Lecture Set 4:
DC Machines and Drives

S.D. Sudhoff

Spring 2021

About this Lecture Set

- Reading
  - *Electromechanical Motion Devices, 2nd Edition,* Sections 3.1-3.9
- Goal
  - Become familiar with DC machines and drives

Lecture 28

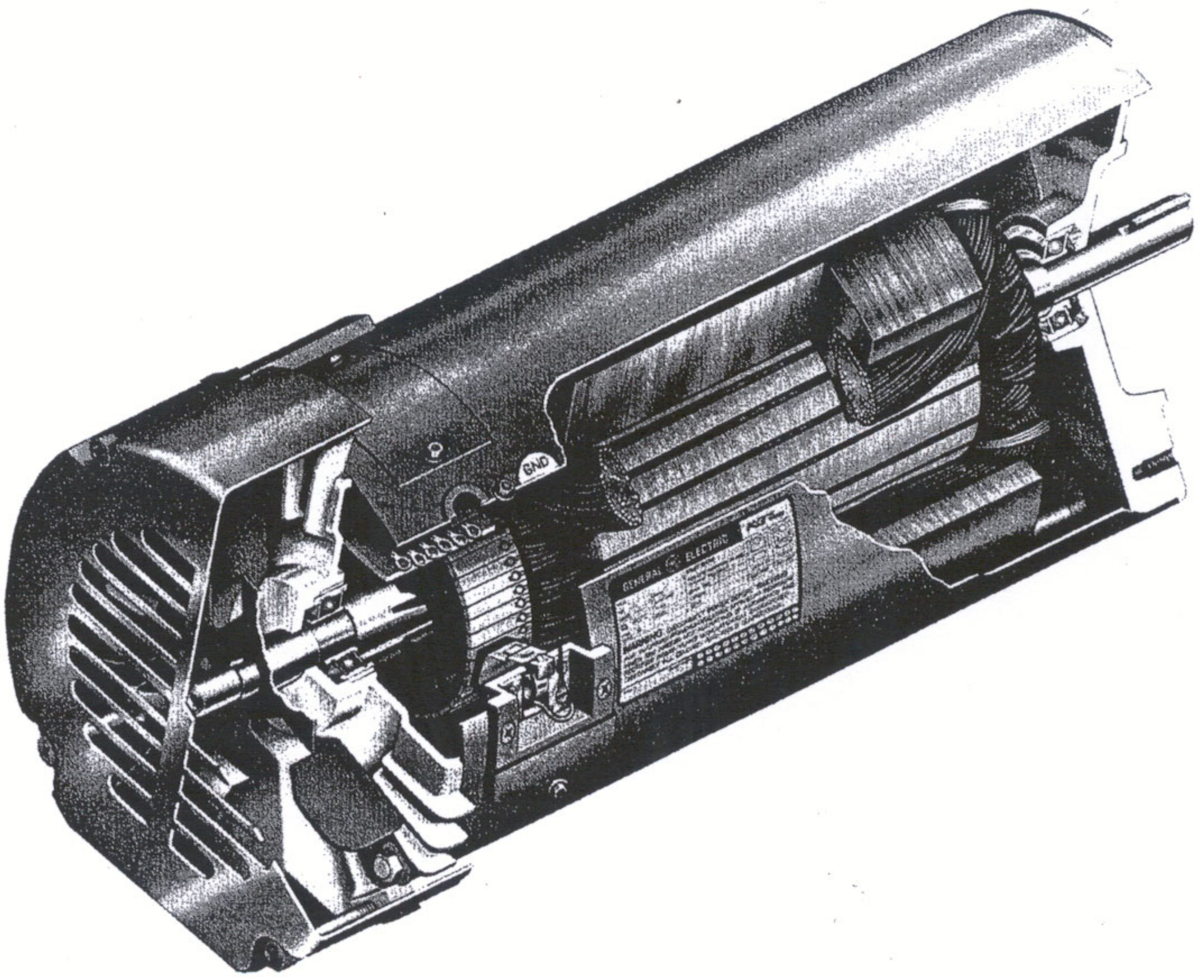
Physical Configuration of the DC Machine

General Comments on DC Machines

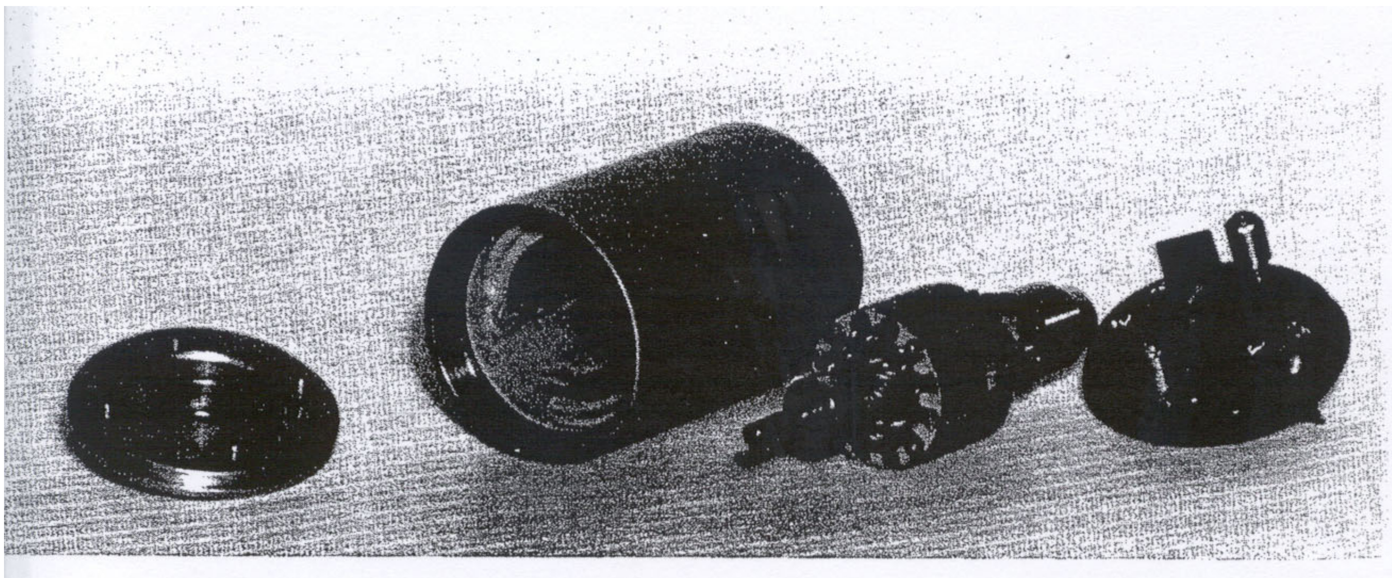
- Attractive Features

- Drawbacks

DC Machine Cutaway View



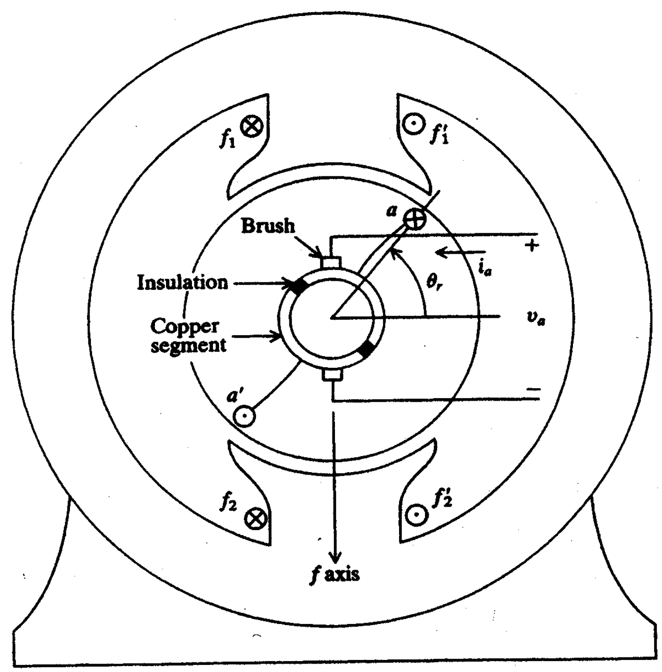
DC Machine Cutaway View

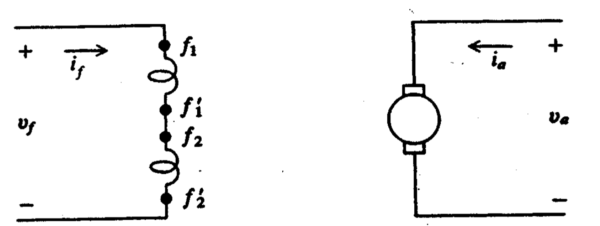


Lecture 29

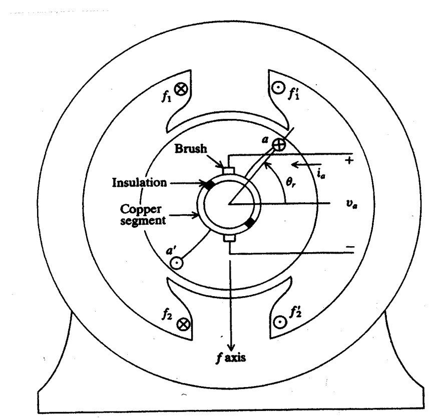
An Elementary DC Machine

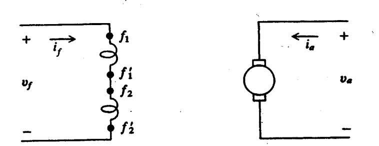
Configuration



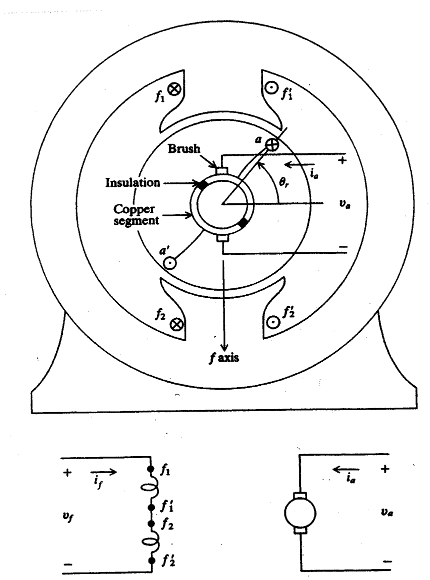


Flux Linkage Equations

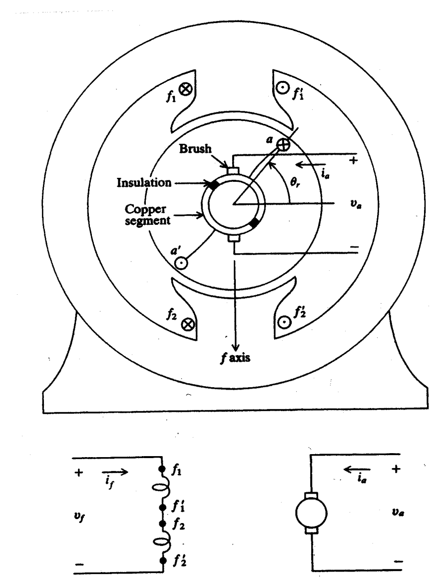




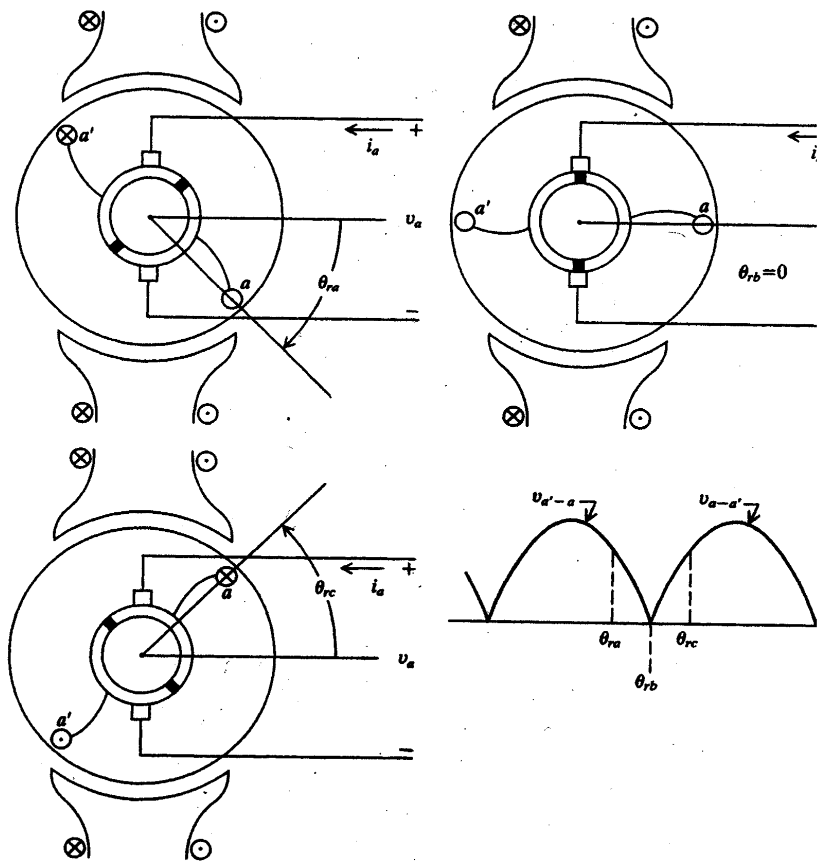
Flux Linkage Equations



Armature Voltage

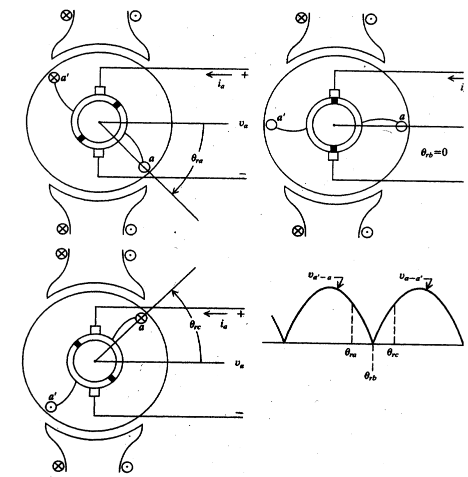


Operation



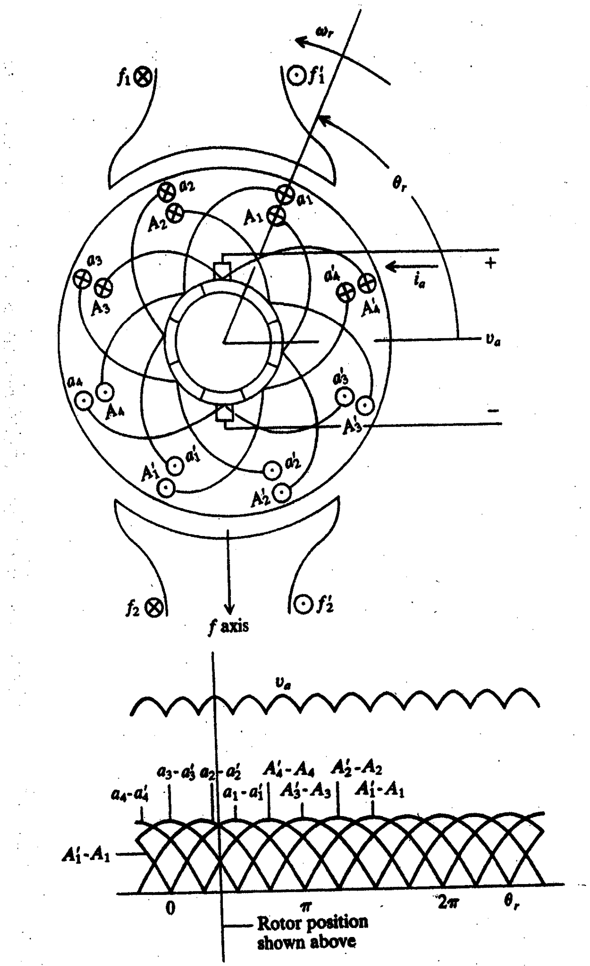
a'
i_a
+
v_a
a
θ_{ra}
−
a'
a
$\theta_{rb}=0$
a
θ_{rc}
i_a
+
v_a
a'
−
$v_{a'-a}$
$v_{a-a'}$
θ_{ra}
θ_{rc}
θ_{rb}

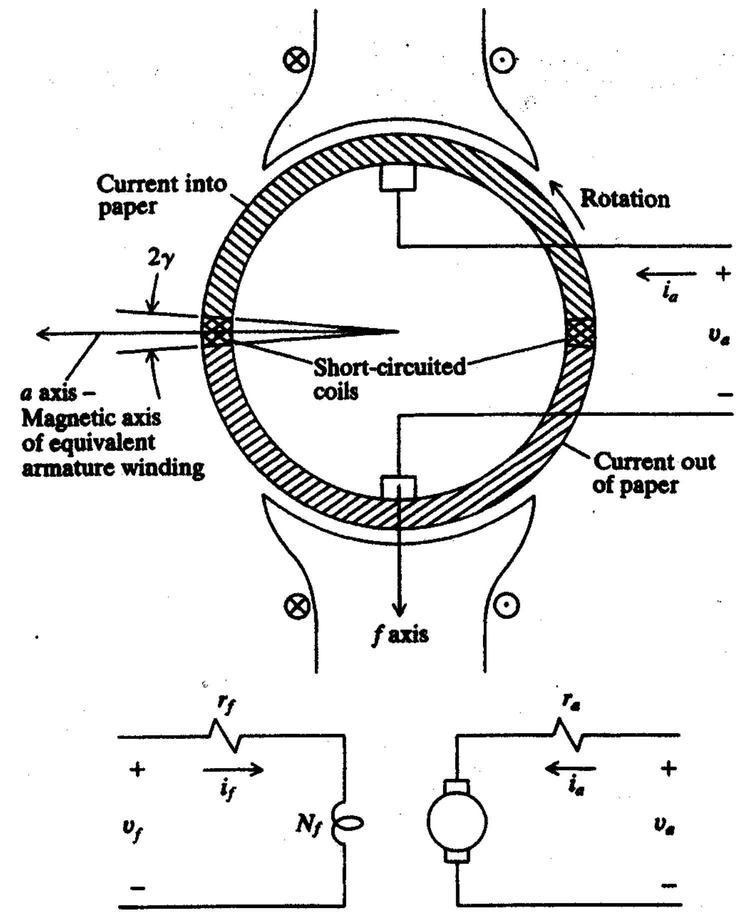
Operation



a'
i_a
+
v_a
a
θ_{ra}
−
a'
a
$\theta_{rb}=0$
a
θ_{rc}
i_a
+
v_a
a'
−
$v_{a'-a}$
$v_{a-a'}$
θ_{ra}
θ_{rc}
θ_{rb}

A More Practical DC Machine

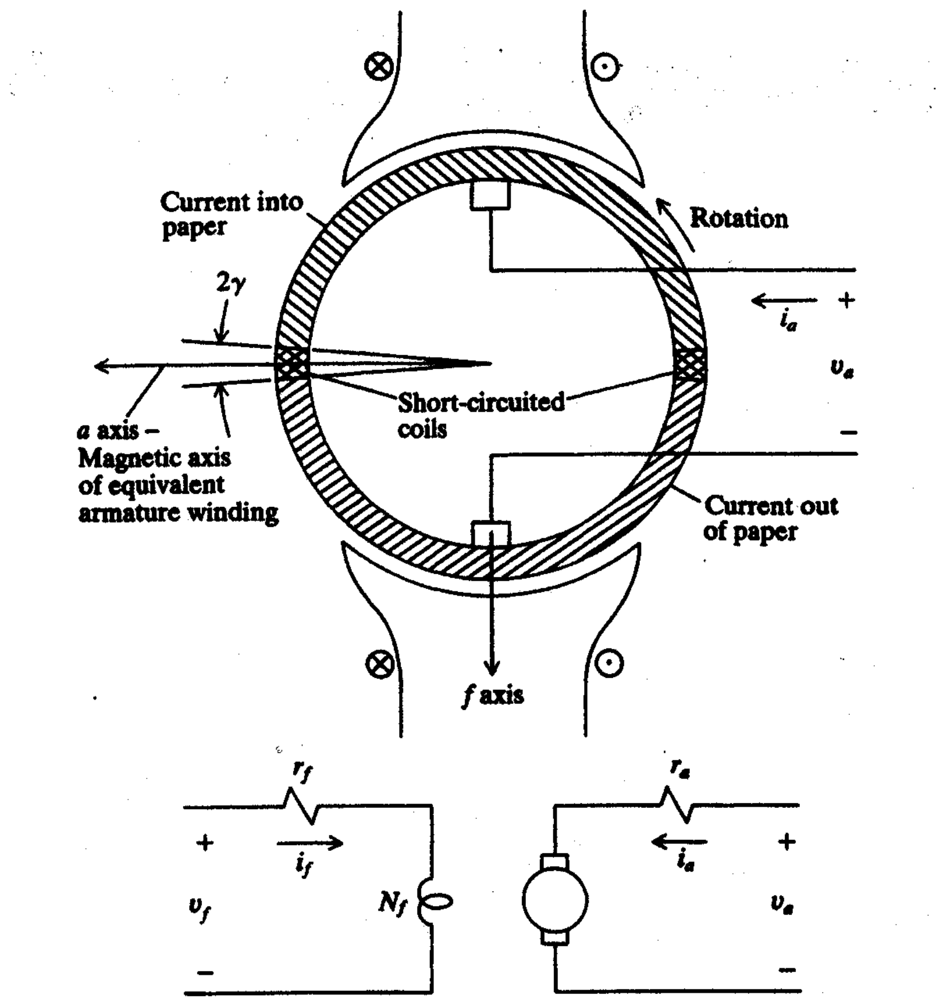




Lecture 30

An Ideal DC Machine

Configuration



Flux Linkage Equations

Flux Linkage Equations

Armature Voltage Equation

Armature Voltage Equation

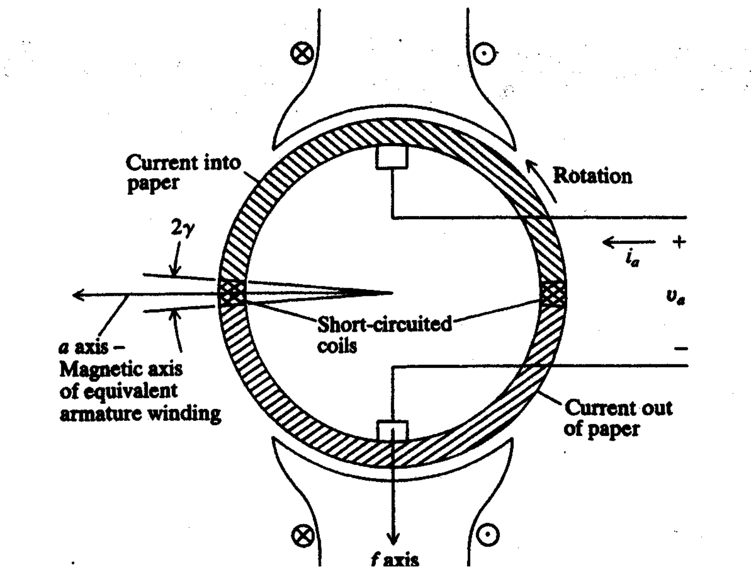
Field Voltage Equation

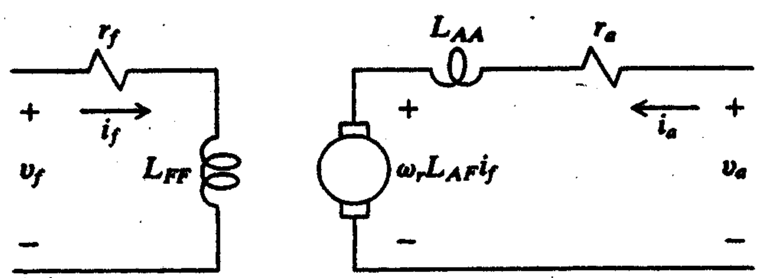
Field Voltage Equation

Torque

Torque

Model Summary



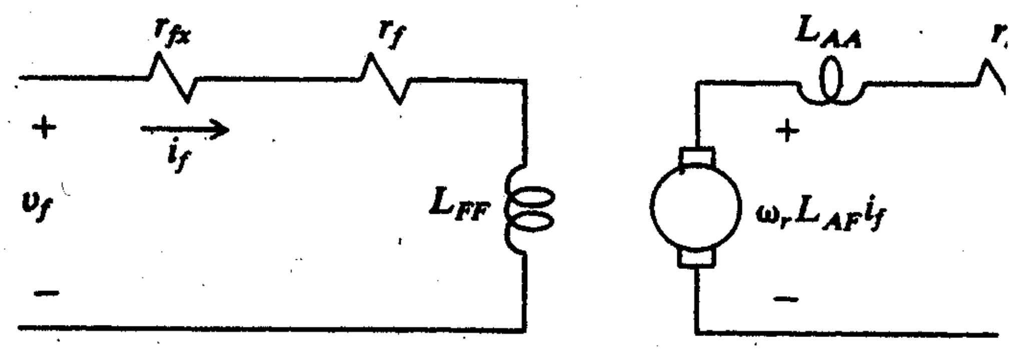


Mechanical Dynamics

Lecture 31

Separately Excited DC Machine

Separately Excited Machine



A Quick Example

- Consider a machine with following parameters
  - r_a=200 mΩ
  - L_{AF}=200 mH
  - R_f=10 Ω
- Suppose the armature voltage is 100 V, the field voltage is 10 V, and the speed is 4600 rpm. Compute the torque, output power, input power and efficiency

A Quick Example

A Quick Example

Derivation of Torque Speed Curve

Derivation of Torque Speed Curve

Capability Curve

- Let's consider a machine with the following parameters
  - $r_a = 200\ m\Omega$
  - $L_{AF} = 200\ mH$
  - $r_f = 10\ \Omega$
- And subject to the following limits
  - Armature current: 20 A
  - Armature voltage: 150 V
  - Field Current: 1 A

Lecture 32

Separately Excited DC Machine
Capability Curve

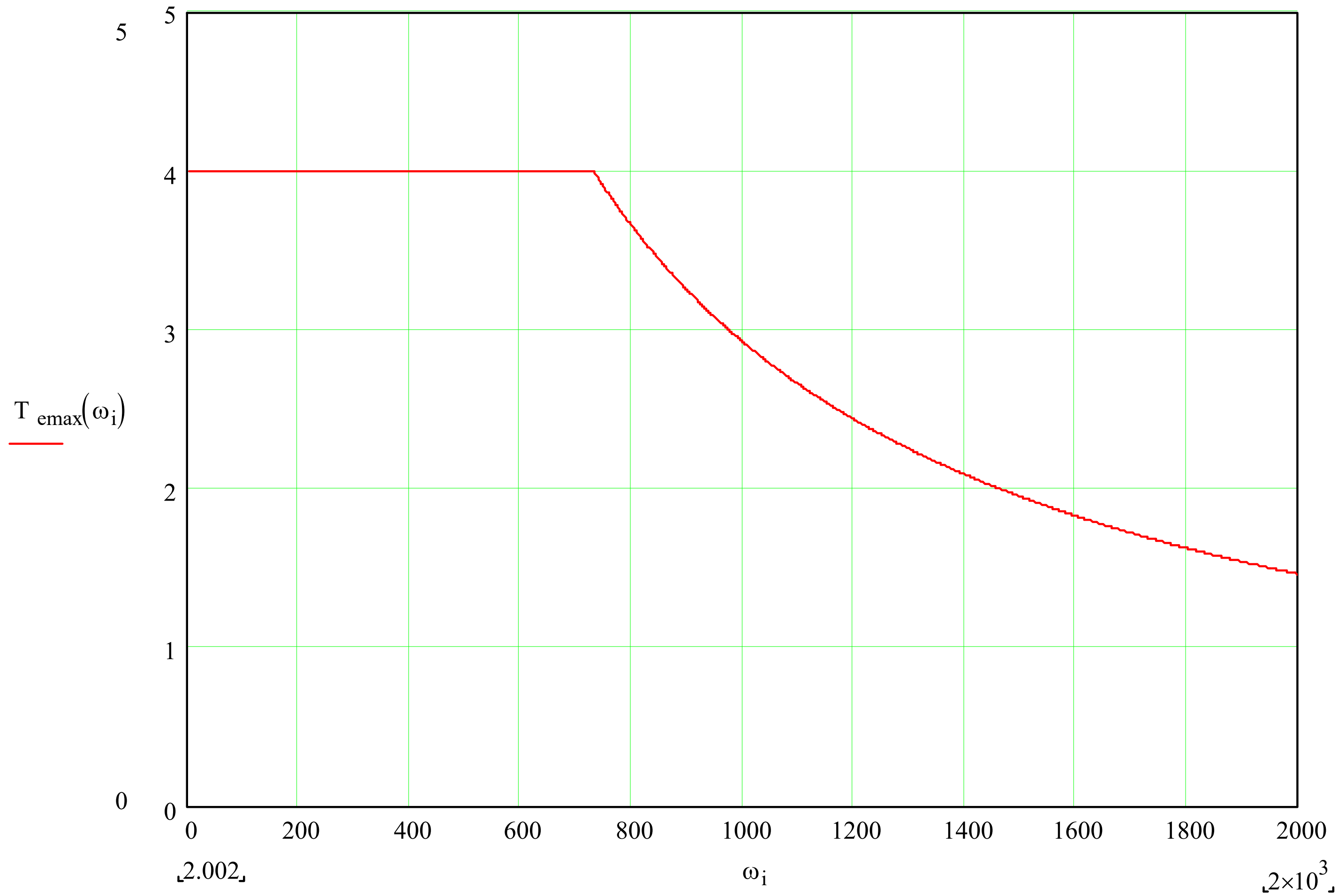
Derivation

Derivation

Derivation

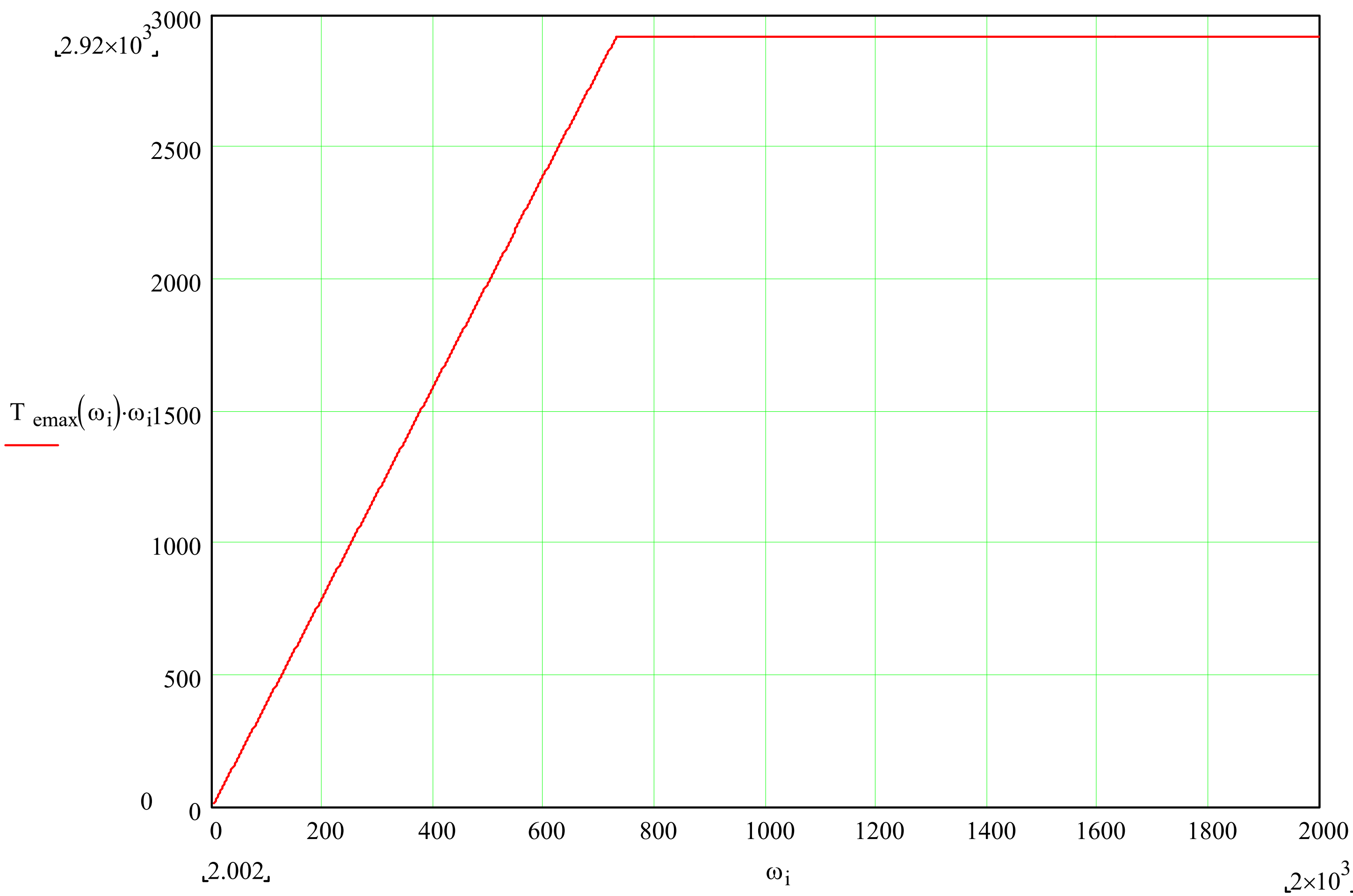
Torque

Capability Curve: Torque



Power

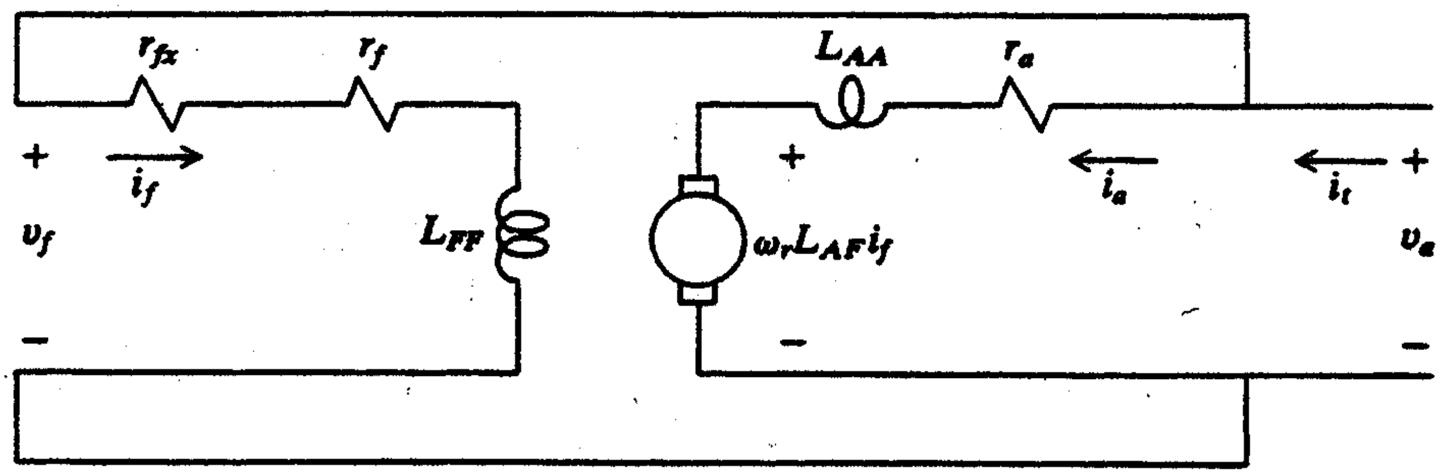
Capability Curve: Power



Lecture 33

Shunt Connected DC Machine

Shunt Connected Machine



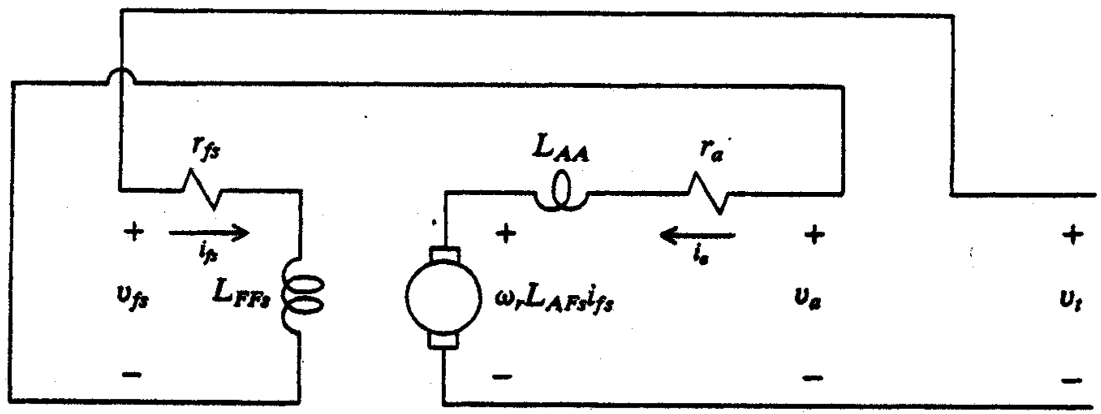
Torque Versus Speed

Torque Versus Speed

Lecture 34

Series Connected DC Machine

Series Connected Machine



Torque Versus Speed

Torque Versus Speed

Lecture 35

Permanent Magnet DC Machine

PM DC Machine

Torque Speed Curve

A Simple Example

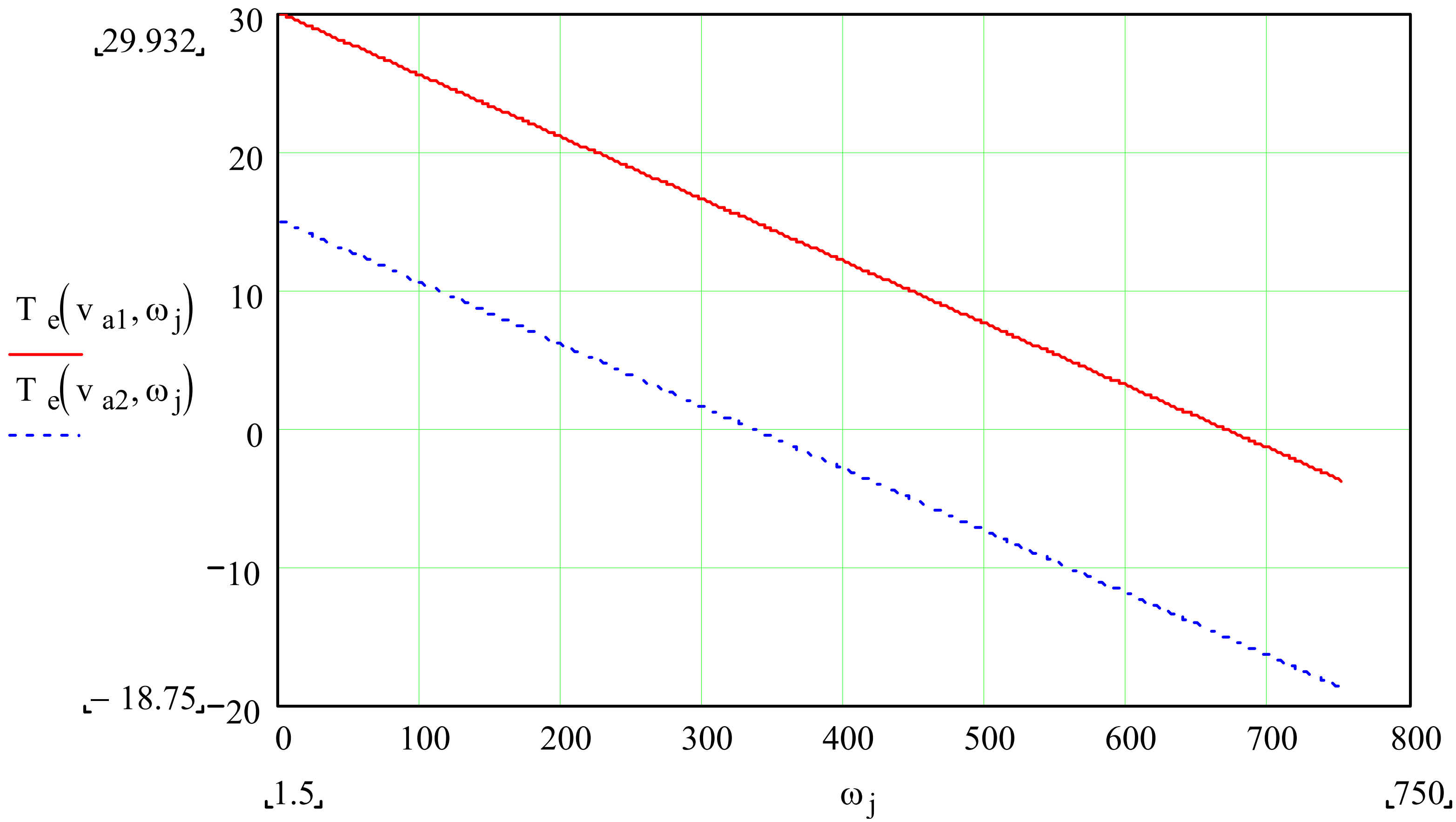
- Consider a machine with an armature resistance of 0.4 Ohms and a back emf constant of 0.2 Vs. Suppose it is desired to operate at a load torque requiring 10 Nm at a speed of 500 rad/s. What is the required armature voltage ?

Machine Properties

- Let's look at the performance of a machine with the following properties: armature resistance 20 mΩ, torque constant 30 mVs.
- We will look at a speed range of 0 to 750 rad/s
- We will apply 10 V and 20 V to the armature

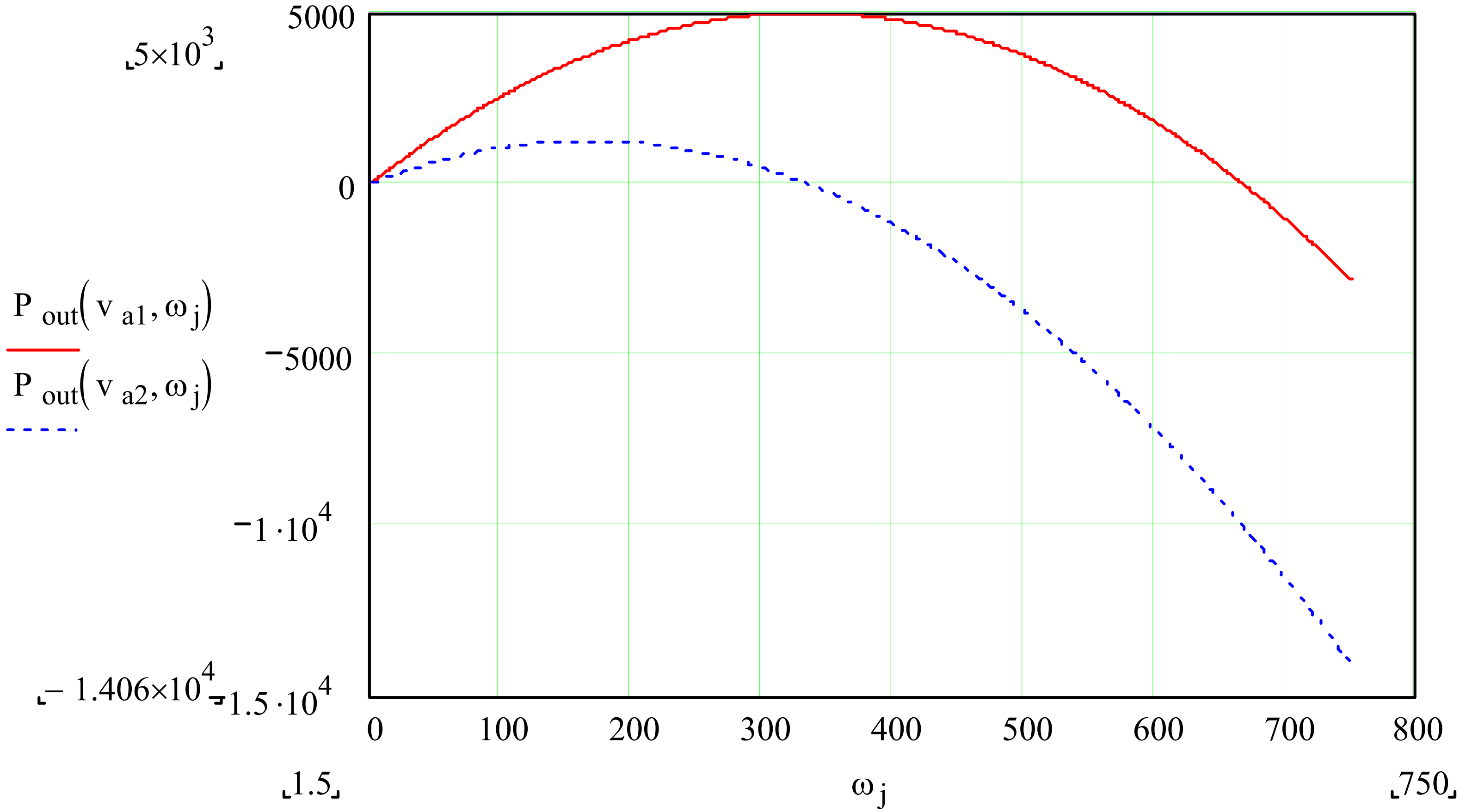
Notes

Torque

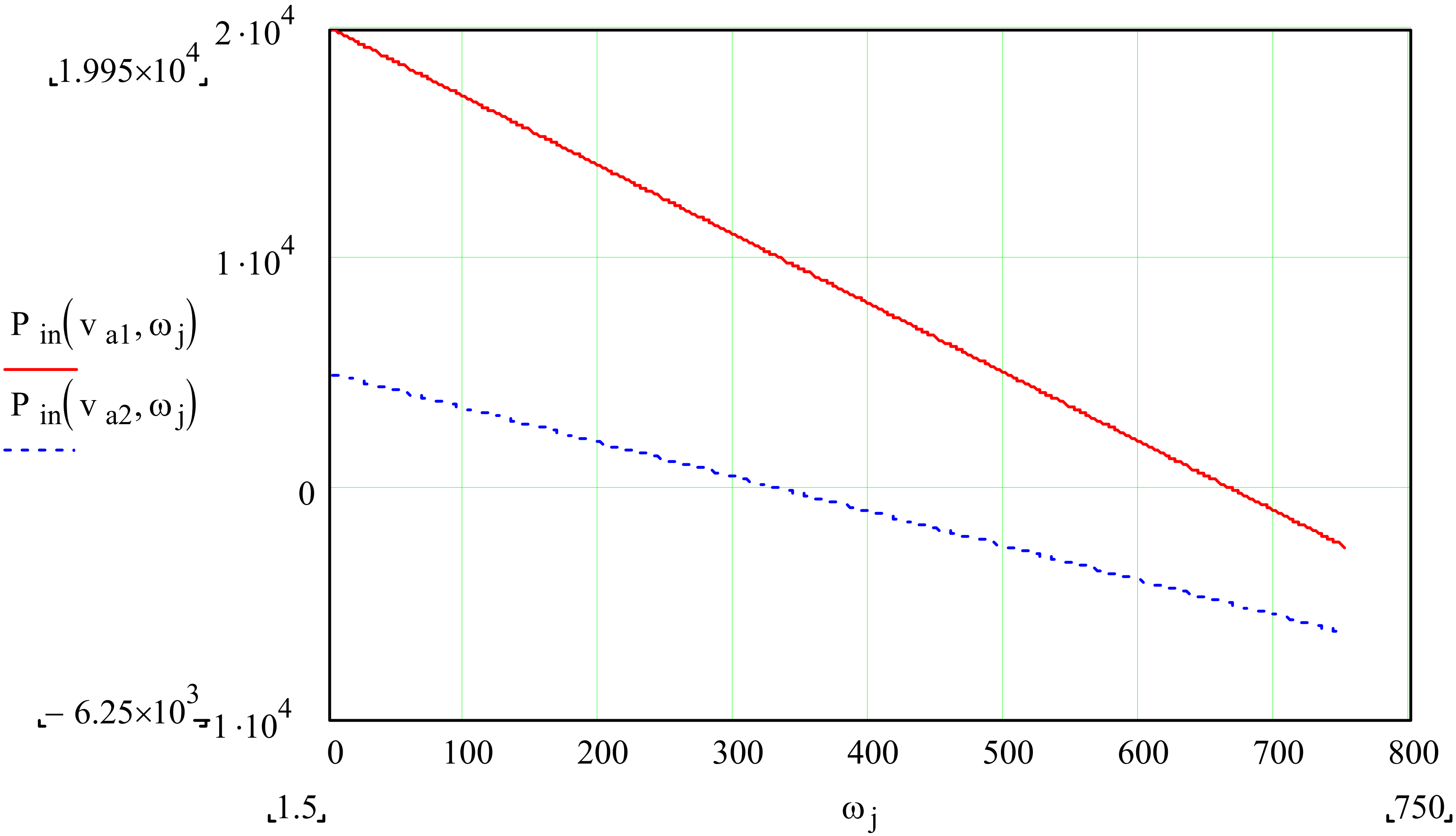


29.932
30
20
10
0
−10
− 18.75
−20
$T_e(v_{a1}, \omega_j)$
$T_e(v_{a2}, \omega_j)$
0
100
200
300
400
500
600
700
800
1.5
ω_j
750

Output Power

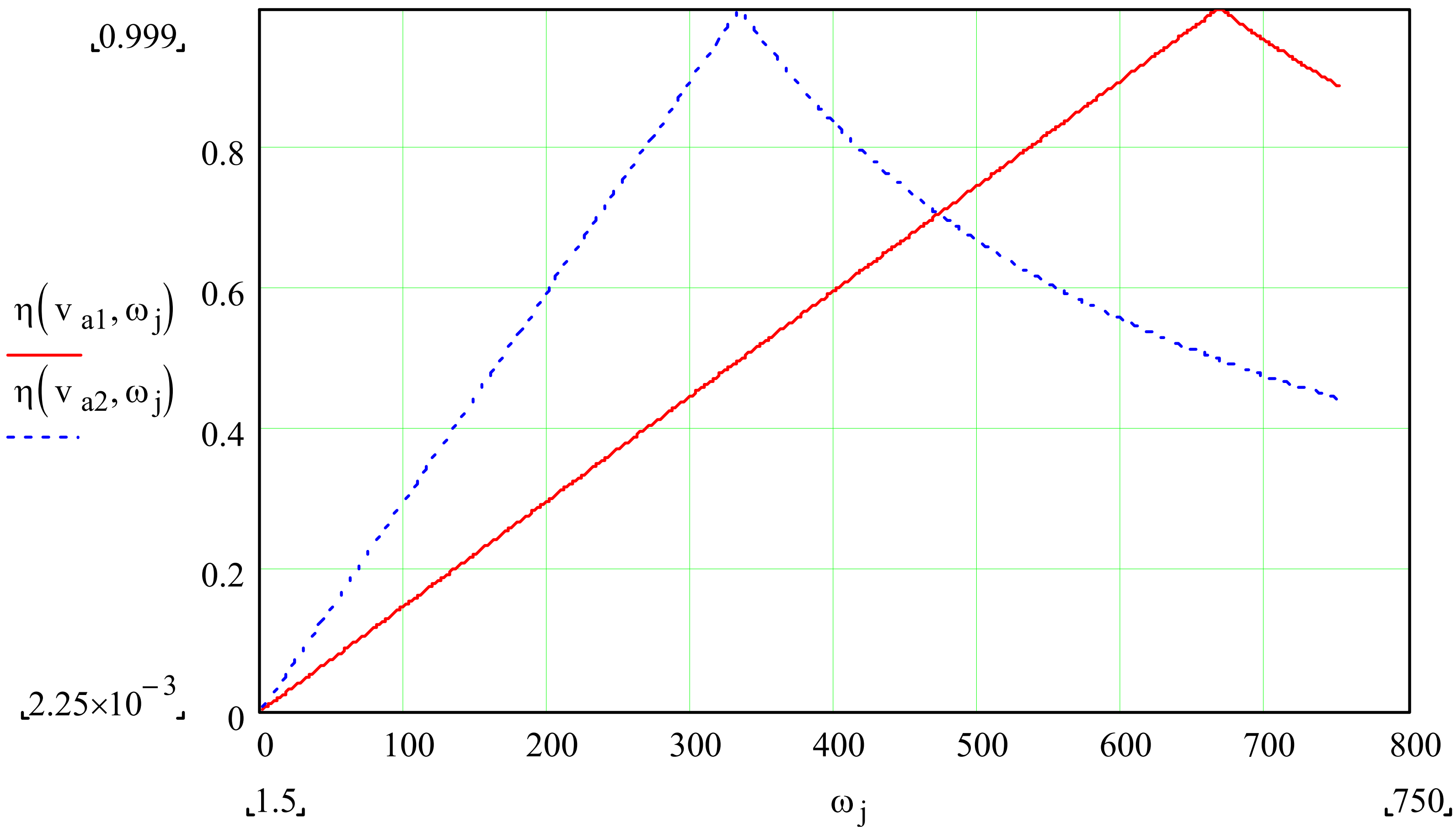


Input Power



2 ·10^4
1.995×10^4
1 ·10^4
0
− 6.25×10^3
−1 ·10^4
P in(v a1, ω j)
P in(v a2, ω j)
0
100
200
300
400
500
600
700
800
1.5
ω j
750

Efficiency



0.999
0.8
0.6
0.4
0.2
0
2.25×10⁻³
η(v a1, ω j)
η(v a2, ω j)
0
100
200
300
400
500
600
700
800
1.5
ω j
750

Lecture 36

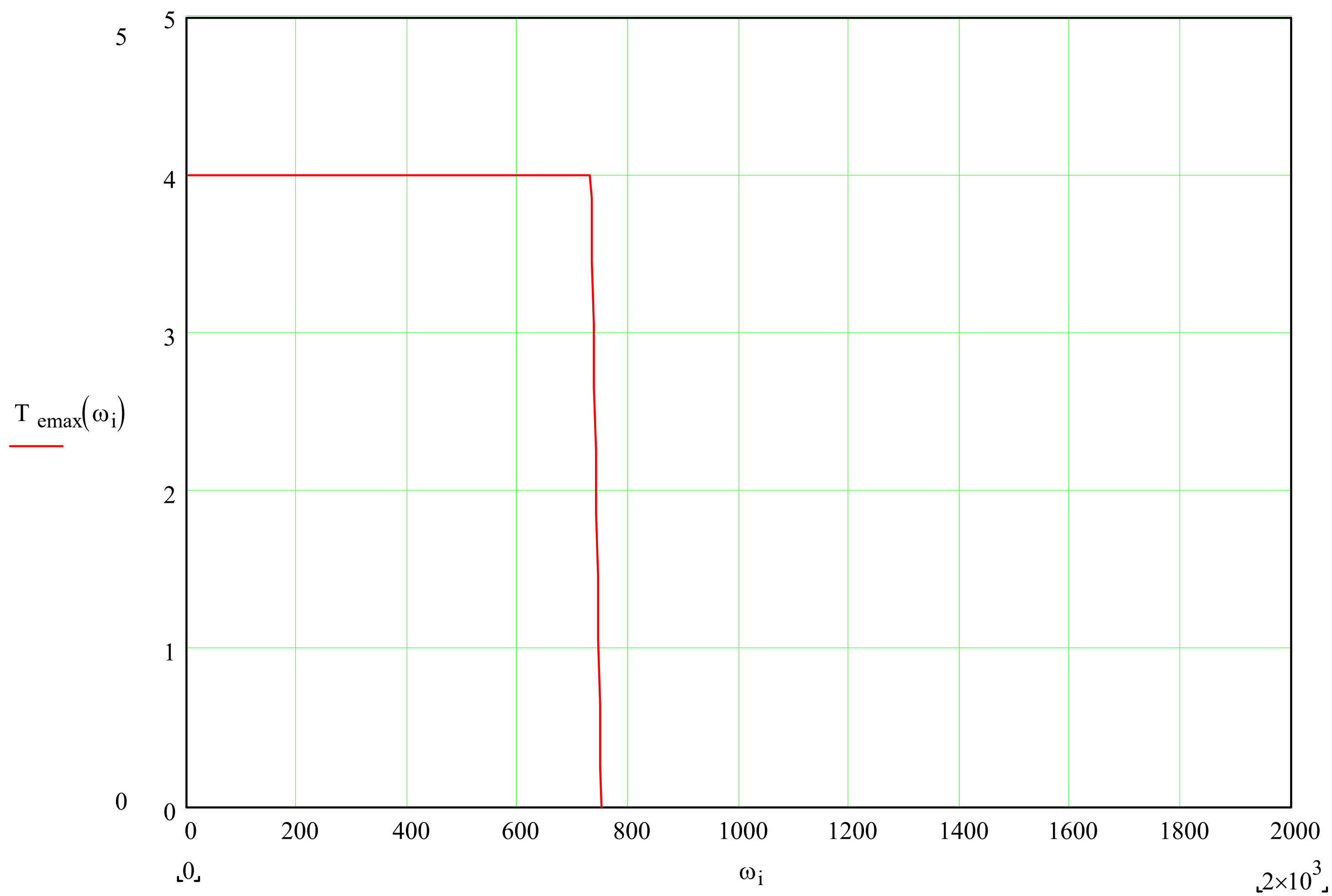
Permanent Magnet DC Machine Capability Curve and Parameter ID

Capability Curve

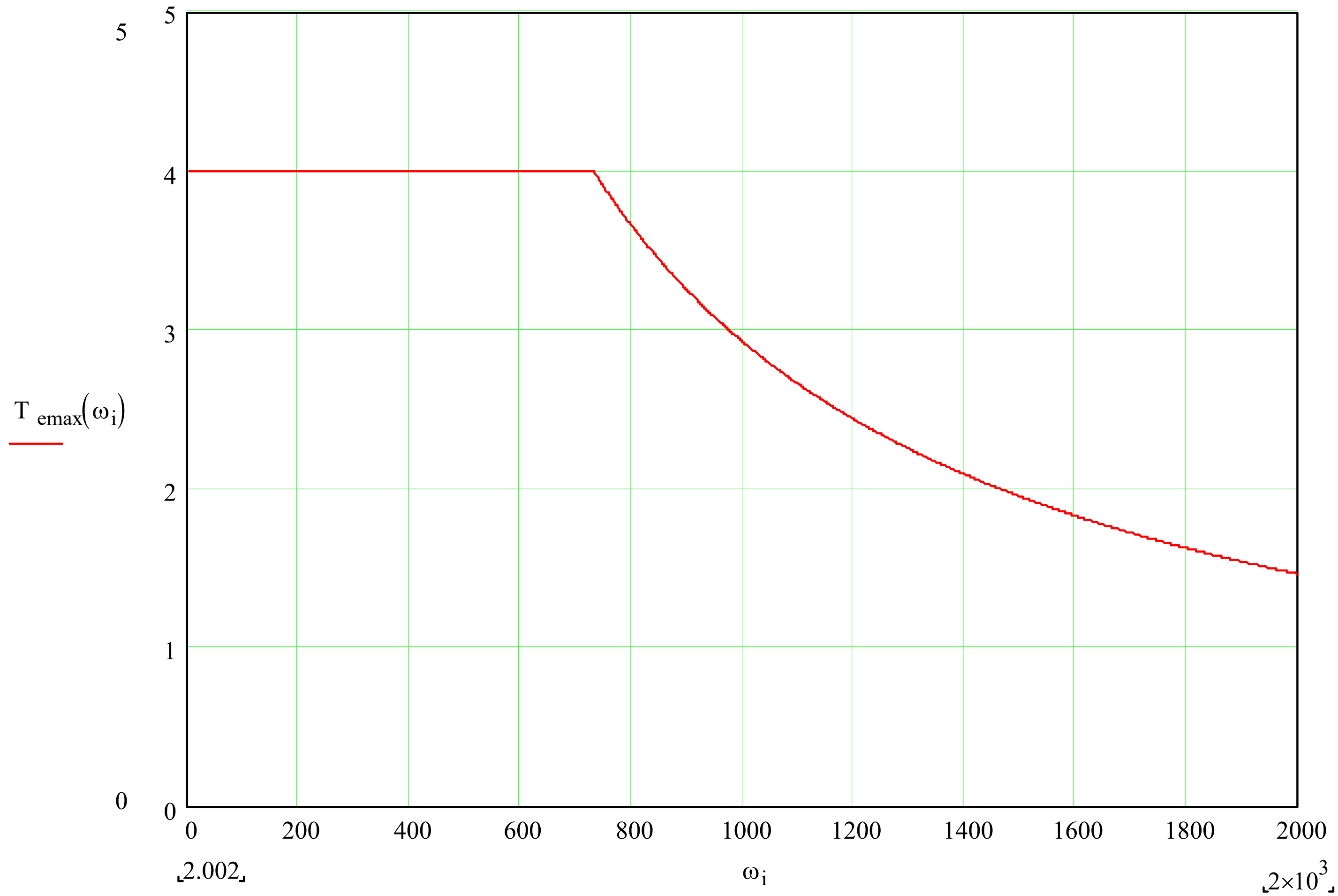
- Consider a machine with a armature resistance of 0.2 Ω, and a back emf constant of 0.2 Vs. If the armature current is limited to 20 A, and the armature voltage to 150 V, what is the operating range

Capability Curve

Capability Curve



Capability Curve (Separately Excited)



Parameter Identification

- One approach

- Another approach

Parameter Identification

Parameter Identification Example

- At operating point 1, the armature voltage is 100 V, the armature current is 20 A, and the speed is 400 rad/s
- At operating point 2, the armature voltage is 90 V, the armature current is 10 A, and the speed is 800 rad/s
- Find the machine parameters

Parameter Identification Example

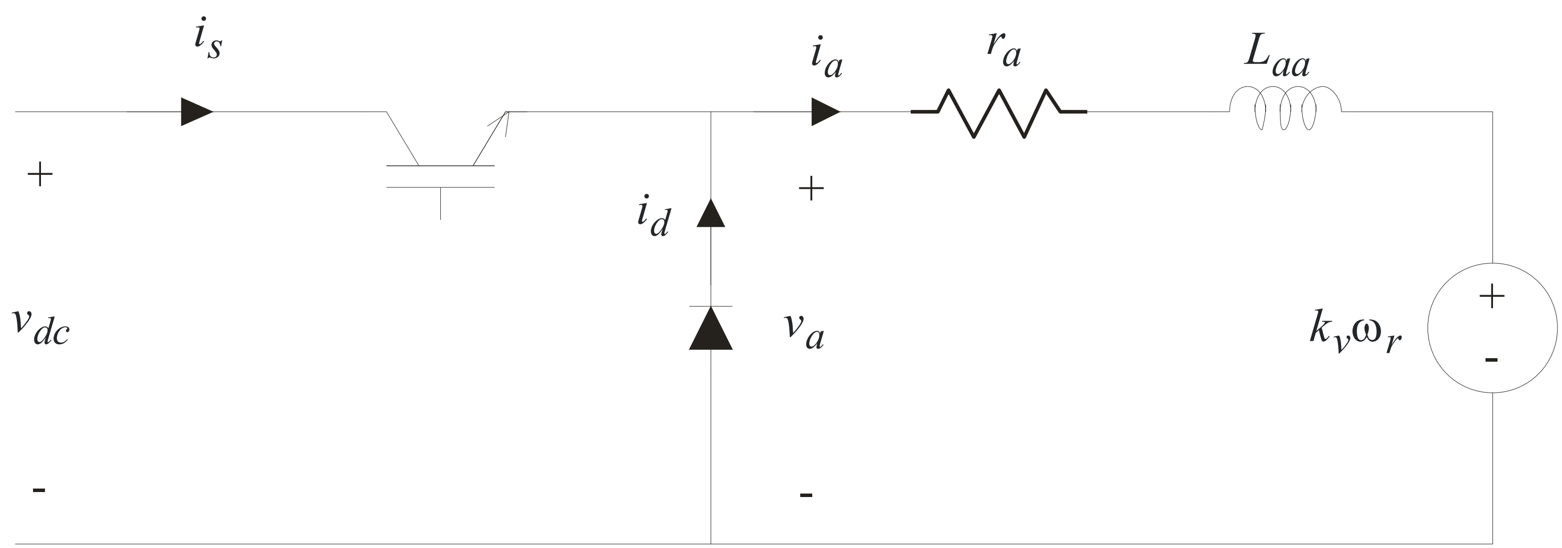
Lecture 37

Permanent Magnet DC Machine Drives

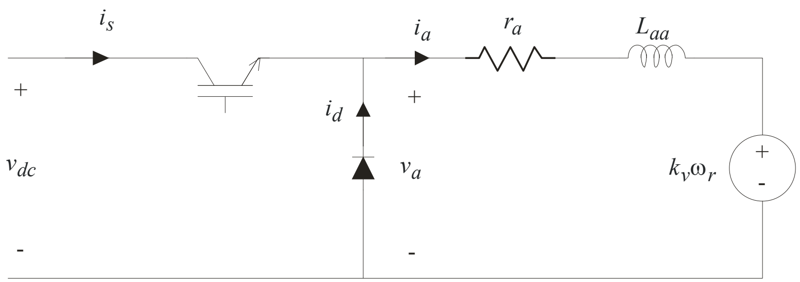
DC Drives

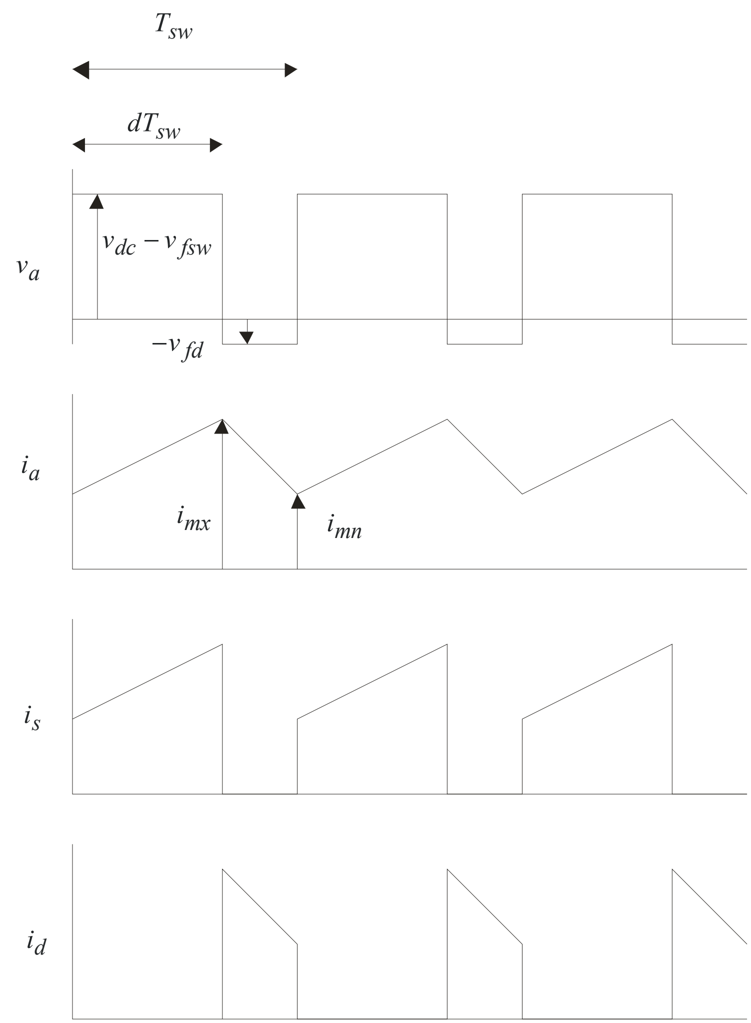
- Motivation: How do we control the armature voltage or current in a dc machine ?

Single Quadrant Chopper



Operating Waveforms (Continuous Mode)





Average-Value Analysis (VSO, Cont. Mode)

- Definition of Steady State Average

$$\bar{x} = \frac{1}{T_{sw}} \int_{t_{ss}}^{t_{ss}+T_{sw}} x(t)dt$$

- Definition of Fast Average

$$\hat{x}(t) = \frac{1}{T_{sw}} \int_{t-T_{sw}}^{t} x(\tau)dt$$

Average-Value Analysis (VSO, Cont. Mode)

Average-Value Analysis (VSO, Cont Mode)

- Armature Voltage Equation

- Torque Equation

- Mechanical Dynamics

Average-Value Analysis (VSO, Cont Mode)

- Derivation of Average Armature Voltage

- Thus we have

$$\hat{v}_a = (v_{dc} - v_{fsw})d - v_{fd}(1-d)$$

Average Value Analysis (VSO, Cont Mode)

- Derivation of armature current

- Thus we have

$$\hat{i}_s = \hat{i}_a d$$

Average Value Model (VSO, Cont Mode)

Average Value Analysis (VSO, Cont Mode)

- Comments on Power
  - Power into converter

$$p_{cnv} = v_{dc} i_s$$

  - Power into motor

$$p_{mtr} = v_a i_a$$

  - Power into mechanical system

$$p_{mech} = T_e \omega_r$$

Average Value Analysis (VSO, Cont Mode)

Average Value Analysis (VSO, Cont Mode)

A Quick Example

- Consider a model with the following parameters
  - k_v= 0.2 Vs
  - r_a = 100 mΩ
- The converter has the following parameters
  - v_{fd} = 2.0
  - v_{fsw} = 2.4
  - v_{dc} =100 V
- Suppose the duty cycle is 0.7 and the speed is 300 rad/s. Find the average armature current, the average switch current, the converter efficiency, the motor efficiency, and the system efficiency.

A Quick Example (Continued)

A Quick Example (Continued)

Lecture 38

Permanent Magnet DC Machine Drive

Current Ripple

Steady-State Current Ripple

- It can be shown that

$$i_{mx} - i_{mn} = \frac{T_{sw}}{L_{aa}}\left(v_{dc} - v_{fsw} + v_{fd}\right)d(1-d)$$

Steady-State Current Ripple

Steady-State Current Ripple

Steady-State Current Ripple

Steady-State Current Ripple

Quick Example (Part 2)

- Consider the previous example. Suppose
  - $L_{AA} = 0.2$ mH
- Find (1) the switching frequency so the peak-to-peak ripple is less than 5% of the average current (2) the minimum switching frequency for continuous operation

Quick Example (Part 2)

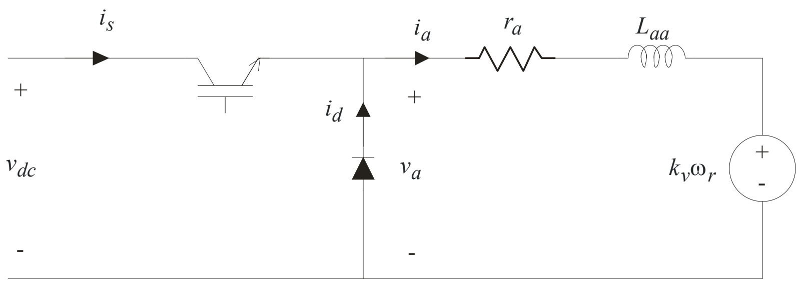
Quick Example (Part 2)

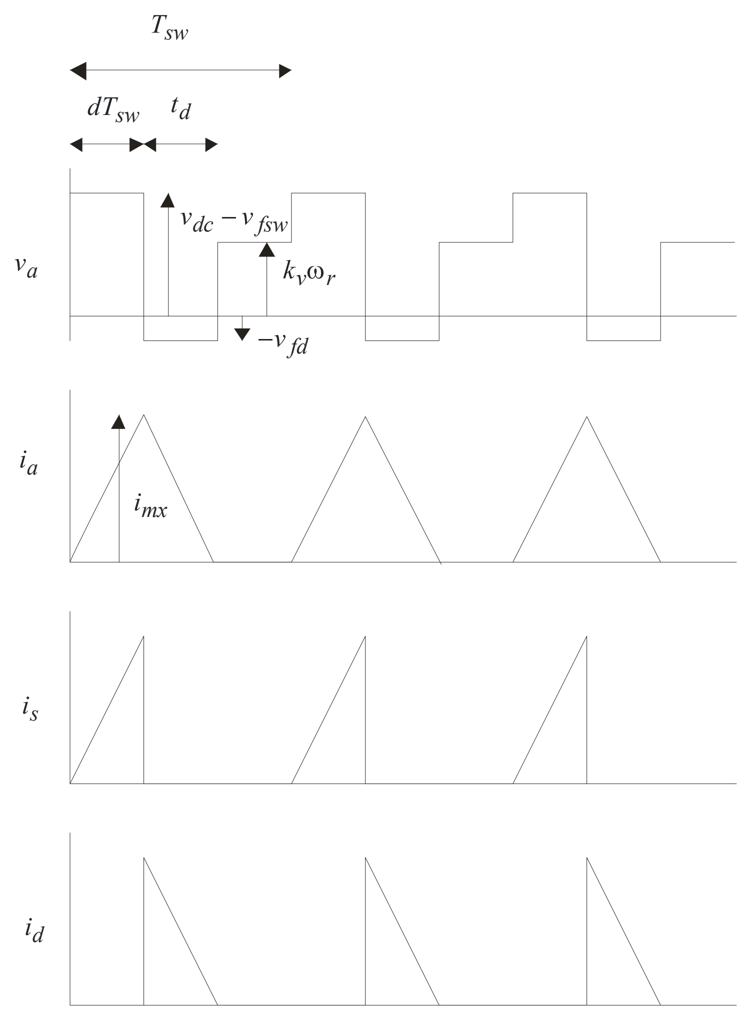
Quick Example (Part 2)

Lecture 39

Permanent Magnet DC Machine Drive
VSO Discontinuous Mode

VSO Discontinuous Mode





VSO Discontinuous Mode

- Peak current

$$i_{mx} = \frac{2d\left(v_{dc} - v_{fsw} - k_v \omega_r\right)}{2L_{aa} f_{sw} + d r_a}$$

VSO Discontinuous Mode

VSO Discontinuous Mode

- Time required for current to go to zero

$$t_d = \frac{L_{aa} i_{mx}}{v_{fd} + r_a \frac{i_{mx}}{2} + k_v \omega_r}$$

VSO Discontinuous Mode

VSO Discontinuous Mode

- Average Current

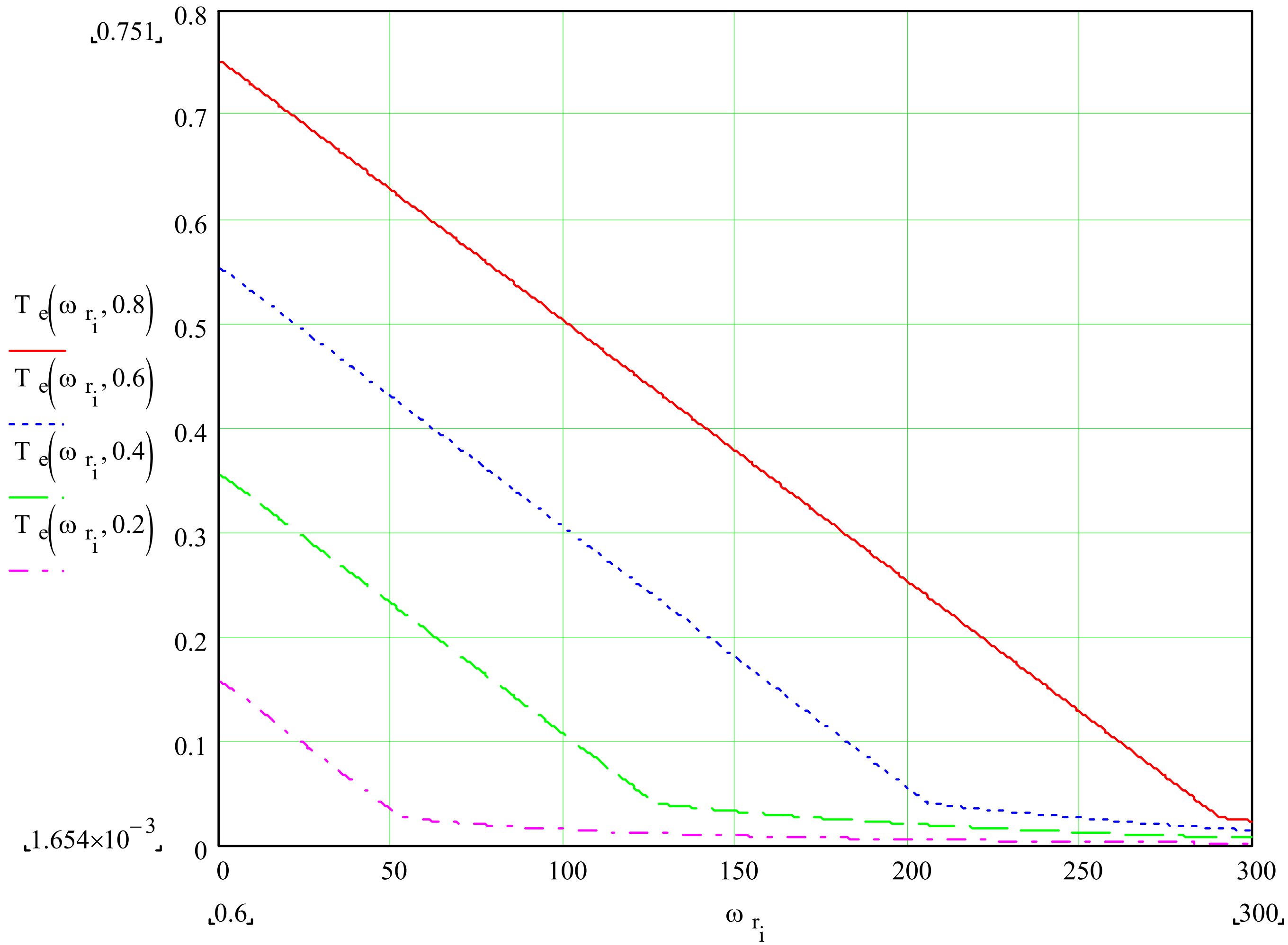
$$\bar{i}_a = \frac{1}{T_{sw}}\left(\frac{1}{2}dT_{sw}i_{mx} + \frac{1}{2}t_d i_{mx}\right) = \frac{1}{2}i_{mx}\left(d + \frac{t_d}{T_{sw}}\right)$$

Example

- Consider a machine with the following parameters
  - $V_{dc} = 20$ V
  - $r_a = 1\ \Omega$
  - $k_v = 0.05$ Vs
  - $L_{aa} = 3$ mH
  - $v_{fsw} = 1$ V
  - $v_{fd} = 0.8$ V
  - $f_{sw} = 1$ kHz
- Plot the torque speed curve for a duty cycles of 0.2, 0.4, 0.6, and 0.8

Solution Algorithm

Results



0.751
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.654×10^{-3}
$T_e(\omega_{r_i}, 0.8)$
$T_e(\omega_{r_i}, 0.6)$
$T_e(\omega_{r_i}, 0.4)$
$T_e(\omega_{r_i}, 0.2)$
0
50
100
150
200
250
300
0.6
ω_{r_i}
300

Lecture 40

Permanent Magnet DC Machine Drive
Current Source Operation

Hysteresis Current Control

Current Source Operation

Current Source Operation

Current Source Operation

Lecture 41

Permanent Magnet DC Machine Drive
Two and Four Quadrant Converters

Two Quadrant Converter

Two Quadrant Converter

Two Quadrant Converter

Four Quadrant Converter