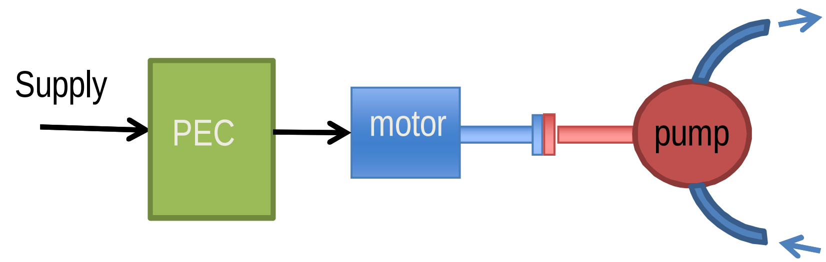
Example on VSD application

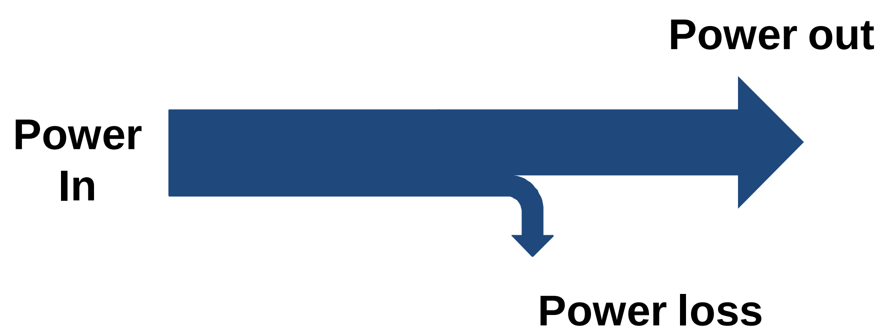
<u>Constant speed</u>





<u>Variable Speed Drives</u>





Modern Electrical Drive Systems

Example on VSD application

Electric motor consumes more than half of electrical energy in the US

Fixed speed **Variable speed**

Improvements in energy utilization in electric motors give large impact to the overall energy consumption

HOW ?

Replacing fixed speed drives with variable speed drives

Using the high efficiency motors

Improves the existing power converter–based drive systems

Modern Electrical Drive Systems

Overview of AC and DC drives

DC drives: Electrical drives that use DC motors as the prime mover

Regular maintenance, heavy, expensive, speed limit

Easy control, decouple control of torque and flux

AC drives: Electrical drives that use AC motors as the prime mover

Less maintenance, light, less expensive, high speed

Coupling between torque and flux – variable spatial angle between rotor and stator flux

Modern Electrical Drive Systems

Overview of AC and DC drives

Before semiconductor devices were introduced (<1950)

- AC motors for fixed speed applications
- DC motors for variable speed applications

After semiconductor devices were introduced (1960s)

- Variable frequency sources available – AC motors in variable speed applications
    - Coupling between flux and torque control
    - Application limited to medium performance applications – fans, blowers, compressors – scalar control
- High performance applications dominated by DC motors – tractions, elevators, servos, etc

Modern Electrical Drive Systems

Overview of AC and DC drives

After vector control drives were introduced (1980s**)**

- AC motors used in high performance applications – elevators, tractions, servos
- AC motors favorable than DC motors – however control is complex hence expensive
- Cost of microprocessor/semiconductors decreasing –predicted 30 years ago AC motors would take over DC motors

Modern Electrical Drive Systems

Overview of AC and DC drives

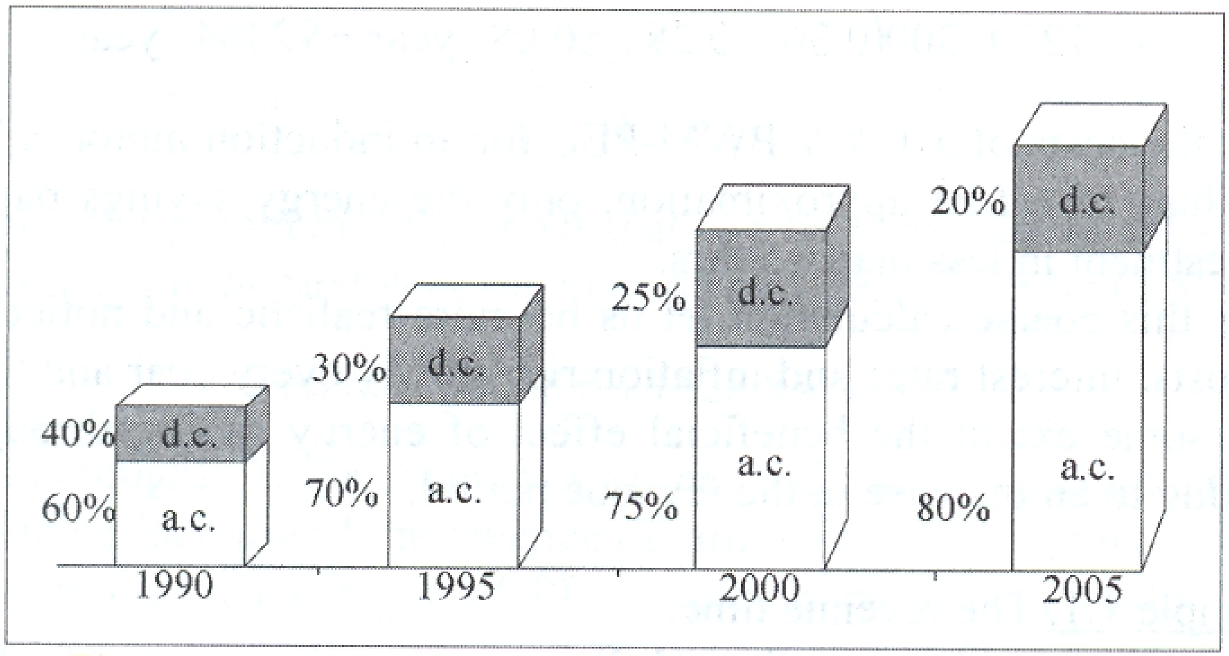
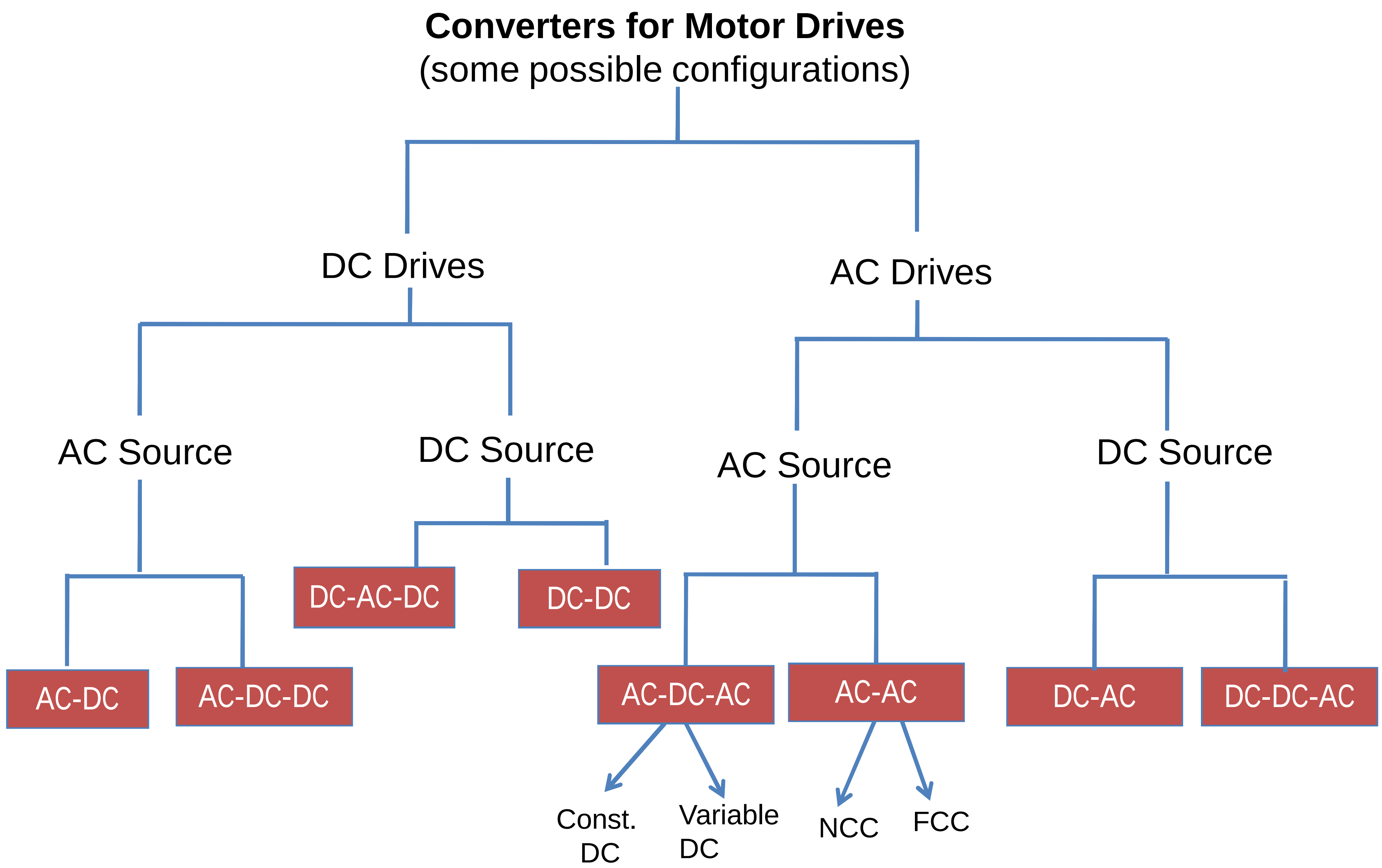


Figure 1.4. A.c. versus d.c. electric drives market dynamics

Extracted from *Boldea & Nasar*

Power Electronic Converters in ED Systems



Power Electronic Converters in ED Systems

Converters for Motor Drives

Configurations of Power Electronic Converters depend on:

Sources available

Type of Motors

Drive Performance - applications

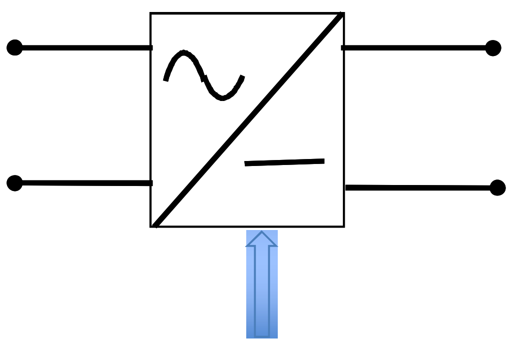
- Braking
- Response
- Ratings

Power Electronic Converters in ED Systems

DC DRIVES

Available AC source to control DC motor (brushed)

AC-DC

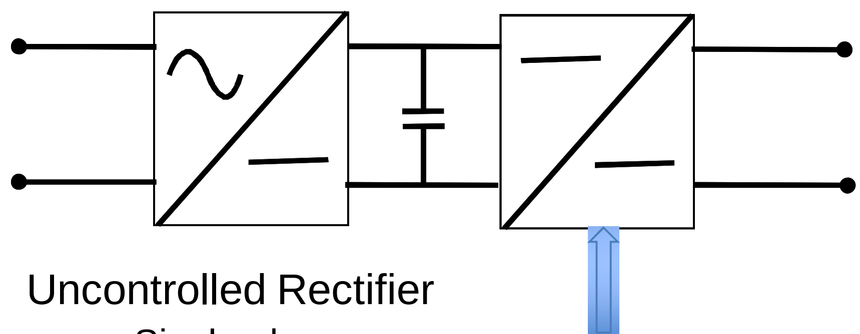


Control

Controlled Rectifier

Single-phase
Three-phase

AC-DC-DC



Uncontrolled Rectifier

Single-phase
Three-phase

Control

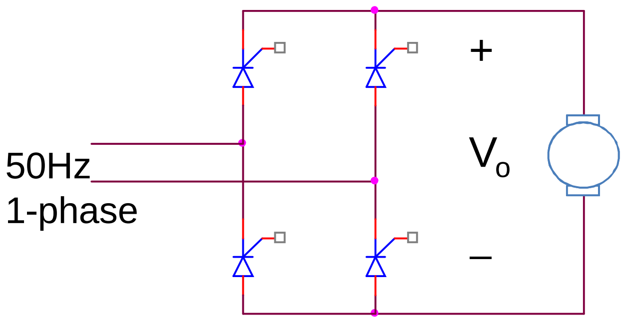
DC-DC Switched mode

1-quadrant, 2-quadrant
4-quadrant

Power Electronic Converters in ED Systems

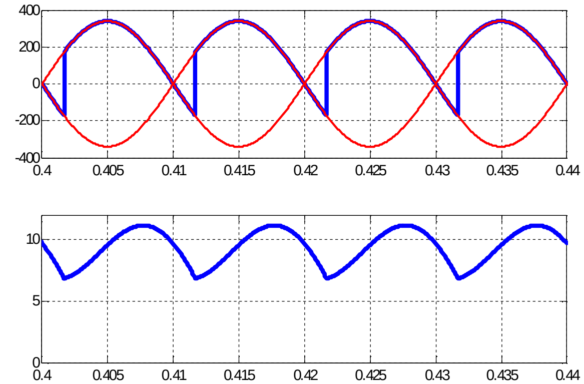
DC DRIVES

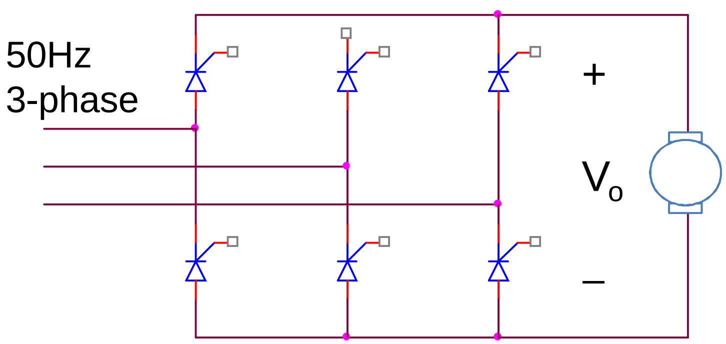
AC-DC



$$V_o = \frac{2V_m}{\pi}\cos\alpha$$

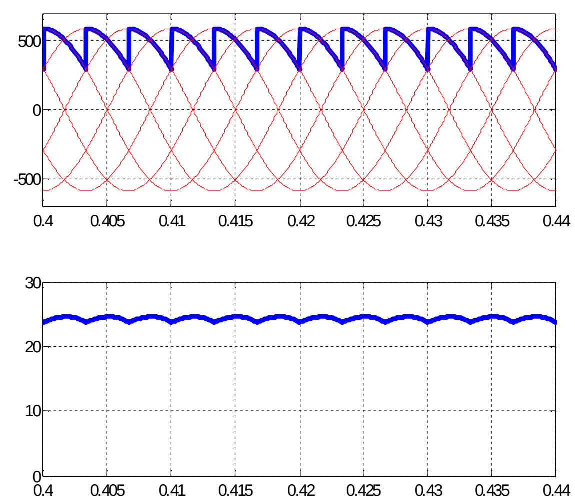
Average voltage over 10ms





$$V_o = \frac{3V_{L-L,m}}{\pi}\cos\alpha$$

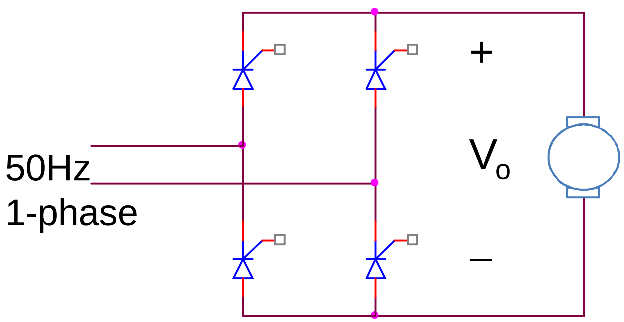
Average voltage over 3.33 ms



Power Electronic Converters in ED Systems

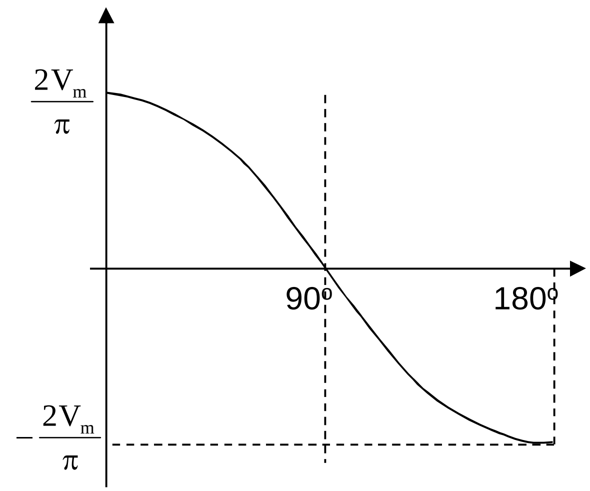
DC DRIVES

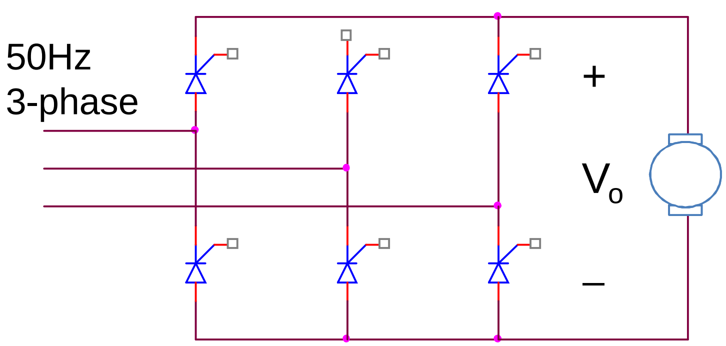
AC-DC



$$V_o = \frac{2V_m}{\pi}\cos\alpha$$

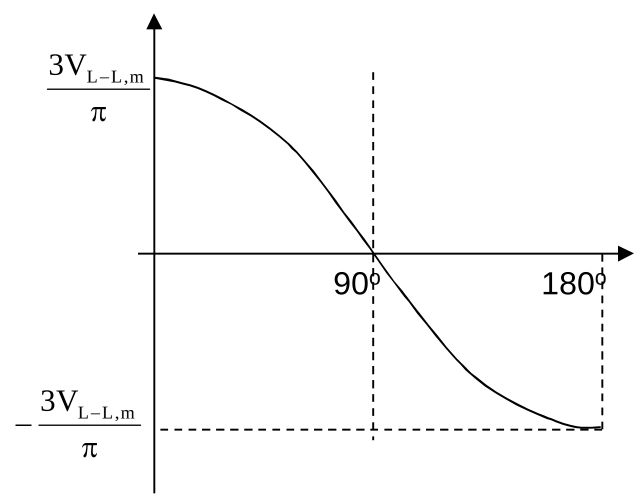
Average voltage over 10ms





$$V_o = \frac{3V_{L-L,m}}{\pi}\cos\alpha$$

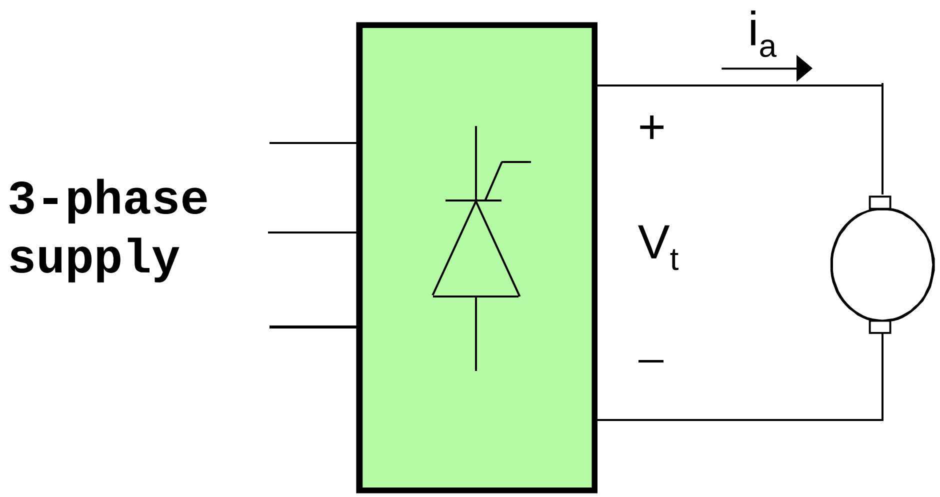
Average voltage over 3.33 ms

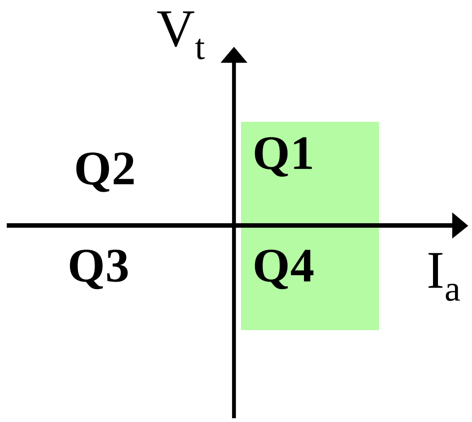


Power Electronic Converters in ED Systems

DC DRIVES

AC-DC



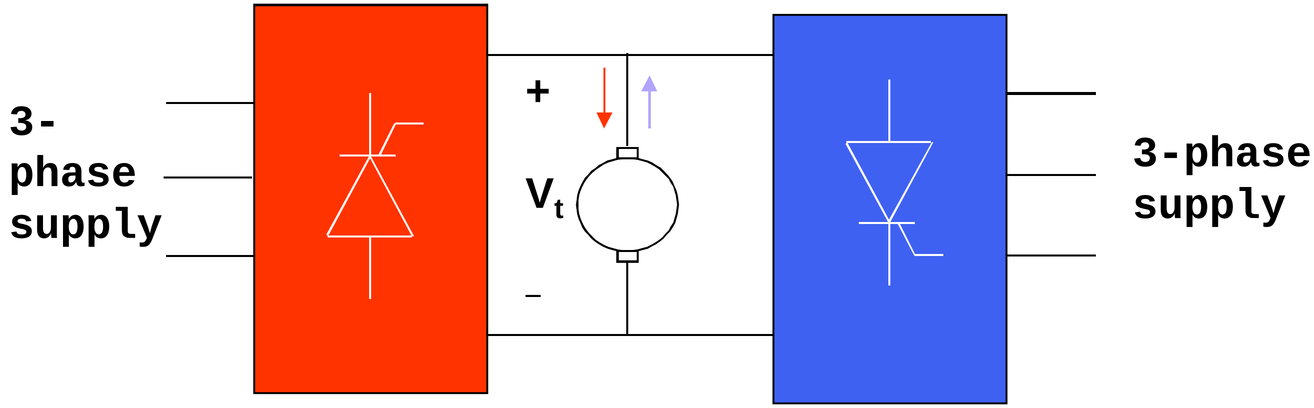


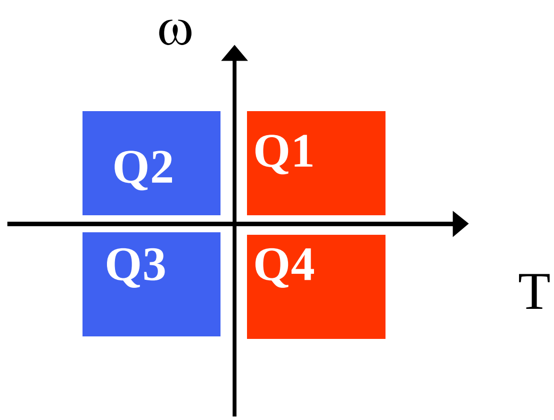
- Operation in quadrant 1 and 4 only

Power Electronic Converters in ED Systems

DC DRIVES

AC-DC

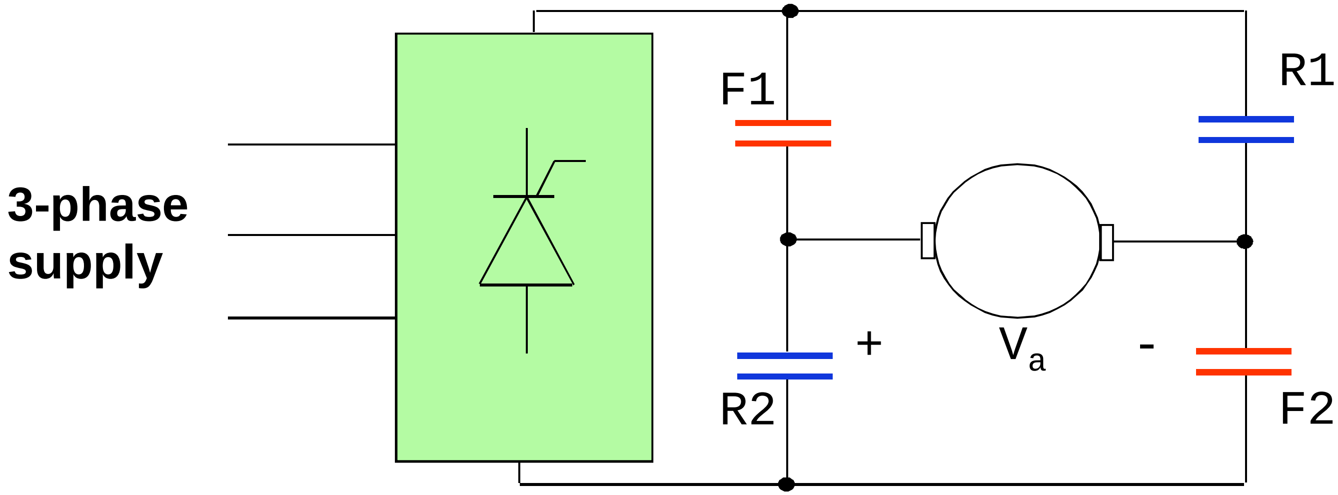


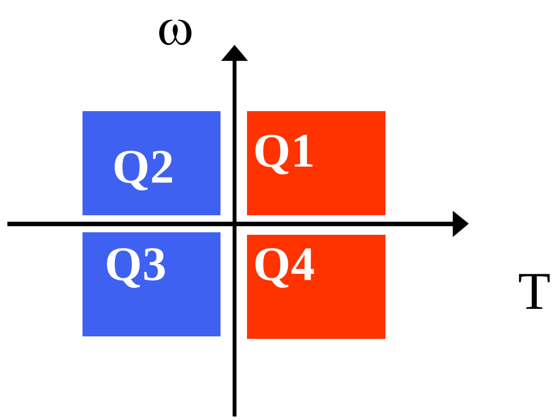


Power Electronic Converters in ED Systems

DC DRIVES

AC-DC



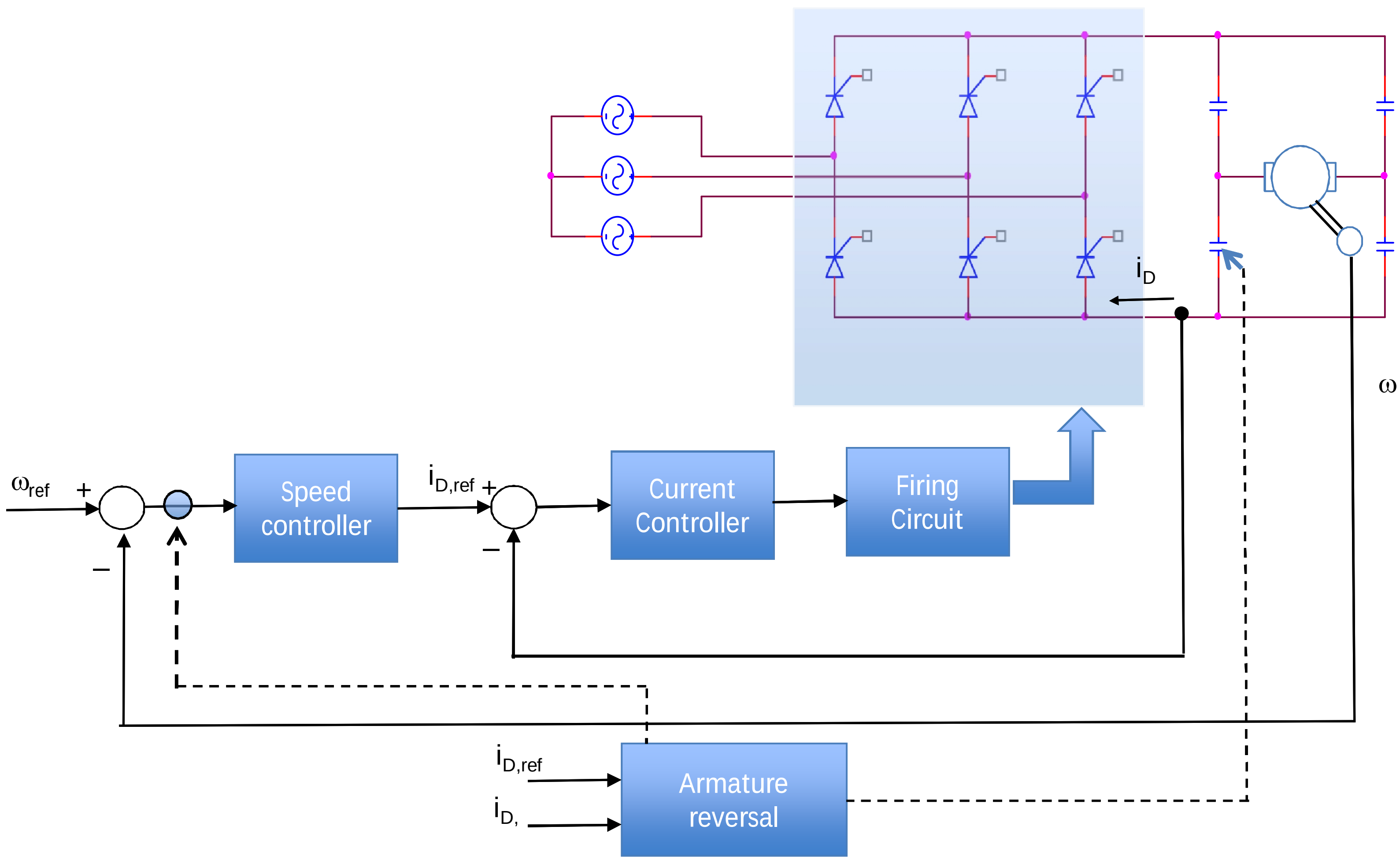


Power Electronic Converters in ED Systems

DC DRIVES

AC-DC

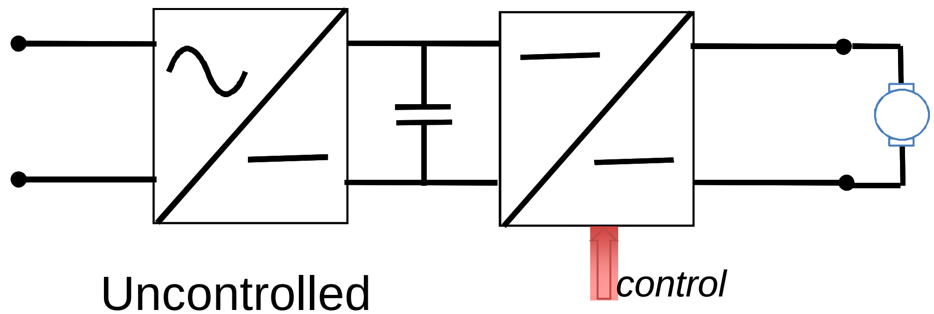
Cascade control structure with armature reversal (4-quadrant):



Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC



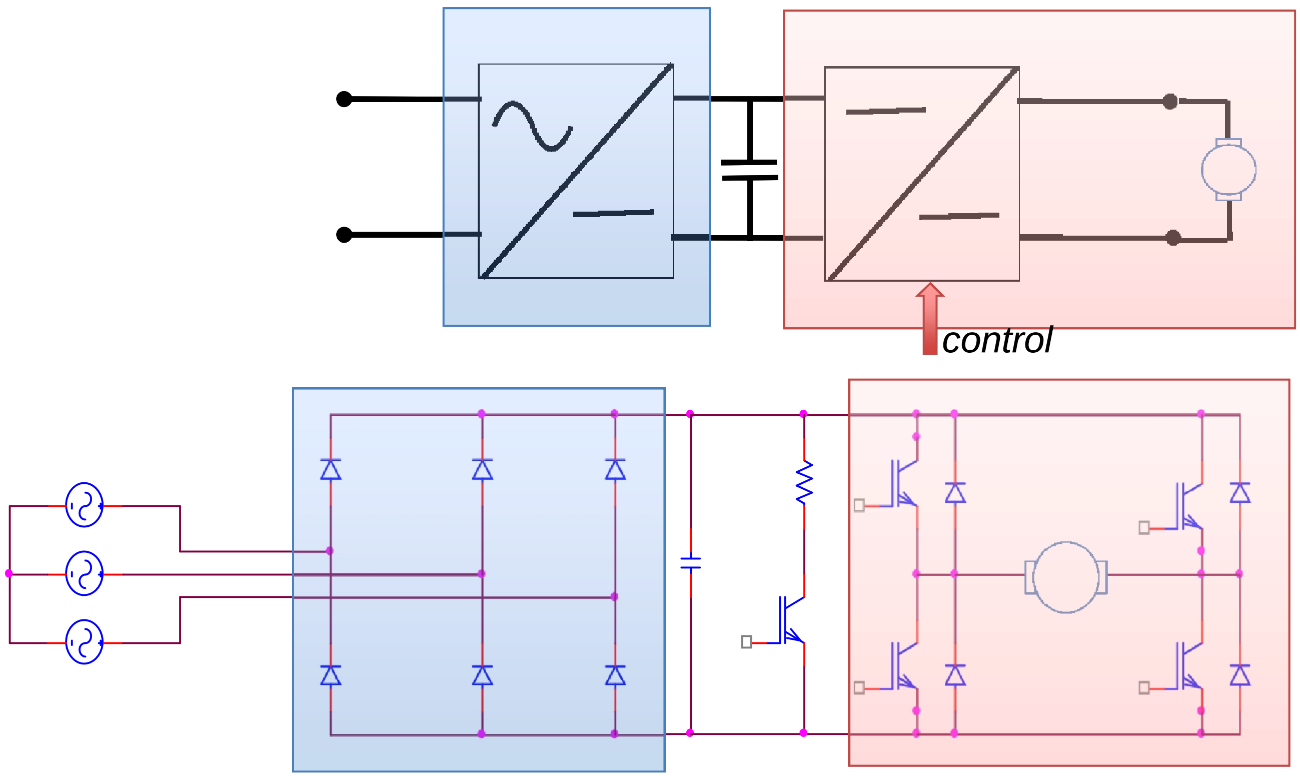
Uncontrolled
rectifier

Switch Mode DC-DC
1-Quadrant
2-Quadrant
4-Quadrant

Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

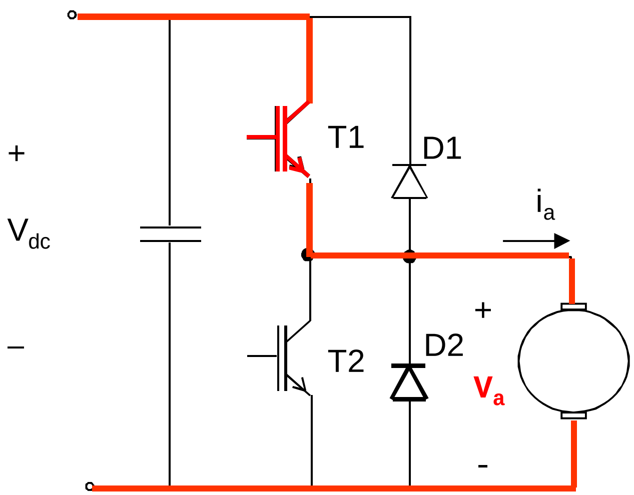


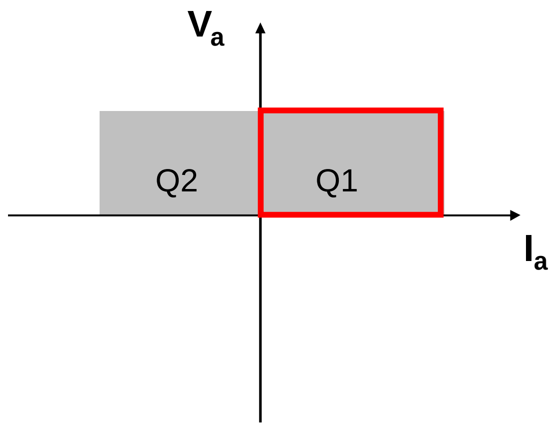
Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

DC-DC: Two-quadrant Converter





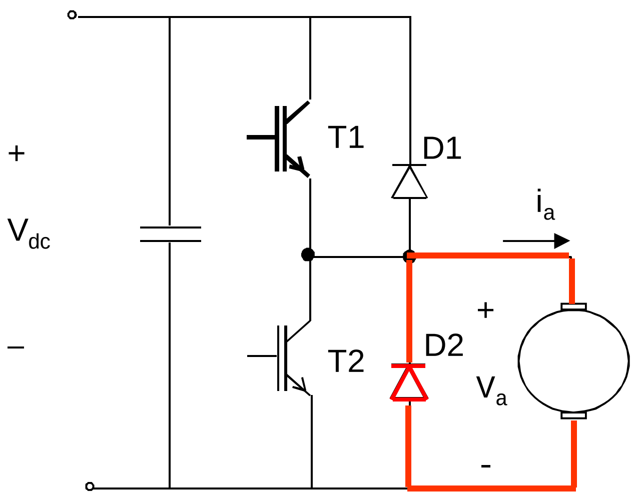
T1 conducts $\rightarrow$ $\mathbf{v_a = V_{dc}}$

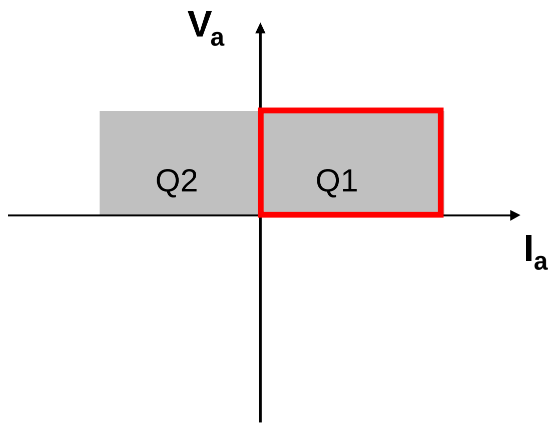
Power Electronic Converters in ED Systems

DC DRIVES

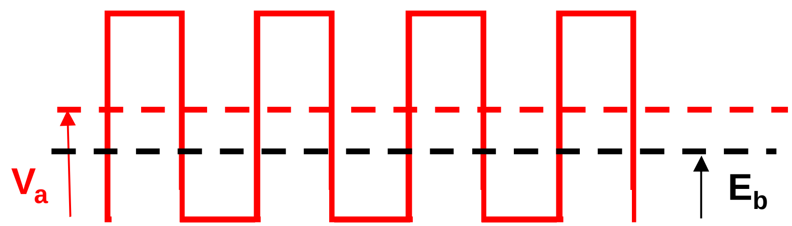
AC-DC-DC

DC-DC: Two-quadrant Converter





D2 conducts → $v_a = 0$ T1 conducts → $v_a = V_{dc}$



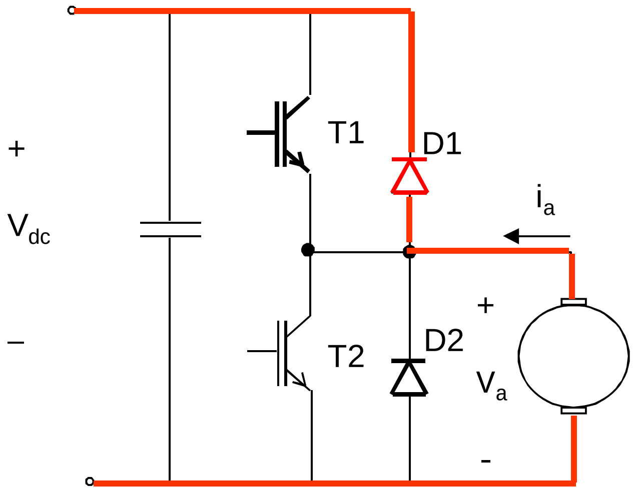
Quadrant 1 The average voltage is made larger than the back emf

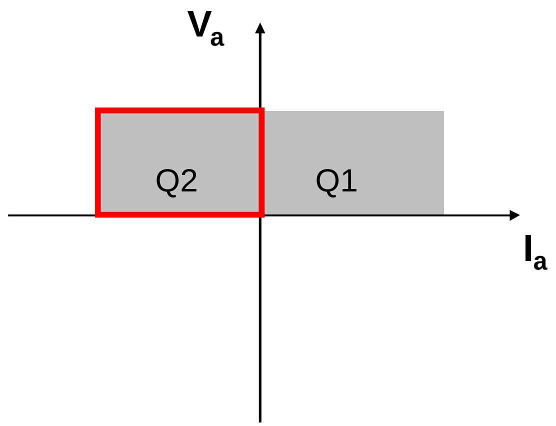
Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

DC-DC: Two-quadrant Converter





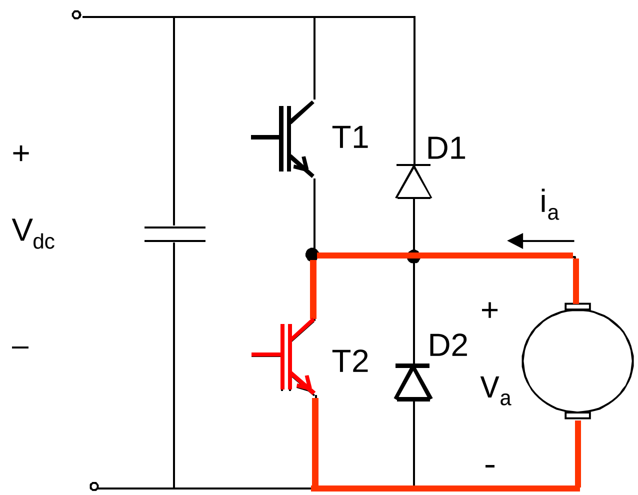
D1 conducts $\rightarrow$ $\mathbf{v_a = V_{dc}}$

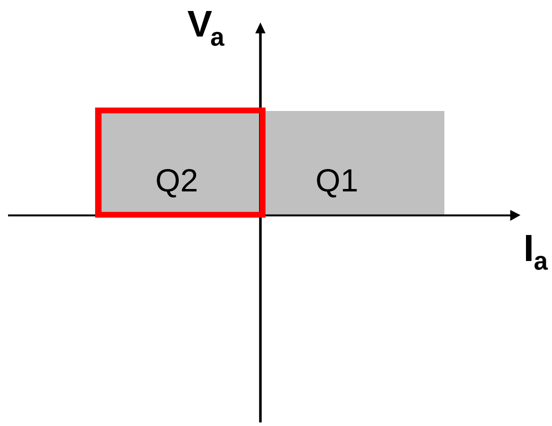
Power Electronic Converters in ED Systems

DC DRIVES

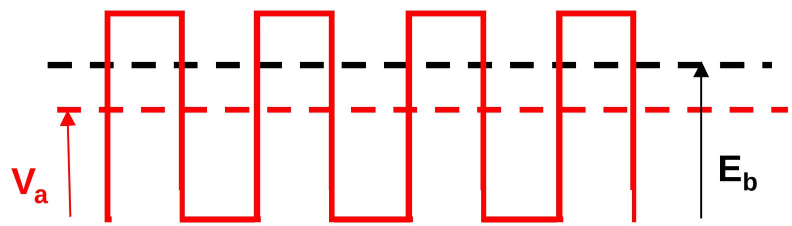
AC-DC-DC

DC-DC: Two-quadrant Converter





T2 conducts → $v_a = 0$ D1 conducts → $v_a = V_{dc}$



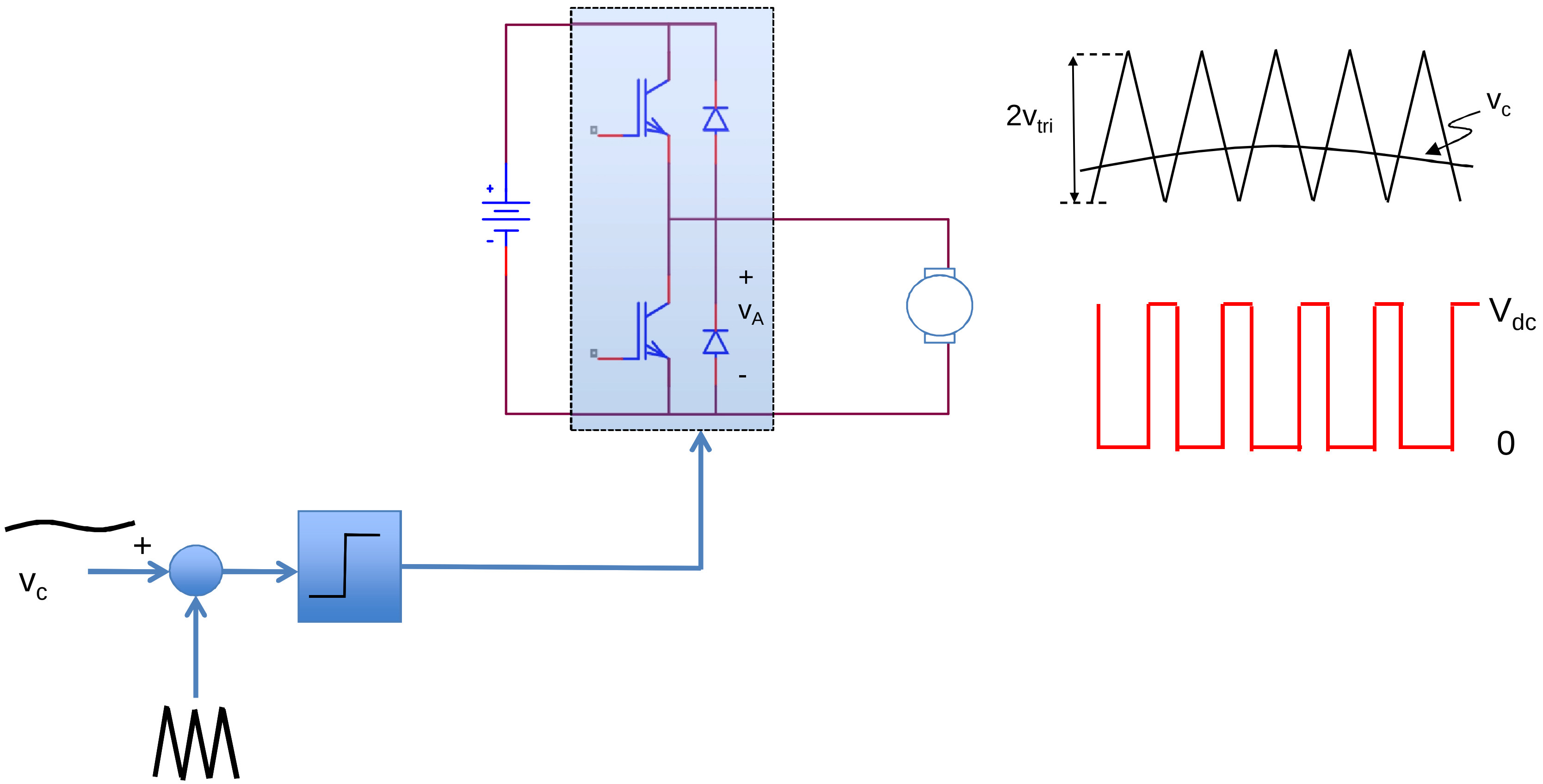
Quadrant 2 The average voltage is made smallerr than the back emf, thus forcing the current to flow in the reverse direction

Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

DC-DC: Two-quadrant Converter

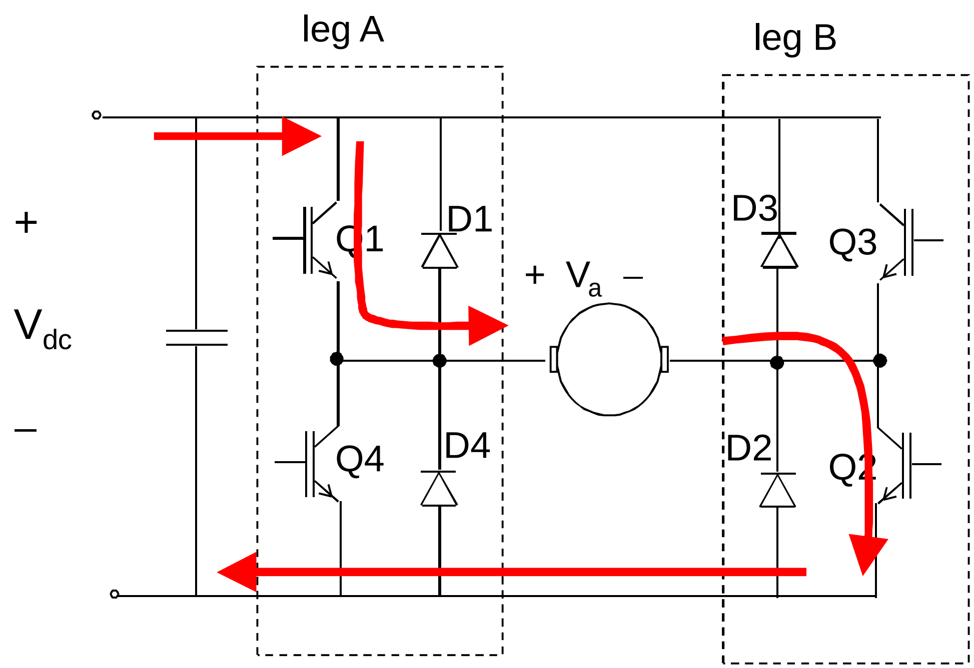


Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

DC-DC: Four-quadrant Converter



Positive current

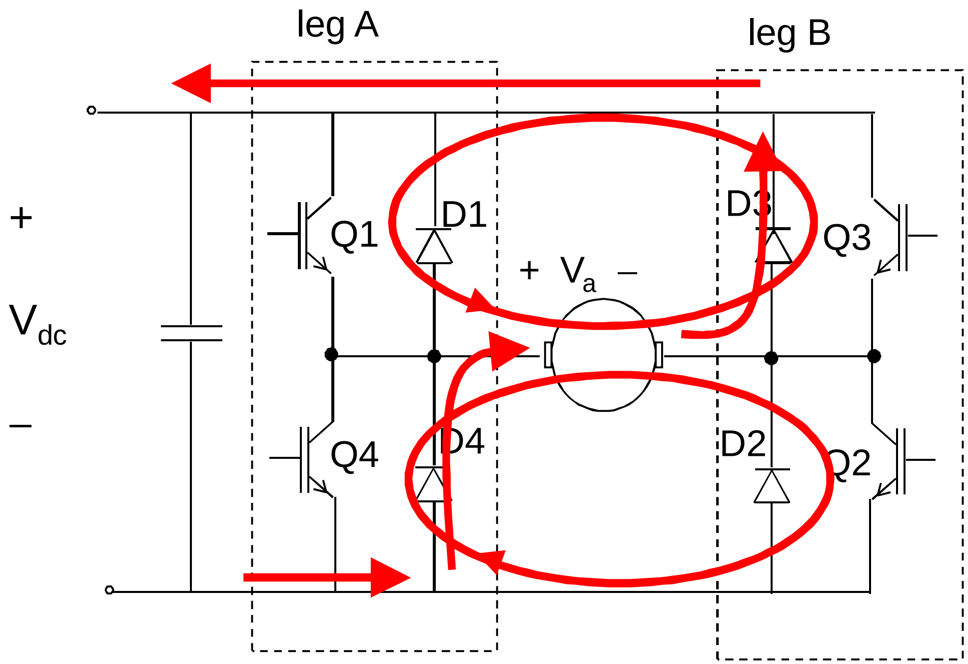
$v_a = V_{dc}$ **when Q1 and Q2 are ON**

Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

DC-DC: Four-quadrant Converter



Positive current

$v_a = V_{dc}$ when Q1 and Q2 are ON

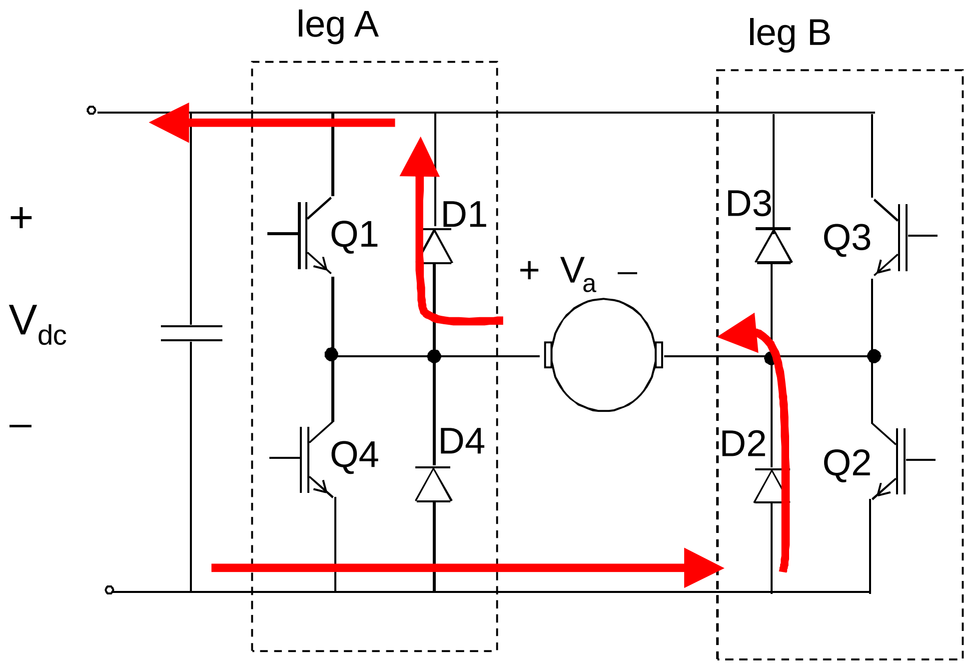
$v_a = -V_{dc}$ when D3 and D4 are ON

$v_a = 0$ when current freewheels through Q and D

Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC   DC-DC: Four-quadrant Converter



Positive current

$v_a = V_{dc}$ when Q1 and Q2 are ON

$v_a = -V_{dc}$ when D3 and D4 are ON

$v_a = 0$ when current freewheels through Q and D

Negative current

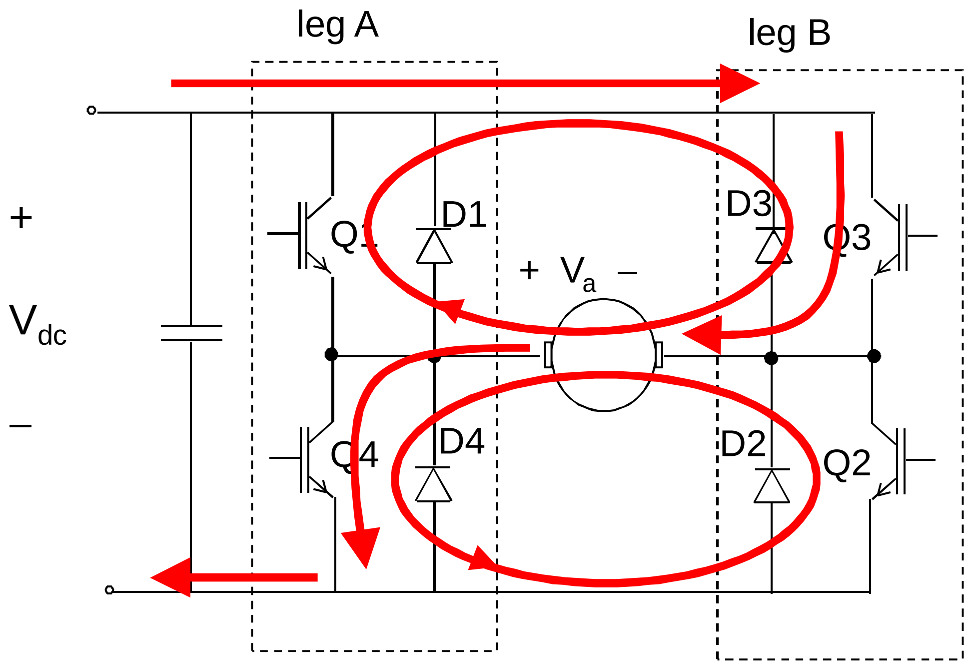
$v_a = V_{dc}$ when D1 and D2 are ON

Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

DC-DC: Four-quadrant Converter



Positive current

$v_a = V_{dc}$ when Q1 and Q2 are ON

$v_a = -V_{dc}$ when D3 and D4 are ON

$v_a = 0$ when current freewheels through Q and D

Negative current

$v_a = V_{dc}$ when D1 and D2 are ON

$v_a = -V_{dc}$ when Q3 and Q4 are ON

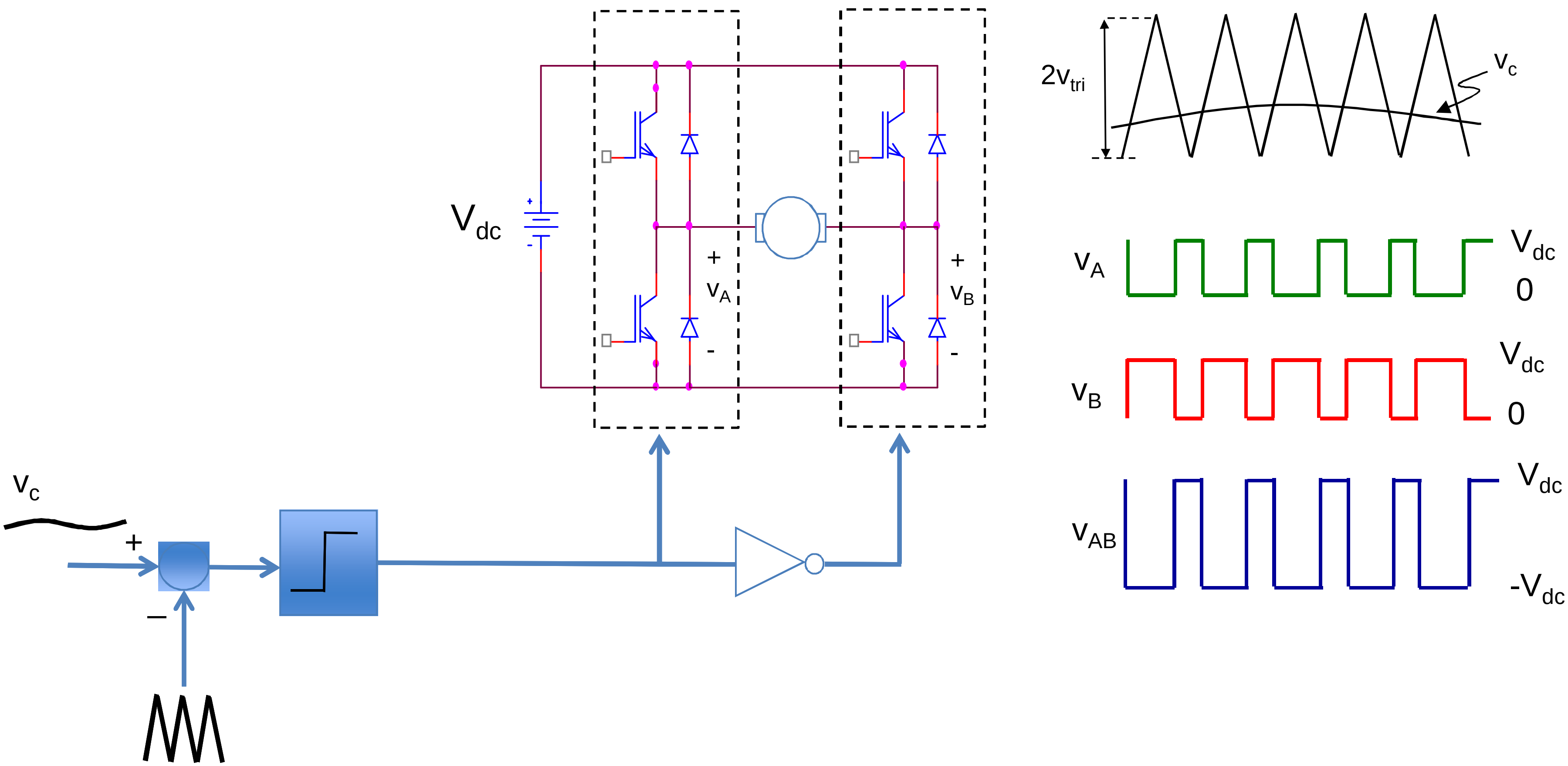
$v_a = 0$ when current freewheels through Q and D

Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

Bipolar switching scheme – output swings between V_{DC} and $-V_{DC}$

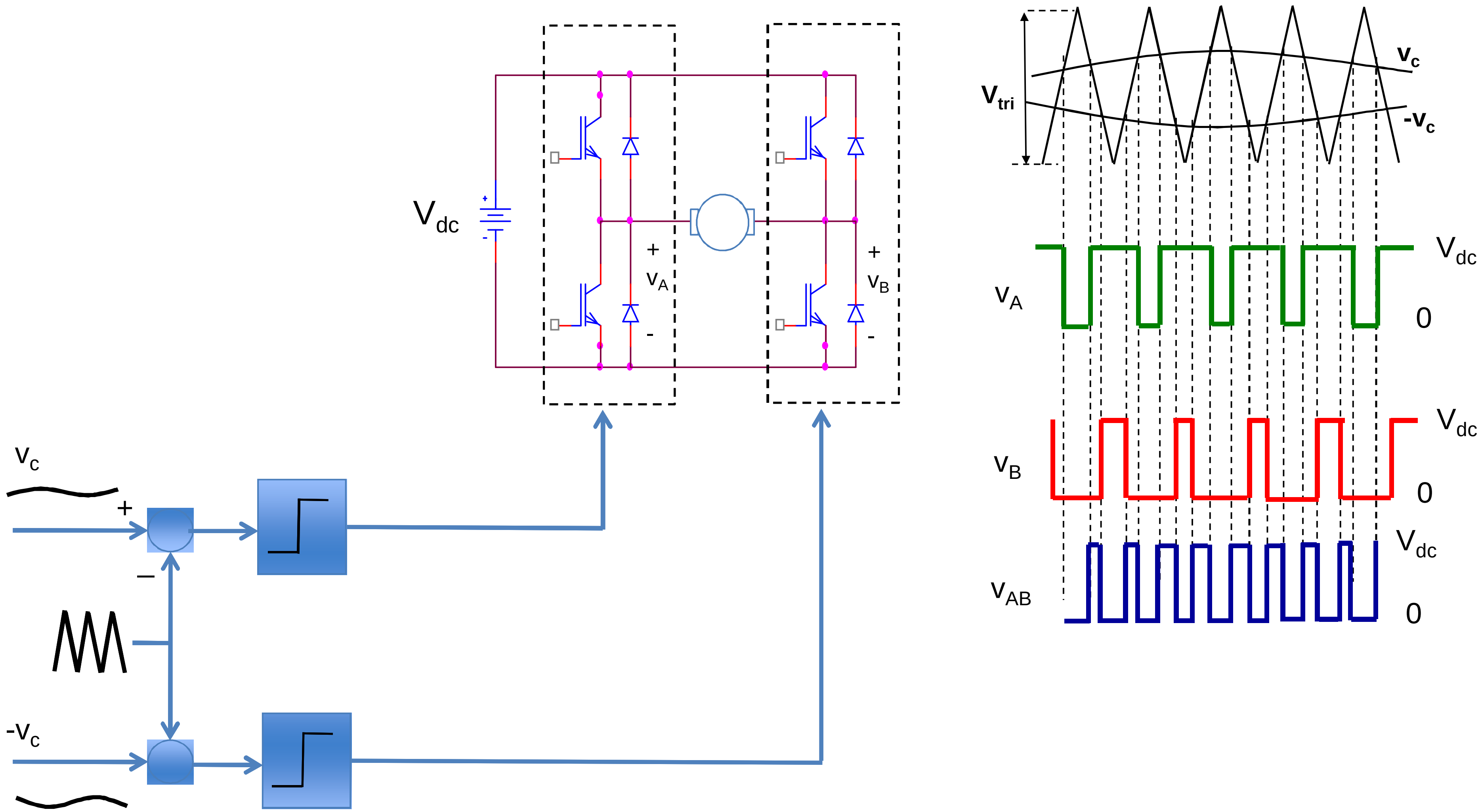


Power Electronic Converters in ED Systems

DC DRIVES

AC-DC-DC

Unipolar switching scheme – output swings between V_{dc} and $-V_{dc}$

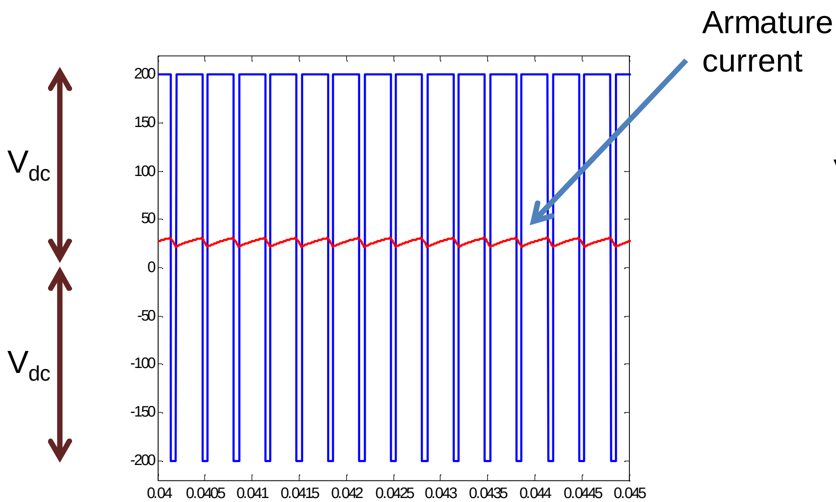


Power Electronic Converters in ED Systems

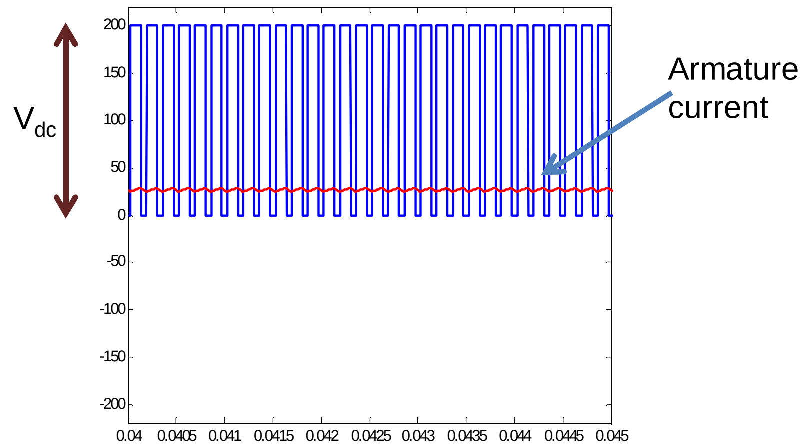
DC DRIVES

AC-DC-DC

DC-DC: Four-quadrant Converter



Bipolar switching scheme



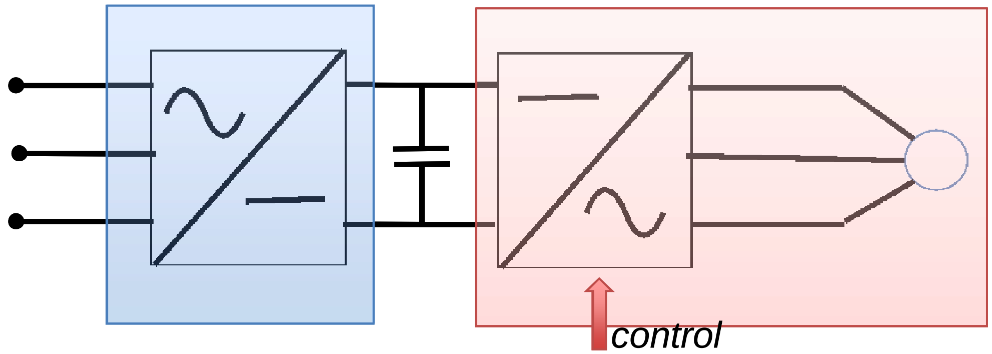
Unipolar switching scheme

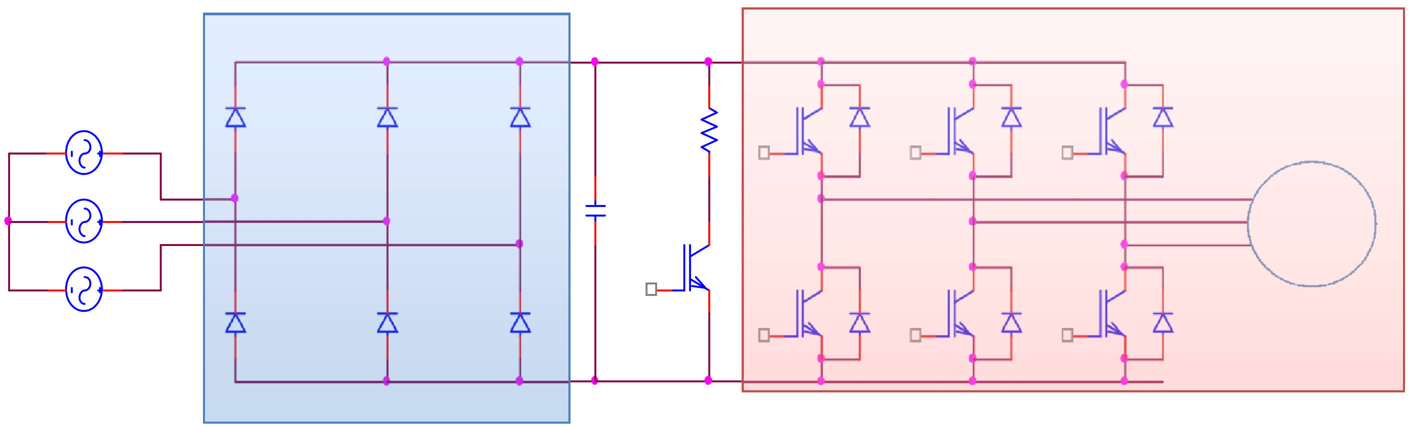
- Current ripple in unipolar is smaller
- Output frequency in unipolar is effectively doubled

Power Electronic Converters in ED Systems

AC DRIVES

AC-DC-AC





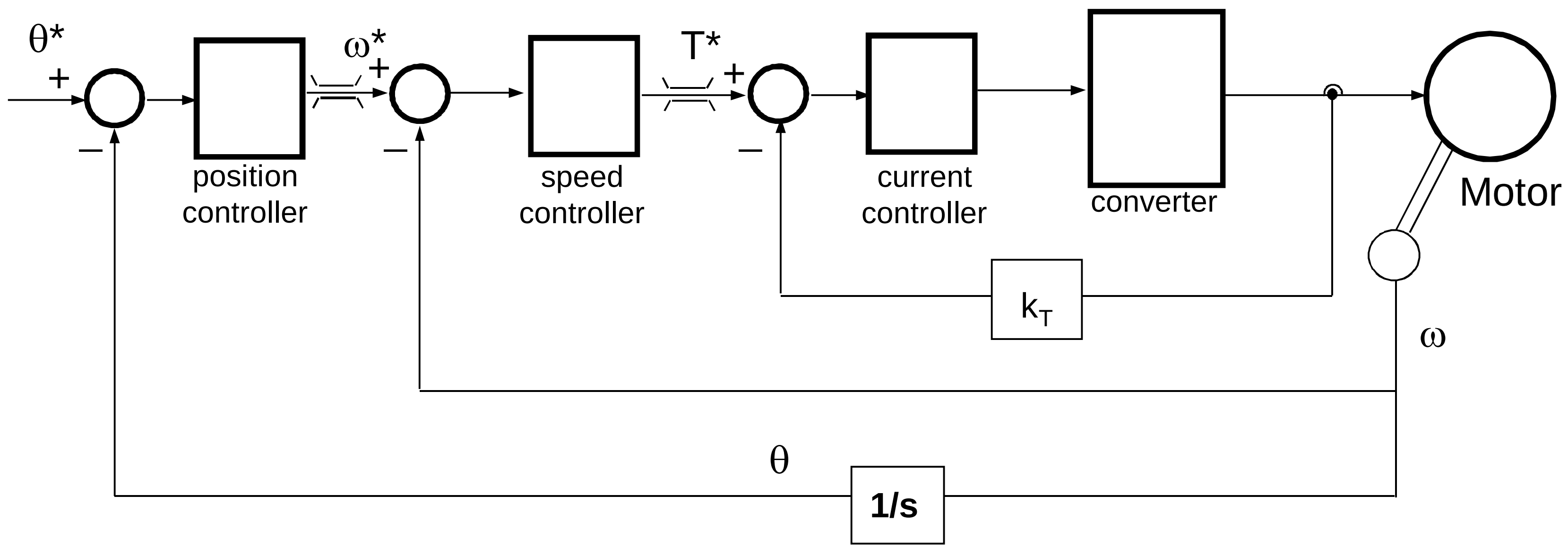
The common PWM technique: CB-SPWM with ZSS

SVPWM

Modeling and Control of Electrical Drives

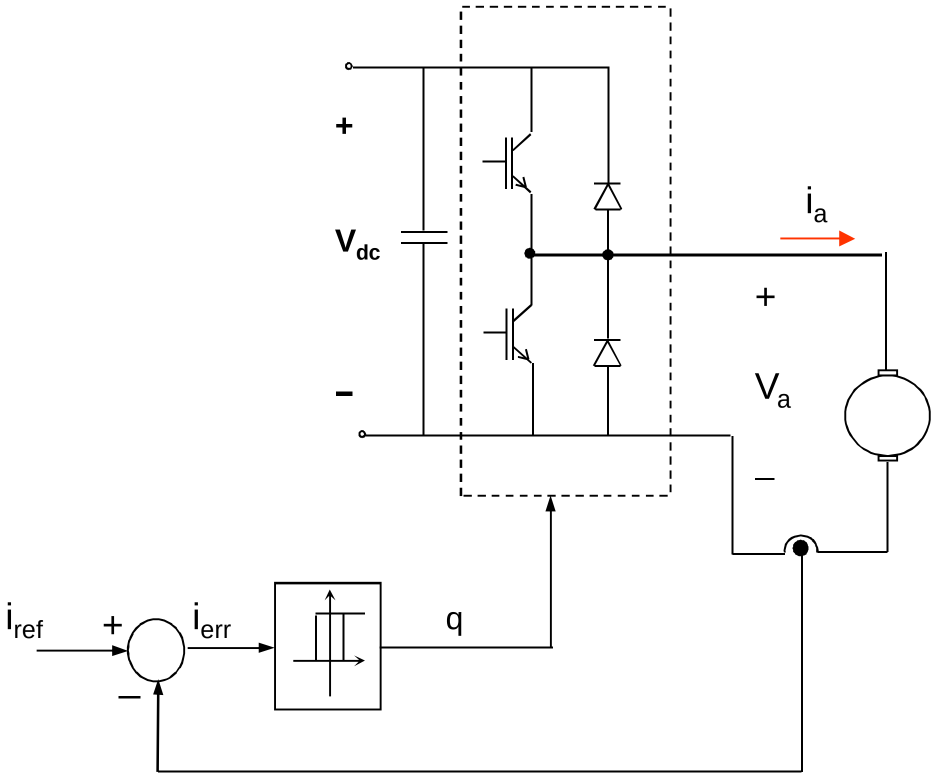
- Control the torque, speed or position
- Cascade control structure

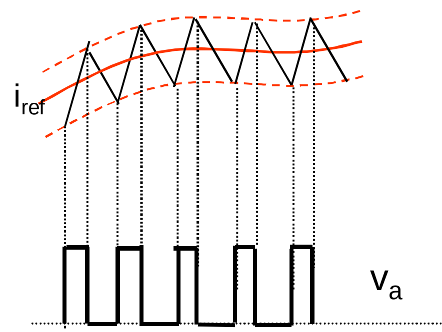
Example of current control in cascade control structure

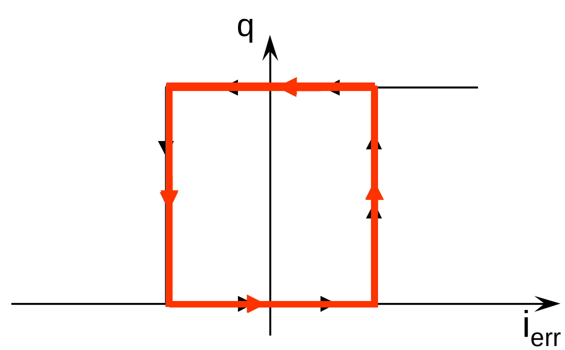


Modeling and Control of Electrical Drives

Current controlled converters in DC Drives - Hysteresis-based





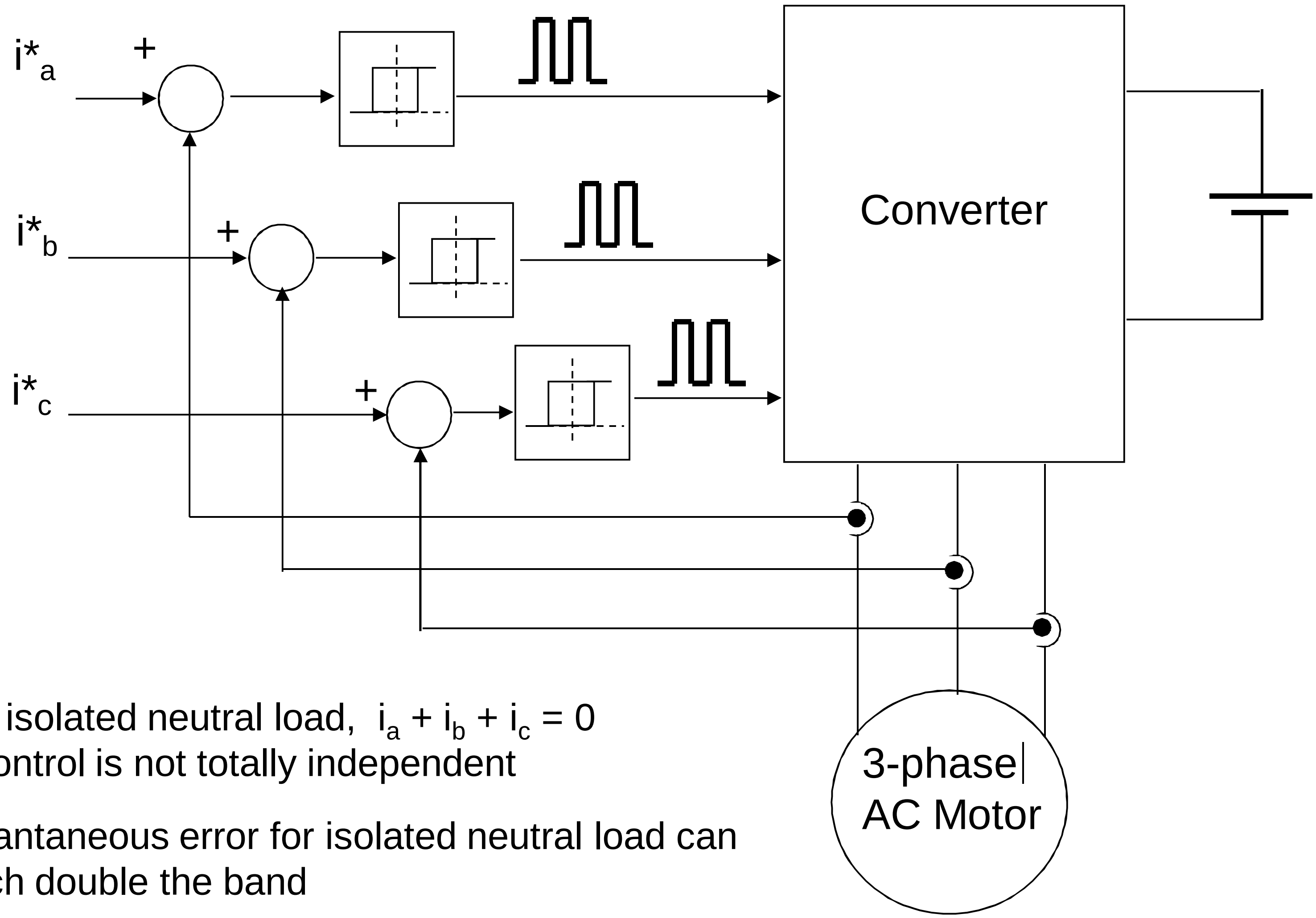


- High bandwidth, simple implementation, insensitive to parameter variations

- Variable switching frequency – depending on operating conditions

Modeling and Control of Electrical Drives

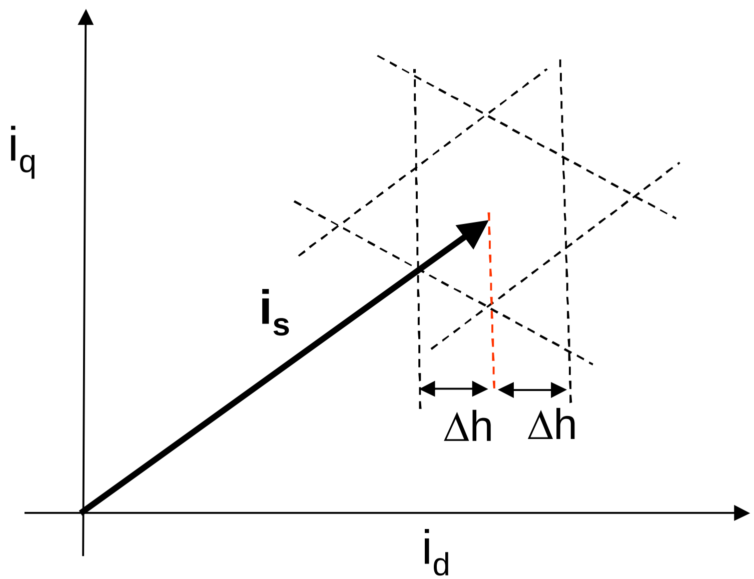
Current controlled converters in AC Drives - Hysteresis-based

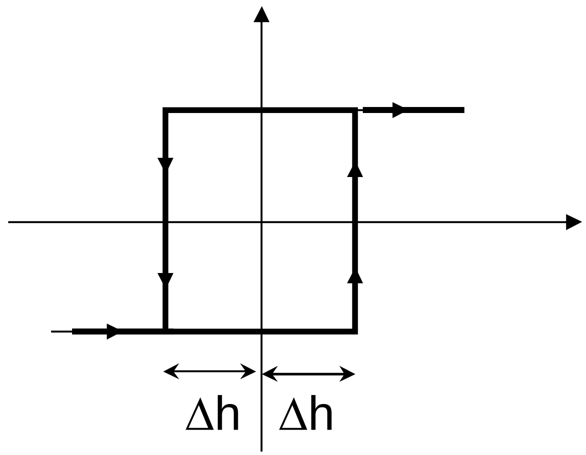


- For isolated neutral load, $i_a + i_b + i_c = 0$
  $\therefore$ control is not totally independent
- Instantaneous error for isolated neutral load can reach double the band

Modeling and Control of Electrical Drives

Current controlled converters in AC Drives - Hysteresis-based





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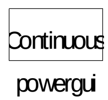
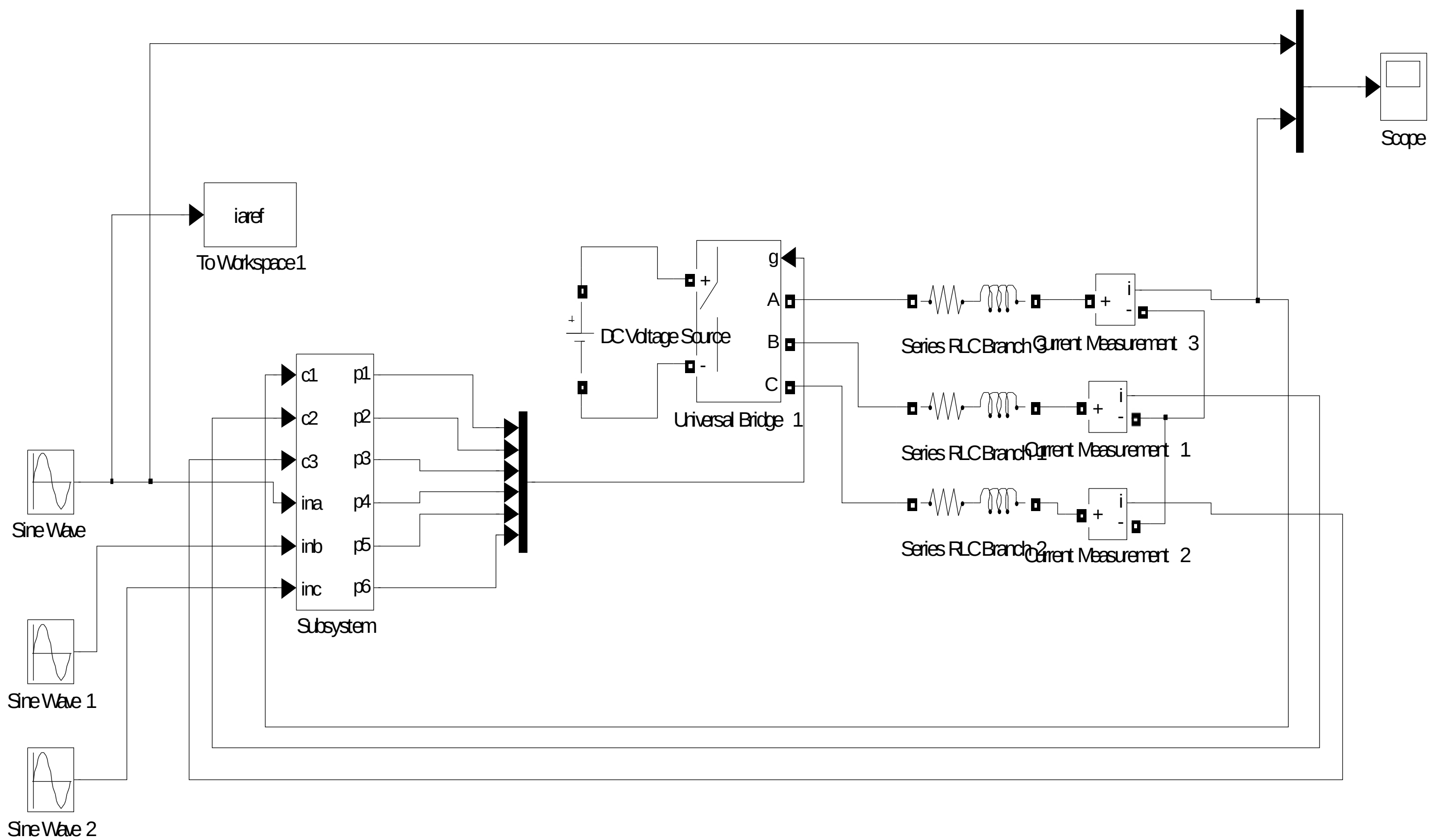
Modeling and Control of Electrical Drives

Current controlled converters in AC Drives - Hysteresis-based



- $\Delta h = 0.3$ A
- Sinusoidal reference current, 30Hz
- Vdc = 600V
- 10Ω, 50mH load

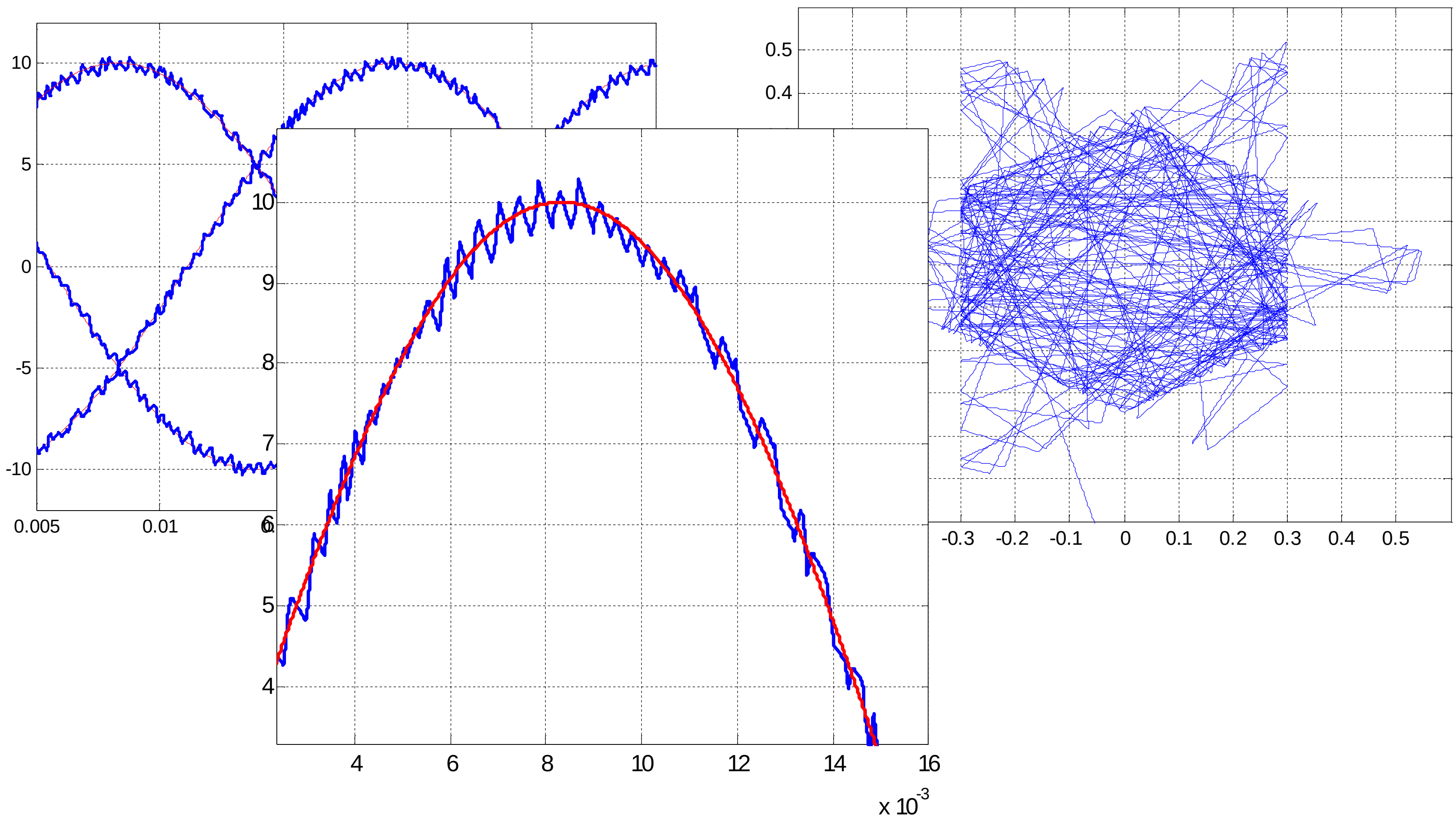


Modeling and Control of Electrical Drives

Current controlled converters in AC Drives - Hysteresis-based

Actual and reference currents

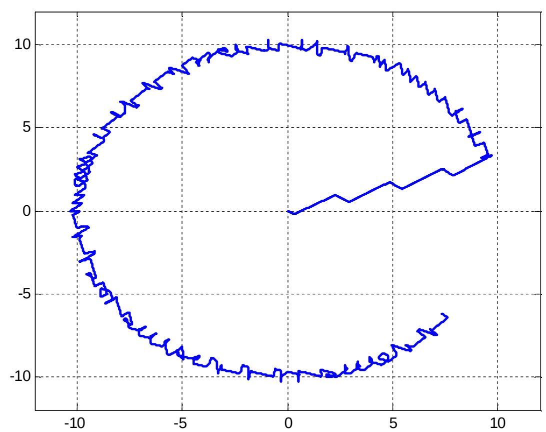
Current error



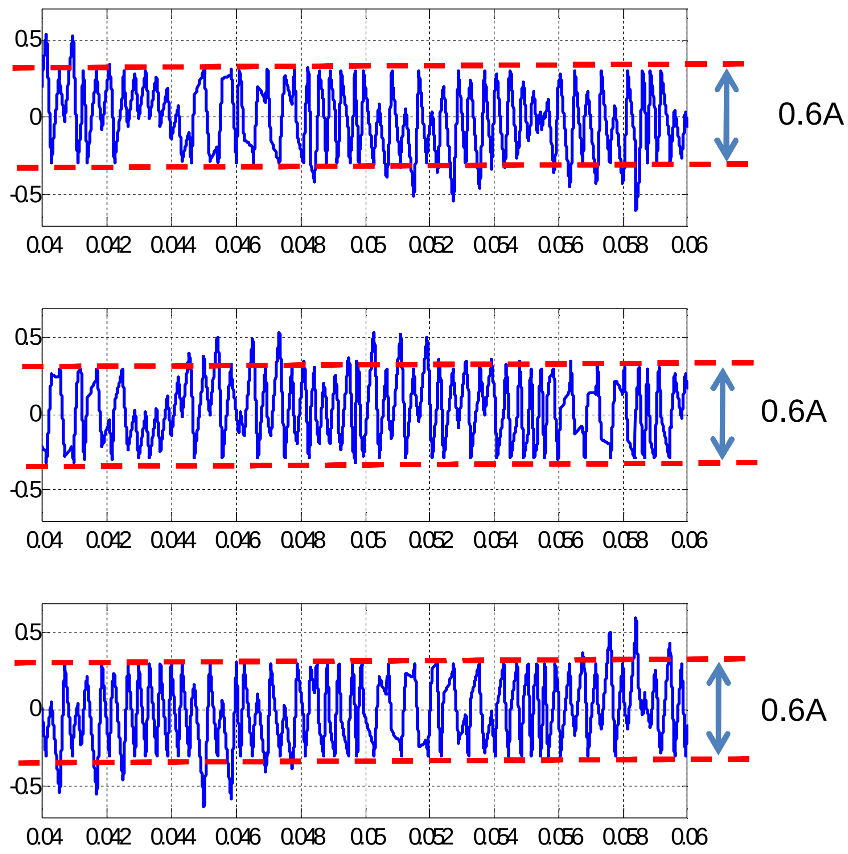
Modeling and Control of Electrical Drives

Current controlled converters in AC Drives - Hysteresis-based

Actual current locus

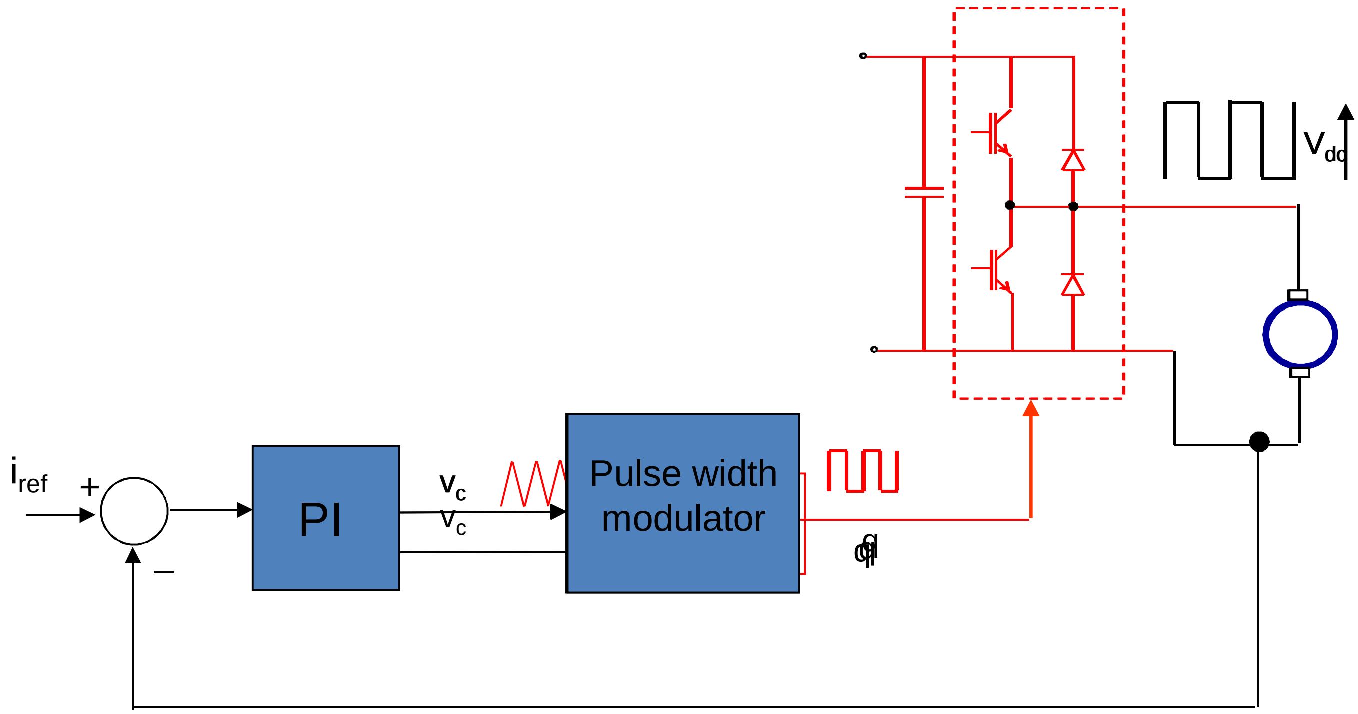


Current error

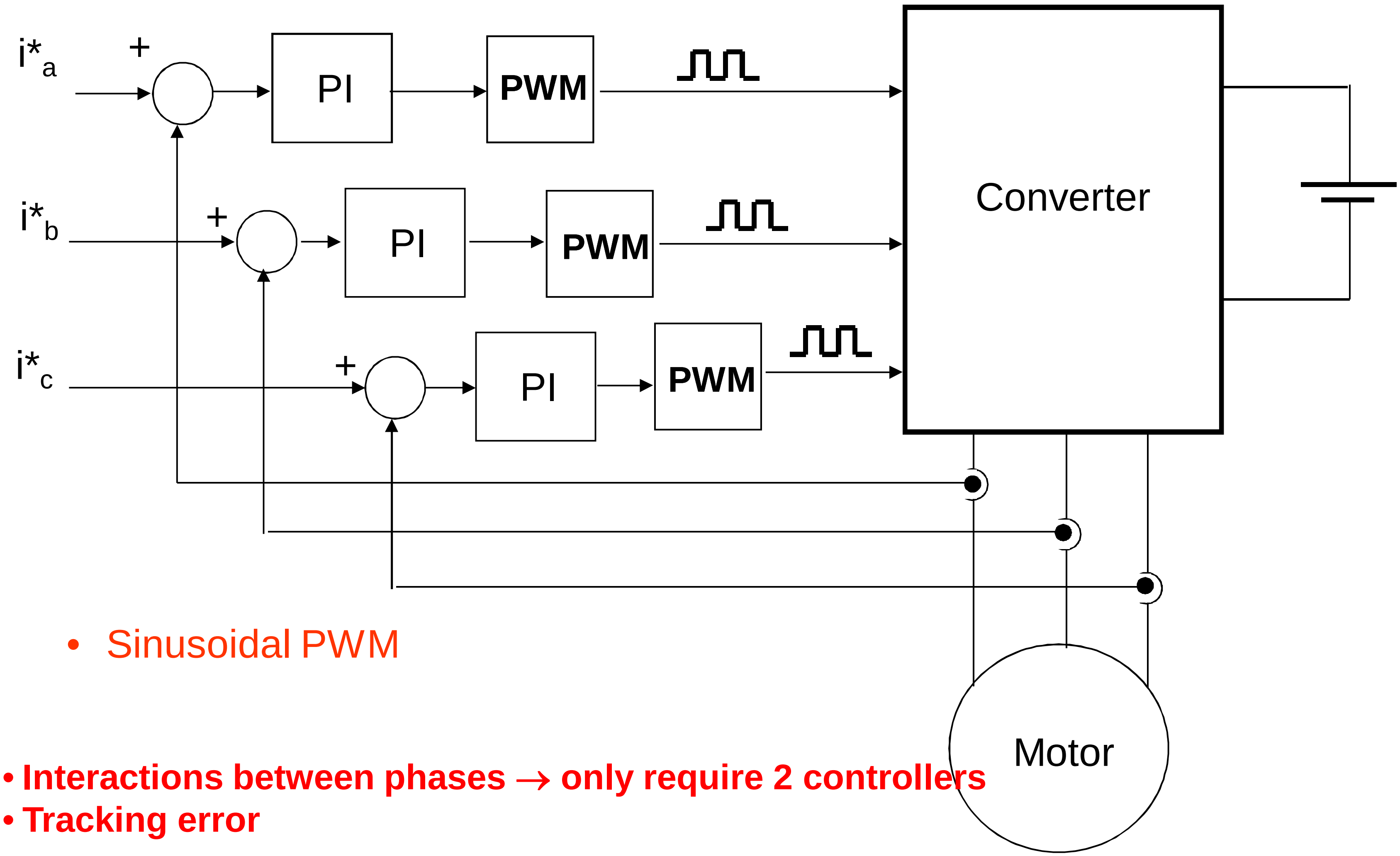


Modeling and Control of Electrical Drives

Current controlled converters in DC Drives - PI-based



Current controlled converters in DC Drives - PI-based



- Sinusoidal PWM

- **Interactions between phases → only require 2 controllers**
- **Tracking error**

Modeling and Control of Electrical Drives

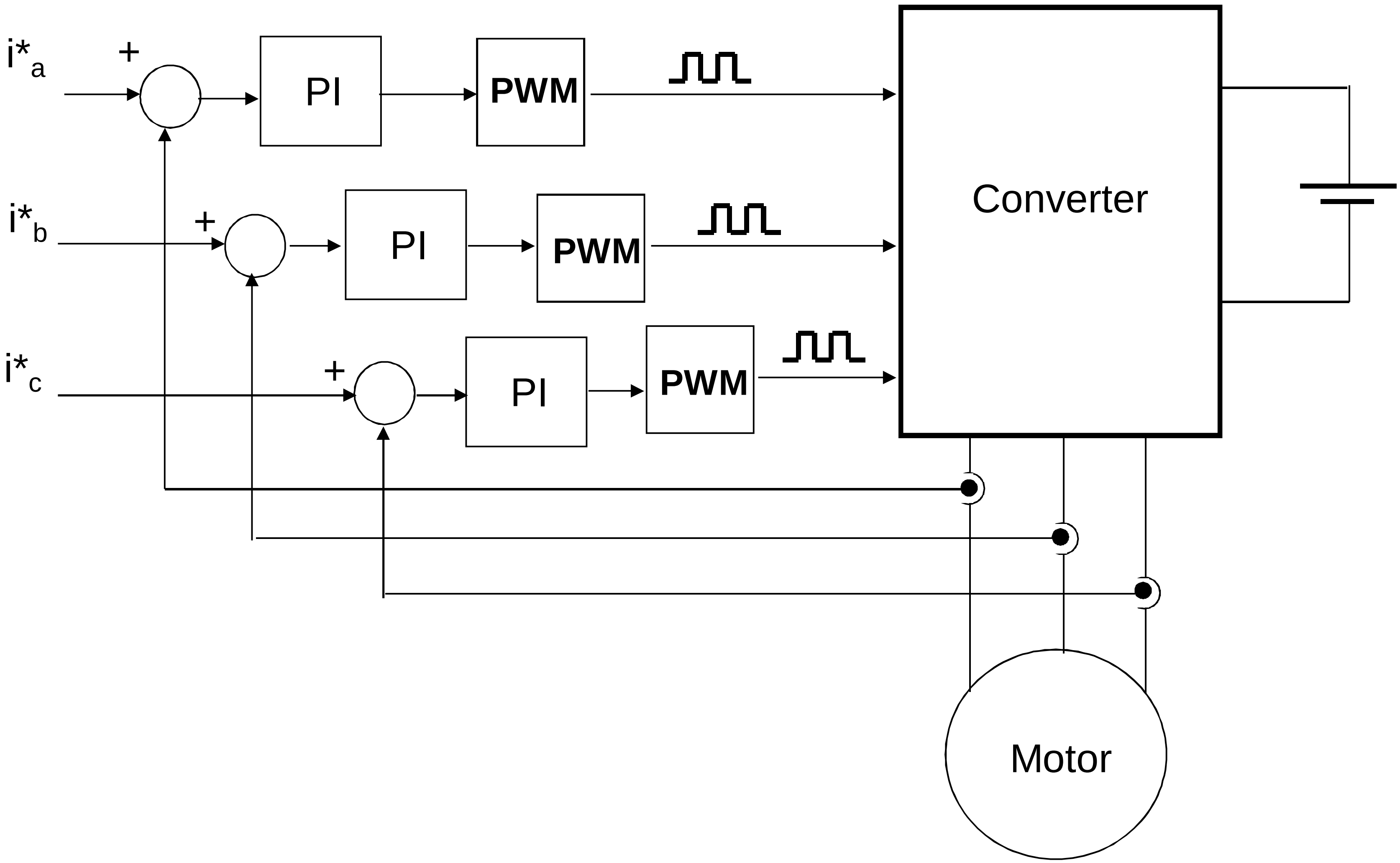
Current controlled converters in DC Drives - PI-based

- **Perform the 3-phase to 2-phase transformation**
  - only two controllers (instead of 3) are used
- **Perform the control in synchronous frame**
  - the current will appear as DC

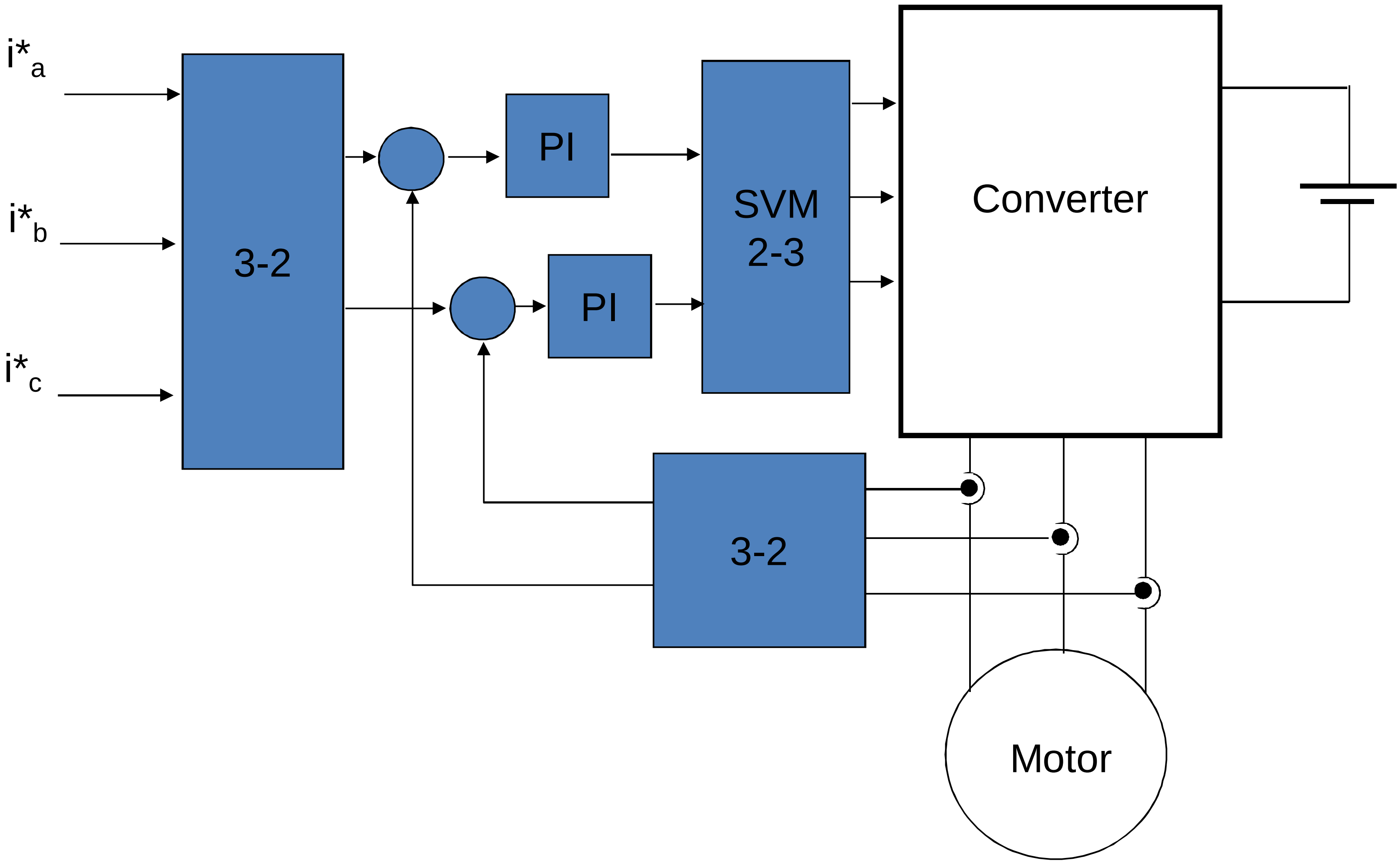
- **Interactions between phases → only require 2 controllers**
- **Tracking error**

Modeling and Control of Electrical Drives

Current controlled converters in AC Drives - PI-based

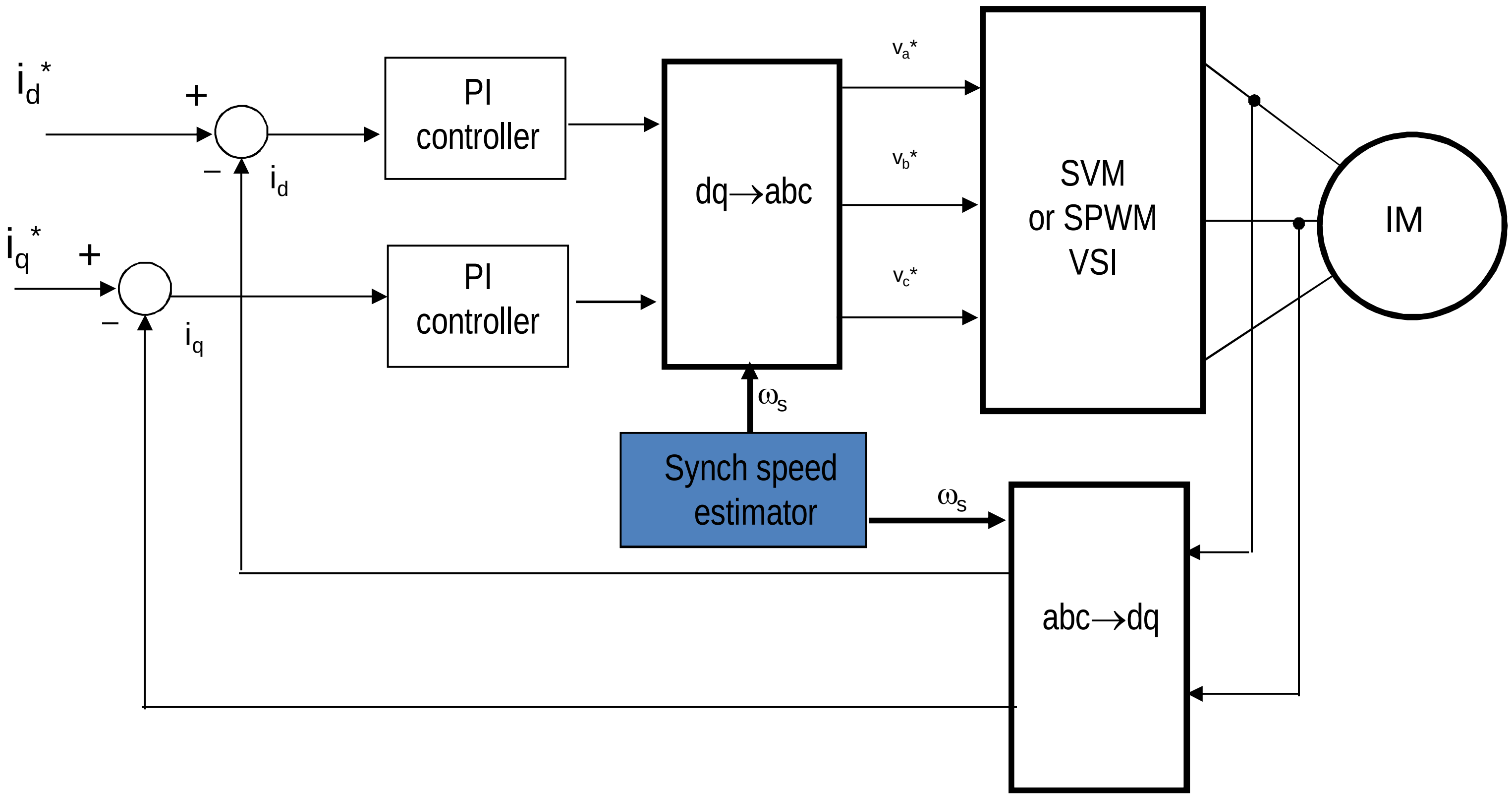


Current controlled converters in AC Drives - PI-based



Modeling and Control of Electrical Drives

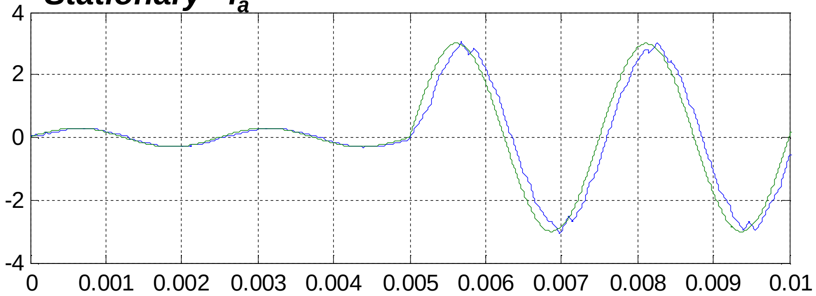
Current controlled converters in AC Drives - PI-based



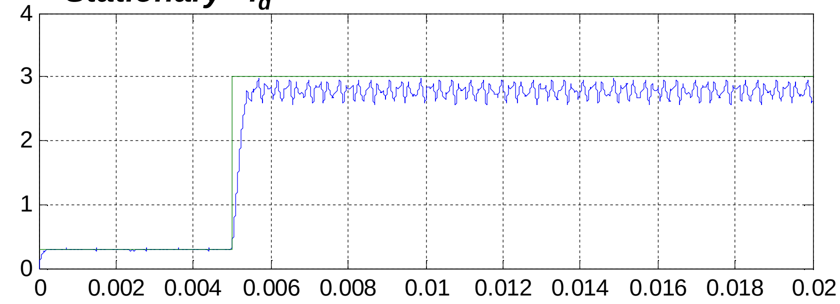
Modeling and Control of Electrical Drives

Current controlled converters in AC Drives - PI-based

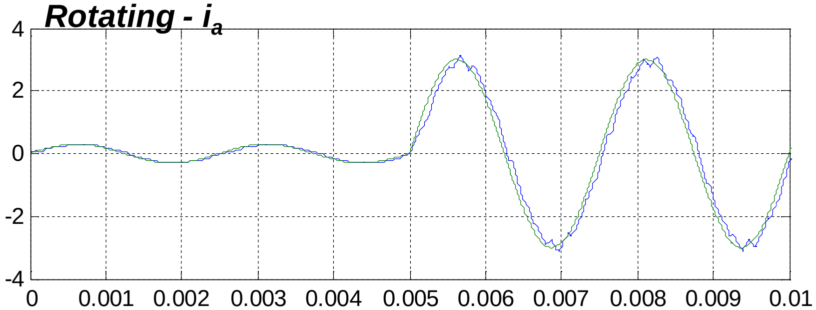
Stationary - i_a



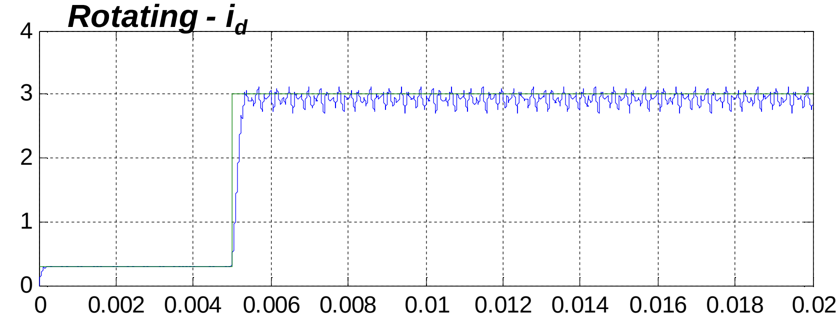
Stationary - i_d



Rotating - i_a

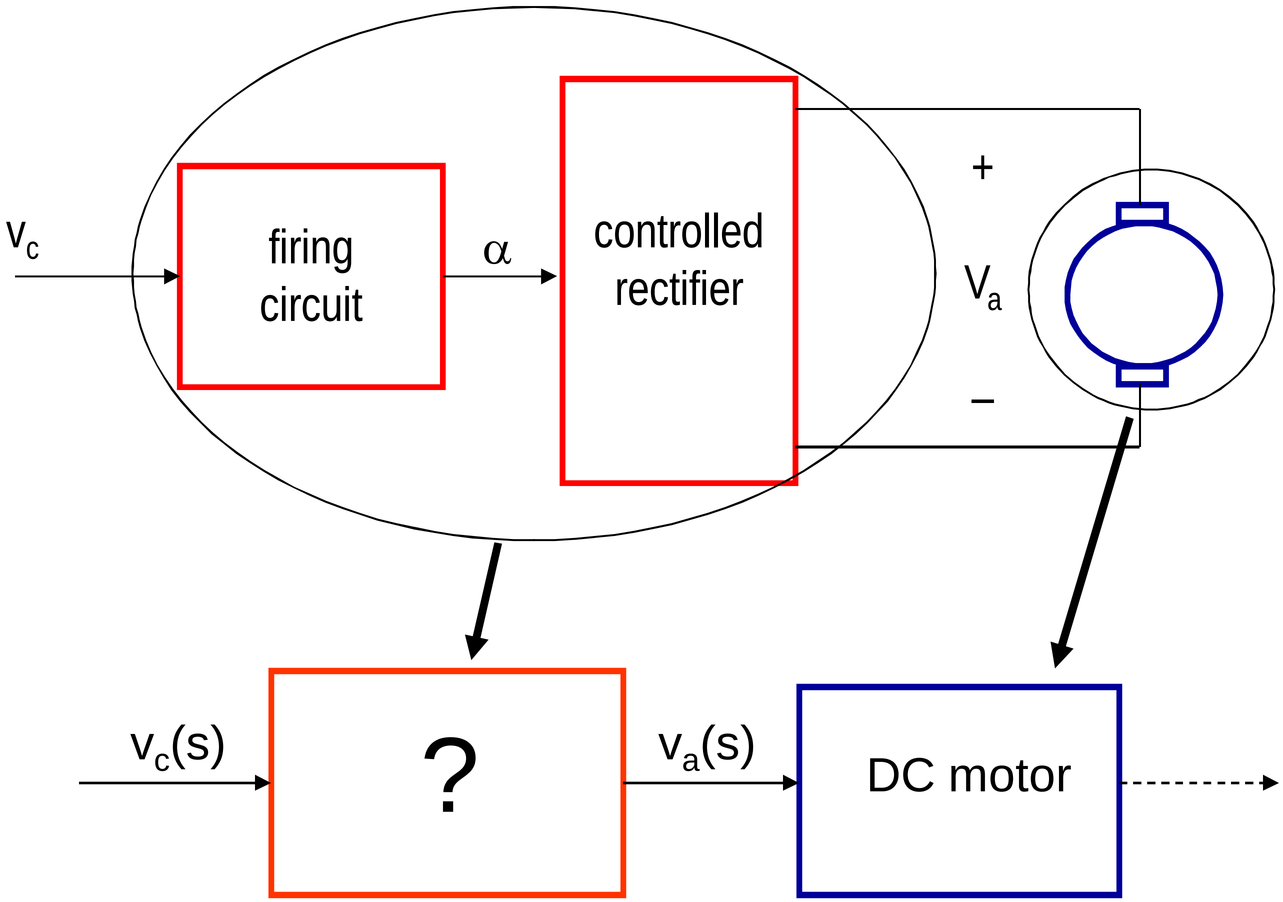


Rotating - i_d



Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier



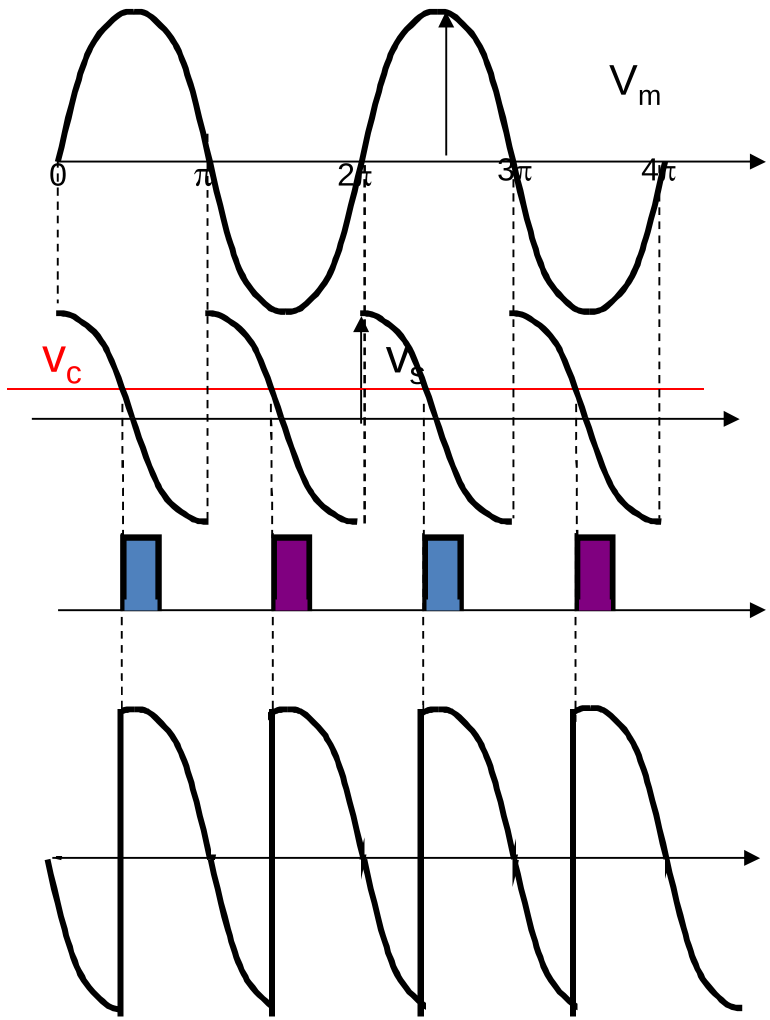
The relation between v_c and v_a is determined by the firing circuit

It is desirable to have a linear relation between v_c and v_a

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier

Cosine-wave crossing control



Input voltage

Cosine wave compared with v_c

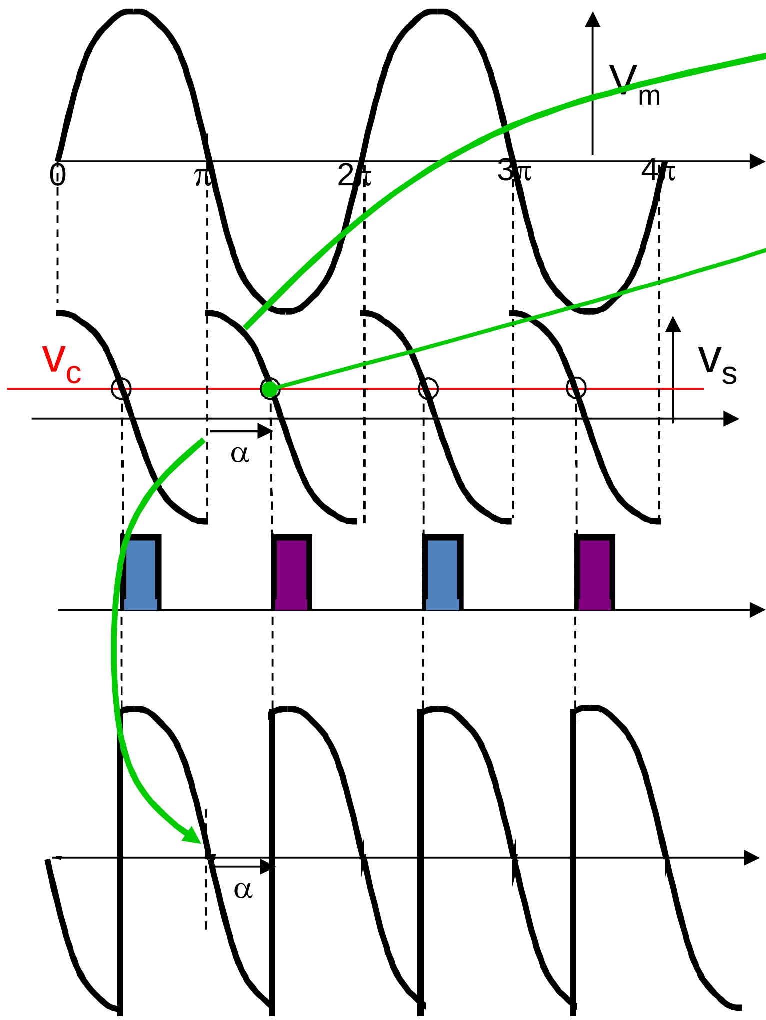
Results of comparison trigger SCRs

Output voltage

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier

Cosine-wave crossing control



$$V_s\cos(\alpha) = v_c$$

$$\alpha = \cos^{-1}\left(\frac{v_c}{V_s}\right)$$

$$V_a = \frac{2V_m}{\pi}\cos\left(\cos^{-1}\left(\frac{v_c}{V_s}\right)\right)$$

$$V_a = \frac{2V_m}{\pi}\frac{v_c}{V_s}$$

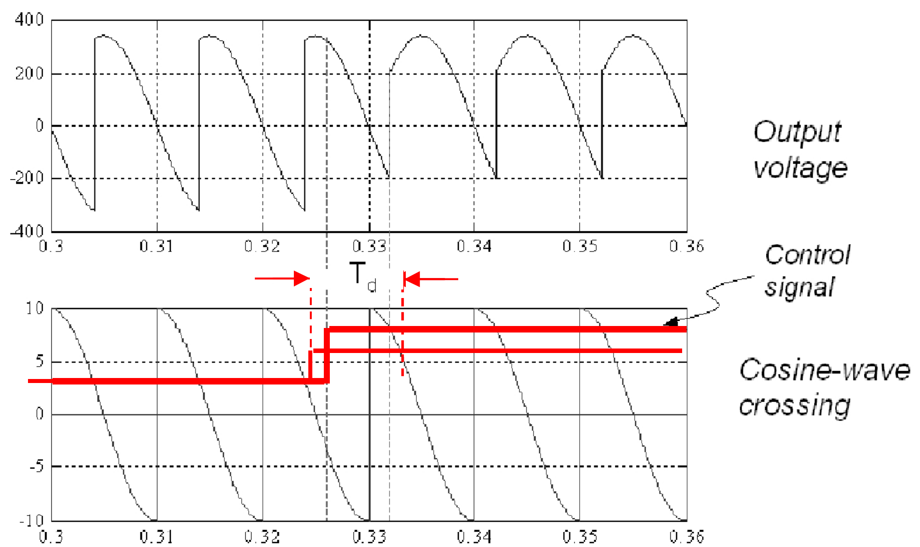
A linear relation between v_c and V_a

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier

V_a is the average voltage over one period of the waveform
- sampled data system

Delays depending on when the control signal changes – normally taken as half of sampling period



T_d – Delay in average output voltage generation
0 – 10 ms for 50 Hz single phase system

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier

V_a is the average voltage over one period of the waveform
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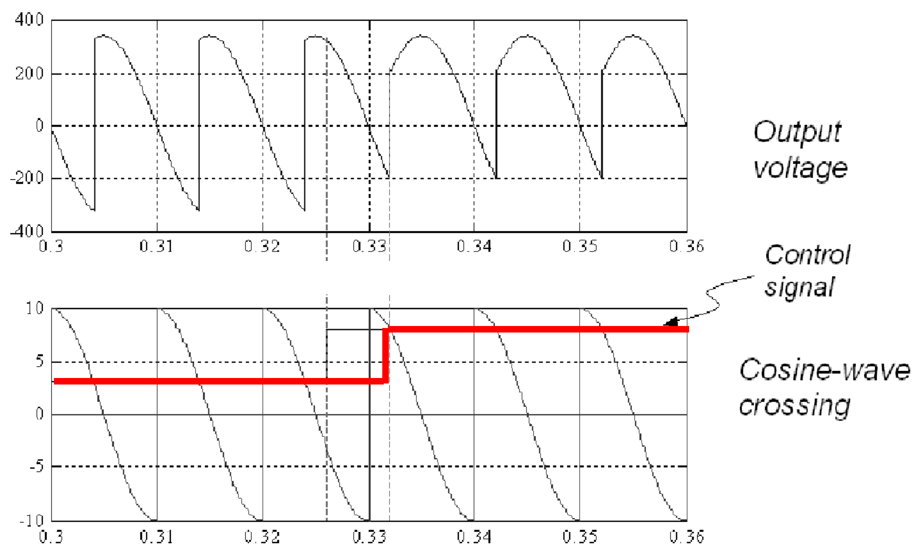
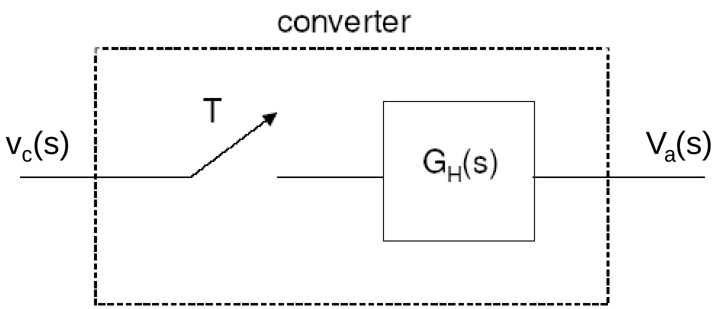


T_d – Delay in average output voltage generation
0 – 10 ms for 50 Hz single phase system

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier

$$G_H(s) = Ke^{-\frac{T}{2}s}$$



<u>Single phase, 50Hz</u>

$$K = \frac{2V_m}{\pi V_s}$$ T=10ms

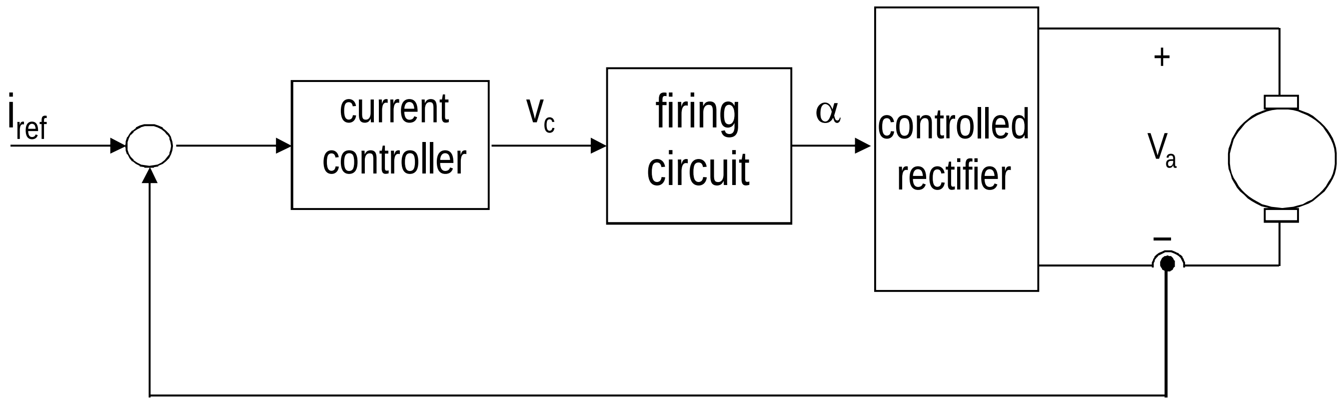
<u>Three phase, 50Hz</u>

$$K = \frac{3V_{L-L,m}}{\pi V_s}$$ T=3.33ms

Simplified if control bandwidth is reduced to much lower than the sampling frequency

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier

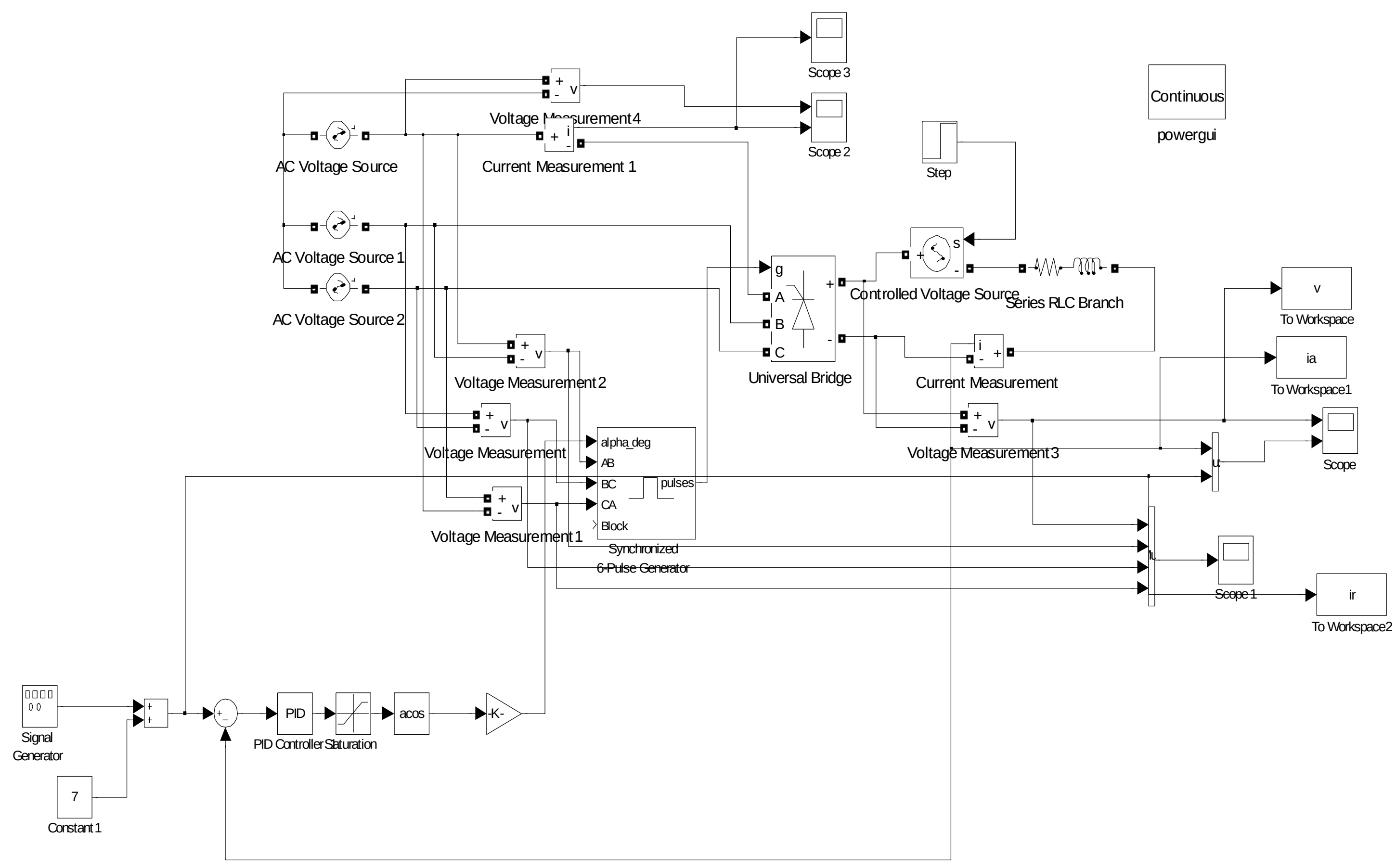


- To control the current – current-controlled converter
- Torque can be controlled
- Only operates in Q1 and Q4 (single converter topology)

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier

- Input 3-phase, 240V, 50Hz
- Closed loop current control with PI controller



Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with Controlled rectifier

- Input 3-phase, 240V, 50Hz
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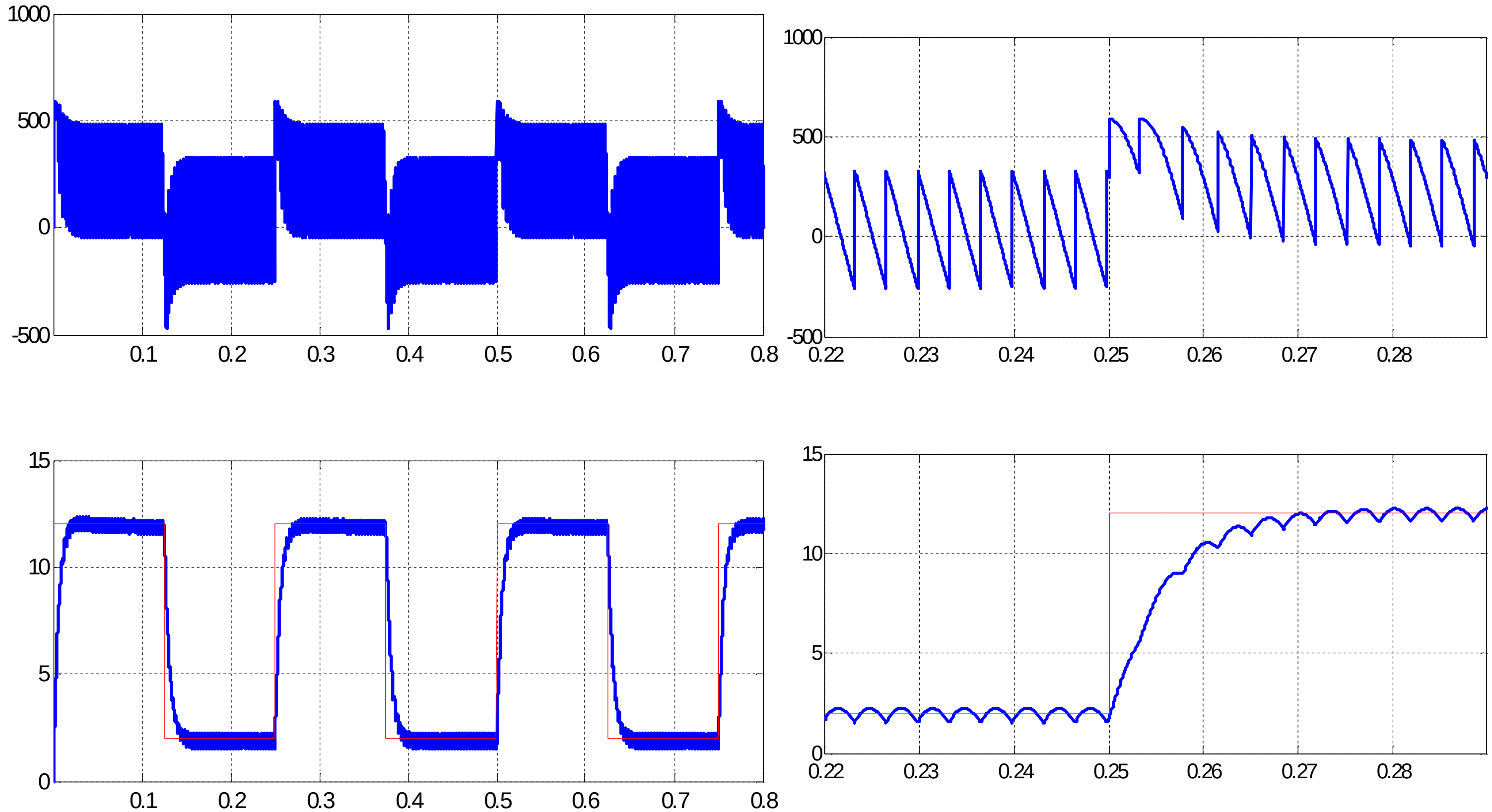


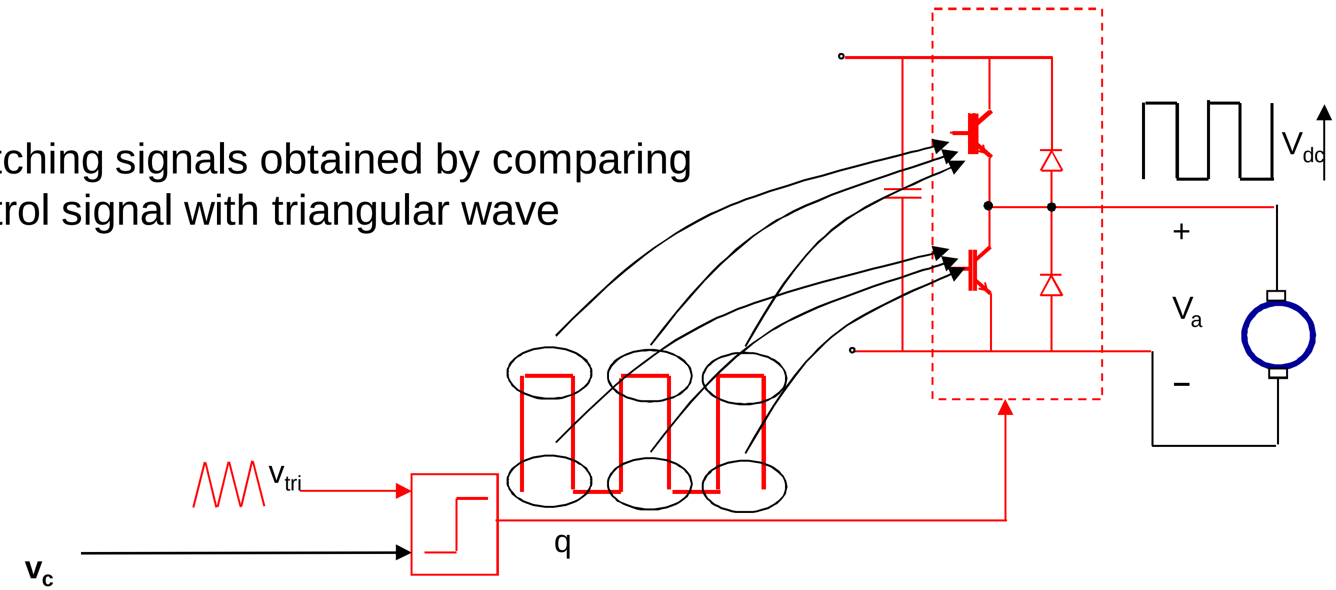
Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Modeling and Control of Electrical Drives

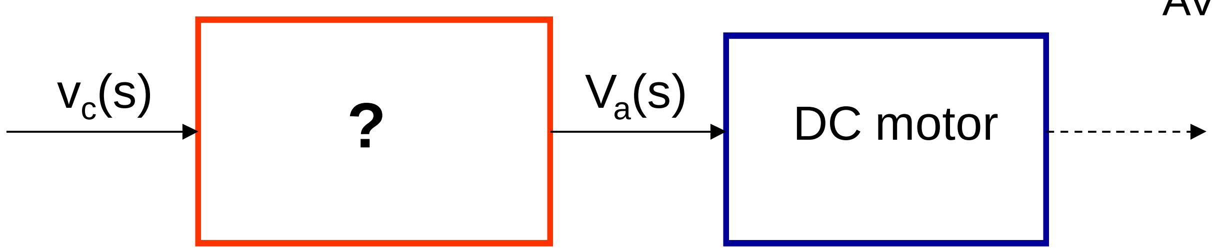
Modeling of the Power Converters: DC drives with SM Converters

Switching signals obtained by comparing control signal with triangular wave



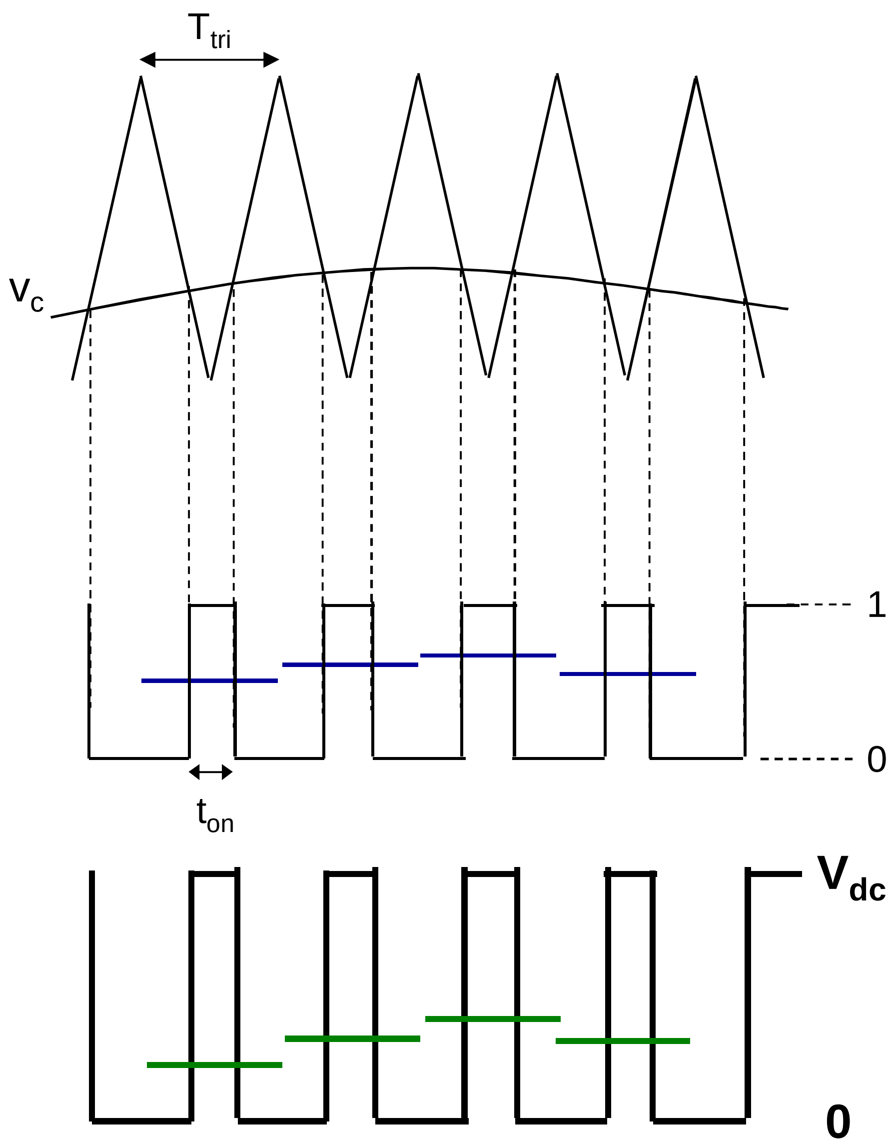
We want to establish a relation between $\mathbf{v_c}$ and $\mathbf{\underline{V_a}}$

AVERAGE voltage



Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters



$$q = \begin{cases} 1 & V_c > V_{tri} \\ 0 & V_c < V_{tri} \end{cases}$$

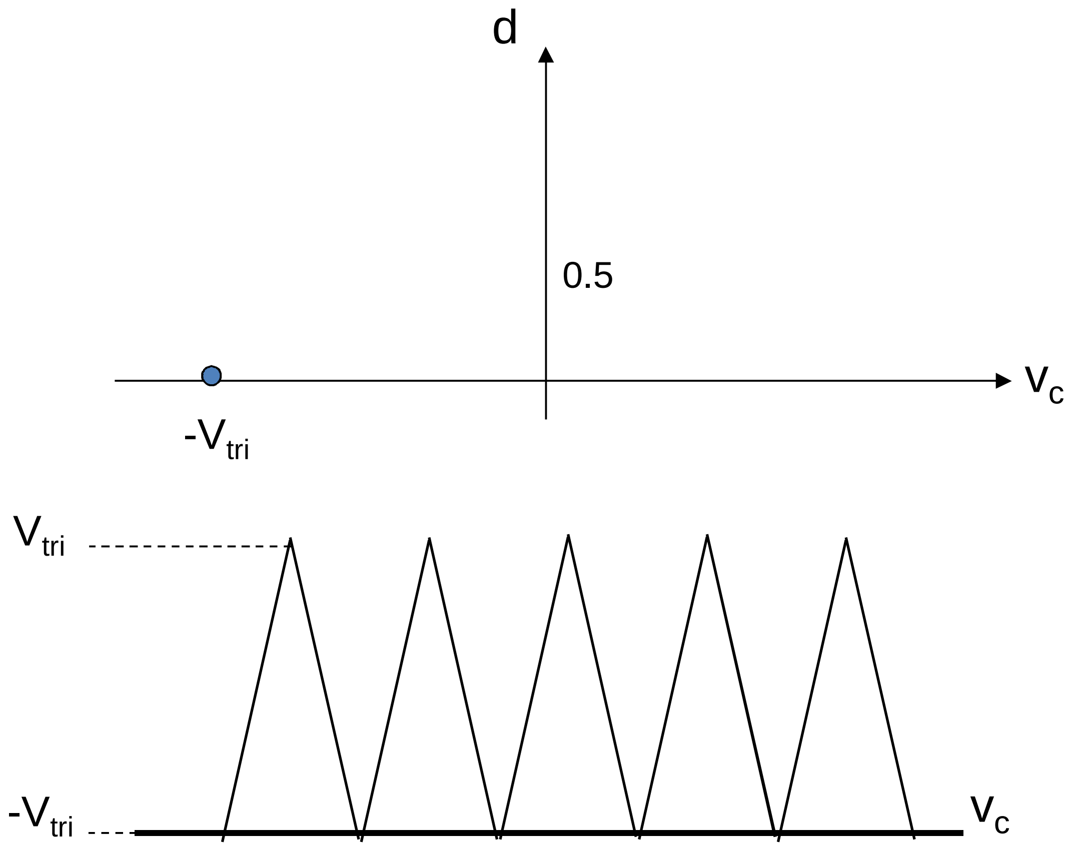
$$d = \frac{1}{T_{tri}} \int_t^{t+T_{tri}} q\,dt$$

$$= \frac{t_{on}}{T_{tri}}$$

$$V_a = \frac{1}{T_{tri}} \int_0^{dT_{tri}} V_{dc}\,dt = dV_{dc}$$

Modeling and Control of Electrical Drives

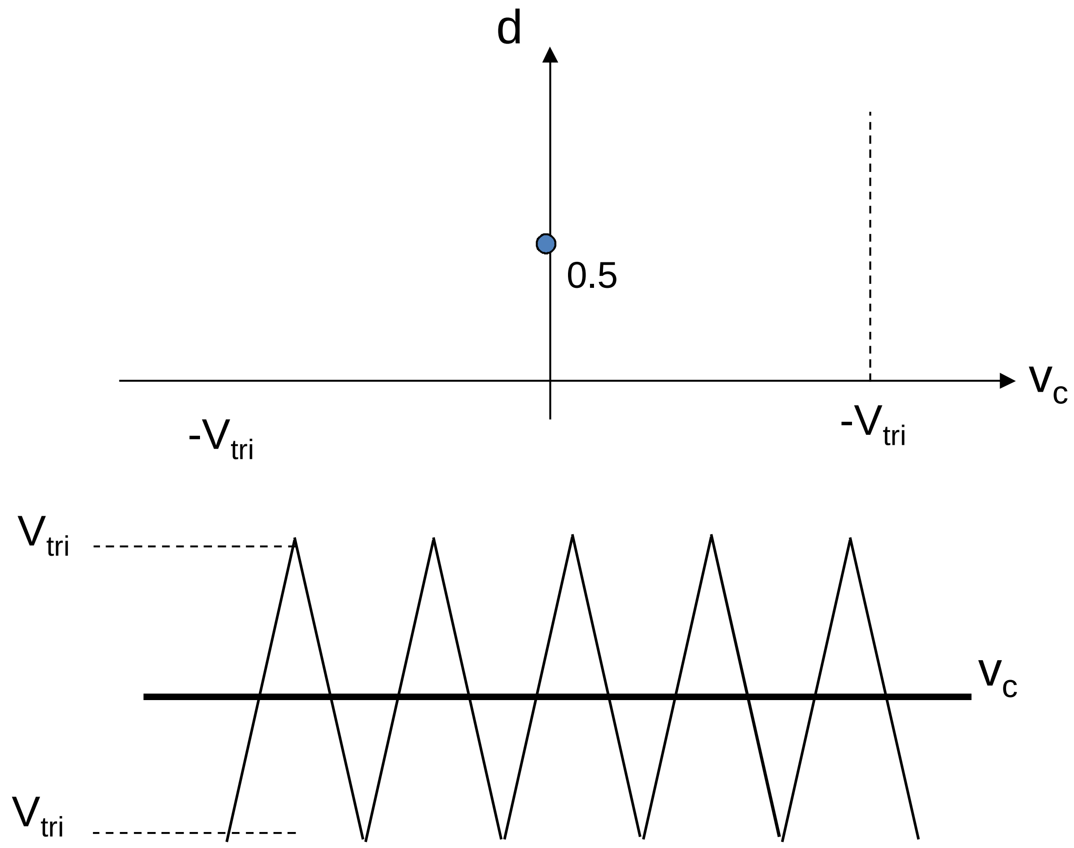
Modeling of the Power Converters: DC drives with SM Converters



For $v_c = -V_{tri} \rightarrow d = 0$

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

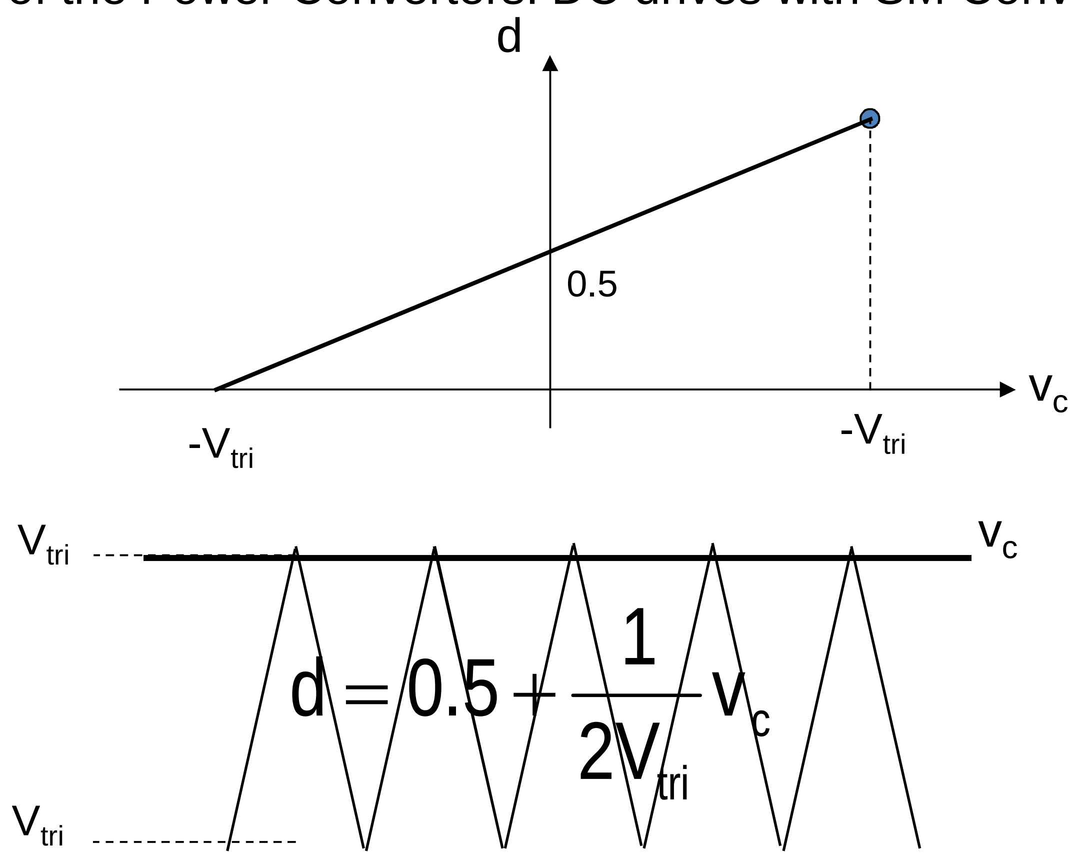


For $v_c = -V_{tri} \rightarrow d = 0$

For $v_c = 0 \rightarrow d = 0.5$

For $v_c = V_{tri} \rightarrow d = 1$

Modeling of the Power Converters: DC drives with SM Converters



$$d = 0.5 + \frac{1}{2V_{tri}} v_c$$

For $v_c = -V_{tri}$ $\rightarrow$ $d = 0$

For $v_c = 0$ $\rightarrow$ $d = 0.5$

For $v_c = V_{tri}$ $\rightarrow$ $d = 1$

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Thus relation between v_c and V_a is obtained as:

$$V_a = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri}} v_c$$

Introducing perturbation in v_c and V_a and separating DC and AC components:

DC:

$$V_a = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri}} v_c$$

AC:

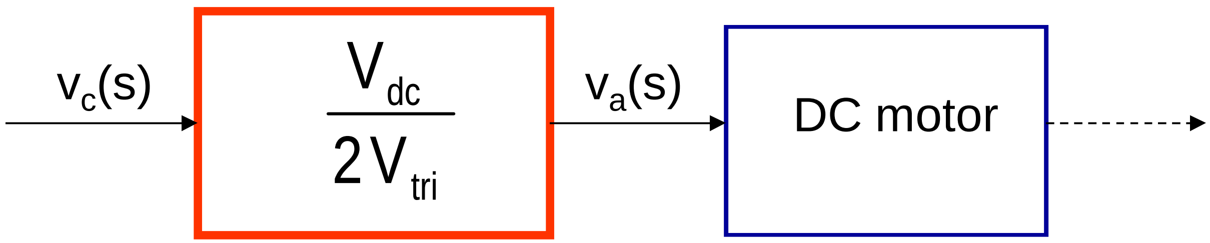
$$\tilde{v}_a = \frac{V_{dc}}{2V_{tri}} \tilde{v}_c$$

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Taking Laplace Transform on the AC, the transfer function is obtained as:

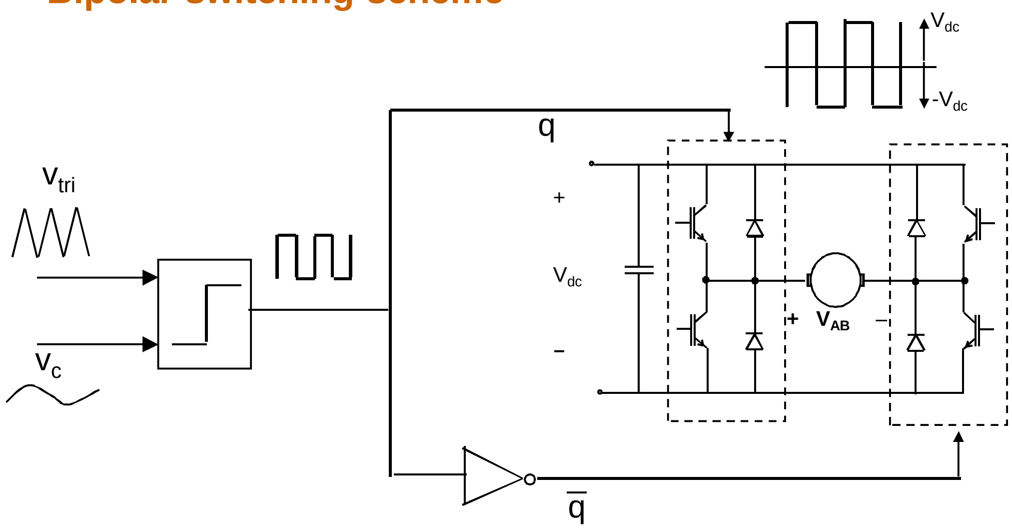
$$\frac{v_a(s)}{v_c(s)} = \frac{V_{dc}}{2V_{tri}}$$

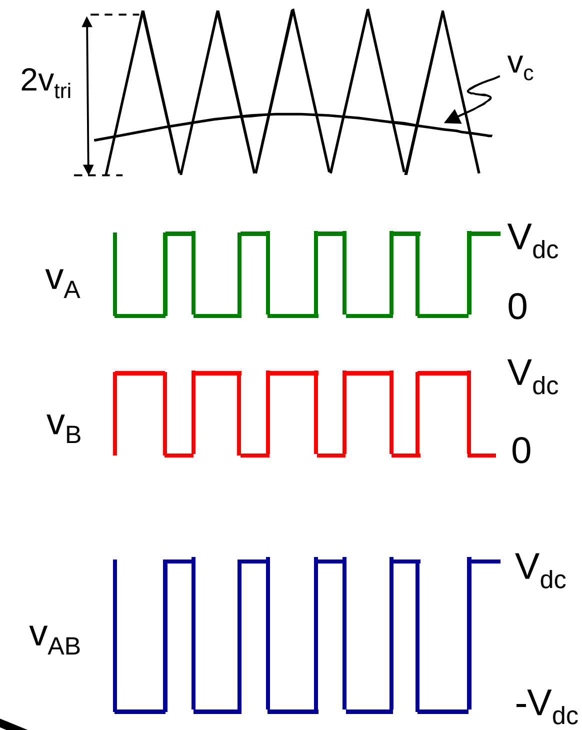


Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Bipolar switching scheme





$$d_A = 0.5 + \frac{v_c}{2V_{tri}}$$

$$d_B = 1 - d_A = 0.5 - \frac{v_c}{2V_{tri}}$$

$$V_A = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri}} v_c$$

$$V_B = 0.5V_{dc} - \frac{V_{dc}}{2V_{tri}} v_c$$

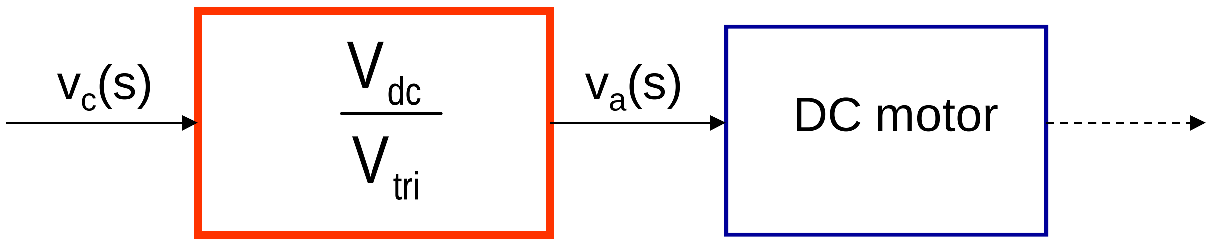
$$V_A - V_B = V_{AB} = \frac{V_{dc}}{V_{tri}} v_c$$

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Bipolar switching scheme

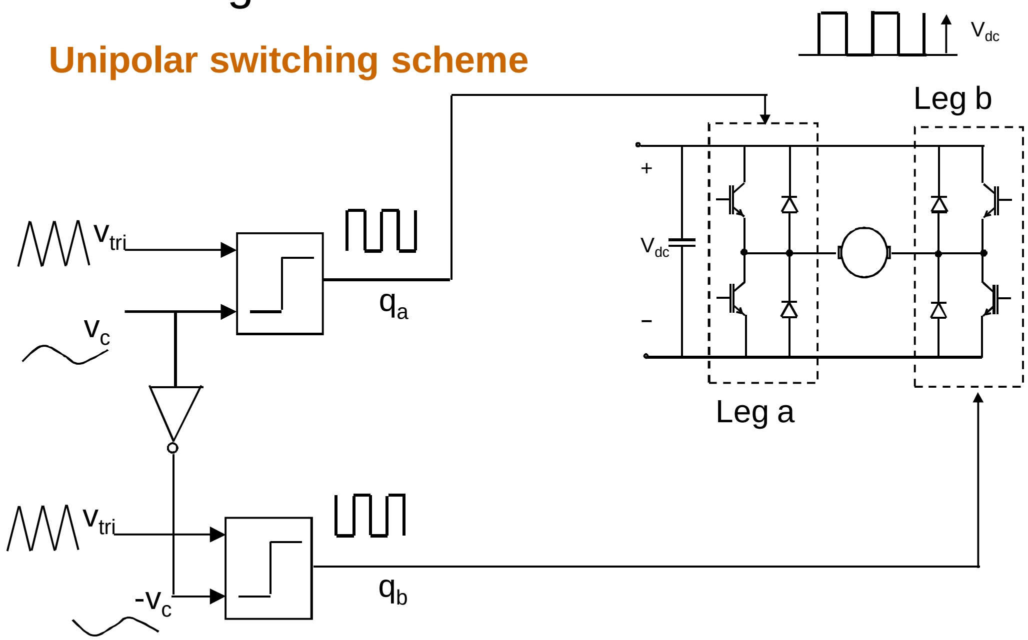
$$\frac{v_a(s)}{v_c(s)} = \frac{V_{dc}}{V_{tri}}$$

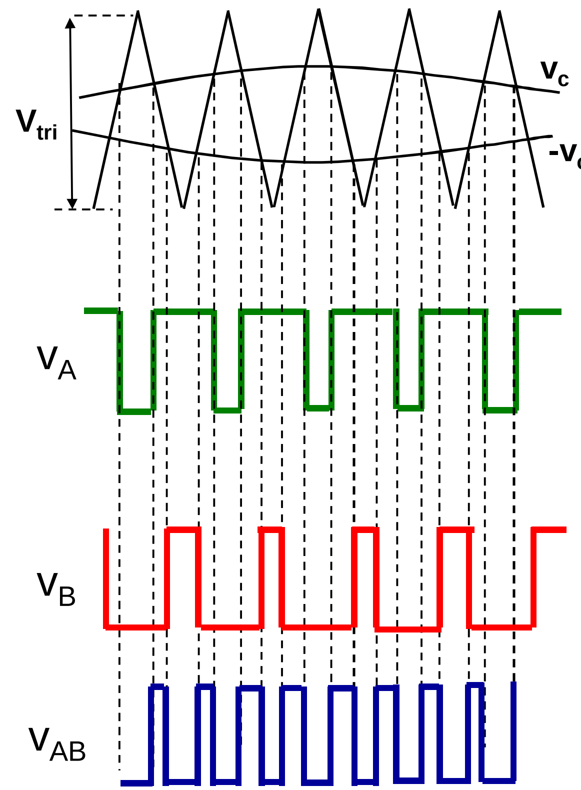


Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Unipolar switching scheme





$$d_A = 0.5 + \frac{v_c}{2V_{tri}}$$

$$d_B = 0.5 + \frac{-v_c}{2V_{tri}}$$

$$V_A = 0.5V_{dc} + \frac{V_{dc}}{2V_{tri}} v_c$$

$$V_B = 0.5V_{dc} - \frac{V_{dc}}{2V_{tri}} v_c$$

$$V_A - V_B = V_{AB} = \frac{V_{dc}}{V_{tri}} v_c$$

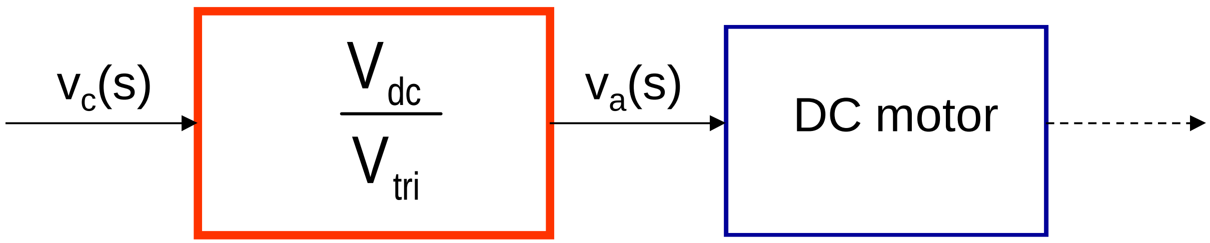
The same average value we've seen for bipolar !

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Unipolar switching scheme

$$\frac{v_a(s)}{v_c(s)} = \frac{V_{dc}}{V_{tri}}$$



Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

DC motor – separately excited or permanent magnet

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

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

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

<u>ac components</u>

$$\tilde{v}_t = \tilde{i}_a R_a + L_a \frac{d\tilde{i}_a}{dt} + \tilde{e}_a$$

$$\tilde{T}_e = k_E(\tilde{i}_a)$$

$$\tilde{e}_e = k_E(\tilde{\omega})$$

$$\tilde{T}_e = \tilde{T}_L + B\tilde{\omega} + J\frac{d(\tilde{\omega})}{dt}$$

<u>dc components</u>

$$V_t = I_a R_a + E_a$$

$$T_e = k_E I_a$$

$$E_e = k_E \omega$$

$$T_e = T_L + B(\omega)$$

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

DC motor – separately excited or permanent magnet

Perform Laplace Transformation on ac components

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

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

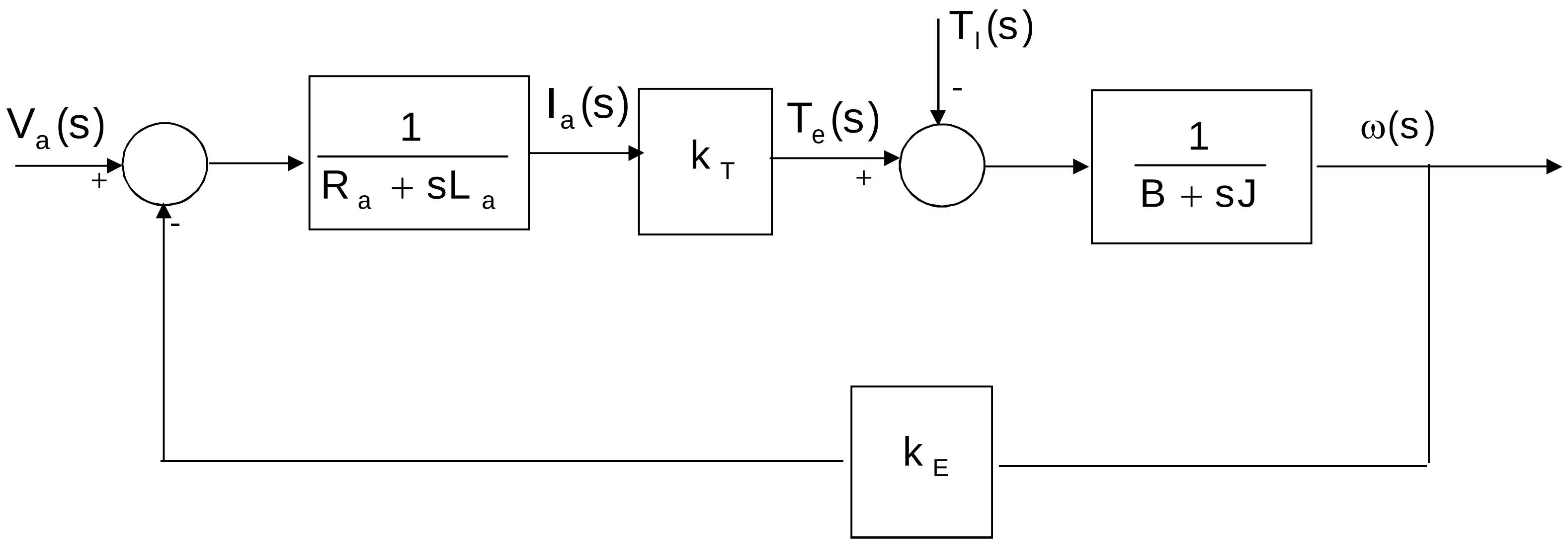
$$\tilde{e}_e = k_E(\tilde{\omega}) \quad \Longrightarrow \quad E_a(s) = k_E \omega(s)$$

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

Modeling and Control of Electrical Drives

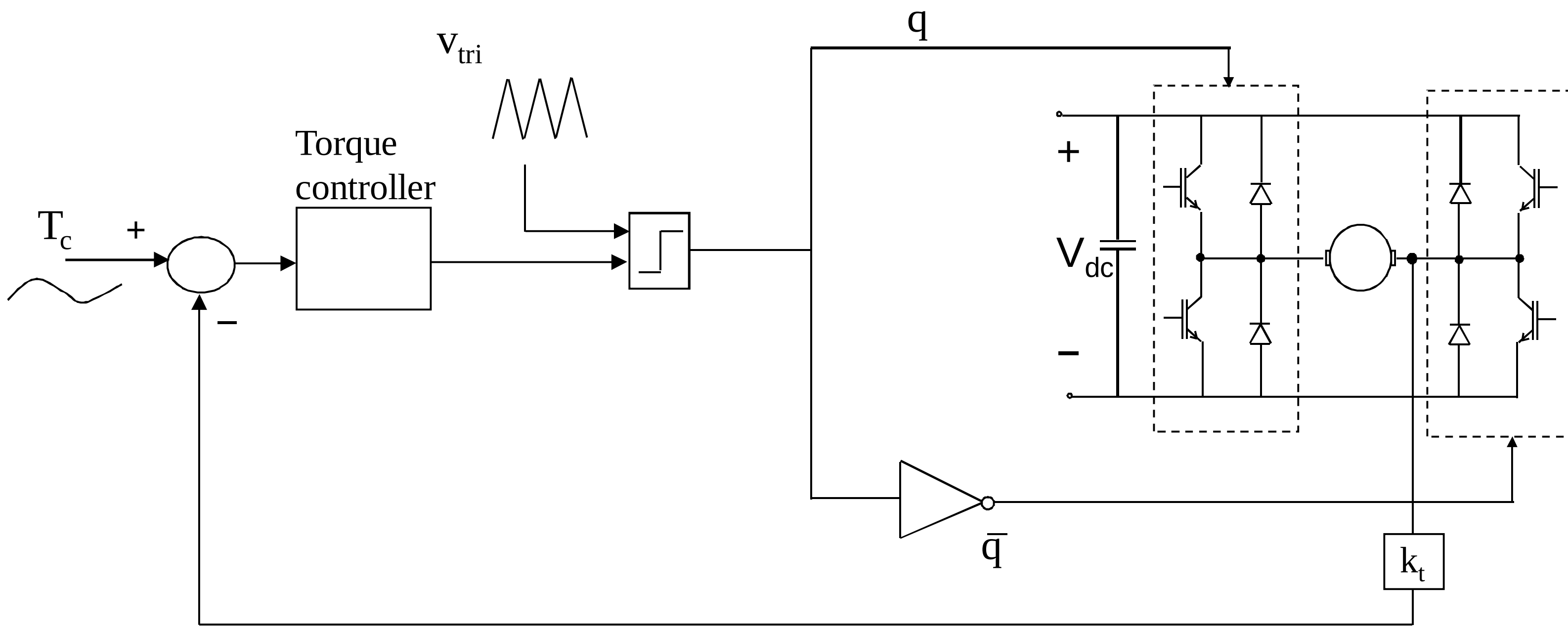
Modeling of the Power Converters: DC drives with SM Converters

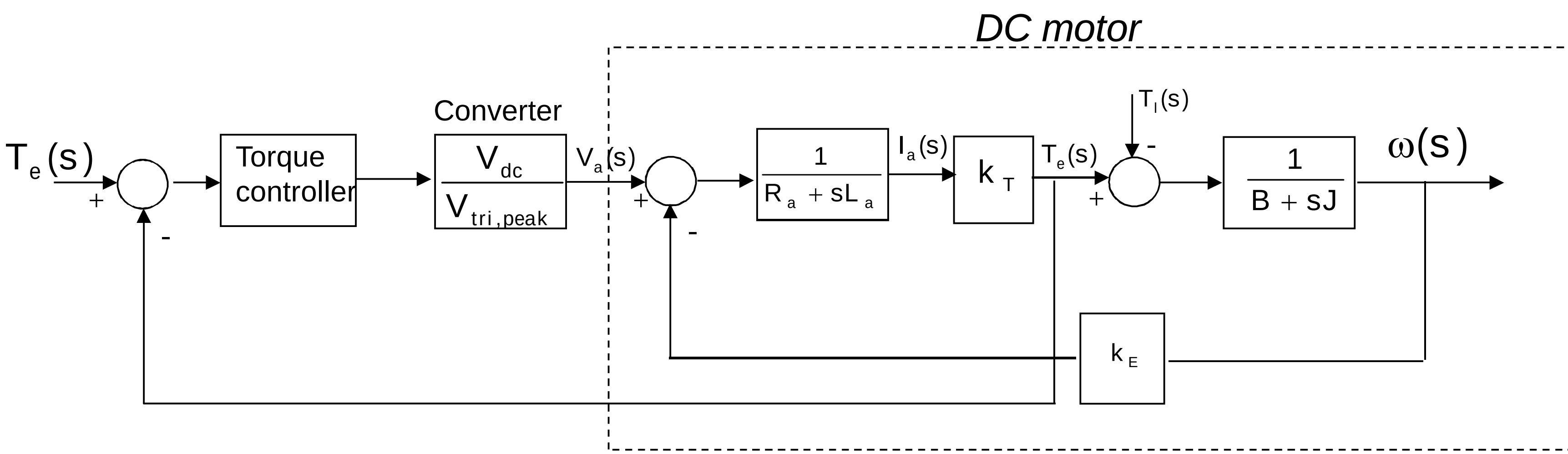
DC motor – separately excited or permanent magnet



Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters





Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Closed-loop speed control – an example

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

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

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

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Closed-loop speed control – an example

$Ra = 2\ \Omega$

$La = 5.2$ 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

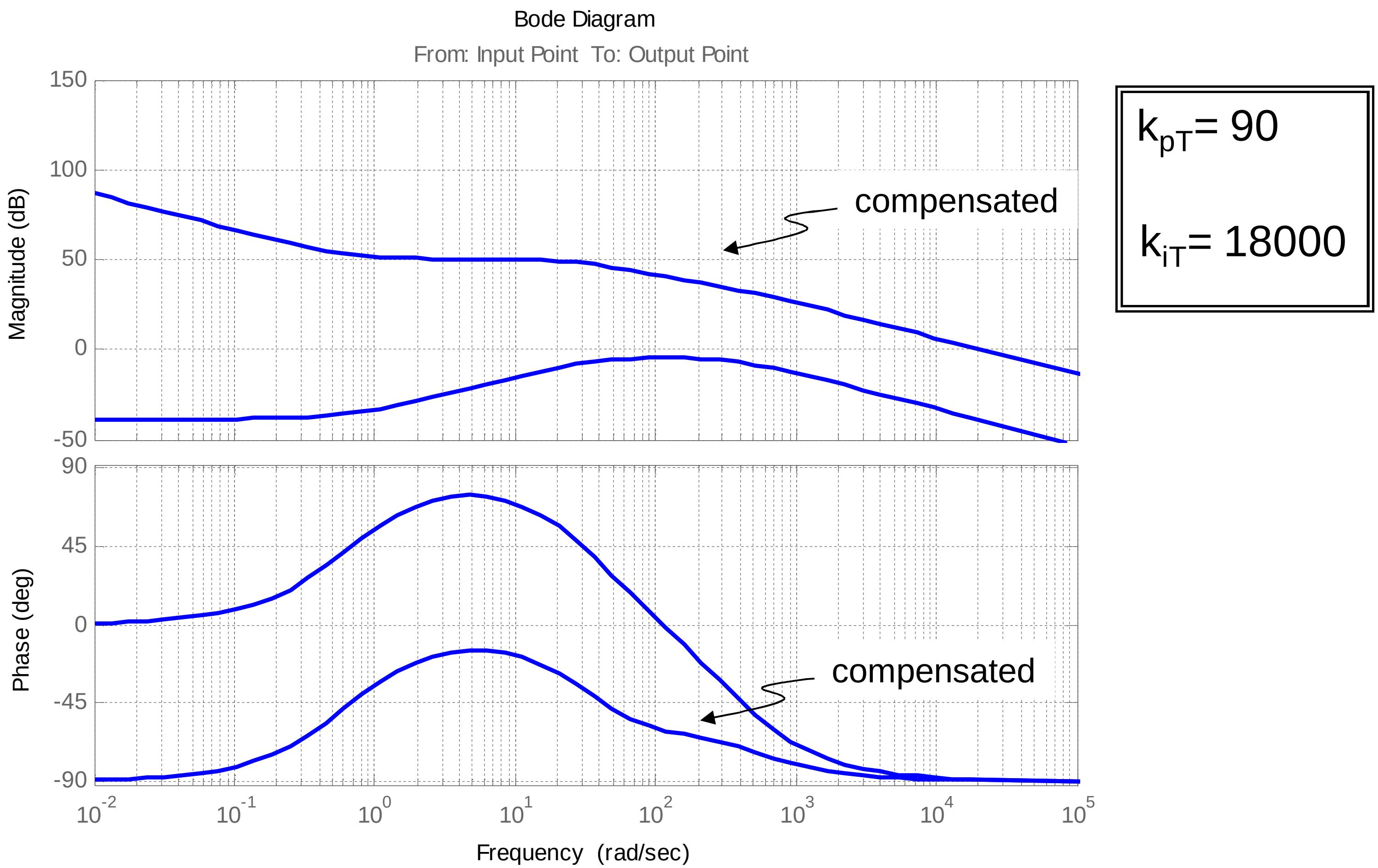
- PI controllers
- Switching signals from comparison of v_c and triangular waveform

Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Torque controller design

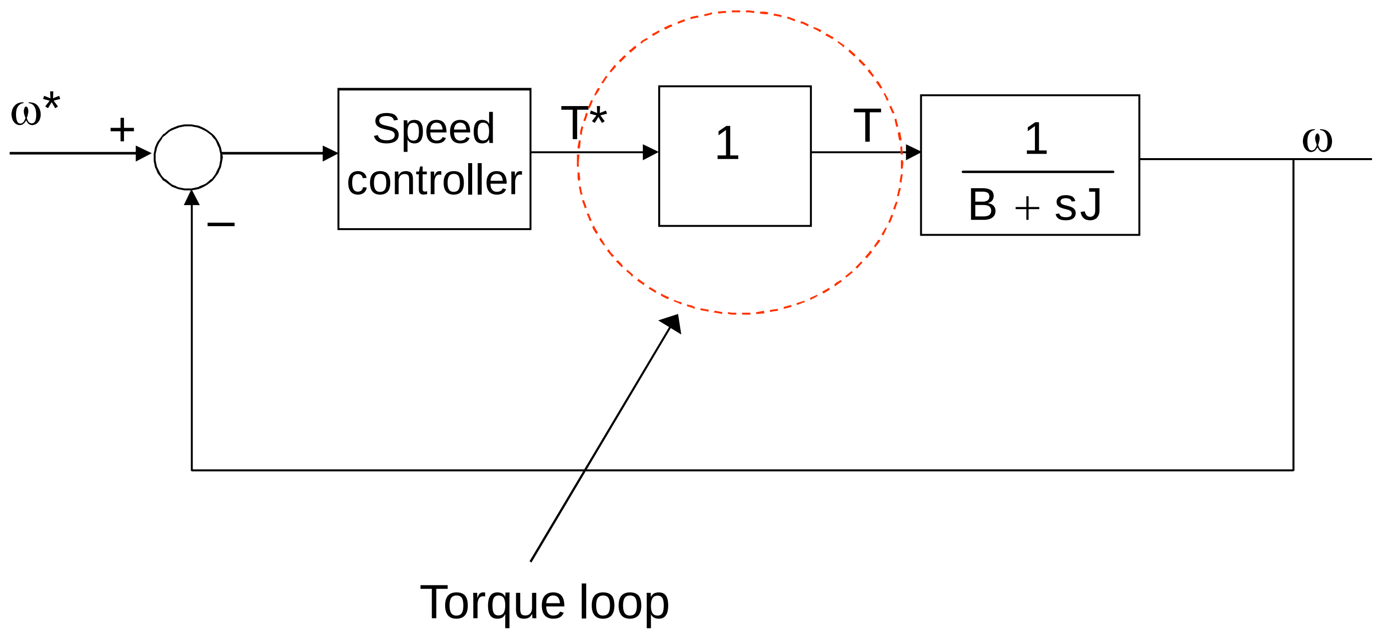
Open-loop gain



Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Speed controller design

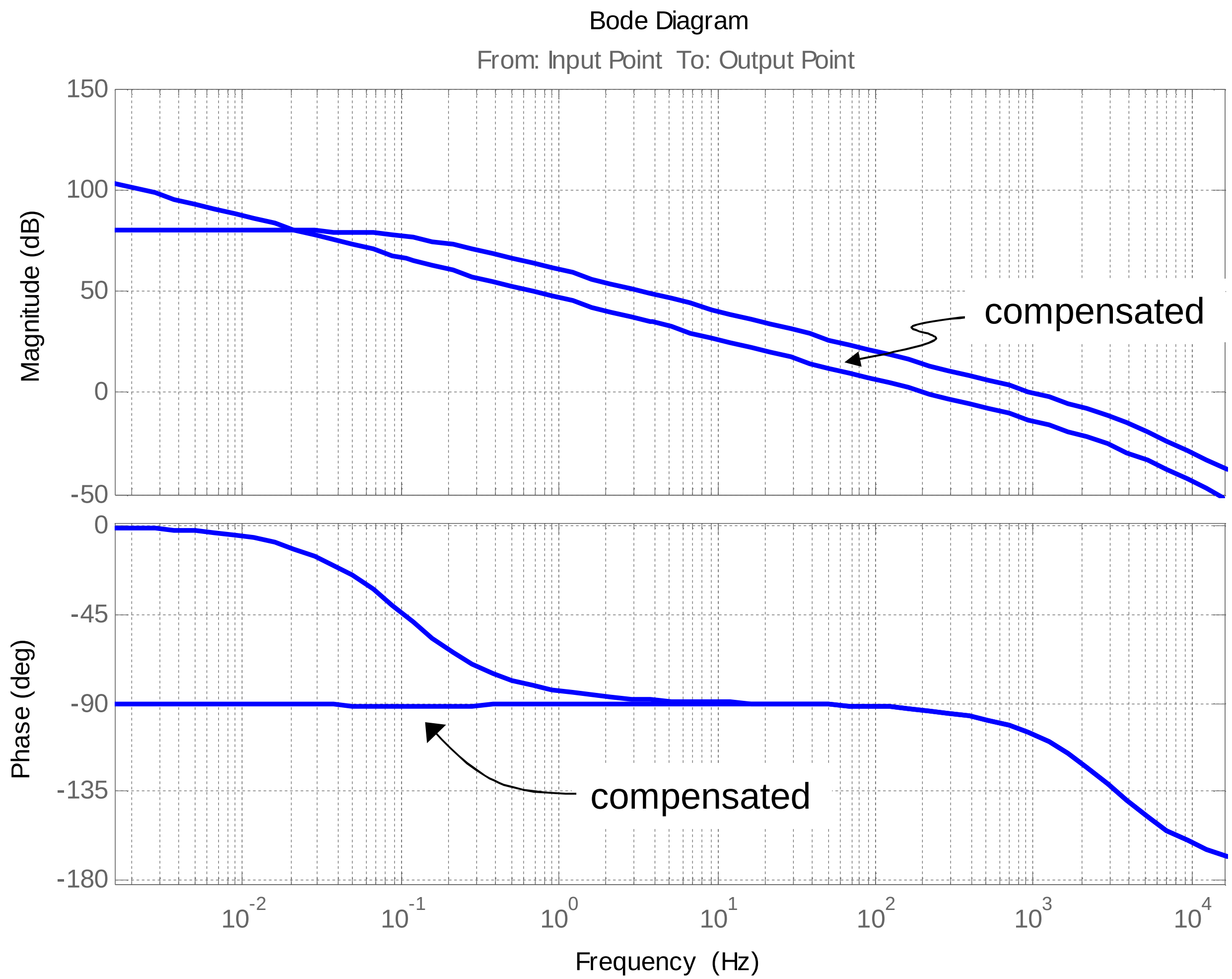


Modeling and Control of Electrical Drives

Modeling of the Power Converters: DC drives with SM Converters

Speed controller design

Open-loop gain



k_{ps}= 0.2

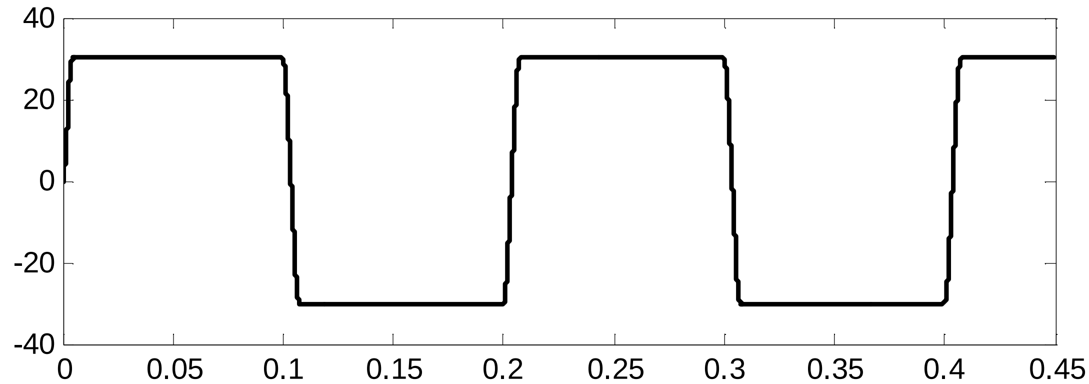
k_{is}= 0.14

Modeling and Control of Electrical Drives

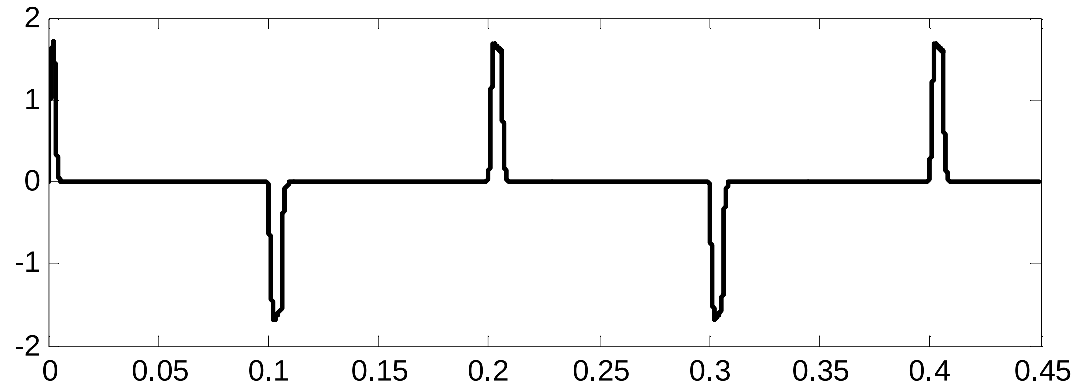
Modeling of the Power Converters: DC drives with SM Converters

Large Signal Simulation results

Speed

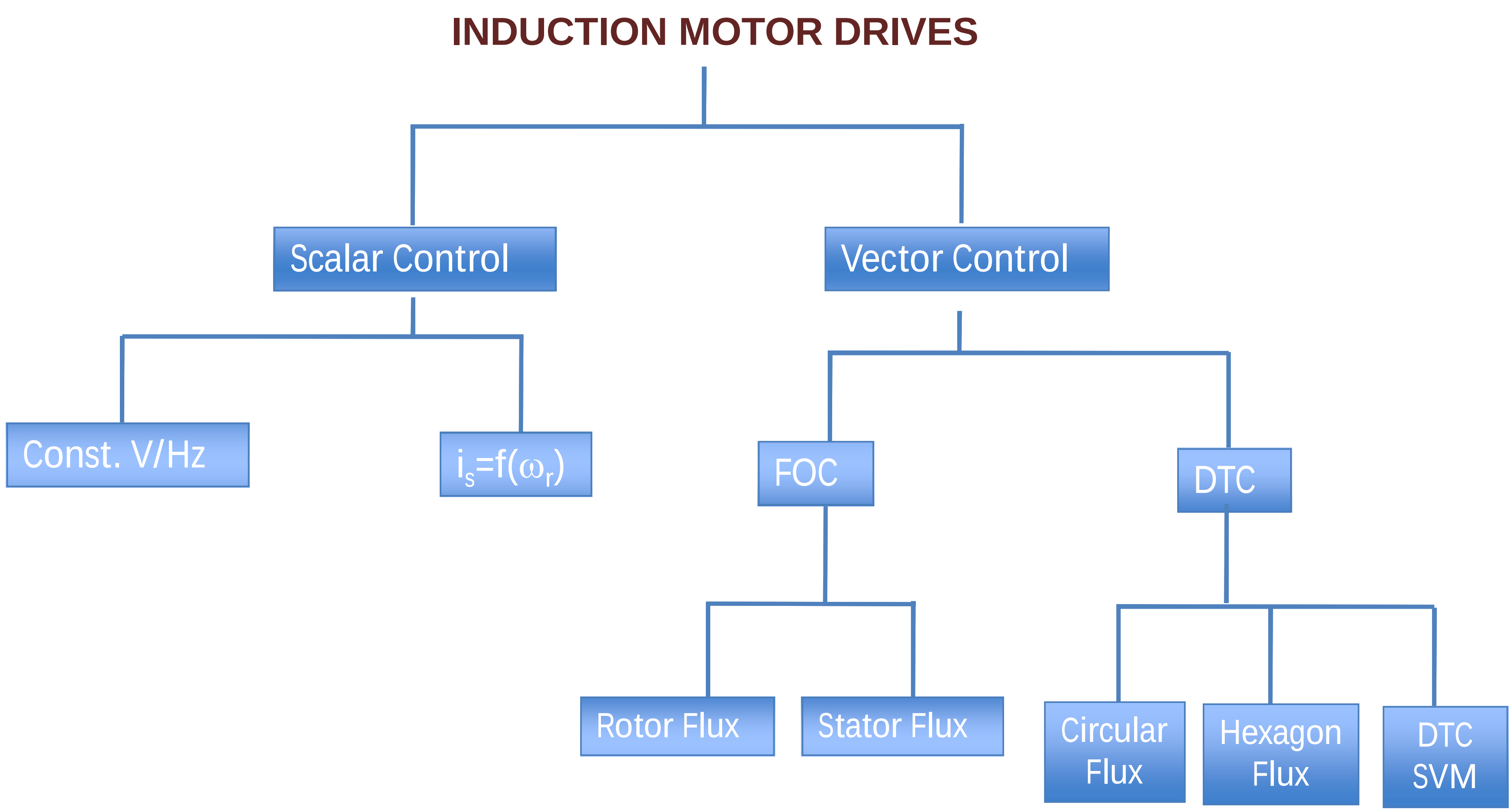


Torque



Modeling and Control of Electrical Drives

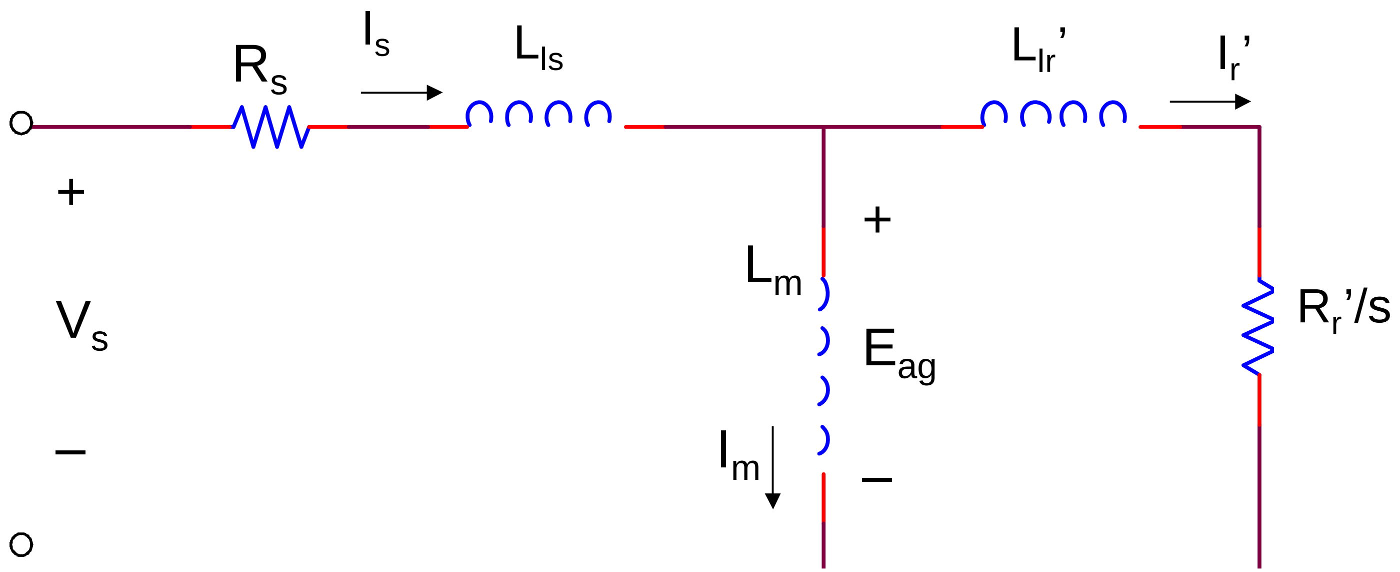
Modeling of the Power Converters: IM drives



Modeling and Control of Electrical Drives

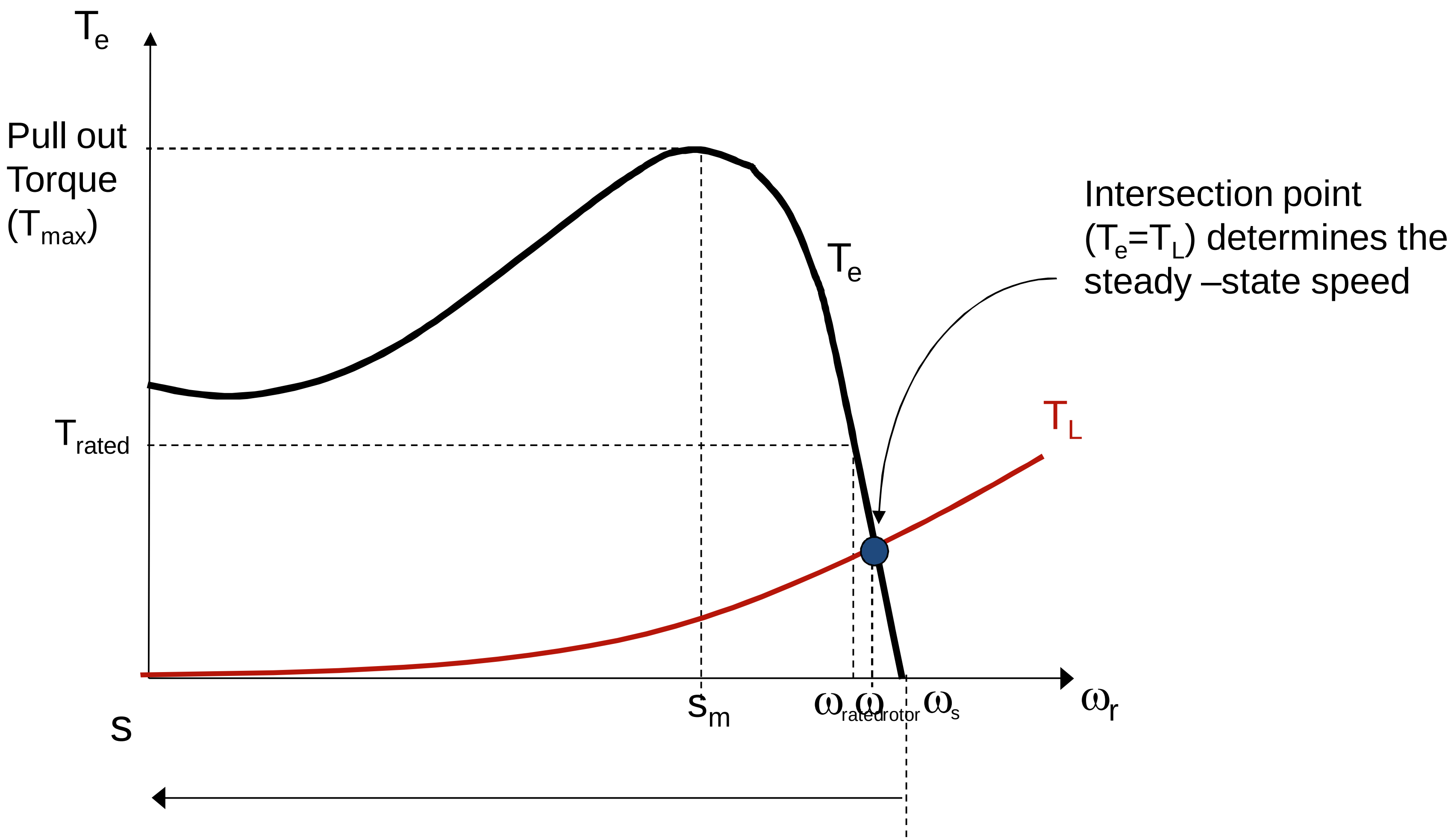
Modeling of the Power Converters: IM drives

Control of induction machine based on steady-state model (per phase SS equivalent circuit):



Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives



Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Given a load T–ω characteristic, the steady-state speed can be changed by altering the T–ω of the motor:

Pole changing
Synchronous speed change with no. of poles
Discrete step change in speed

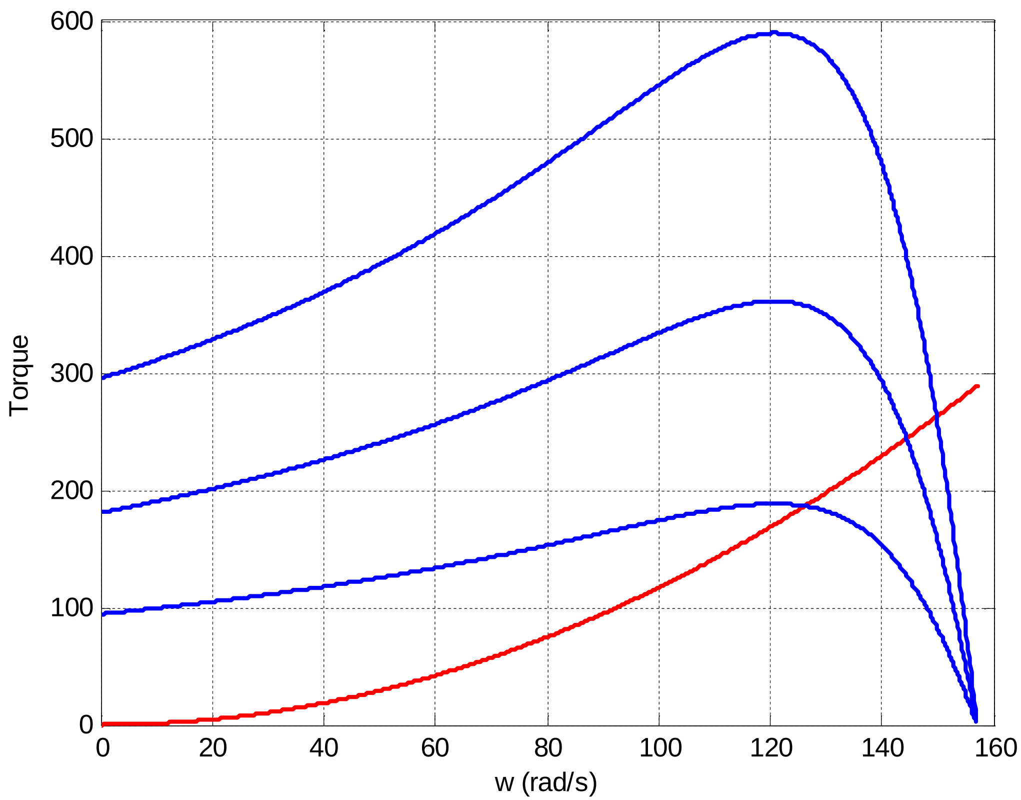
Variable voltage (amplitude), variable frequency (Constant V/Hz)
Using power electronics converter
Operated at low slip frequency

Variable voltage (amplitude), frequency fixed
E.g. using transformer or triac
Slip becomes high as voltage reduced – low efficiency

Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Variable voltage, fixed frequency



e.g. 3–phase squirrel cage IM

V = 460 V R_s= 0.25 Ω

R_r=0.2 Ω $L_r = L_s$ = 0.5/(2*pi*50)

L_m=30/(2*pi*50)

f = 50Hz p = 4

Lower speed → slip higher

Low efficiency at low speed

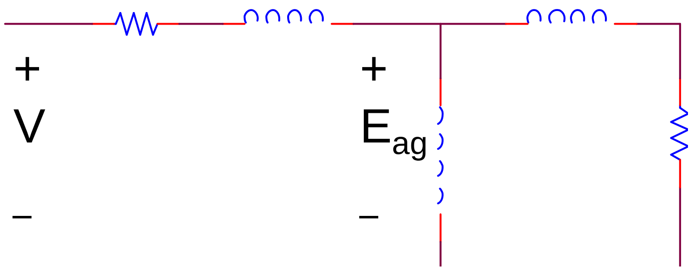
Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Constant V/Hz

To maintain V/Hz constant

Approximates *constant air-gap flux* when E_{ag} is large



$$E_{ag} = k\, f\, \phi_{ag}$$

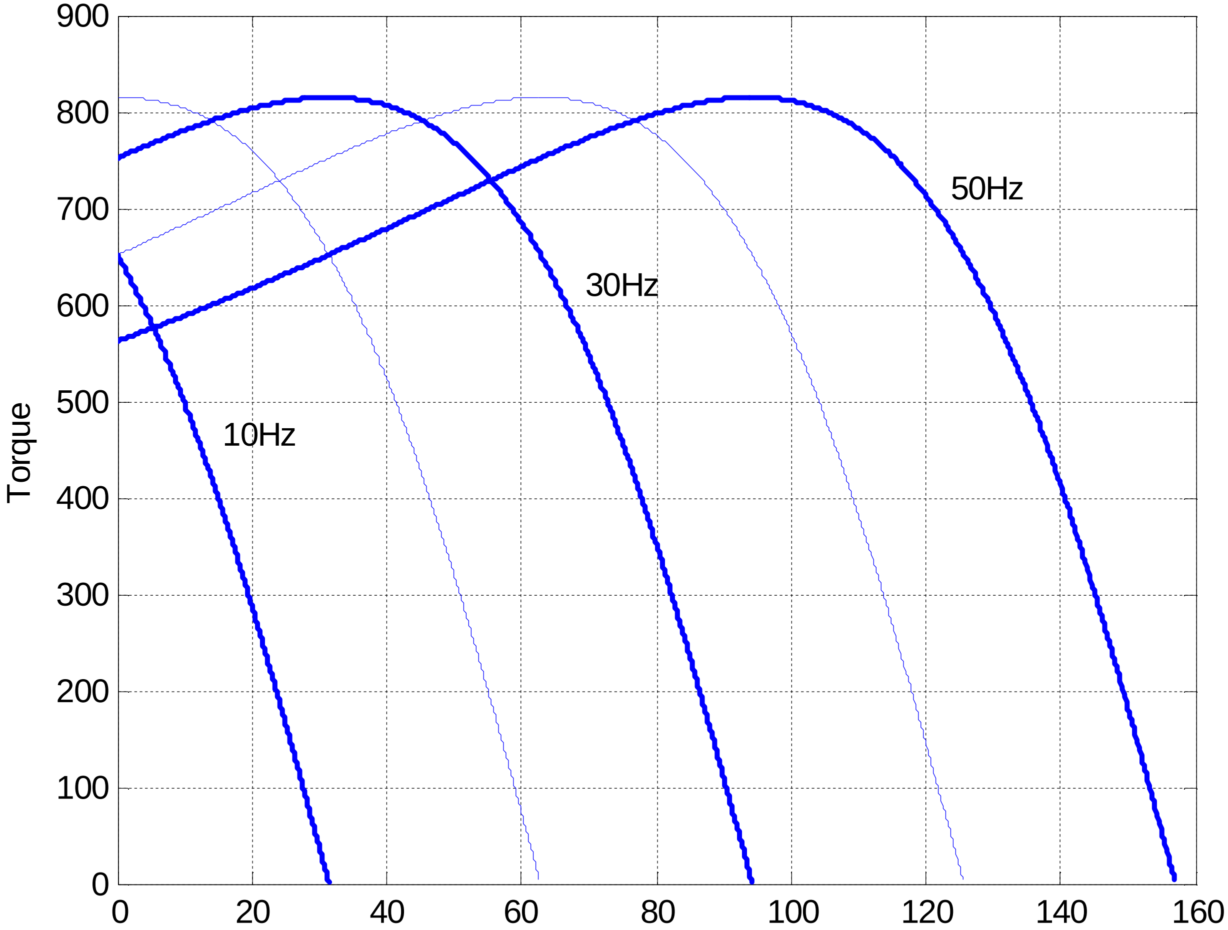
$$\phi_{ag} = \text{constant} = \frac{E_{ag}}{f} \approx \frac{V}{f}$$

Speed is adjusted by varying f - maintaining V/f constant to avoid flux saturation

Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

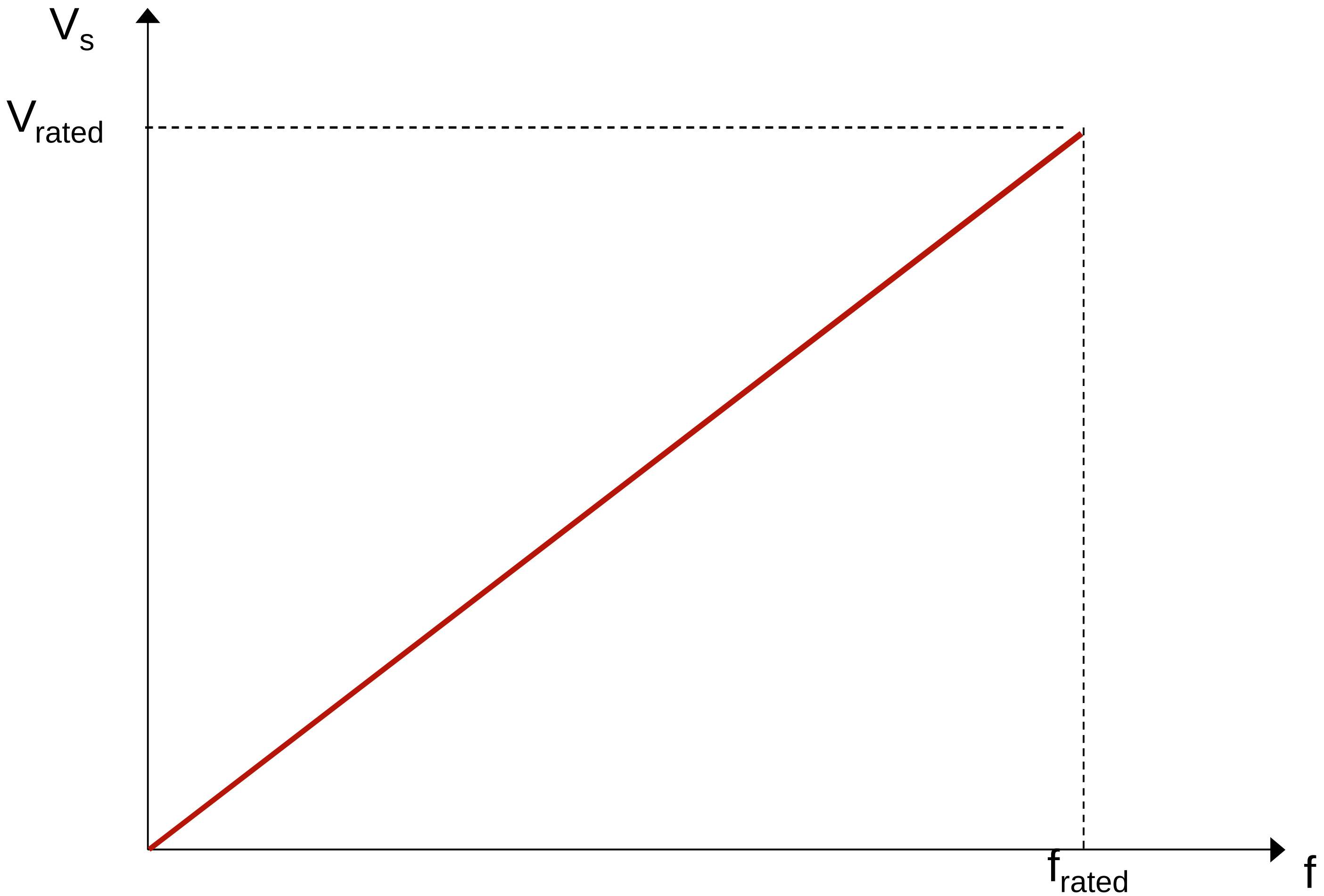
Constant V/Hz



Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

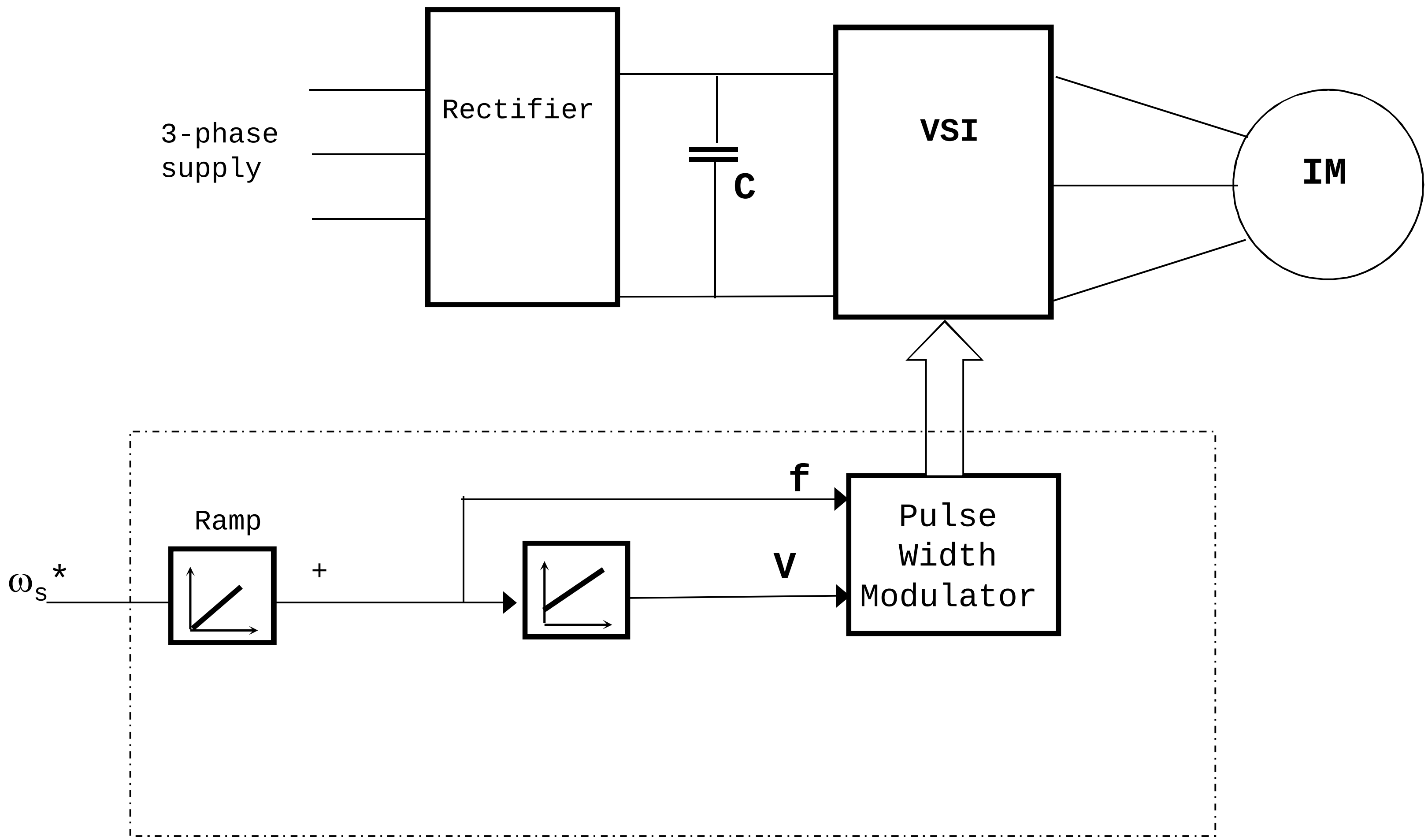
Constant V/Hz



Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

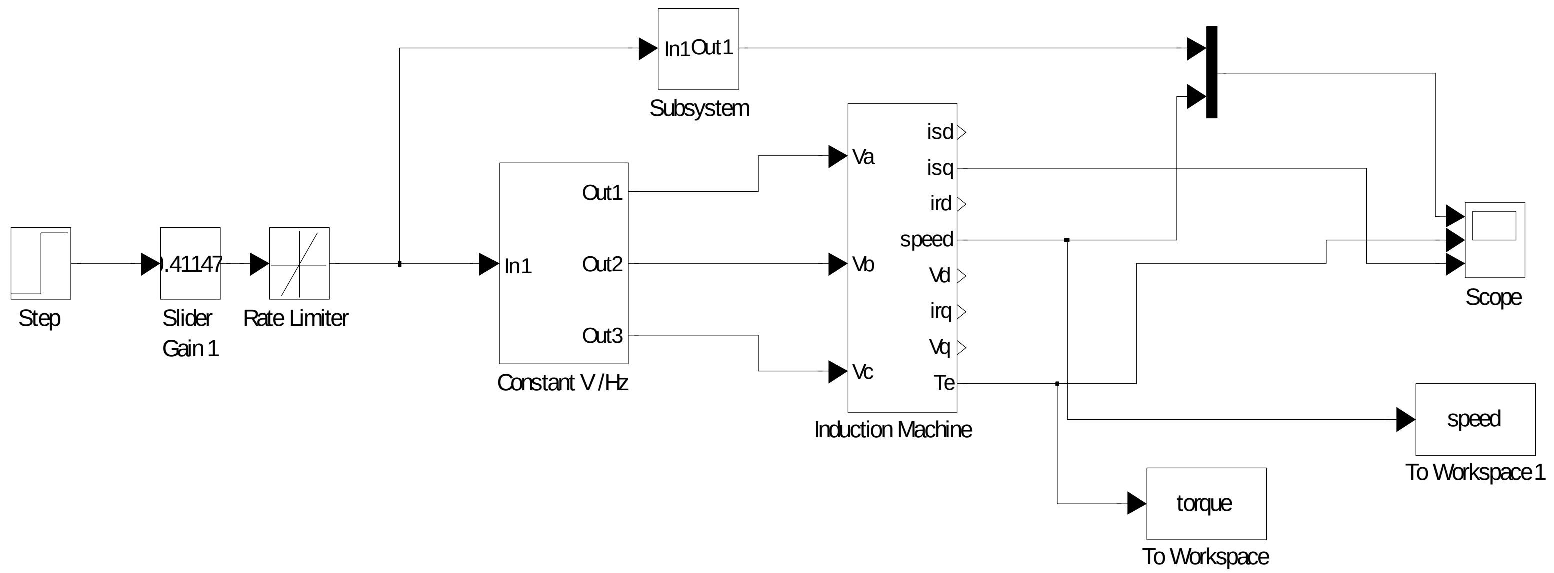
Constant V/Hz



Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Constant V/Hz

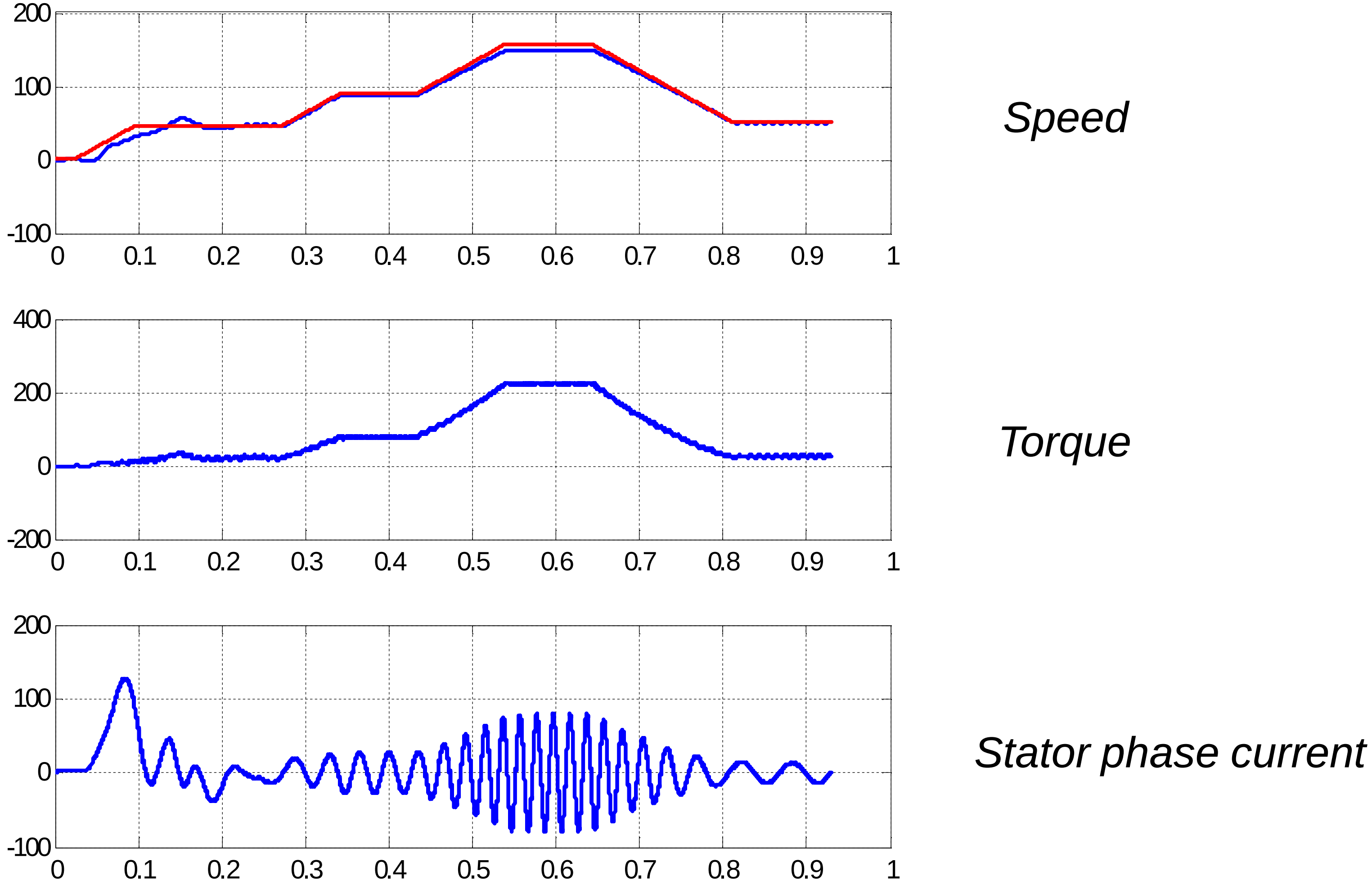


Simulink blocks for Constant V/Hz Control

Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Constant V/Hz



Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Problems with open-loop constant V/f

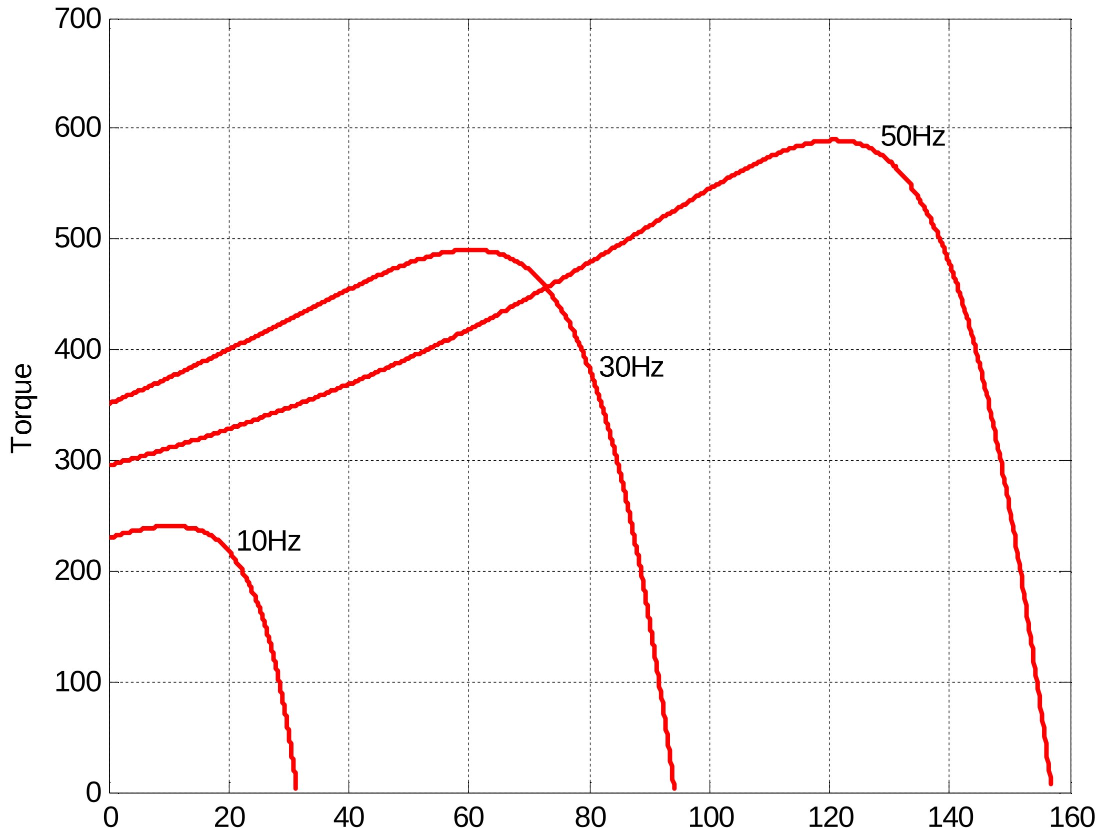
At low speed, voltage drop across stator impedance is significant compared to airgap voltage - poor torque capability at low speed

Solution:

1. Boost voltage at low speed
2. Maintain I_m constant – constant Φ_{ag}

Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

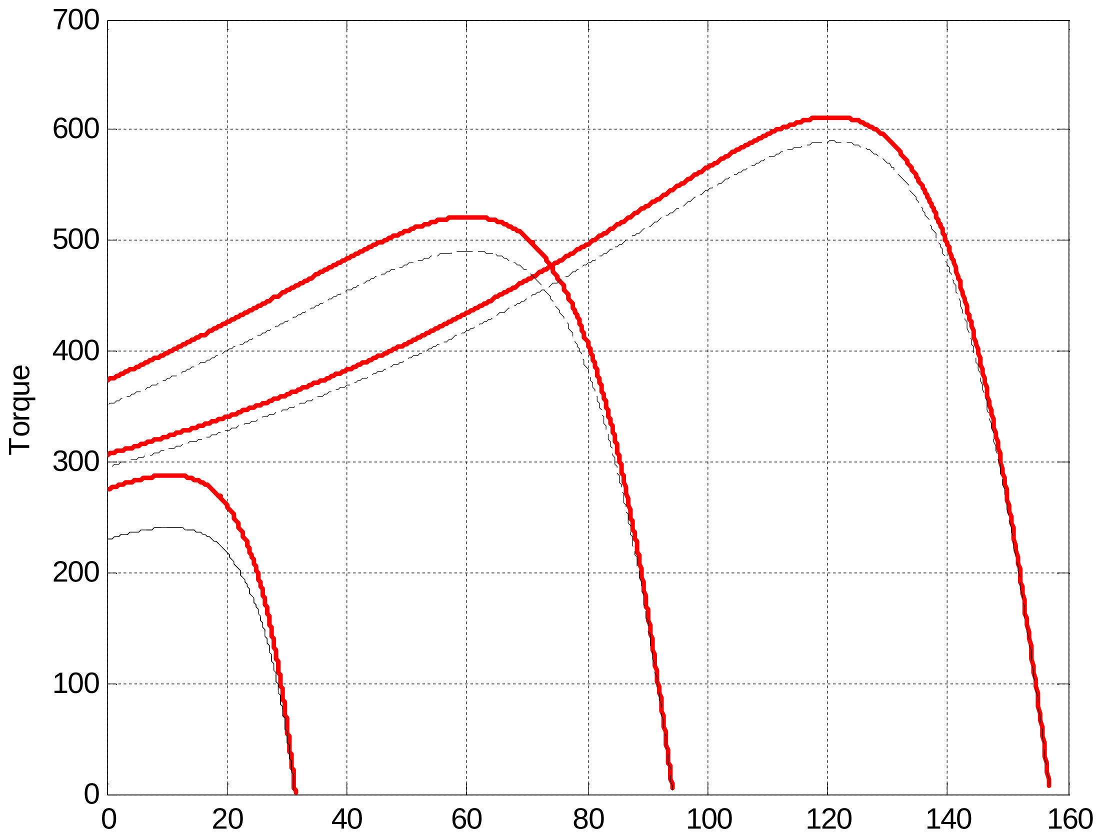


A low speed, flux falls below the rated value

Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

With compensation ($I_{s,rated}R_s$)

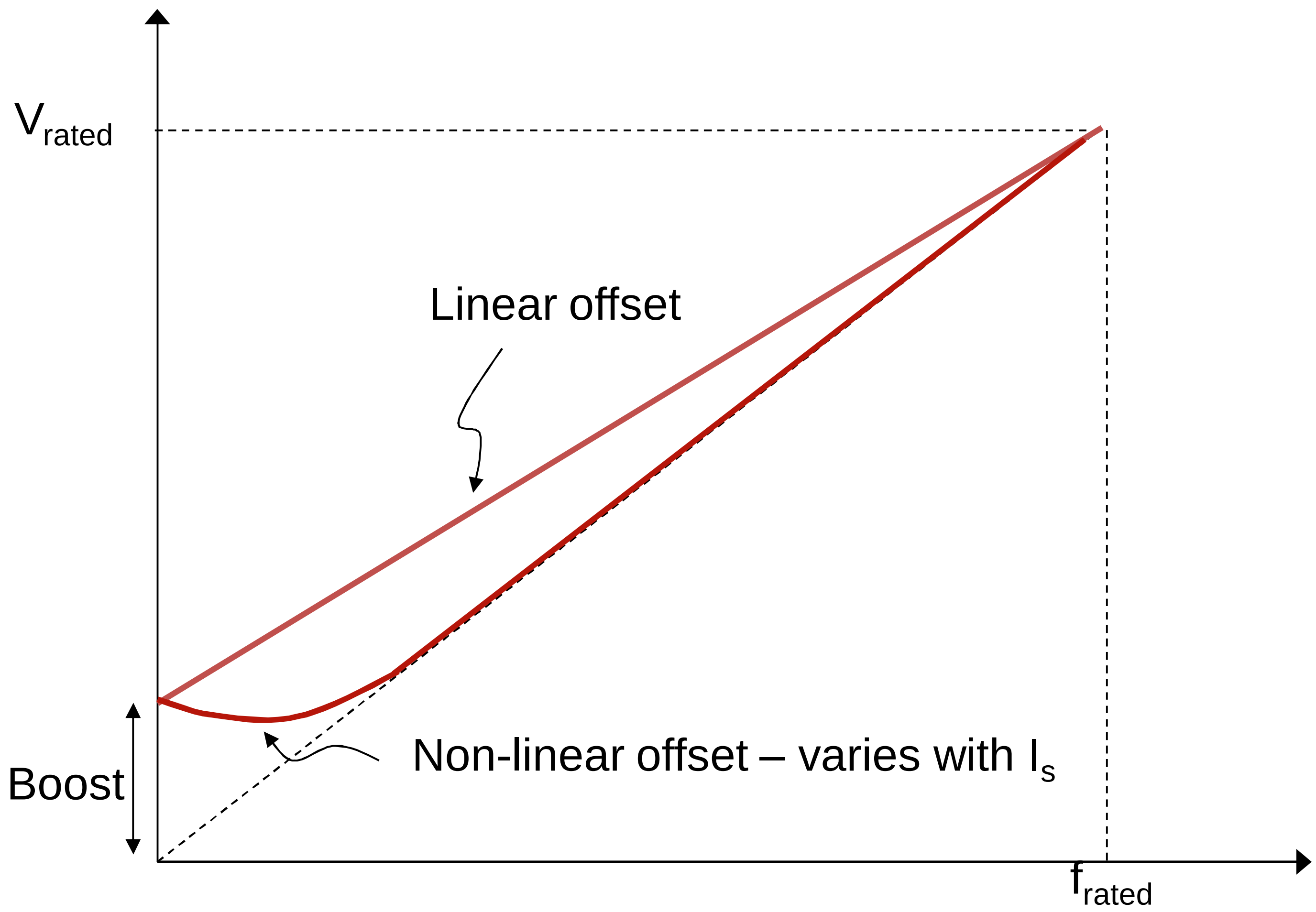


- Torque deteriorate at low frequency – hence compensation commonly performed at low frequency
- In order to truly compensate need to measure stator current – seldom performed

Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

With voltage boost at low frequency

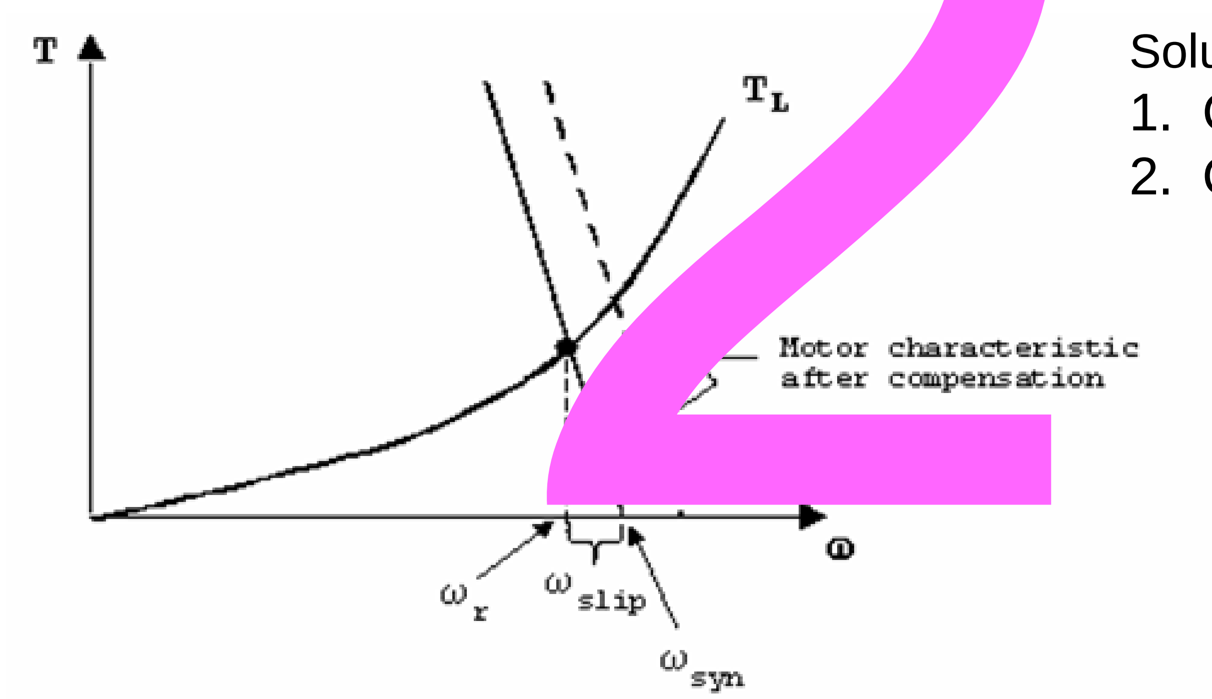


Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Problems with open-loop constant V/f

Poor speed re[illegible]ion

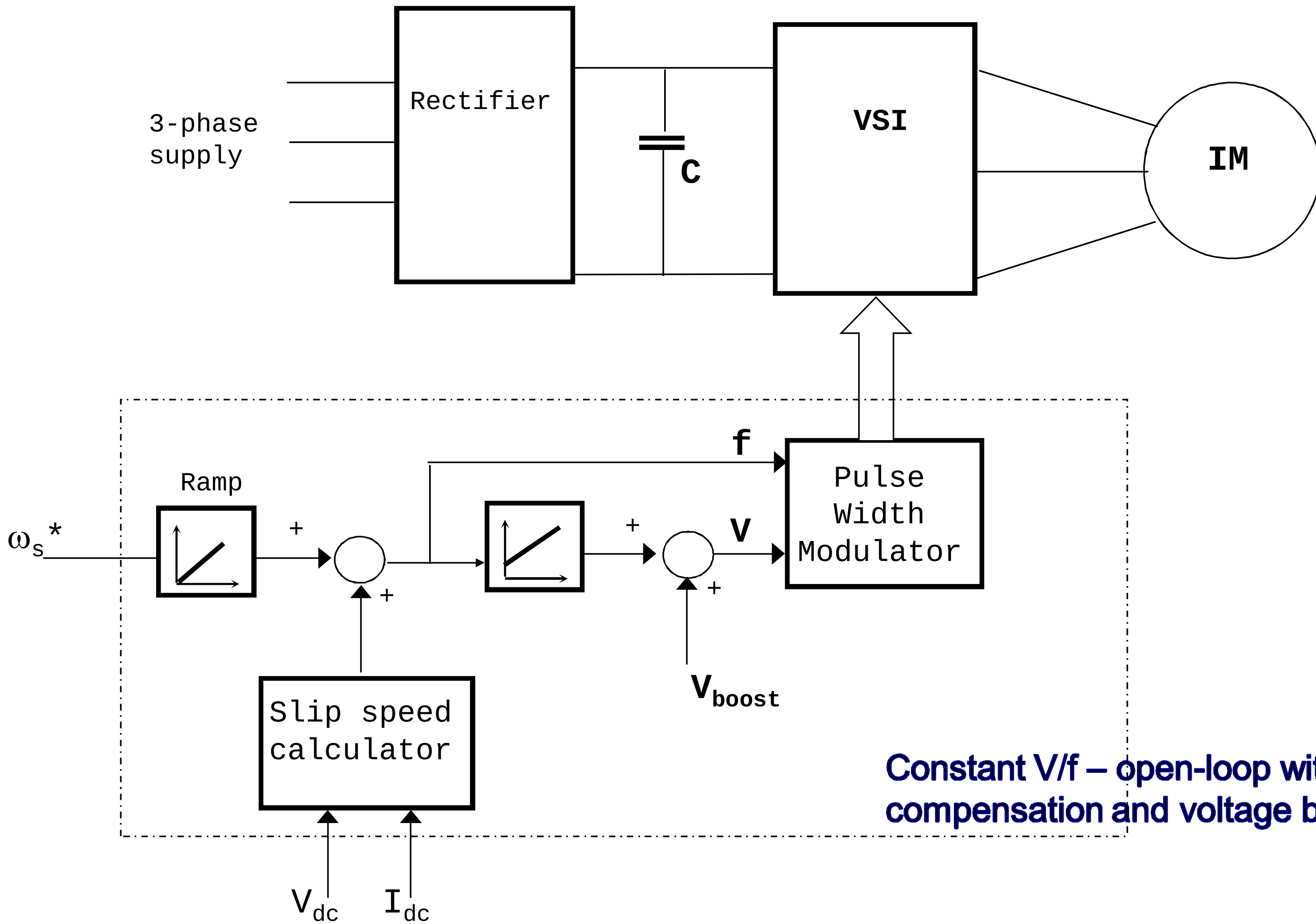


Solution:

1. Compesate slip
2. Closed-loop control

Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives



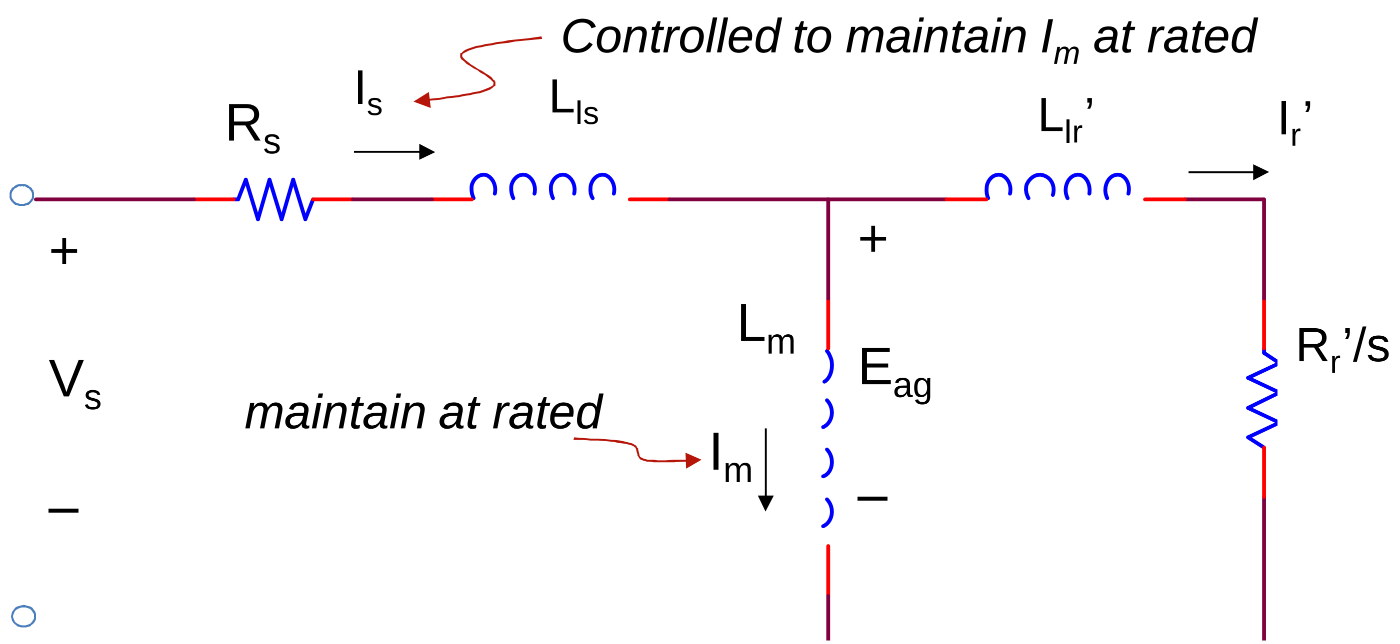
Constant V/f – open-loop with slip compensation and voltage boost

Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

A better solution : maintain Φ_{ag} constant. How?

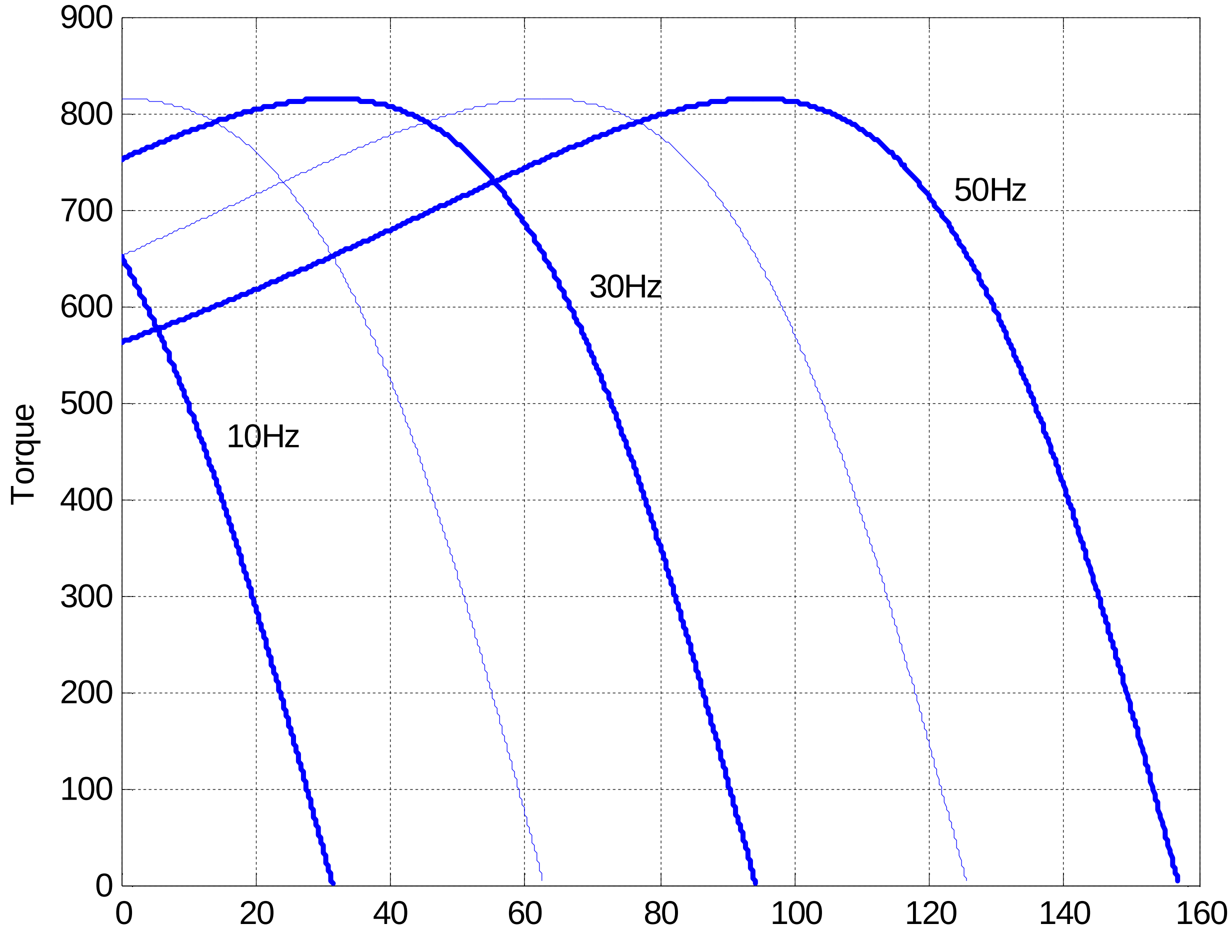
Φ_{ag}, constant $\rightarrow$ E_{ag}/f , constant $\rightarrow$ I_m, constant (rated)



Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Constant air-gap flux



Modeling and Control of Electrical Drives

Modeling of the Power Converters: IM drives

Constant air-gap flux

$$I_m = \frac{j\omega\, L_{lr} + \frac{R_r}{s}}{j\omega\, (L_{lr} + L_m) + \frac{R_r}{s}} I_s$$

$$I_m = \frac{j\omega\, L_r + \frac{R_r}{s}}{j\omega \left(\frac{\sigma_r}{1+\sigma_r}\right) L_r + \frac{R_r}{s}} I_s$$

$$I_m = \frac{j\omega_{slip} T_r + 1}{j\omega_{slip}\left(\frac{\sigma_r}{1+\sigma_r}\right) T_r + 1} I_s,$$

$$I_s = \frac{j\omega_{slip}\left(\frac{\sigma_r}{1+\sigma_r}\right) T_r + 1}{j\omega_{slip} T_r + 1} I_m,$$

- Current is controlled using current-controlled VSI
- Dependent on rotor parameters – sensitive to parameter variation

Modeling of the Power Converters: IM drives

Constant air-gap flux