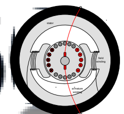
EE 56 – ELECTRIC MACHINES AND DRIVES

Course Information

EE 560
Electric Machines & Drives

Dr. Nicholas Nagel

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University of Washington
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&
Turntide Technologies
EML: nick.nagel@turntide.com
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EE 560 – Electric Machines & Drives

Course Purpose:

This course will focus on the fundamentals of electric machines and drives. Electric machines and drives are pervasive in industry and are the largest consumer of electrical energy. While the topic of electric machines and drives is broad, this course will focus on specific areas of interest consistent with robotics, machine tools, industrial automation, and electric vehicles. All four of these areas require servo control of the electric machine in order to meet the requirements of the application.

Course Description:

Servo control requires proper knowledge and understanding of electric machines and power electronic drives. This course gives fundamental principles of AC and DC drive systems including machine structures and driver topologies. The fundamentals of brush DC, Brushless DC (BLDC), PM synchronous, and induction machines are explored. In addition, inverter topologies and control techniques are presented. The course begins with the basics of DC machines and extends to the concept of field orientation in AC machines.

EE 560 – Electric Machines & Drives

Course Objectives:

- To review the physics of DC and AC machines
- To develop techniques to control the electromagnetic torque of the machine using our understanding of physics
- To compare various forms of control of electric machines
- To provide the student with sufficient background to understand and apply the tremendous wealth of knowledge presented in IEEE publications on this topic
- To provide specific application examples of motors and drives (Robotics, Automation, and Electric Vehicles)

Prerequisites: EE 453 or similar, or consent of instructor

Grading:

HW……………………………..…75%

Term Project…………………..…25%

EE 560 – Electric Machines & Drives

Course Text:

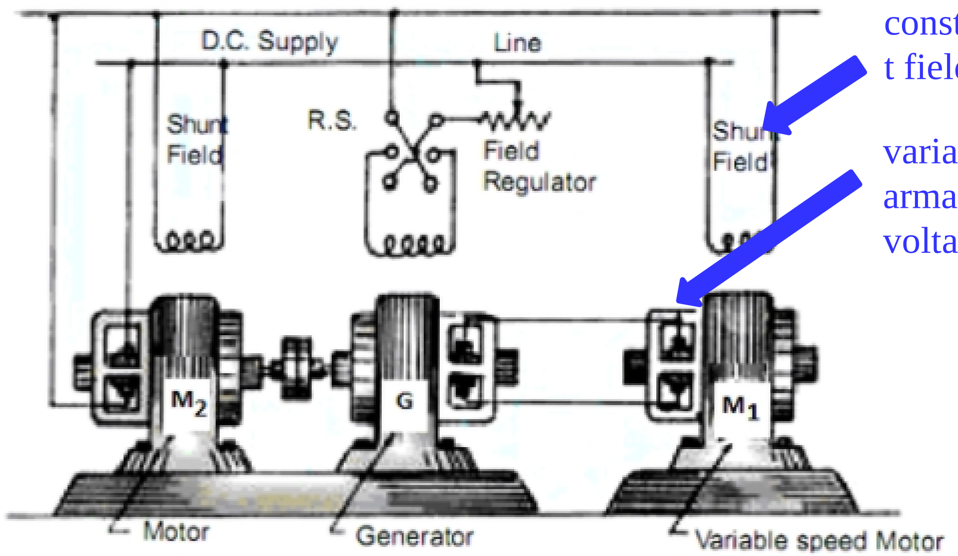
There is no assigned textbook for this course. Technical papers, reports, and notes will be provided to the students. The following books can be used as reference.

1. *Introduction to Electric Machines and Drives,* D.W. Novotny, T.A. Lipo, and T. M. Jahns, Wisconsin Power Electronics Research Center, Madison, Wi, 2009.
2. *Fundamentals of Electric Drives,* Mohamed A. El-Sharkawi, Brooks/Cole, Pacific Grove, Ca, 2000.
3. *Vector Control and Dynamics of AC Drives*, D.W. Novotny and T.A. Lipo, Clarendon Press, Oxford, 1996.
4. *Brushless Permanent Magnet and Reluctance Motor Drives*, T. J. E. Miller, Magna Physics Publishing, Madison, WI, 1993.
5. *The Field Orientation Principle in Control of Induction Motors*, A. M. Trzynadlowski, Kluwer Academic Publishers, Norwell, MA, 1994.
6. *Vector Control of AC Machines*, P. Vas, Oxford Science Publications, New York, 1990.

Overview – *Why Are Electric Drives Used*

- When the application requires variable speed operation.
  - Difficult to achieve mechanically
  - Mechanical solutions for pump or fan applications often involve throttling (speed control).
- When the type of electric machine requires a drive for operation.
  - Variable Speed of Induction Machines (VFD, Vector Drive)
  - Synchronous Machines
  - Switched Reluctance Machines
- When motion control is required.
  - Factory Automation
  - Manufacturing

Overview – *Ward Leonard System - 1891*



WARD LEONARD SYSTEM OF SPEED CONTROL

constan
t field

variable
armature
voltage

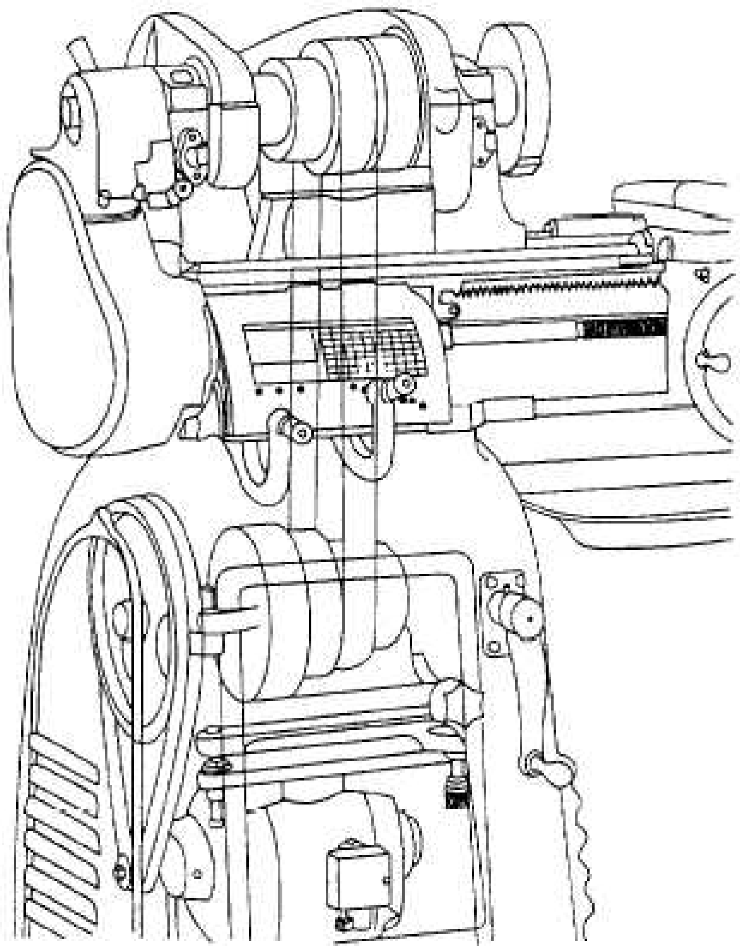
modern drives vary armature voltage with power electronics

copied from: https://www.pinterest.co.uk/pin/639229740838133480/

Variable Speed DC Motor (only three motors needed!)

Overview – *Variable Speed Technology*

Adjustable Speed (3) Drive of a Lathe



Overview – *Variable Speed Technology*

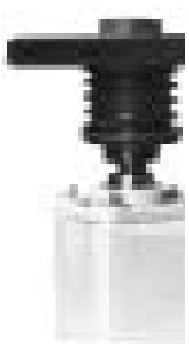
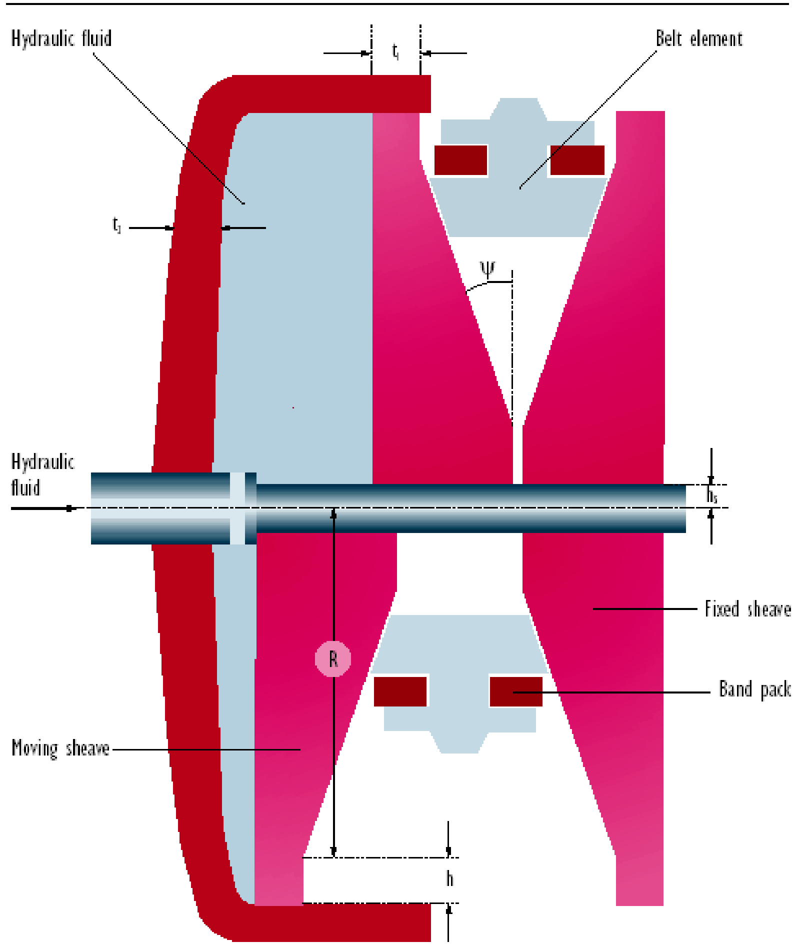


Figure 1: Cross-section of CVT pulley



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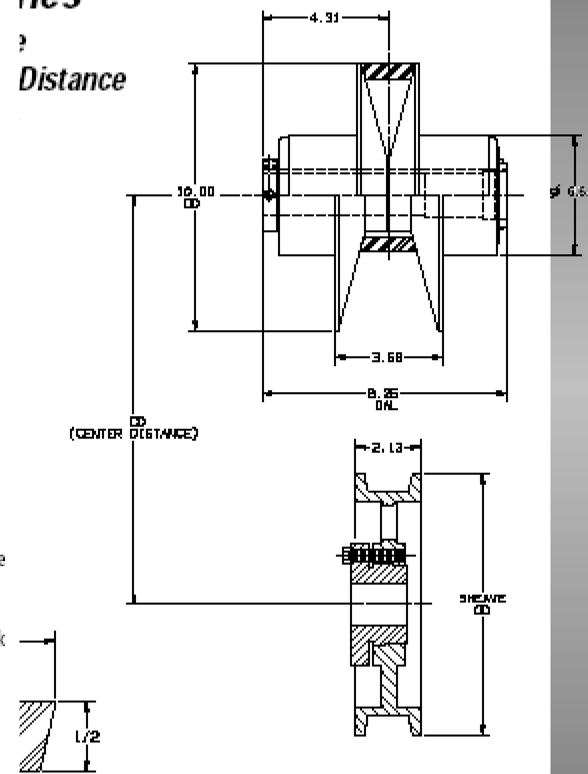
Distance



F

note:

copied from: Continuously Variable Transmission Design for Optimum Vehicle Performance by Analytical Target Cascading *a report by*

Dr Georges M Fadel, Dr Vincent Y Blouin *and* **Dr Imtiaz Haque**

Department of Mechanical Engineering, Clemson University

Overview – *Mechanical Variable Speed Technology*

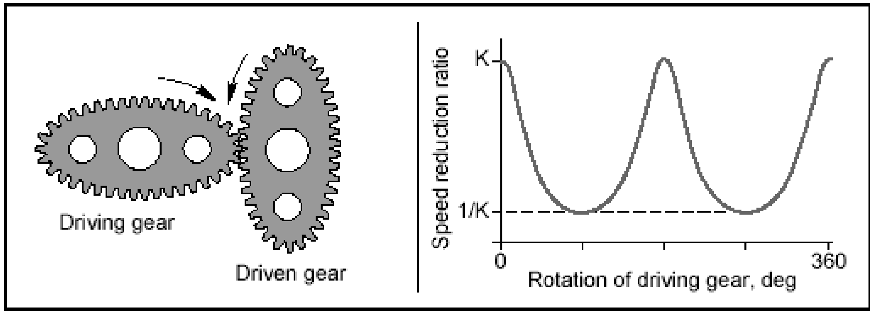


Figure 14 — Elliptical gears with two lobes (bilobes) provide twice as many periods of variable output speed.

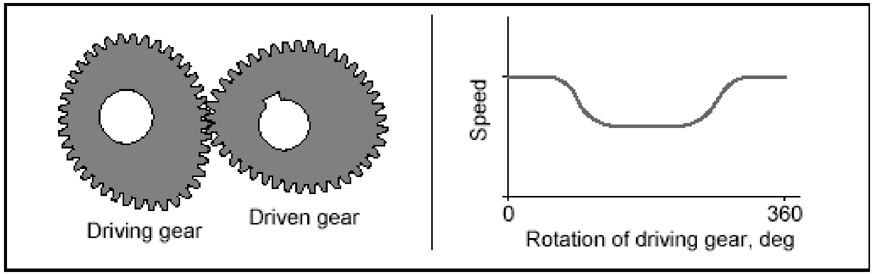


Figure 15 — Multispeed gears give one constant speed for part of a cycle and a different constant speed for a second part of the cycle.

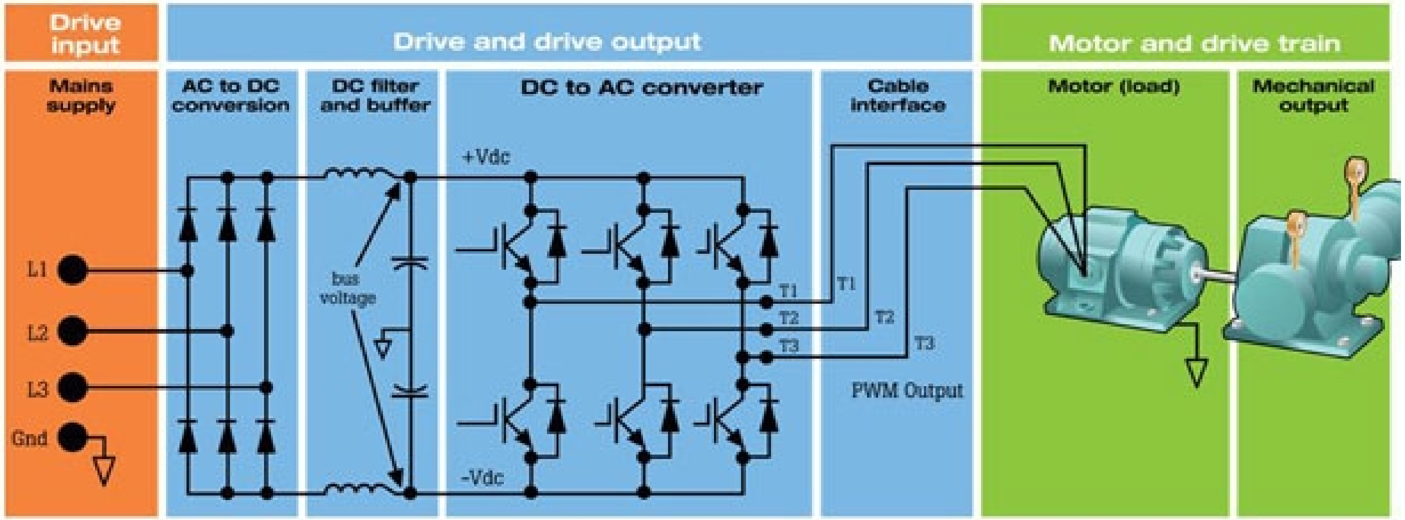
copied from: 2001 **MSD** . Motion System Design

The output does not need to be a simple ratio of the input motion control.

Motor Drives Overview

Overview – *General Purpose Drive Applications*

- General purpose industrial drives
  - Typically used with induction machines.
  - A small number of general-purpose drives support different types of synchronous machines (SRM, SynRM, PM). This is increasing.



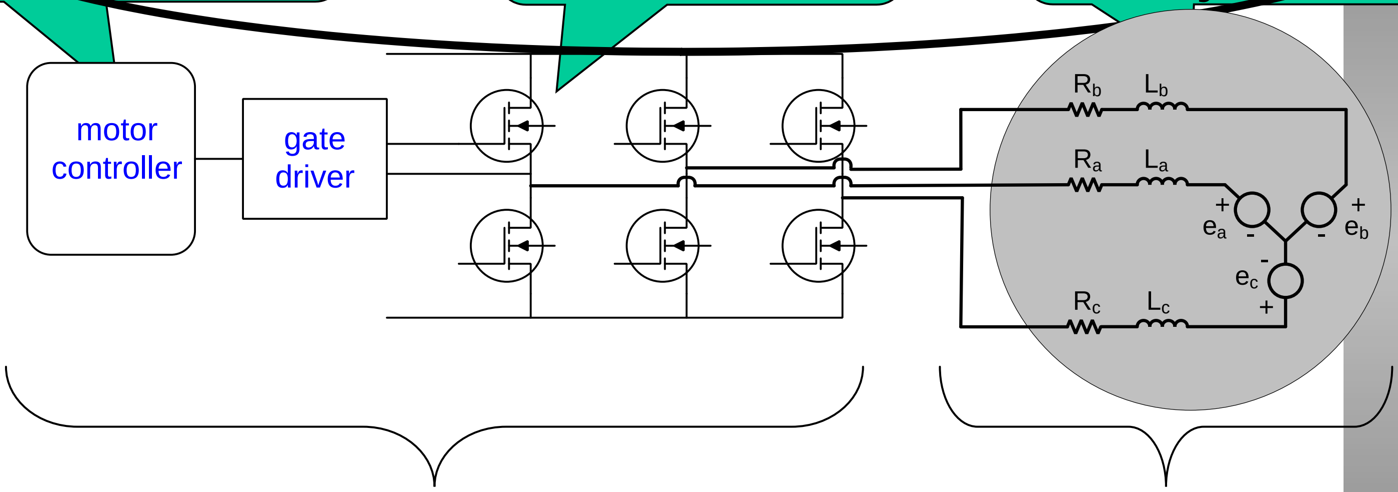
copied from:
http://en-us.fluke.com/community/fluke-news-plus/motors-drives-pumps-compressors/how-to-troubleshoot-motors-and-drives-starting-at-the-inputs.html

Overview – *Power Electronic Motor Drive*

Control Theory

Power Electronics

Machine Physics



drive

motor

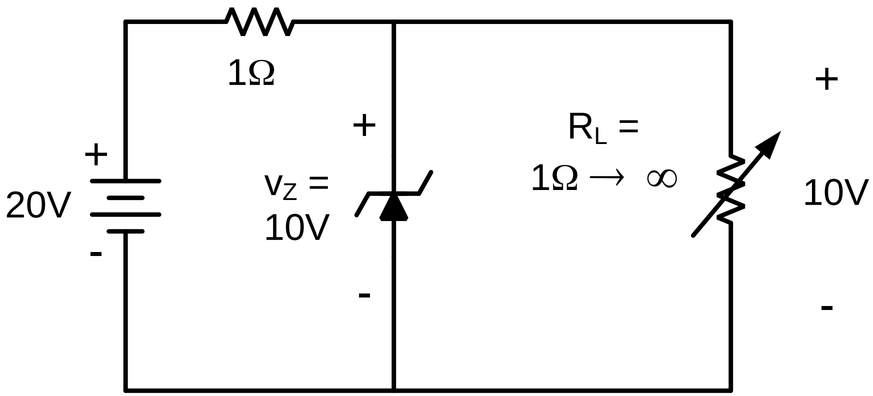
Signal Processing (for Sensors, Sensorless Operation)

Mechanical Packaging, Thermal Design

Overview – *Why Are Power Electronics Used*

- Power Processing and Control → Enabling Technology
- Efficiency

Linear Passive
Voltage Regulator

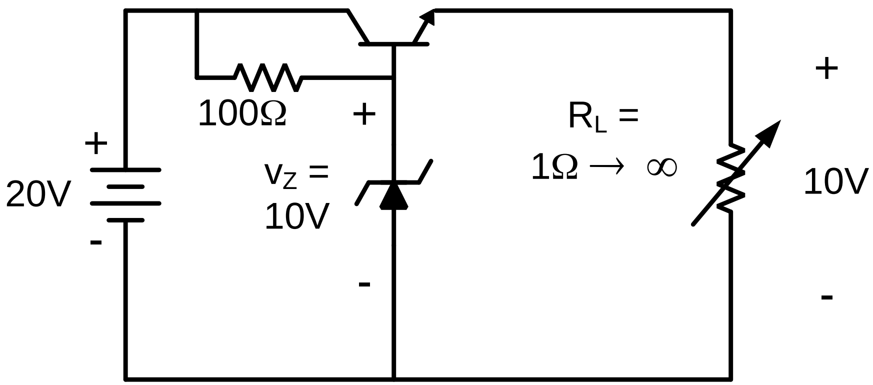


<u>Full Load</u>	<u>No Load</u>
P_{input} = 200W	P_{input} = 200W
Efficiency → 50%	Efficiency → 0%

Overview – *Why Are Power Electronics Used*

- Power Processing and Control → Enabling Technology
- Efficiency

Linear Active
Voltage Regulator



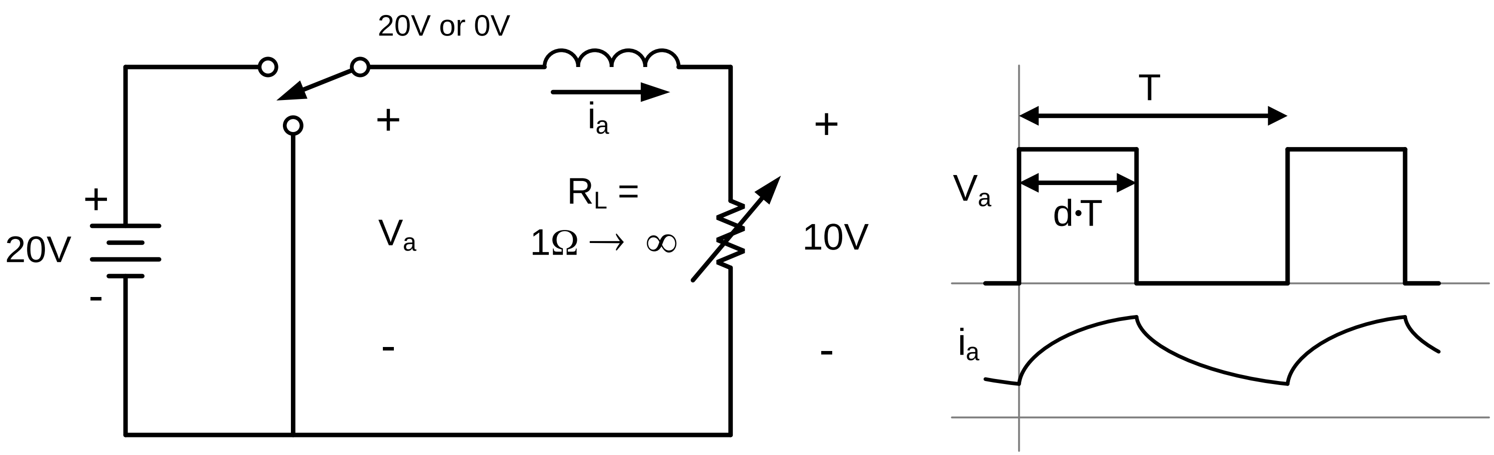
<u>Full Load</u>
P_{input} = 200W
Efficiency → 50%

<u>No Load</u>
P_{input} = 2W
Efficiency → 0%

Overview – *Why Are Power Electronics Used*

- Power Processing and Control → Enabling Technology
- Efficiency

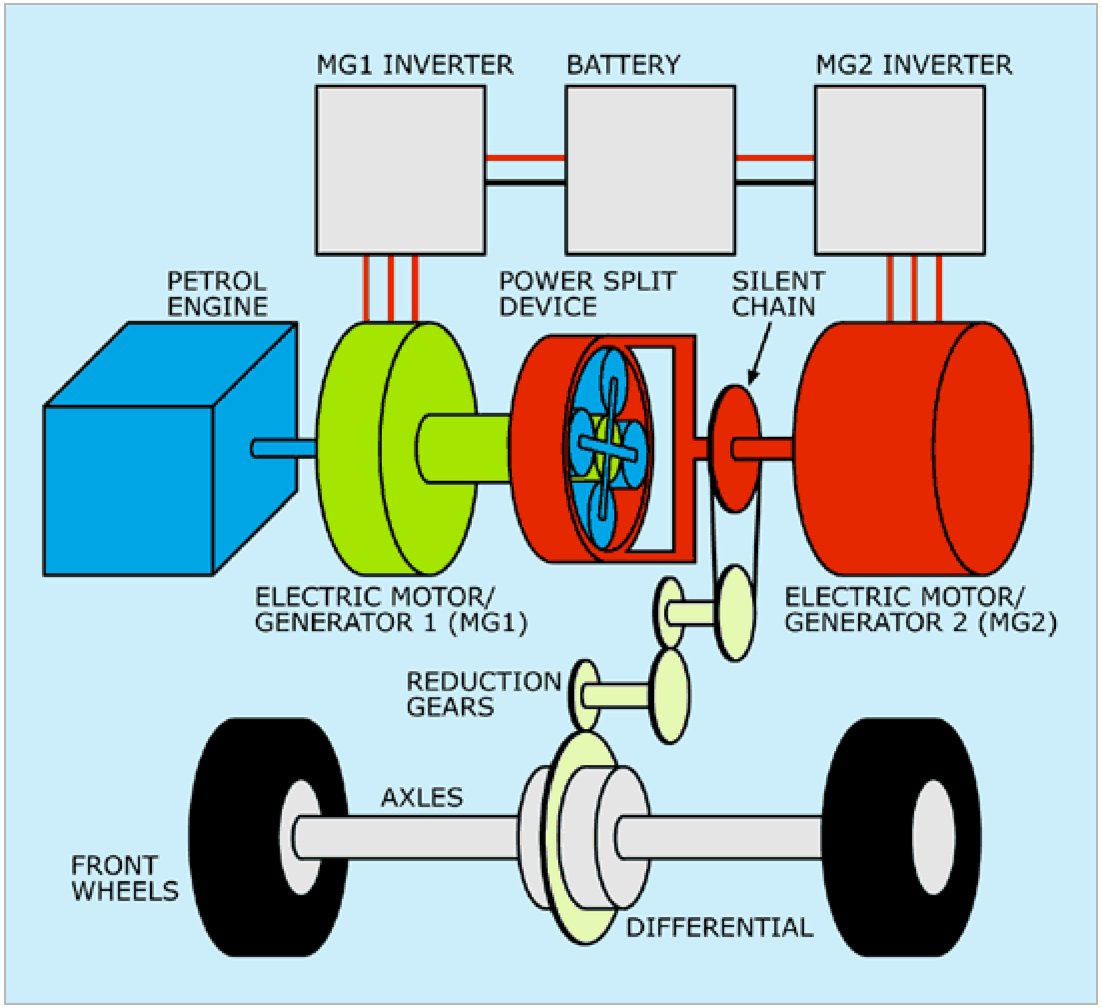
Switching Power Supply



Efficiencies can be in the high 90’s at full load

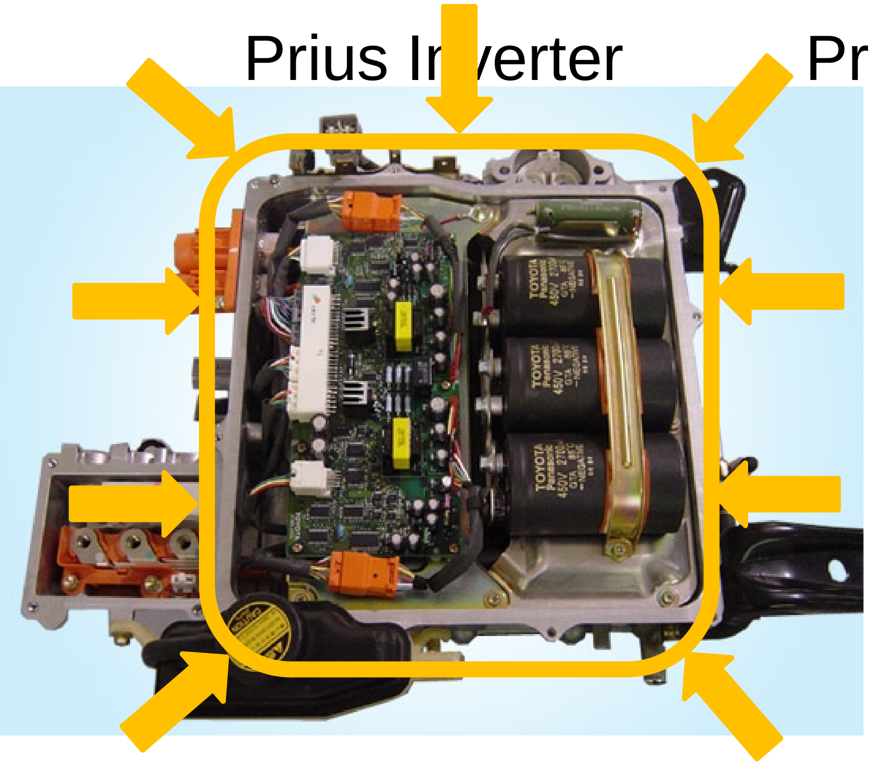
Motor Drives Applications

Overview – *Electric Vehicle Applications – Toyota Prius*

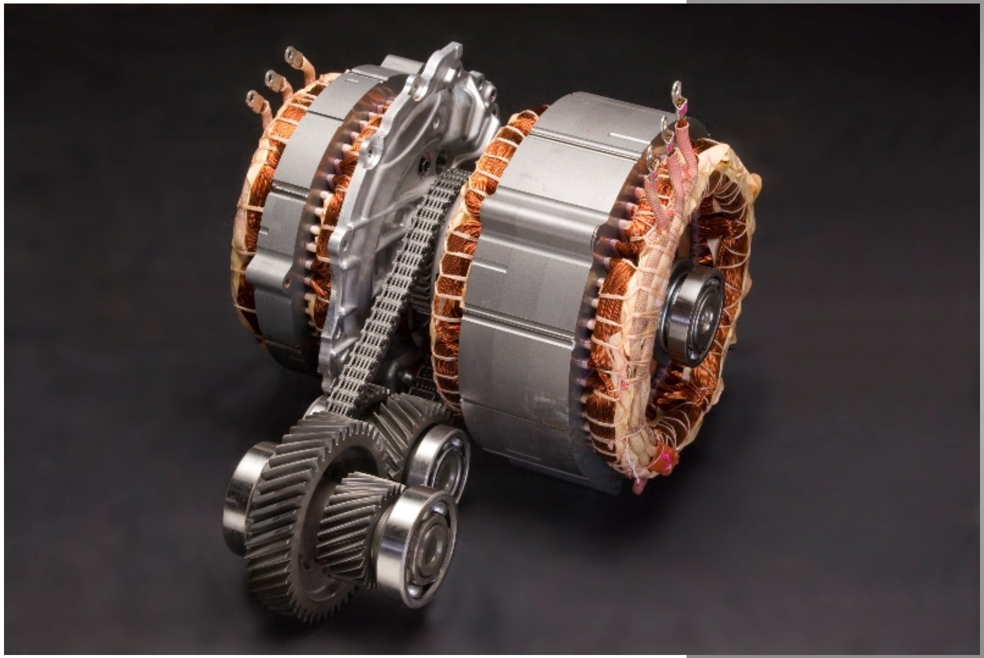


Overview – *Electric Vehicle Applications – Toyota Prius*

Prius Inverter



Prius Motor Generator Transaxle

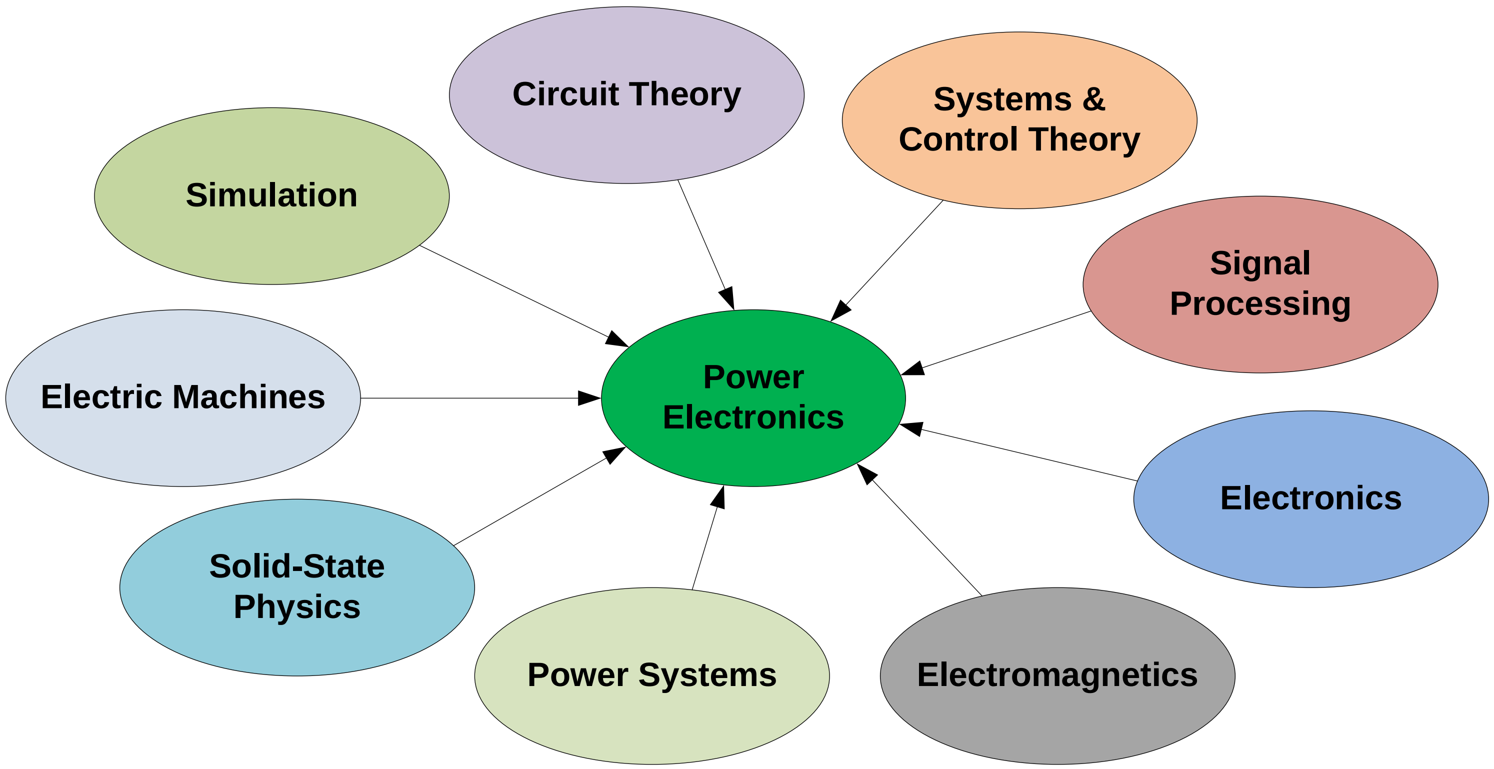


Overview – *MEA Applications*

Overview – *Robotic Applications*

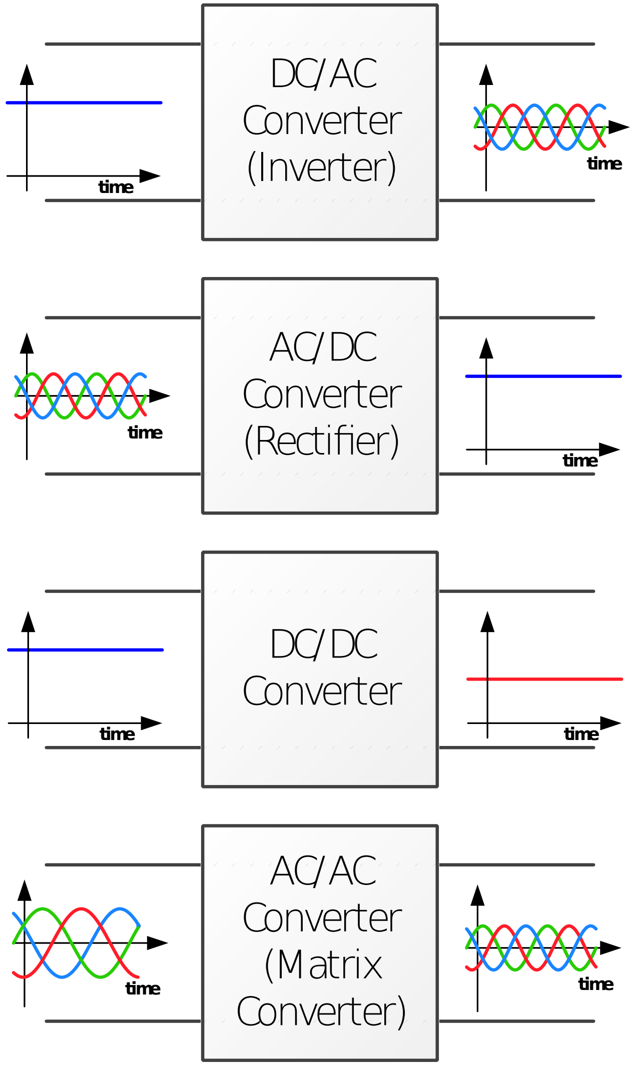
Power Electronics Overview

Overview – *Power Electronics*



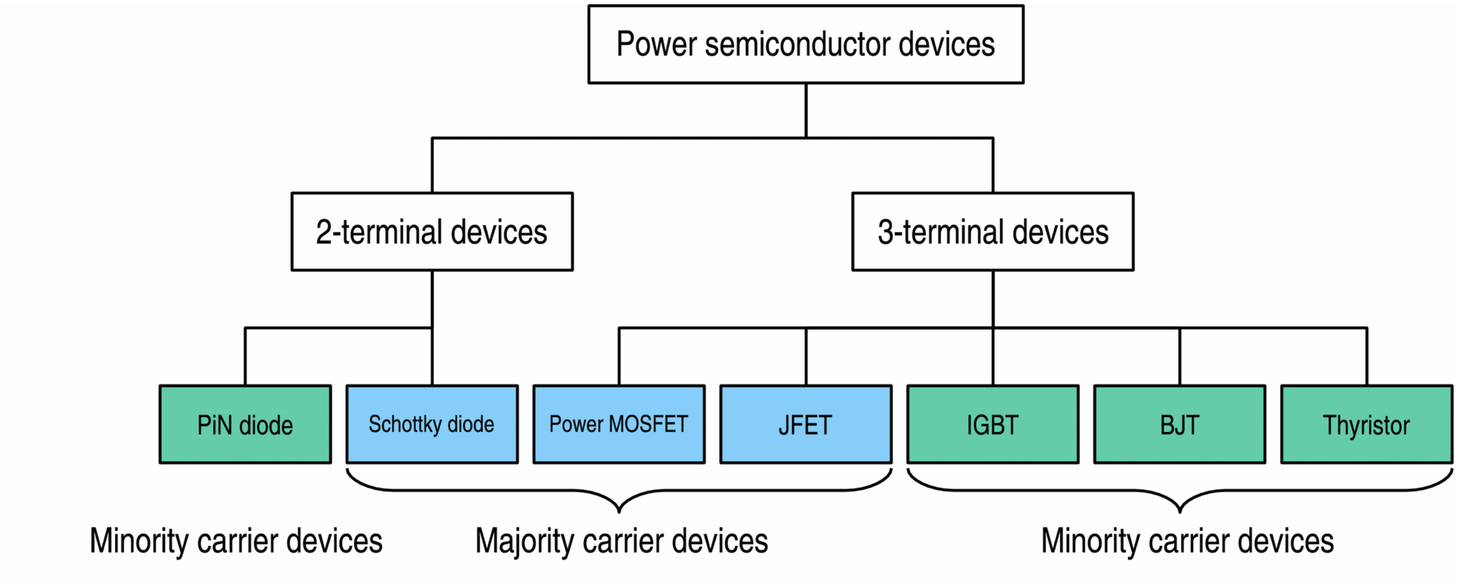
Interdisciplinary Nature of Power Electronics

Overview – *Converter Topologies*



electrical power processing

Semiconductors – *Power Electronics Devices*



Power Electronic Devices (copied from https://commons.wikimedia.org/wiki/File:Power_devices_family.png)

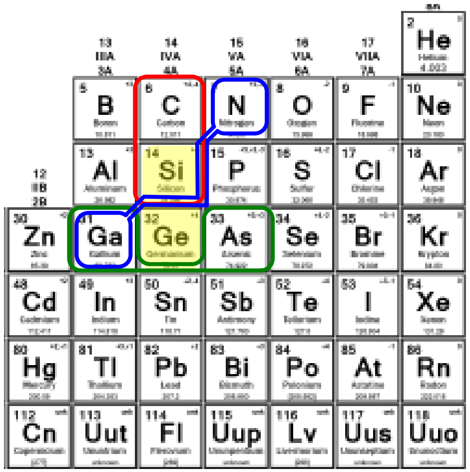
Semiconductors – *Power Electronics Devices*

Common Semicodoctors:

Material	Symbol	Group
Germanium	Ge	IV
Silicon	S	IV
Gallium Arsenide	GaAs	III-V
Silicon Carbide	SiC	IV
Gallium Nitride	GaN	III-V
Gallium Phosphide	GaP	III-V

Elemental Semiconductors

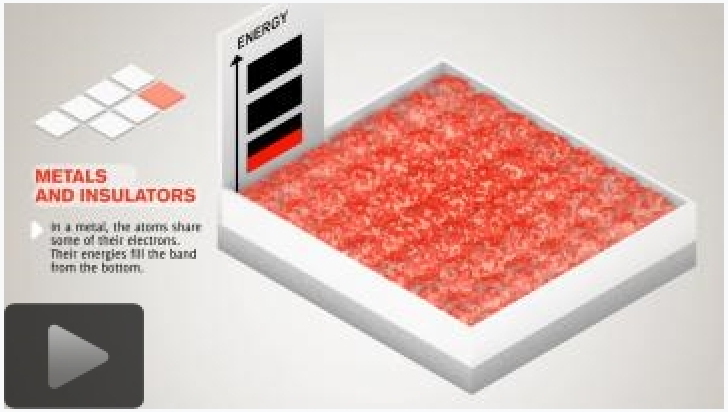
Compound Semiconductors



Semiconductors – *Power Electronics Devices*

The Fermi-Dirac distribution function gives the probability that (at thermodynamic equilibrium) a state having energy ϵ is occupied by an electron:

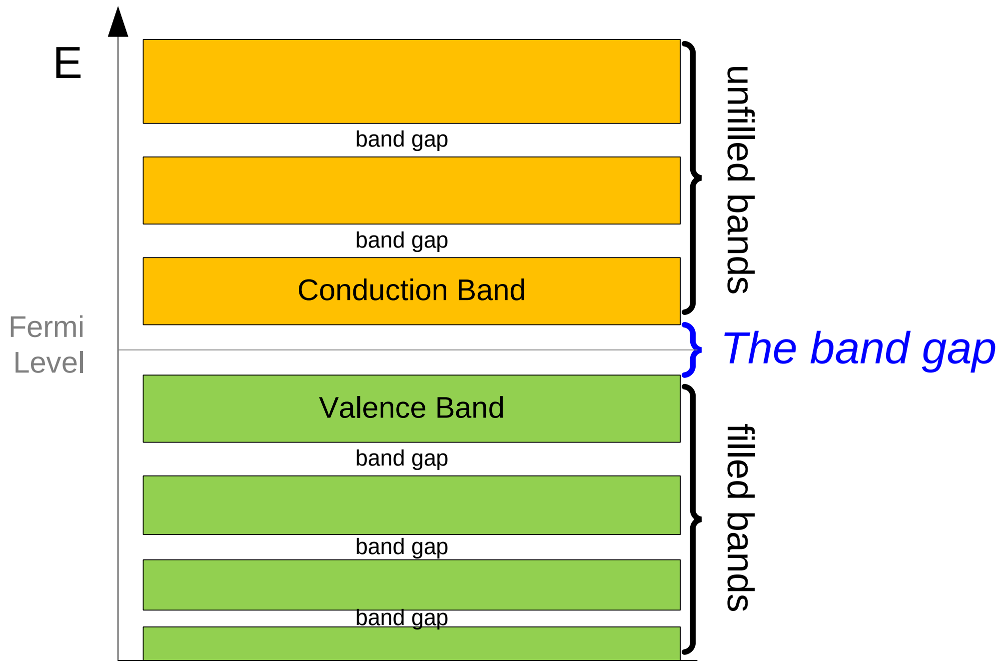
at Fermi Level



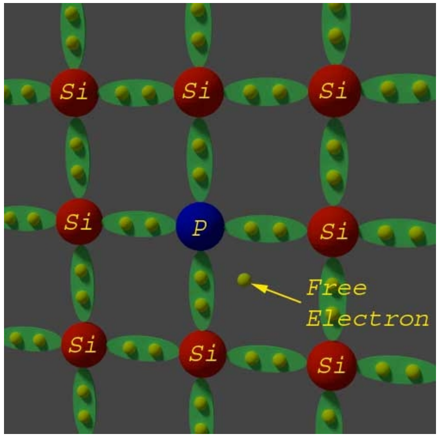
Animation of band formation and how electrons fill them in a metal and an insulator

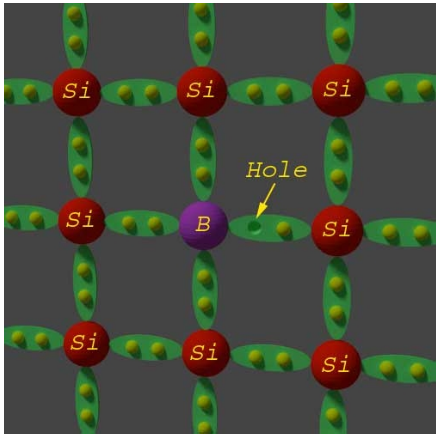
Copied from (https://en.wikipedia.org/wiki/Electronic_band_structure)

Semiconductors – *Power Electronics Devices*

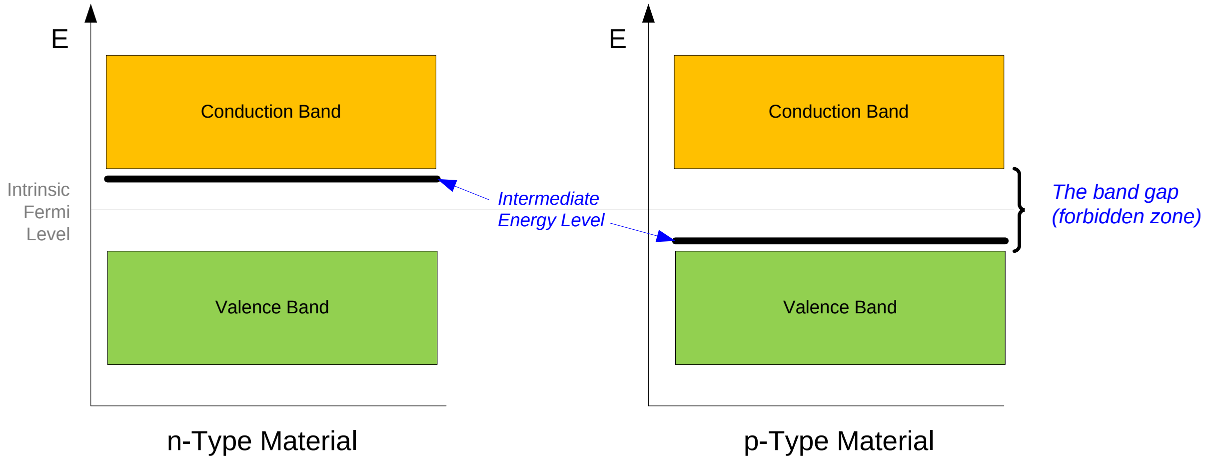


Semiconductors – *Power Electronics Devices*

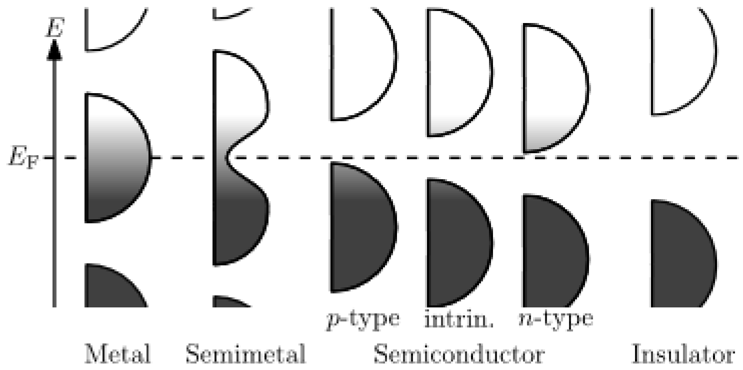




pictures from
http://www.electrical4u.com/donor-and-acceptor-impurities-in-semiconductor/



Semiconductors – *Power Electronics Devices*



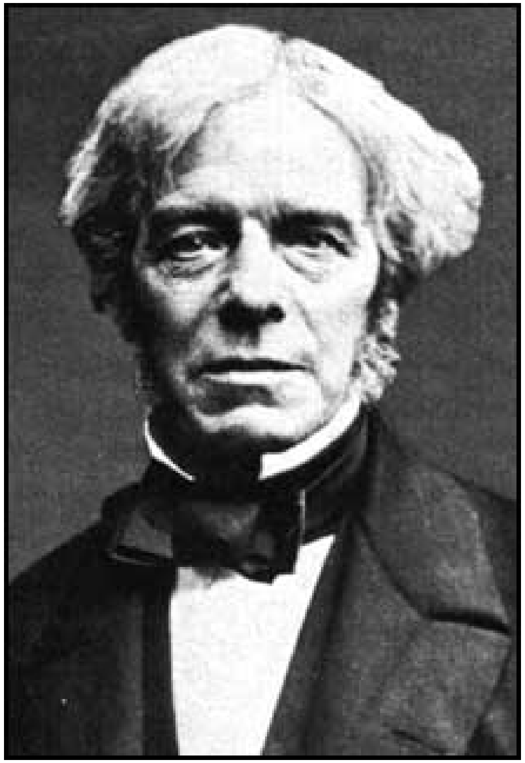
Filling of the electronic states in various types of materials at equilibrium. Here, height is energy while width is the density of available states for a certain energy in the material listed. The shade follows the Fermi–Dirac distribution (black = all states filled, white = no state filled). In metals and semimetals the Fermi level E_F lies inside at least one band. In insulators and semiconductors the Fermi level is inside a band gap; however, in semiconductors the bands are near enough to the Fermi level to be thermally populated with electrons or holes. (Copied from https://en.wikipedia.org/wiki/Fermi_level)

Machine Physics Overview

Electromagnetic Road Map

$$v \xrightarrow[\text{circuit theory}]{} i \xrightarrow{\text{geometry Ampere's Law}} H \xrightarrow[\text{material dependency}]{} \begin{matrix} B \\ \phi \\ \lambda \end{matrix} \xrightarrow{\text{motion or time-varying fields}} \frac{d\lambda}{dt} \xrightarrow[\text{Faraday's Law}]{} e \xrightarrow{\text{Lenz's Law}} i$$

FARADAY'S LAW OF INDUCTION



Michael Faraday
1791-1867

$$e = -\frac{d\lambda}{dt}$$

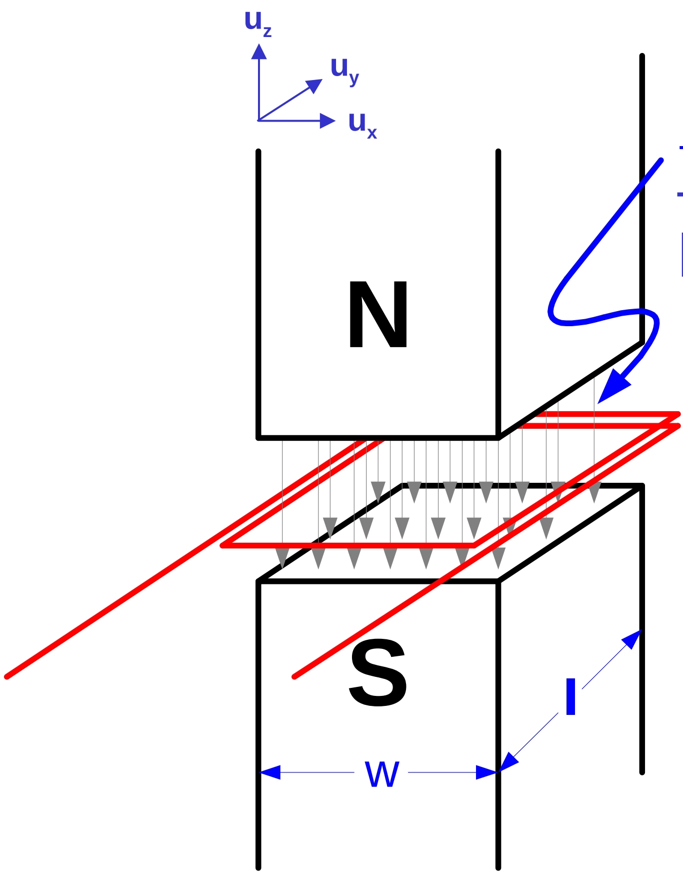
Lenz's Law

e = induced voltage in coil

$\lambda = N\phi$ = total flux linking coil times number of turns

In words: The induced voltage in a coil is equal to the time rate of change of flux linking the coil.

COIL FLUX LINKAGE



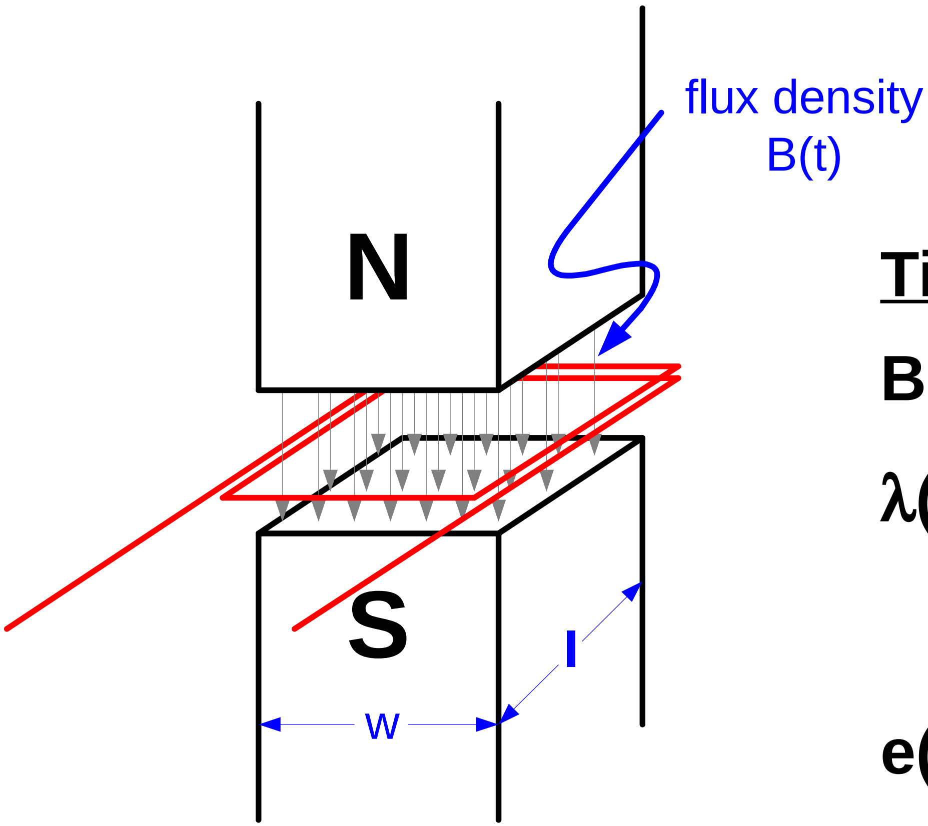
$\overline{B} = -B_o\,\overline{u}_z$

$\overline{A} = wl\,\overline{u}_z$

$$\phi = \int \overline{B} \cdot d\overline{A}$$
$$= \int -B_o\,\overline{u}_z \cdot dA\,\overline{u}_z$$
$$= -wlB$$

$$\lambda = N\phi = -NwlB$$

HOW DO WE GET A $\dfrac{d\lambda}{dt}$?



Time varying flux

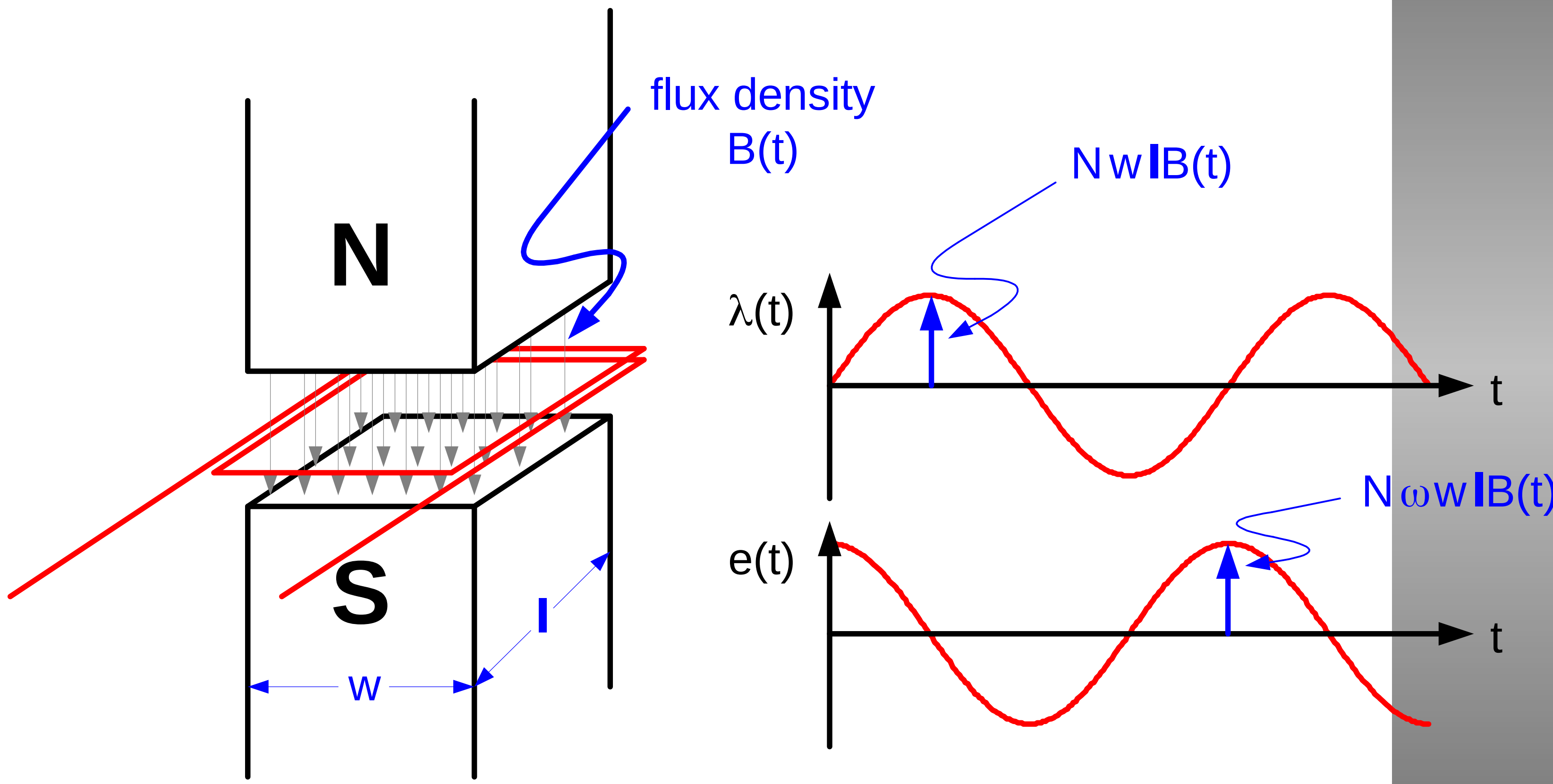
$$B(t) = B_o \sin(\omega t)$$

$$\lambda(t) = N\phi(t)$$

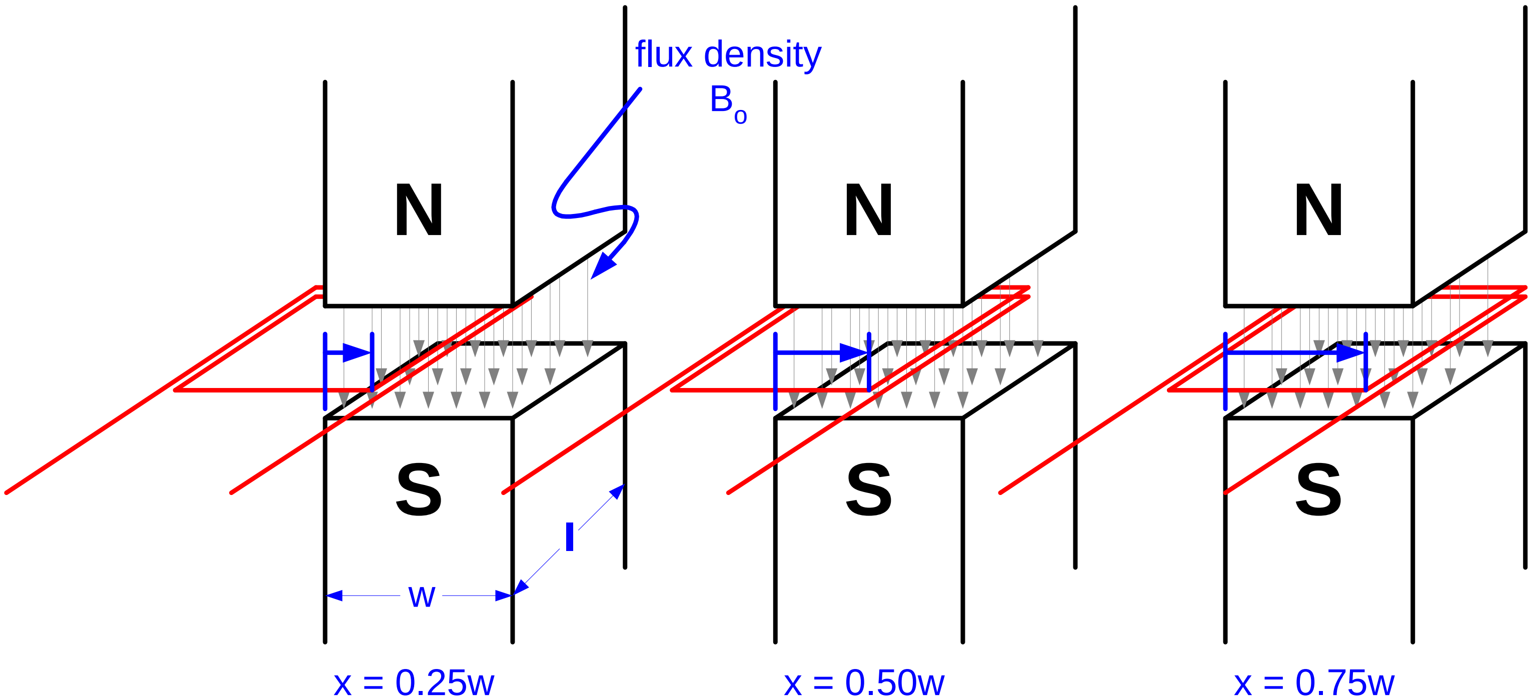
$$= -N w l B_o \sin(\omega t)$$

$$e(t) = -N\omega w l B_o \cos(\omega t)$$

HOW DO WE GET A $\frac{d\lambda}{dt}$?



HOW DO WE GET A $\dfrac{d\lambda}{dt}$?

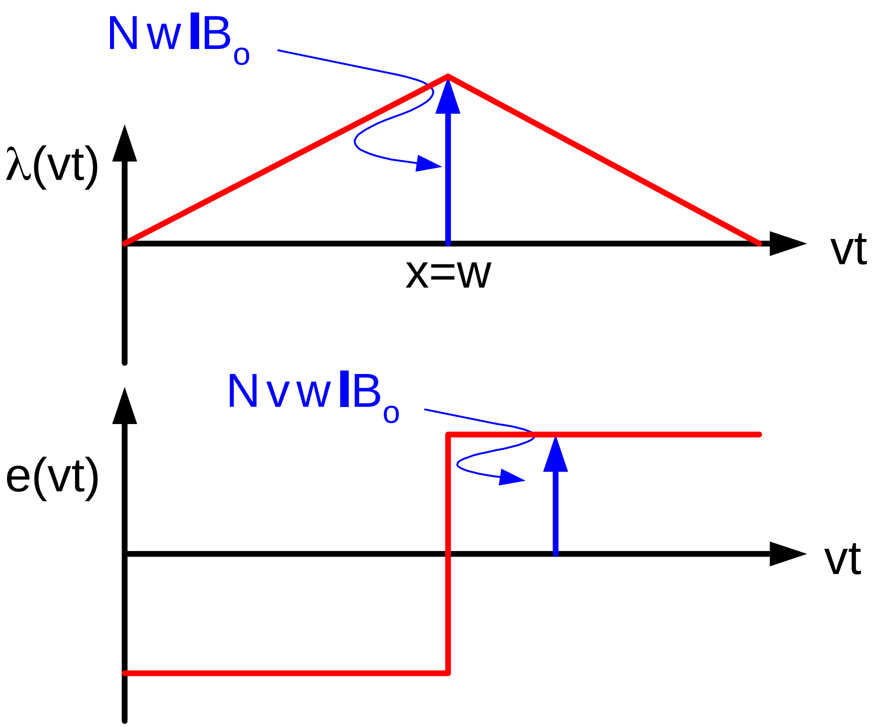


FARADAY'S LAW OF INDUCTION

$$e = \frac{-\,d\lambda}{dt}$$

$$= \frac{-\,d\lambda}{dx}\,\frac{dx}{dt}$$

$$= \frac{-\,d\lambda}{dx}\,v$$



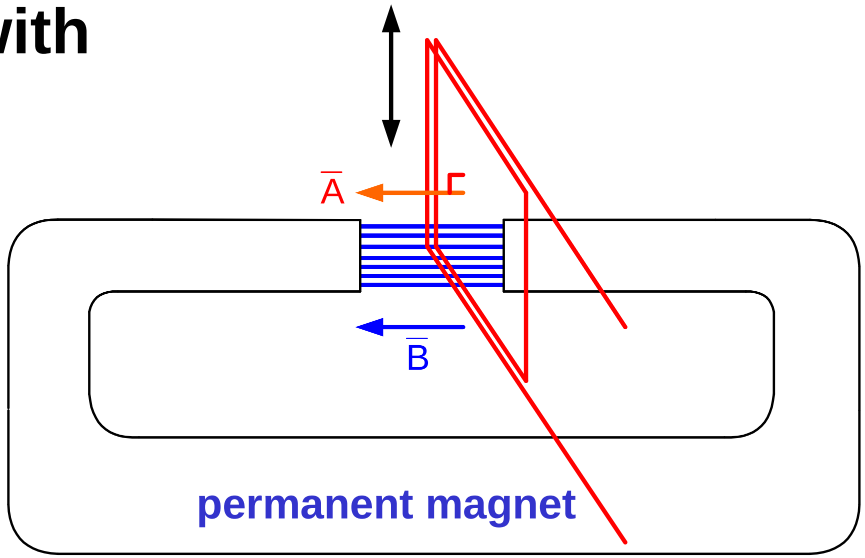
FARADAY'S LAW OF INDUCTION

Is there an induced voltage with motion of coil?

$\Delta\lambda = \Delta N \int \overline{B} \cdot d\overline{A} \neq 0$ with coil motion?

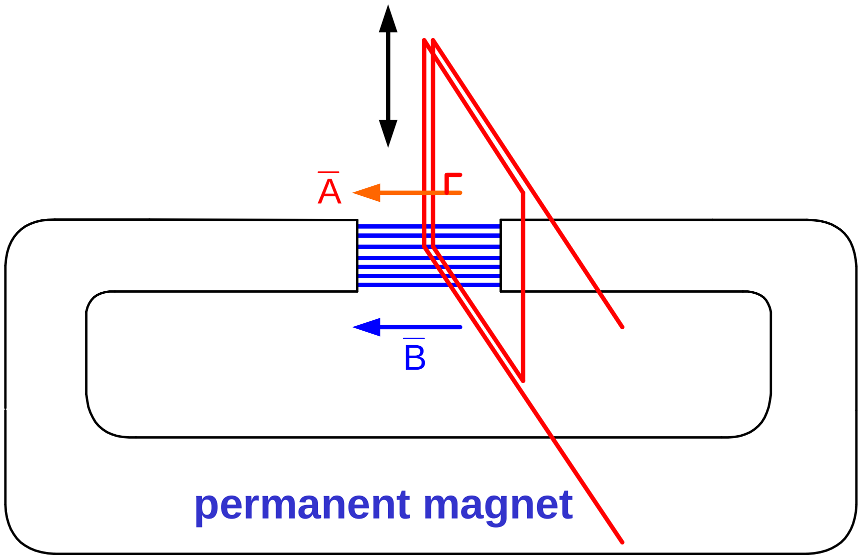
Does flux linkage of coil change with motion of coil?

YES



FARADAY'S LAW OF INDUCTION

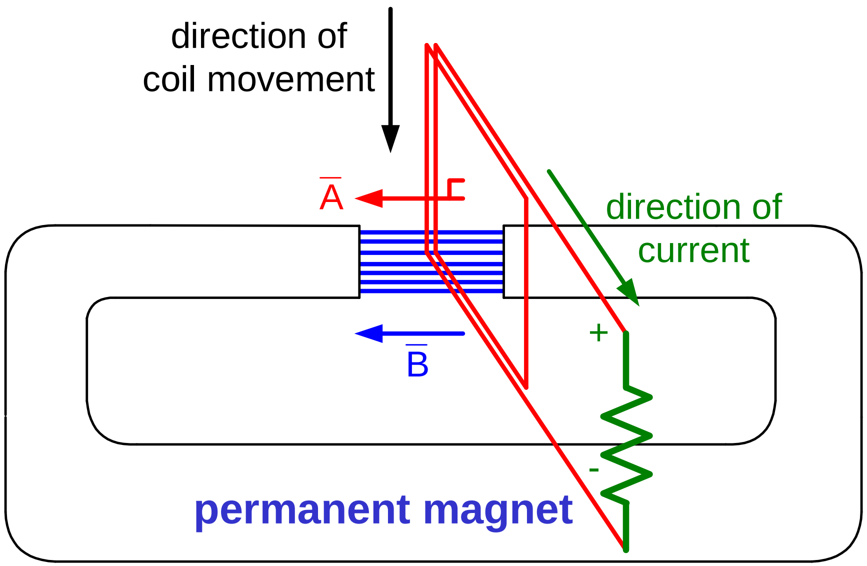
What is polarity of Voltage induced in coil?



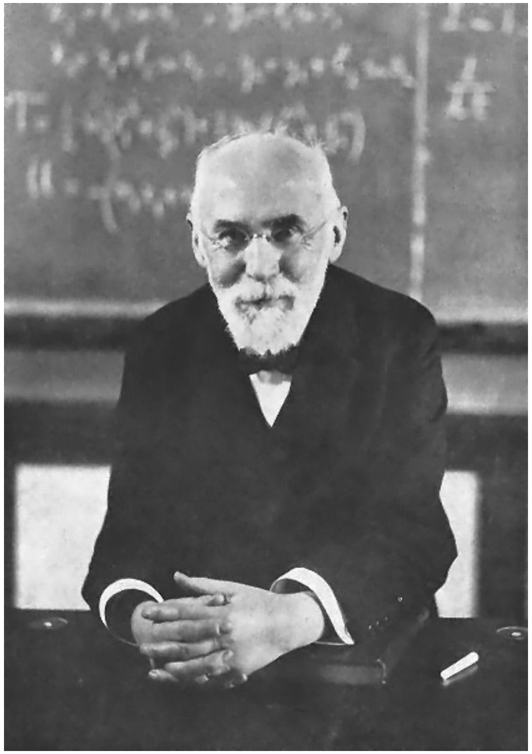
FARADAY'S LAW OF INDUCTION

What is polarity of Voltage induced in coil?

Polarity is such that current flows in a direction which opposes the change of magnetic field.



LORENZ FORCE EQUATION



Hendrik Antoon Lorentz
1853-1928

$$\bar{F} = q\left[\bar{E} + \left(\bar{v} \times \bar{B}\right)\right]$$

F = Electromagnetic Force
q = Electric Charge
E = Electric Field
v = Velocity of Charged Particle
B = Magnetic Flux Density

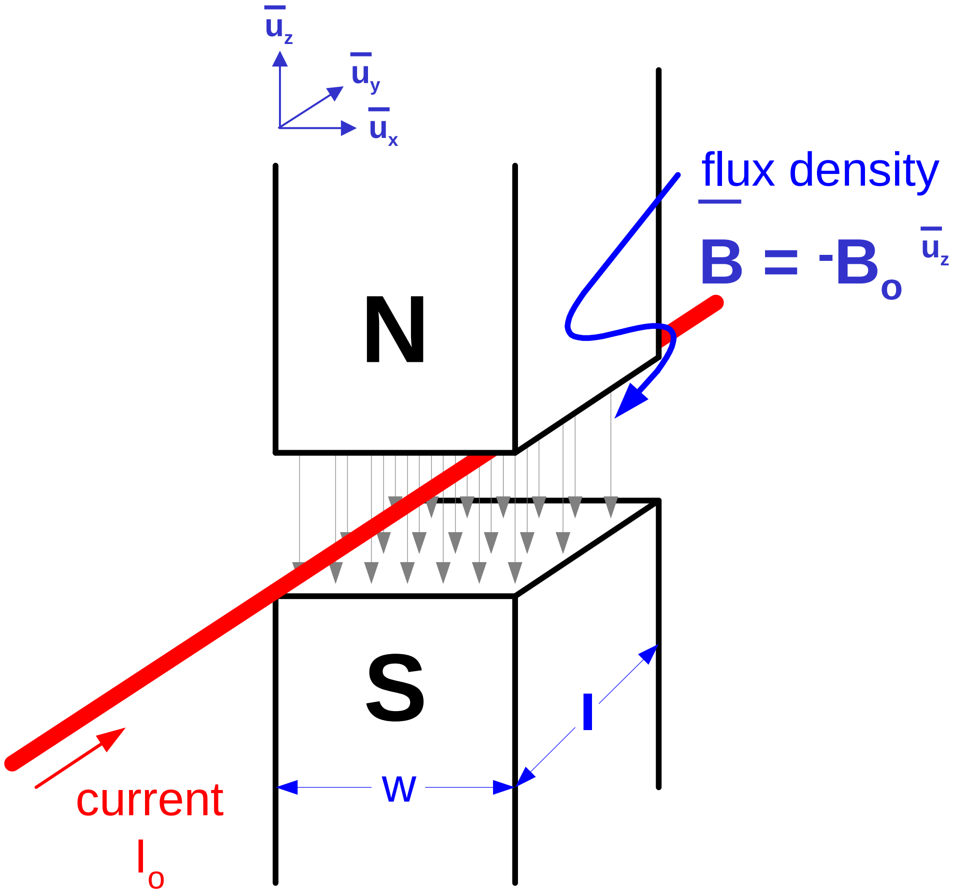
Unit: N

Force on Conductor

$$\bar{F} = I_0\left(\bar{l} \times \bar{B}\right)$$

In words: The force on a conductor is proportional to the current times flux density.

LORENTZ FORCE EQUATION

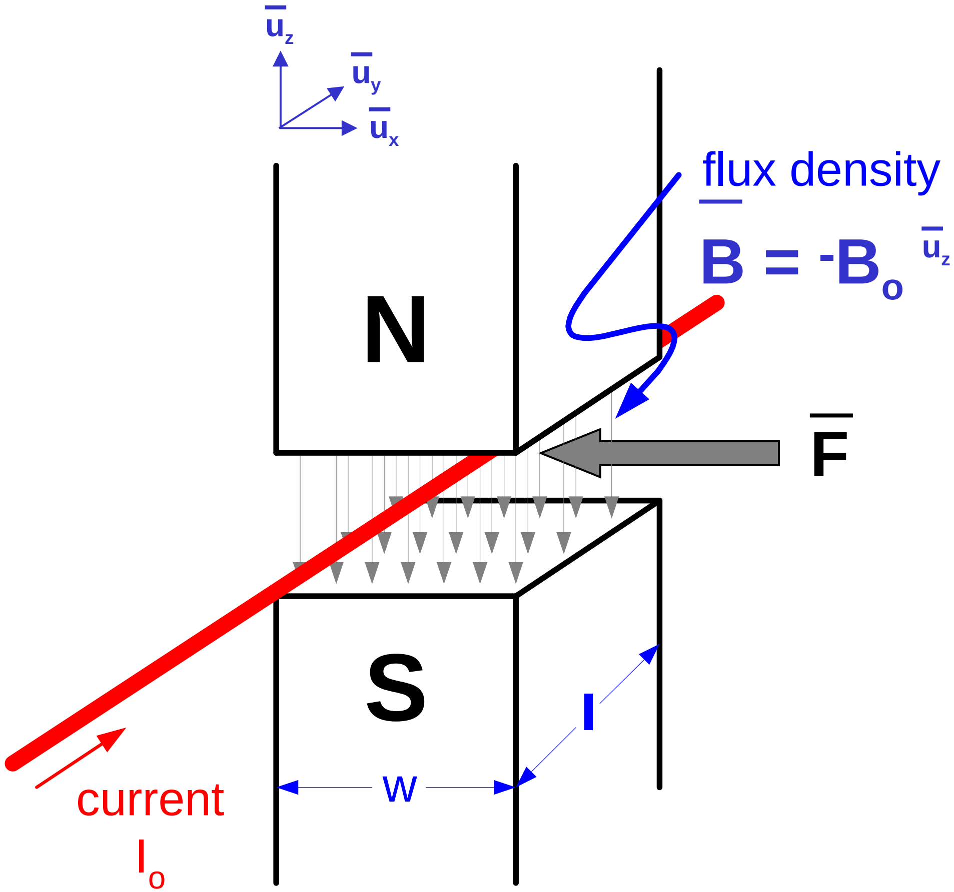


$\bar{l} = l\bar{u}_y$

Force on Conductor

$\bar{F} = I_o \bar{l} \times \bar{B}$

LORENTZ FORCE EQUATION



$\bar{I} = l\,\bar{u}_y$

What is direction of force?

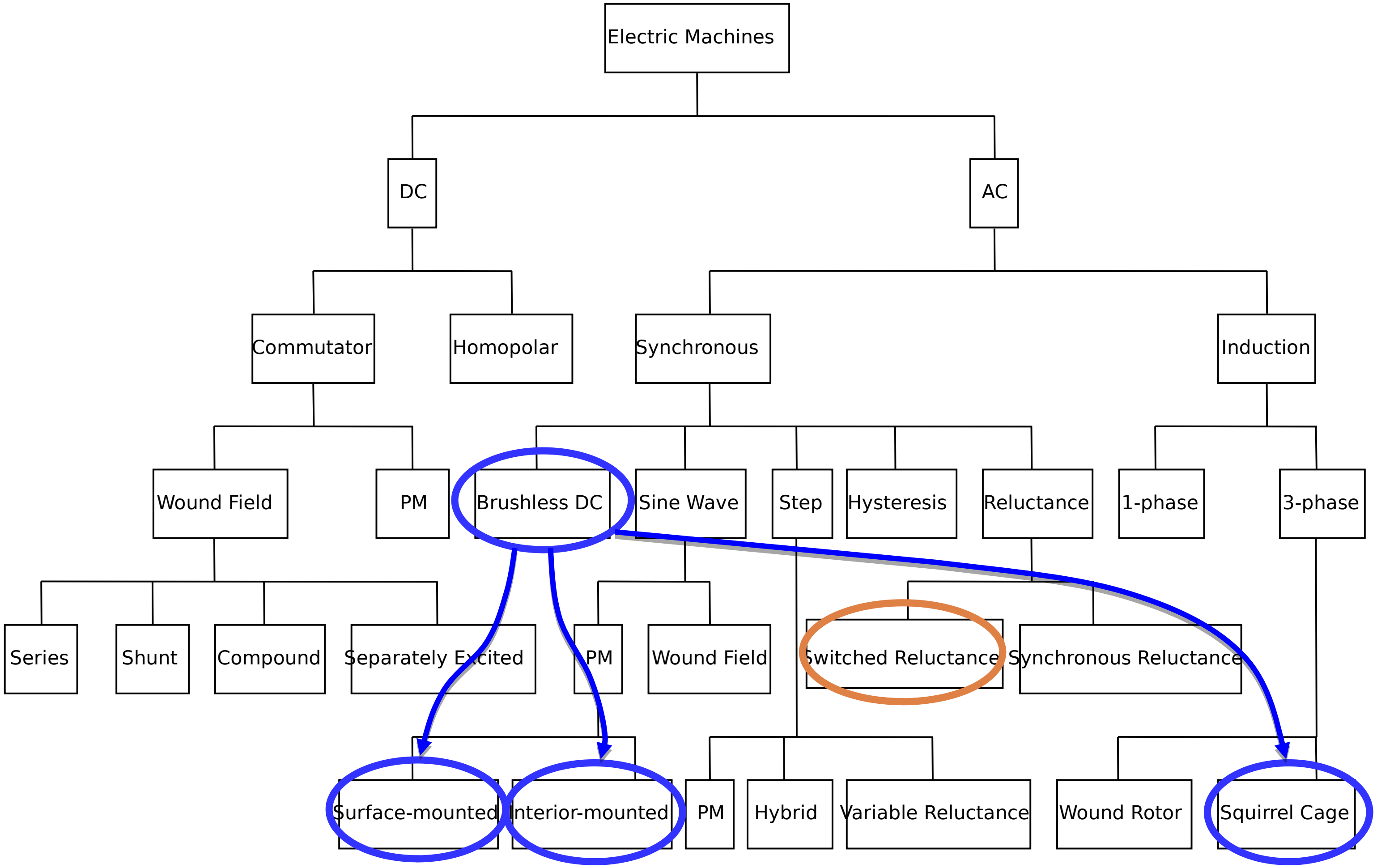
$$\bar{F} = I_o\,\bar{I} \times \bar{B}$$

$$= I_o\, l\,\bar{u}_y \times -B_o\,\bar{u}_z$$

$$= -I_o\, l B_o\,\bar{u}_x$$

Electric Machines Overview

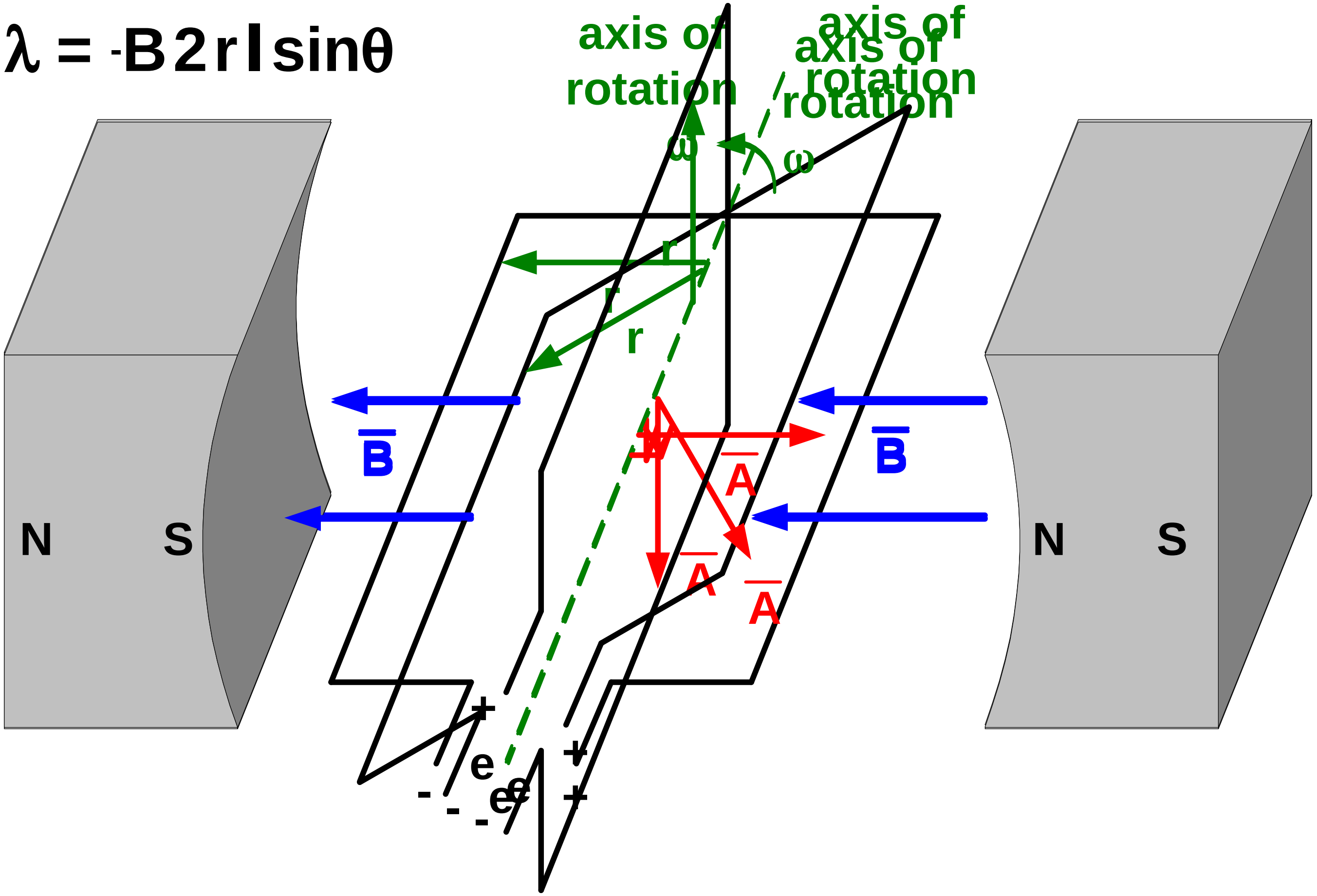
Classification of Machines



DC Machines Overview

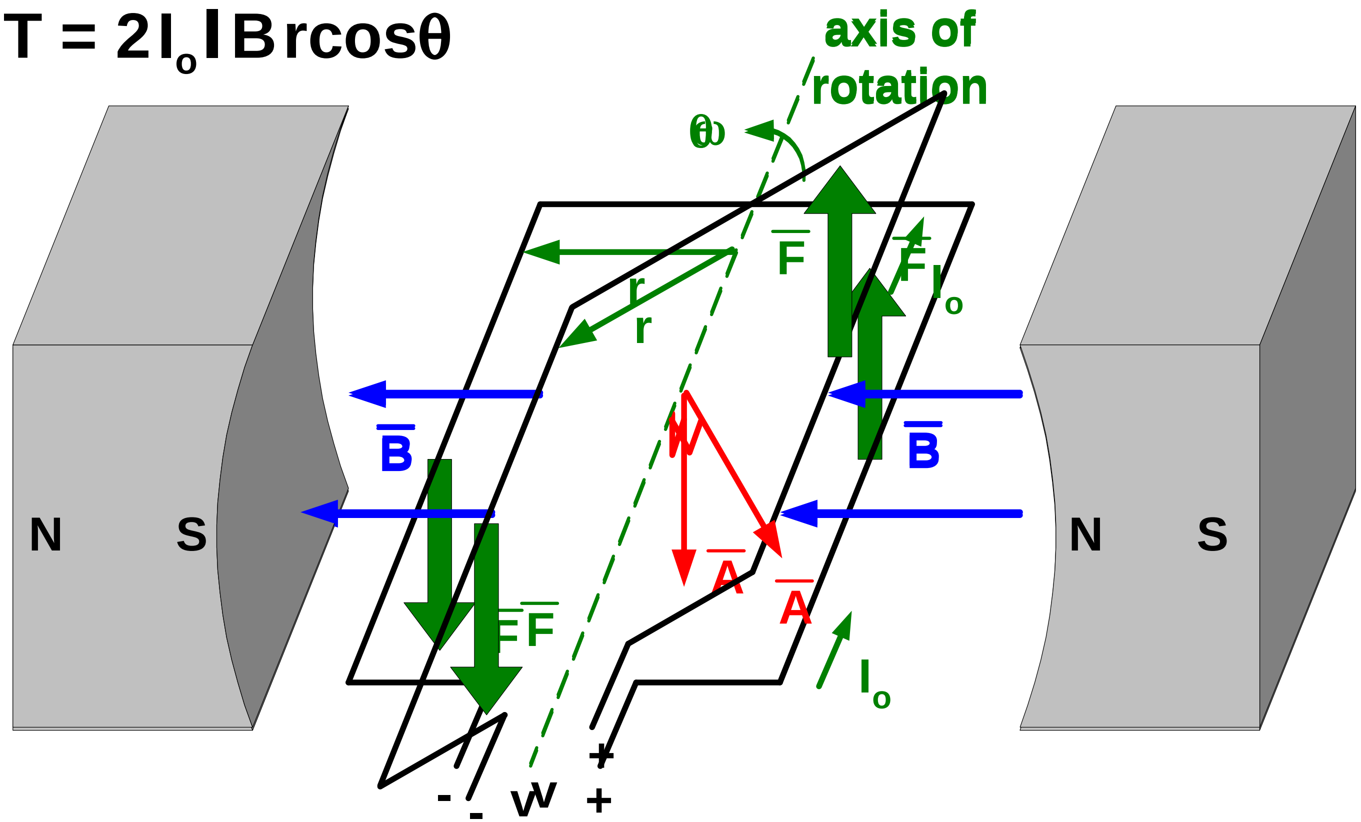
Single Loop Generator

$$\lambda = -B\,2\,r\,l\,\sin\theta$$

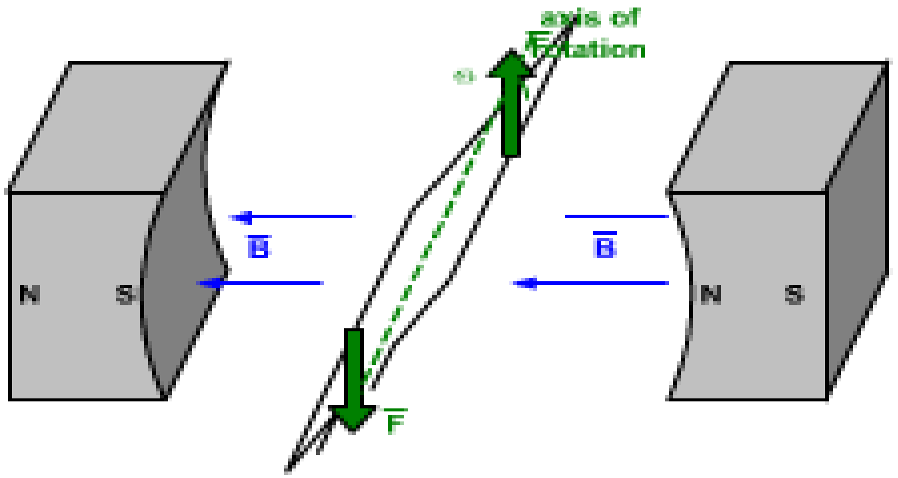


Single Loop Motor

$$\mathbf{T = 2 I_o l B r \cos\theta}$$



Single Loop Motor



Single Loop Generator

$$\lambda = \phi = \int \bar{B} \cdot d\bar{A} = -B\,2\,r\,l\,\sin\theta = -B\,2\,r\,l\,\sin\omega t$$

$$e = \frac{-d\lambda}{dt} = \omega B\,2\,r\,l\cos\omega t = K(\theta)\,\omega$$

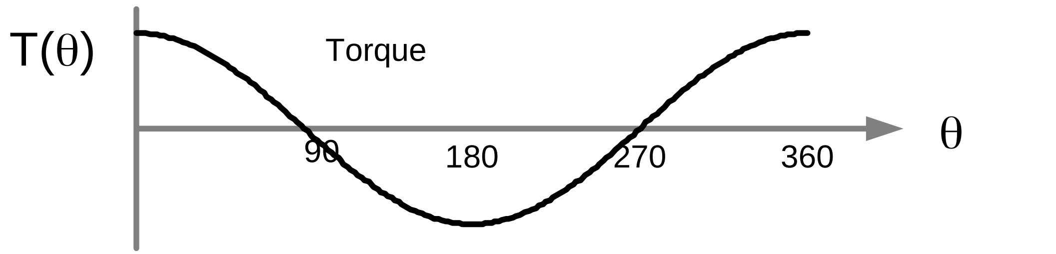
Single Loop Motor

$$T = 2 I_o l B r\cos\theta = K(\theta)\, I$$

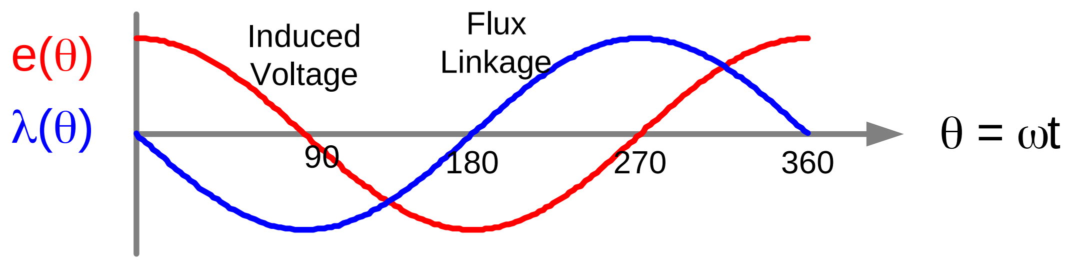
$$K(\theta) = 2rlB\cos\theta$$

DC Machines

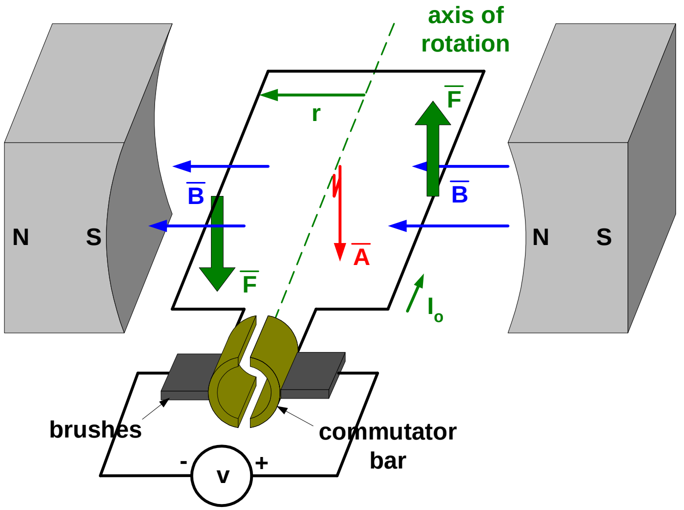
A Single Loop Acting as a Motor

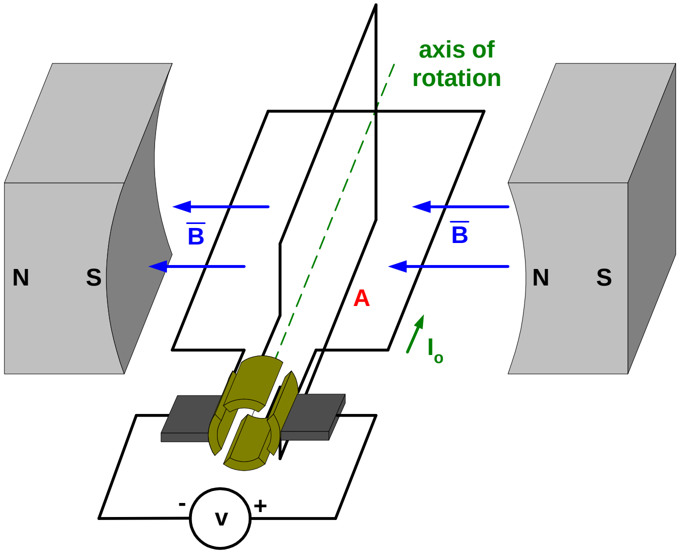


A Single Loop Acting as a Generator

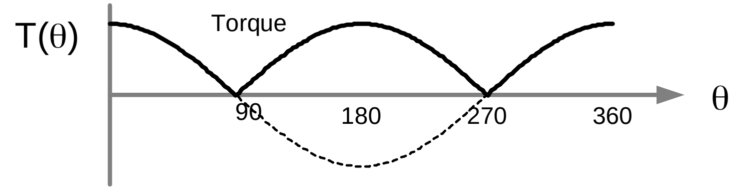


DC Machines

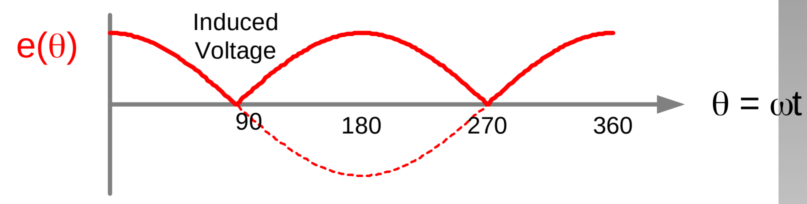




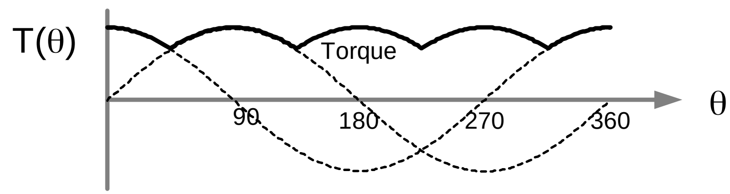
A Single Loop with Commutator Acting as a Motor



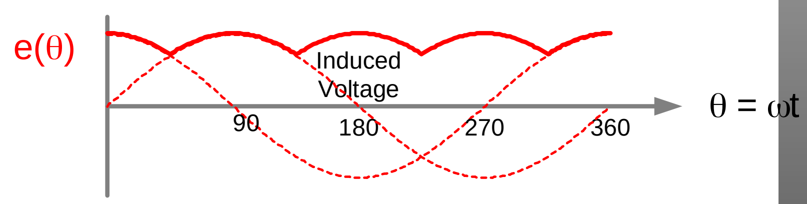
A Single Loop with Commutator Acting as a Generator



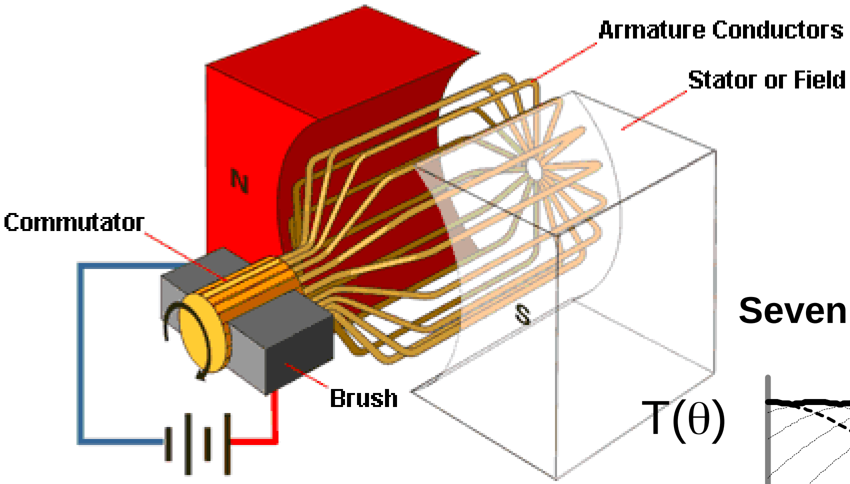
Two Loops with Commutator Acting as a Motor



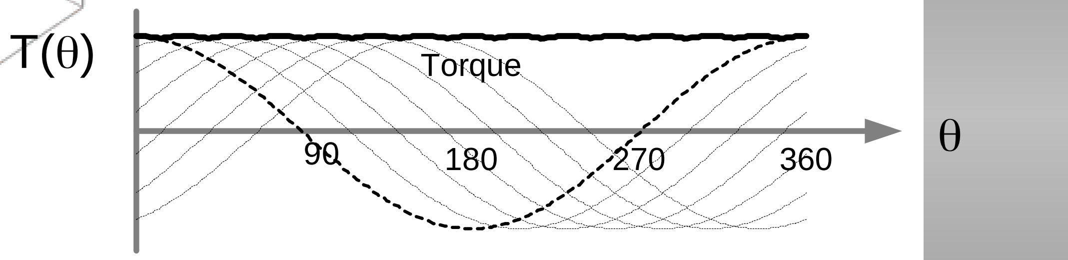
Two Loops with Commutator Acting as a Generator



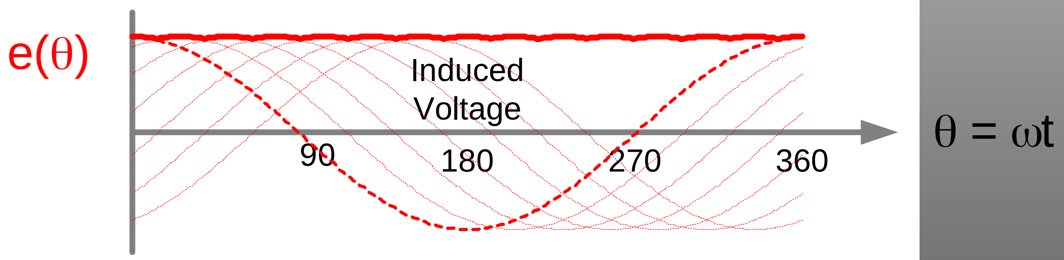
DC Machines



Seven Loops with Commutator Acting as a Motor



Seven Loops with Commutator Acting as a Generator



DC Machines

Machine with N wires per coil and multiple commutator bars:

$$\mathbf{T = 2NBrl\ I_o}$$
$$\mathbf{= K_t I_o}$$

Torque constant

$$\mathbf{e = 2NBrl\ \omega}$$
$$\mathbf{= K_e \omega}$$

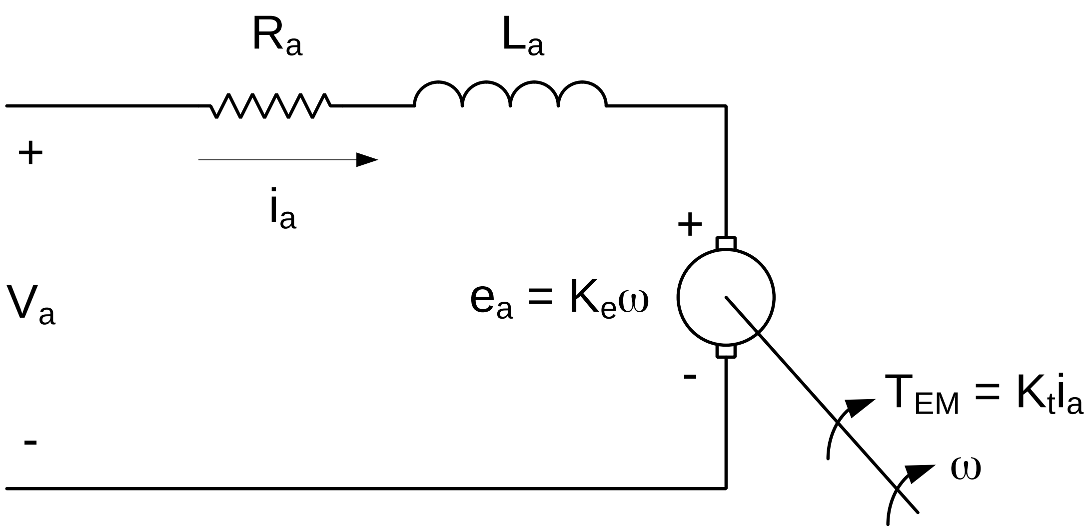
back emf constant

$\Rightarrow$ **$K_t = K_e$ (in SI units)**

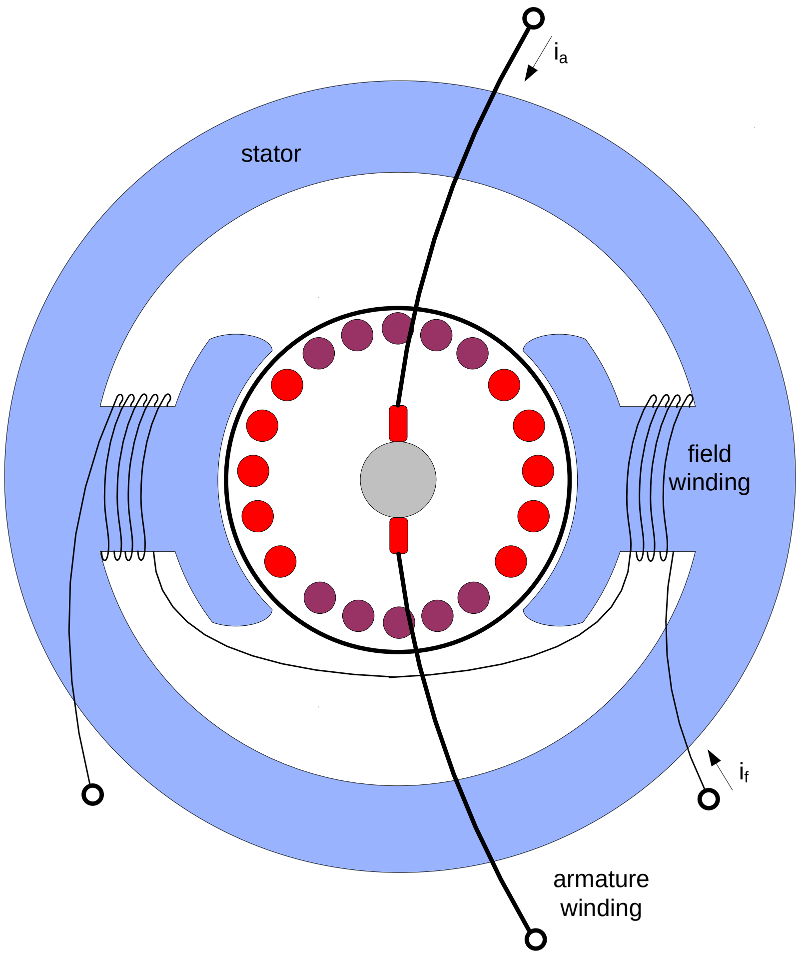
DC Machines

transient equation $$v_a = R_a i_a + L_a \frac{d i_a}{dt} + e_a$$

steady state equation $$V_a = R_a I_a + E_a$$

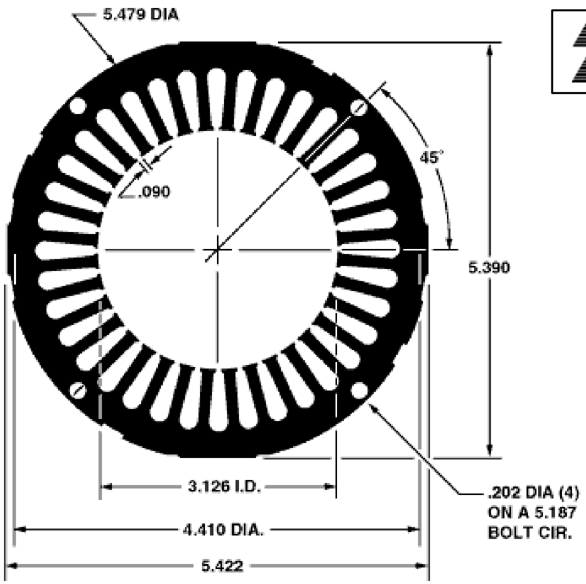


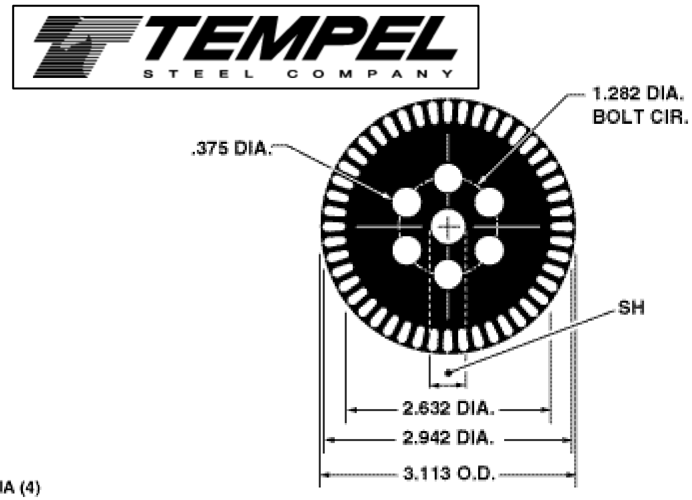
Wound Field DC Machines



Induction Machines Overview

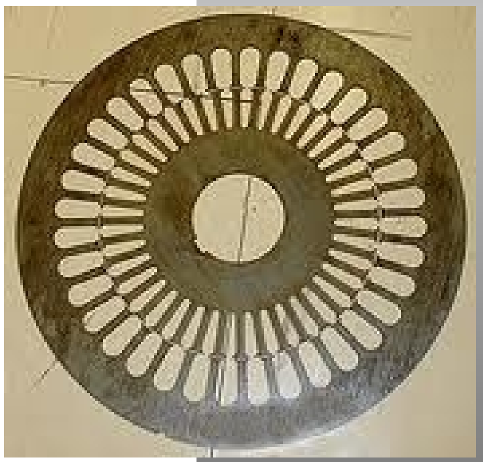
Induction Machine Modeling





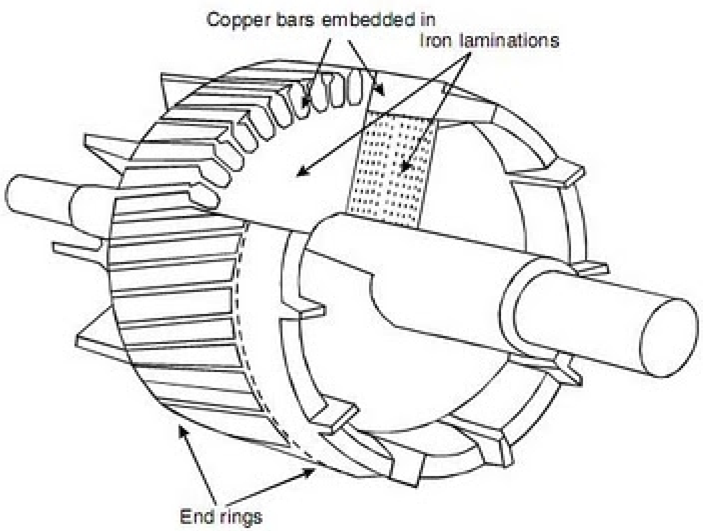
Induction Motor Stator *Induction Motor Rotor*

Stator and Rotor Laminations from Tempel Steel Company



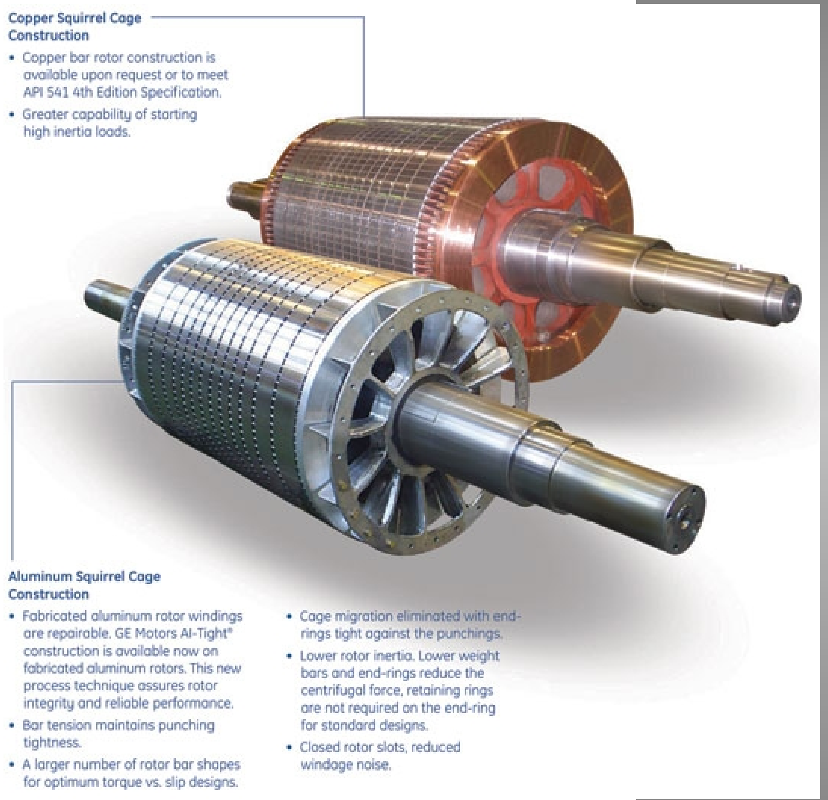
from http://en.m.wikipedia.org/
wiki/Squirrel-cage_rotor

Induction Machine Modeling



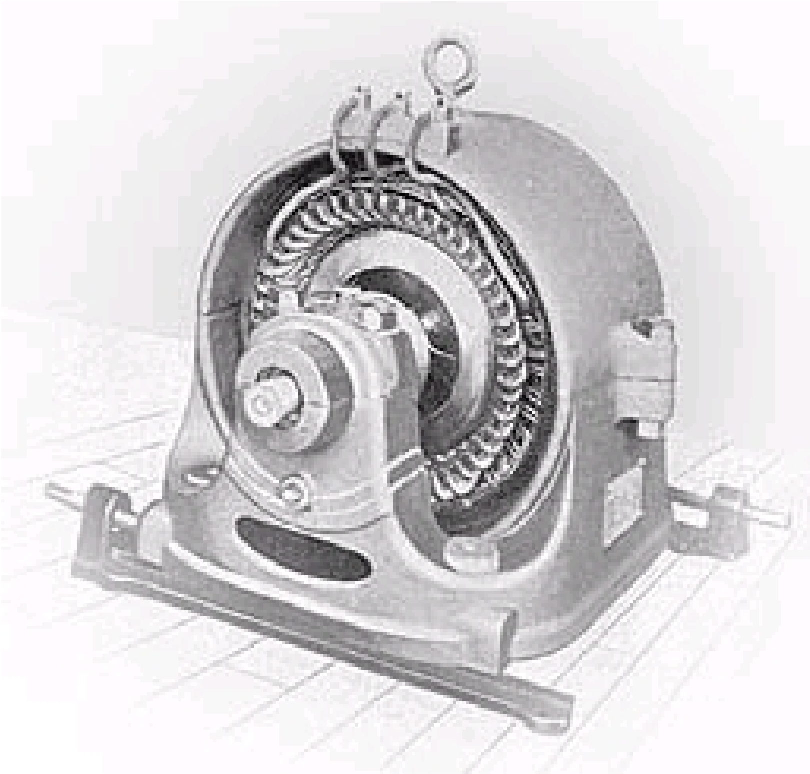
Squirrel-cage induction motor

from http://emadrlc.blogspot.com/2010/01/squirrel-cage-induction-motor.html



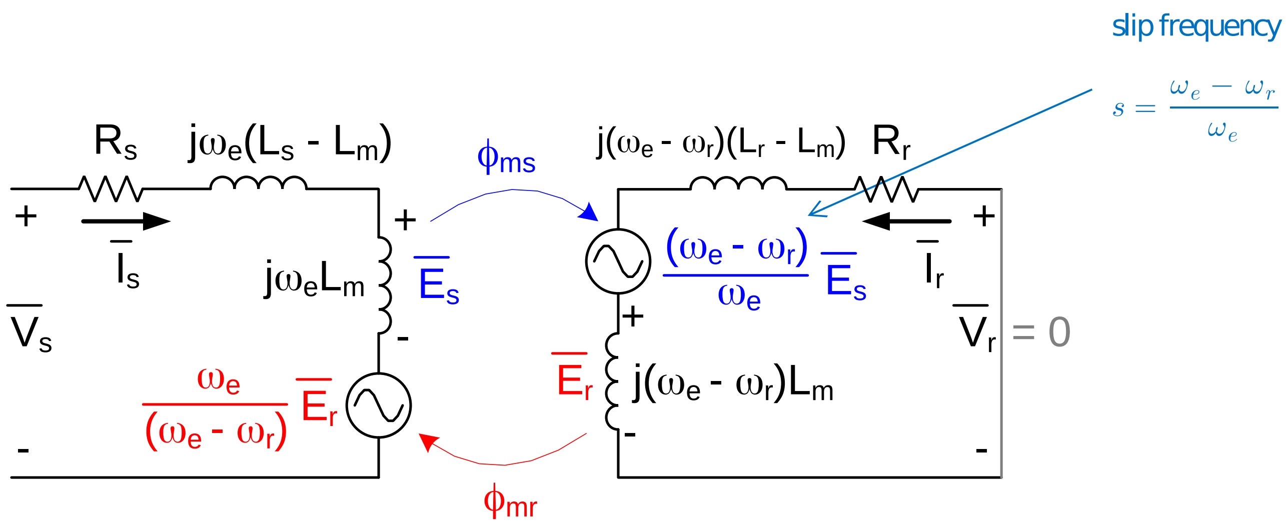
from http://www.gemotors.com.br/products/motors/squirrel/

Induction Machine Modeling



An 1895 Westinghouse 3-Phase Induction Motor

Induction Machine Modeling



Per Phase Equivalent Schematic of Induction Motor

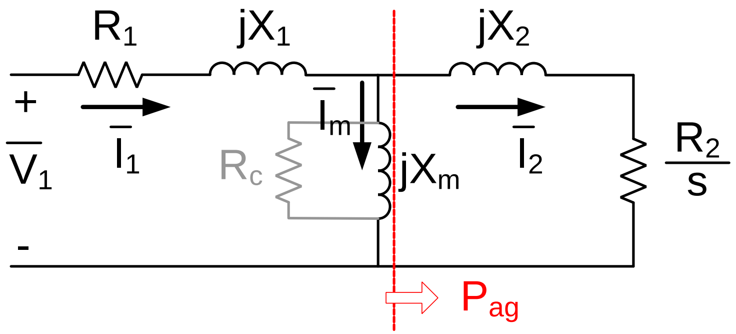
Circuit Model of Induction Motor

$$\text{stator:}\quad \overline{V}_s = \left[R_s + j\,\omega_e\left(L_s - L_m\right)\right]\overline{I}_s + j\,\omega_e L_m \overline{I}_s + j\,\omega_e L_m \overline{I}_r$$

$$\text{rotor:}\quad 0 = j\left(\omega_e - \omega_r\right)L_m \overline{I}_s + j\left(\omega_e - \omega_r\right)L_m \overline{I}_r + \left[R_r + j\left(\omega_e - \omega_r\right)\left(L_r - L_m\right)\right]\overline{I}_r$$

Induction Machine Modeling

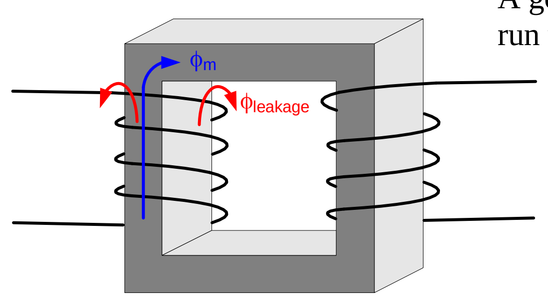
Conventional Per Phase Equivalent Circuit:



Per Phase Equivalent Schematic of Induction Motor Reflected to Stator

$$a = \frac{N_s}{N_r} \qquad R_2 = \left(\frac{N_s}{N_r}\right)^2 R_r$$

X_1 & X_2 are called "Leakage" Inductances



$$X_1 = \omega_e\left(L_s - \frac{N_s}{N_r}L_m\right)$$

$$X_m = \frac{N_s}{N_r}L_m\omega_e$$

Airgap Power:

$$P_{ag} = \frac{3I_2^2R_2}{s} \rightarrow 3I_2^2R_2 = sP_{ag}$$

$$\text{Rotor Loss} = s\,P_{ag}$$

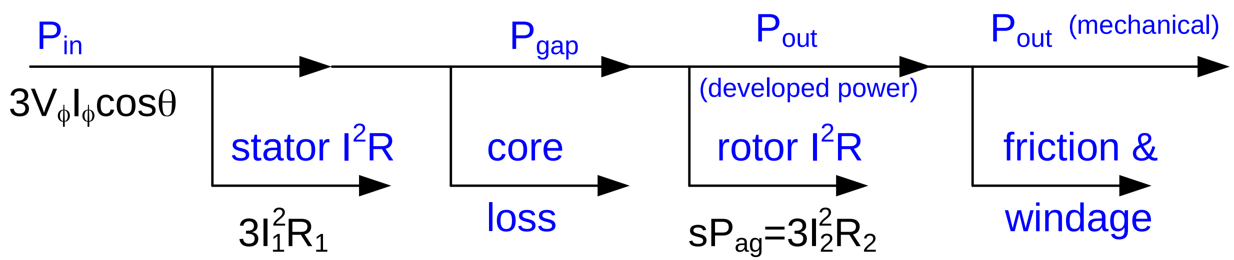
$$P_{out} = \frac{3I_2^2R_2}{s}(1 - s) = P_{ag}(1 - s)$$

A good (efficient) induction motor must run with low slip.

Induction Machine Modeling

Electromagnetic Torque:

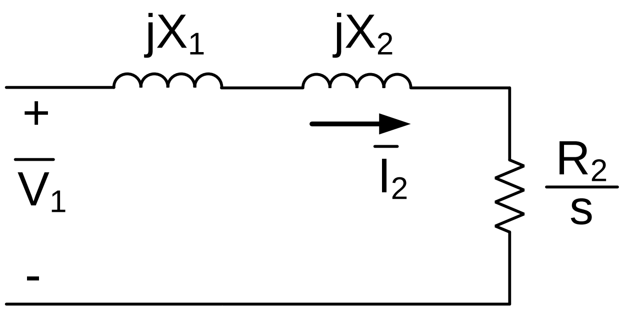
$$T_{em} = \frac{P_{out}}{\omega_{rm}} = \frac{P}{2}\frac{P_{ag}(1-s)}{\omega_r} = \frac{P}{2}\frac{P_{ag}(1-s)}{\omega_e(1-s)} = \frac{P}{2}\frac{P_{ag}}{\omega_e} = \frac{P}{2}\frac{P_{out}}{\omega_r}$$



Power Flow in an Induction Motor

Induction Machine Modeling

Max P_{ag} (assuming small R_1 large X_m):



Per Phase Equivalent Schematic of Induction Assuming Small R_1 and Large X_m

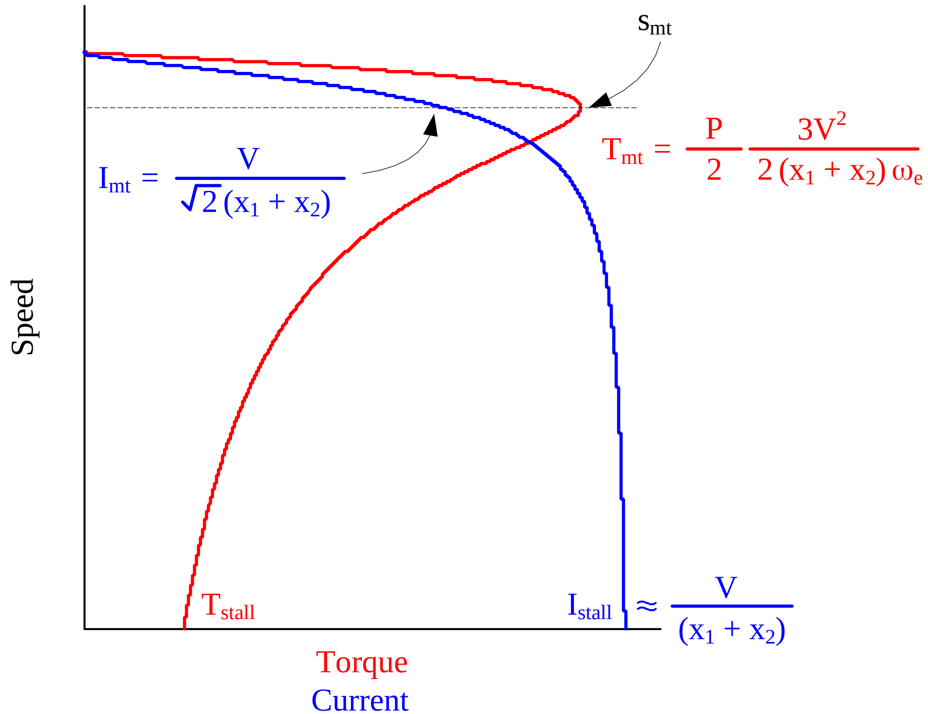
Max P_{ag} when:

$$\frac{R_2}{s_{mt}} = X_1 + X_2$$

$$s_{mt} = \frac{R_2}{X_1 + X_2}$$

$$P_{ag\_mt} = 3I_2^2\frac{R_2}{s_{mt}} = \frac{3V^2(X_1 + X_2)}{\left|\frac{R_2}{s_{mt}} + j(X_1 + X_2)\right|^2} = \frac{3V^2(X_1 + X_2)}{\left[\sqrt{2}(X_1 + X_2)\right]^2} = \frac{3V^2}{2(X_1 + X_2)}$$

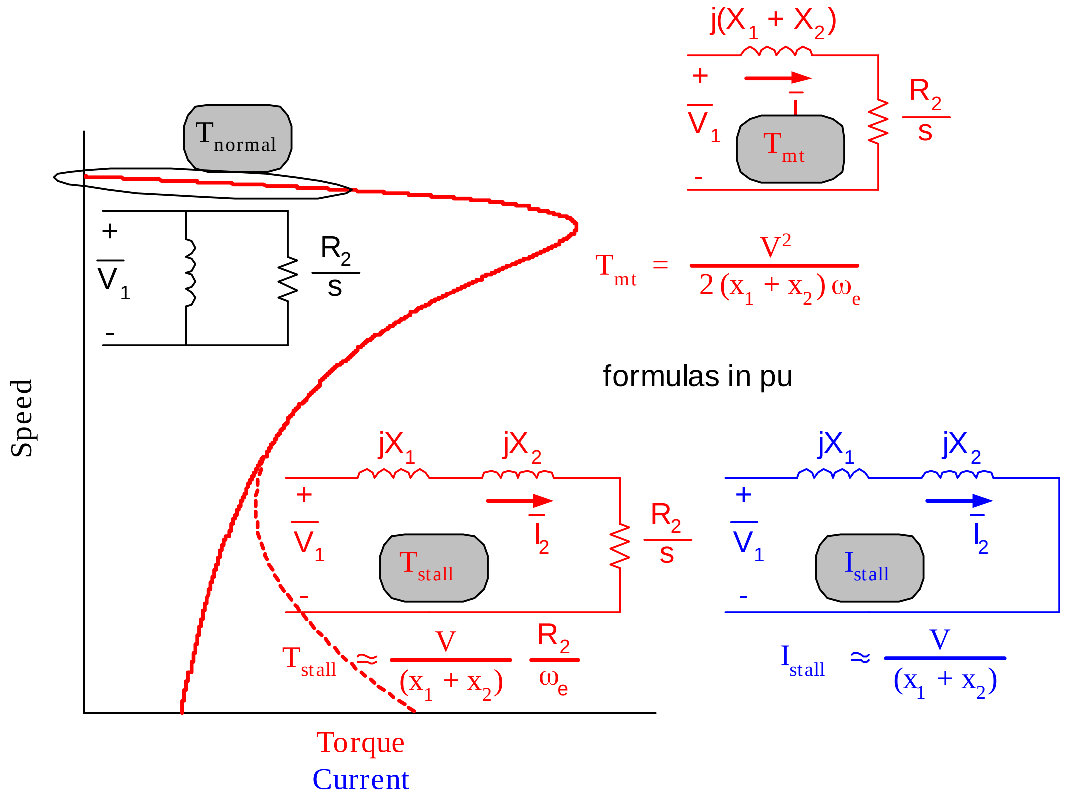
Induction Machine Modeling



Speed vs. Torque and Current for Three Phase Induction Motor

Induction Machine Modeling

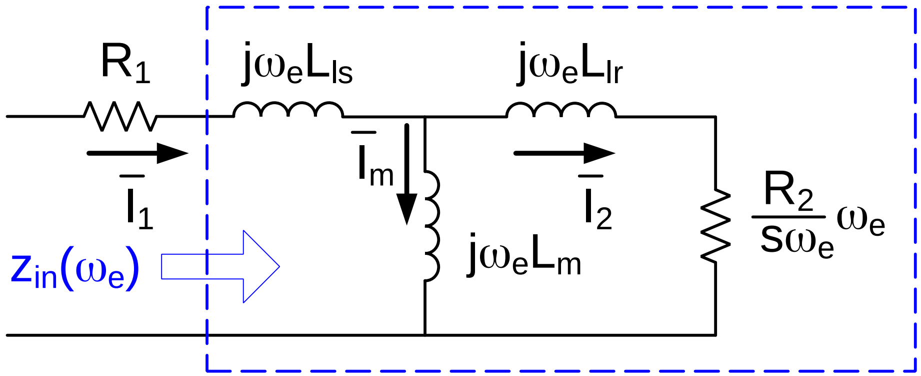
Induction Motor Performance Summary:



Induction Motor Performance Summary

Induction Machine Modeling

$$Z_{in} = R_1 + j\omega_e L_{ls} + j\omega_e L_m // \left(\frac{R_2}{s} + j\omega_e L_{lr}\right)$$



Induction Motor Per Phase Equivalent Circuit

Neglecting R_1:

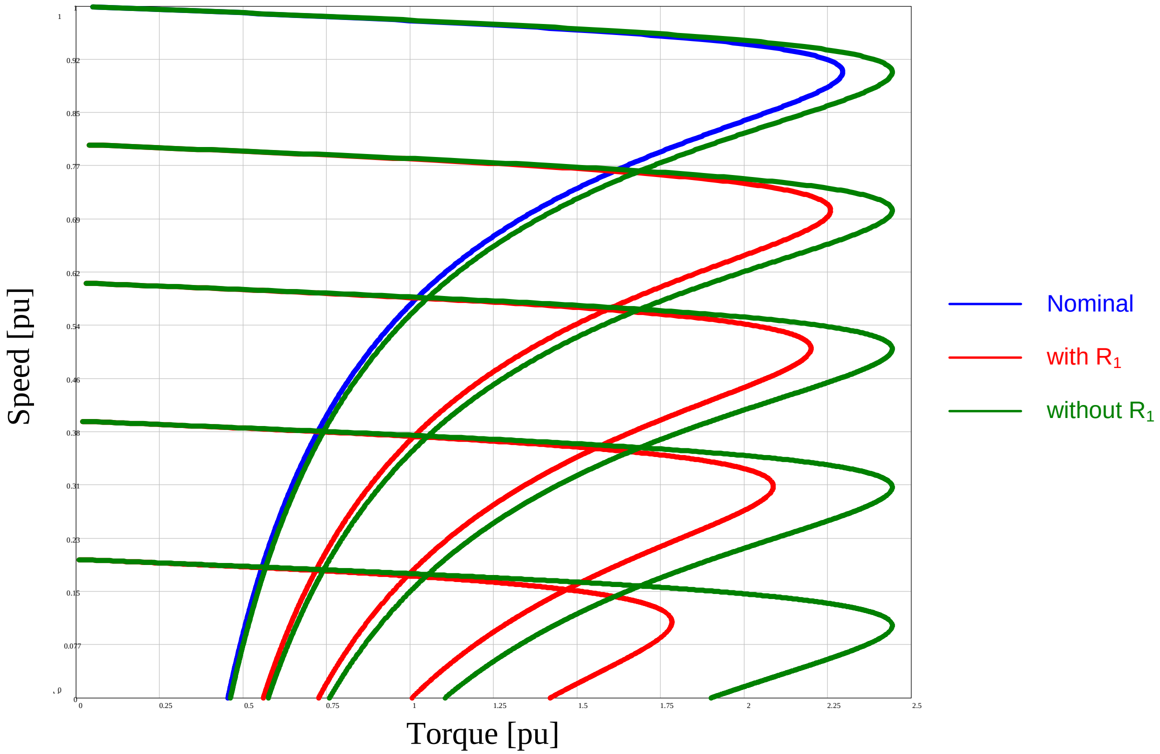
$$Z_{in}(\omega_e) = j\omega_e L_{ls} + j\omega_e L_m // \left(\frac{R_2}{s\,\omega_e}\omega_e + j\omega_e L_{lr}\right)$$

$$T_{em} = 3\frac{P}{2}\frac{I_2^2 R_2}{s\,\omega_e}$$

Maintain constant V/f:

- Maintains circuit (machine) impedance
- Maintains stator current
- Maintains rotor current (and thus torque)
- Maintains magnetizing current (and thus flux)

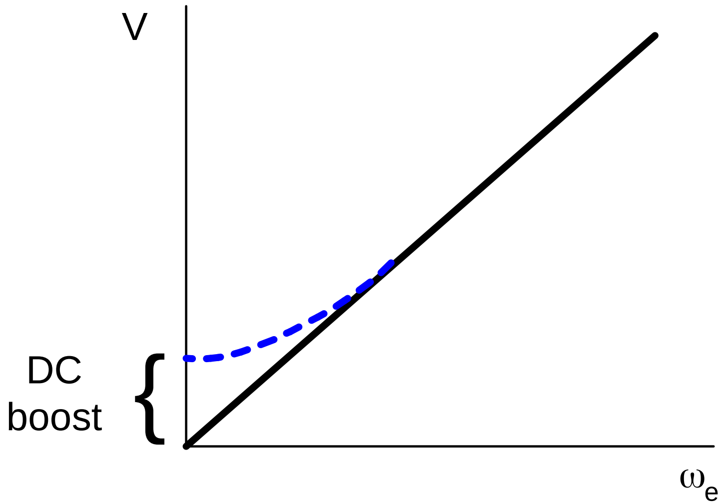
Induction Machine Modeling



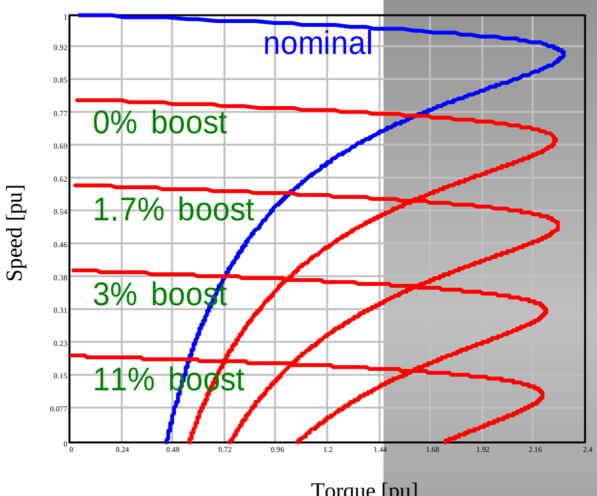
Induction Motor Speed Torque Curves with Constant V/Hz

Induction Machine Modeling

Stator resistance causes deviation from ideal→ use voltage boost to (partially) compensate

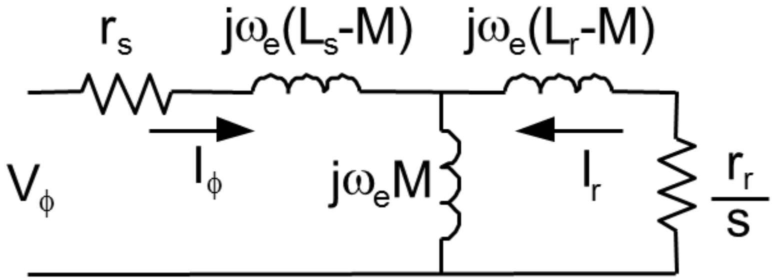


Typical Voltage Boost Strategy for V/Hz Drives



Induction Motor Speed Torque Curves with Constant V/Hz with Boost

Induction Machine Modeling

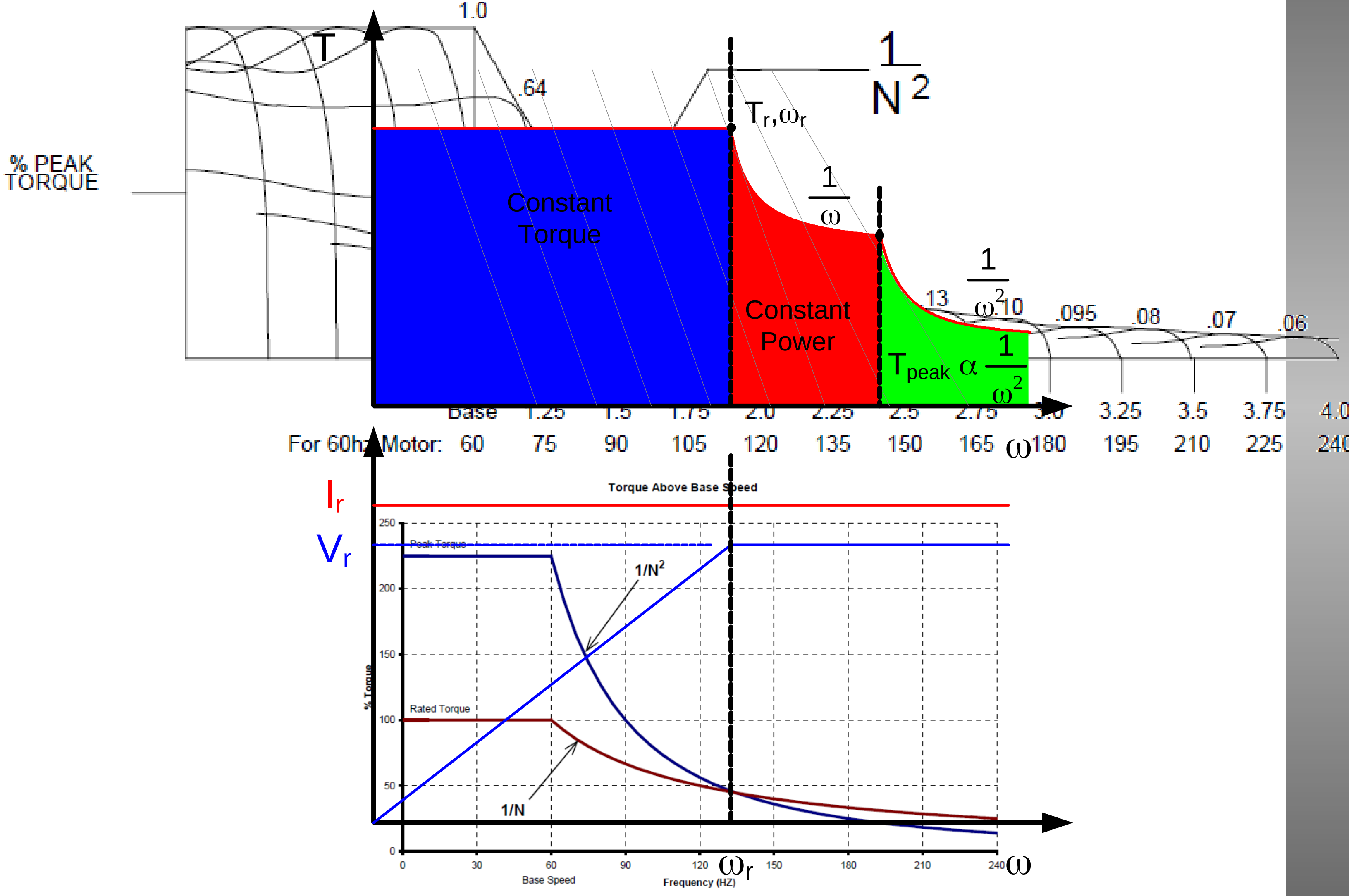


$$s = \frac{\omega_e - \omega_r}{\omega_e}$$

$$s\,\omega_e = \text{slip frequency}$$

$$T_e = \frac{3P}{2}\frac{I_r^2 r_r}{s\omega_e}$$ **Electromagnetic Torque**

Induction Machine Modeling



Induction Machine Modeling

Formalize and simplify notation:

$\overline{f}_{qdx}^{\,y}$

f is a variable (v,i,λ)

x is where the variable comes from (r,s)
(actual location of variables)

y is where variables are referred to (r,s,g)

Induction Machine Modeling

$$T_e = \frac{3}{2}\frac{P}{2} Im\left\{\bar{i}^{\,r}_{qds}\,\bar{\lambda}^{\,r\,*}_{qds}\right\} = \frac{3}{2}\frac{P}{2}\left[\lambda^r_{ds} i^r_{qs} - \lambda^r_{qs} i^r_{ds}\right]$$

$$= \frac{3}{2}\frac{P}{2}\left[\underbrace{L_{md}\, i^r_{qs}\left(i^r_{fd} + i^r_{kd}\right)}_{\text{BLI torque (excitation or reaction torque)}} + \underbrace{-L_{mq}\, i^r_{ds}\left(i^r_{kq}\right)}_{\text{Damping (induction motor) torque}} + \underbrace{\left(L_{md} - L_{mq}\right) i^r_{qs}\, i^r_{qs}}_{\text{Reluctance torque}}\right]$$

Induction Machine Modeling

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r} Im\{\bar{i}^{\,e}_{qdr}\,\bar{\lambda}^{\,e\,*}_{qds}\} = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left[\lambda^e_{dr} i^e_{qs} - \cancel{\lambda^e_{qr} i^e_{ds}}\right] = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} I_{ds} I_{qs}$$

field current

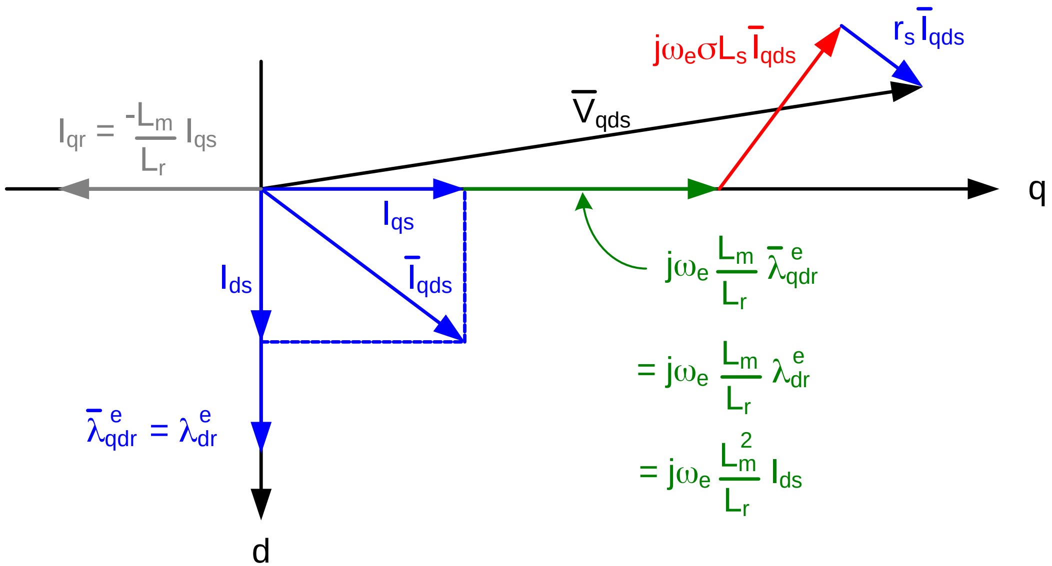
torque producing current

Field oriented control of induction machine is analogous to wound field DC motor. It has a torque producing (armature current) and a field producing current.

Induction Machine Modeling

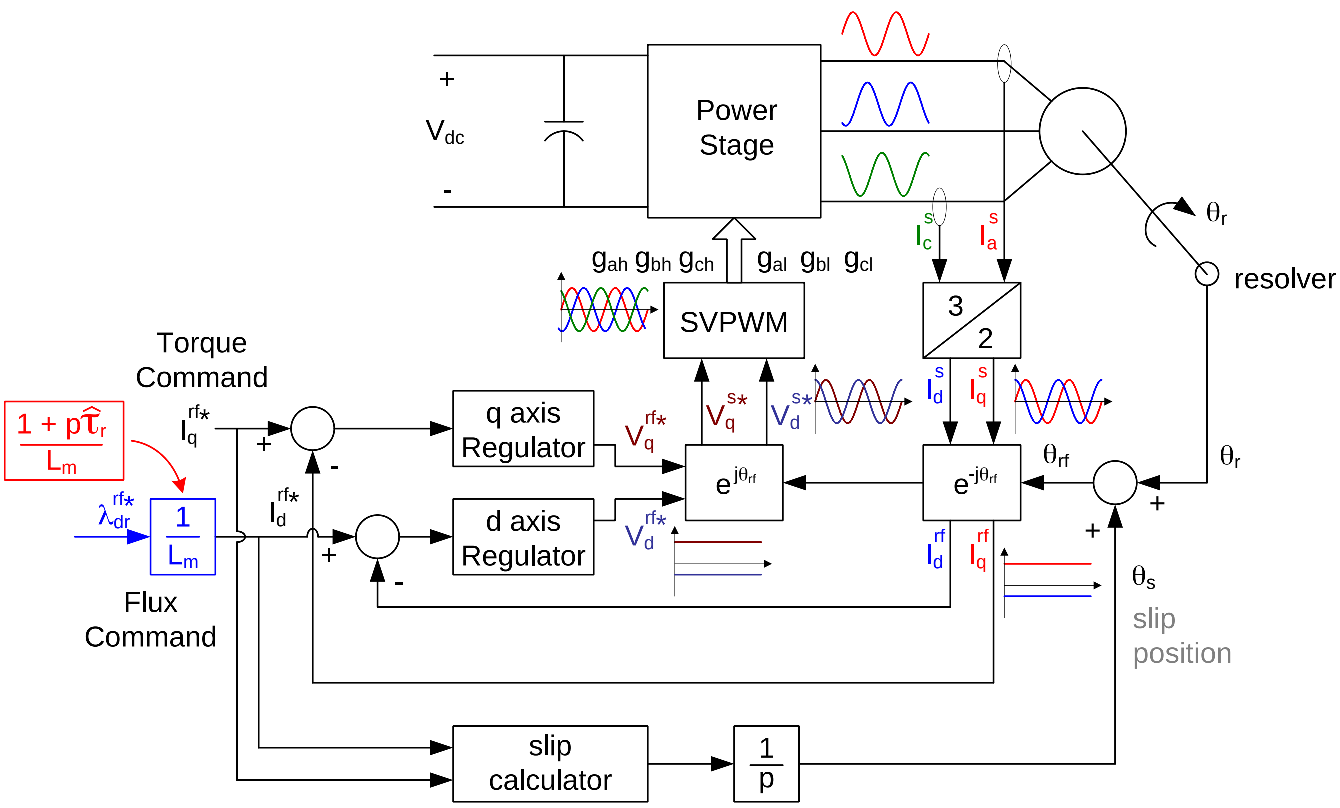
$$\bar{V}_{qds} = (r_s + j\,\omega_e \sigma L_s)\,\bar{I}_{qds} + j\,\omega_e \frac{L_m}{L_r}\bar{\lambda}^{e}_{qdr}$$

I_{qr} is like the compensating winding in a DC machine



Vector Diagram of Steady State Operation of Induction Motor

Induction Machine Modeling

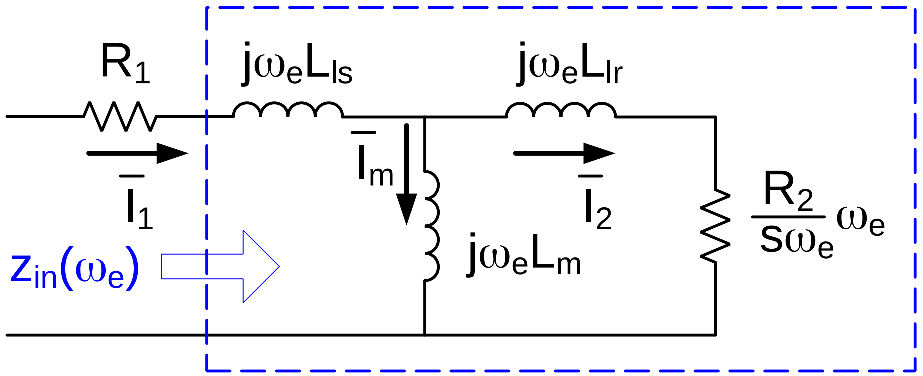


Indirect Field Orientation – Rotor Flux Orientation Induction Machine Control

Motor Drives Overview

Induction Machine Per Phase Equivalent Circuit

$$Z_{in} = R_1 + j\,\omega_e L_{ls} + j\,\omega_e L_m \,//\, \left(\frac{R_2}{s} + j\,\omega_e L_{lr}\right)$$



Induction Motor Per Phase Equivalent Circuit

Neglecting R_1:

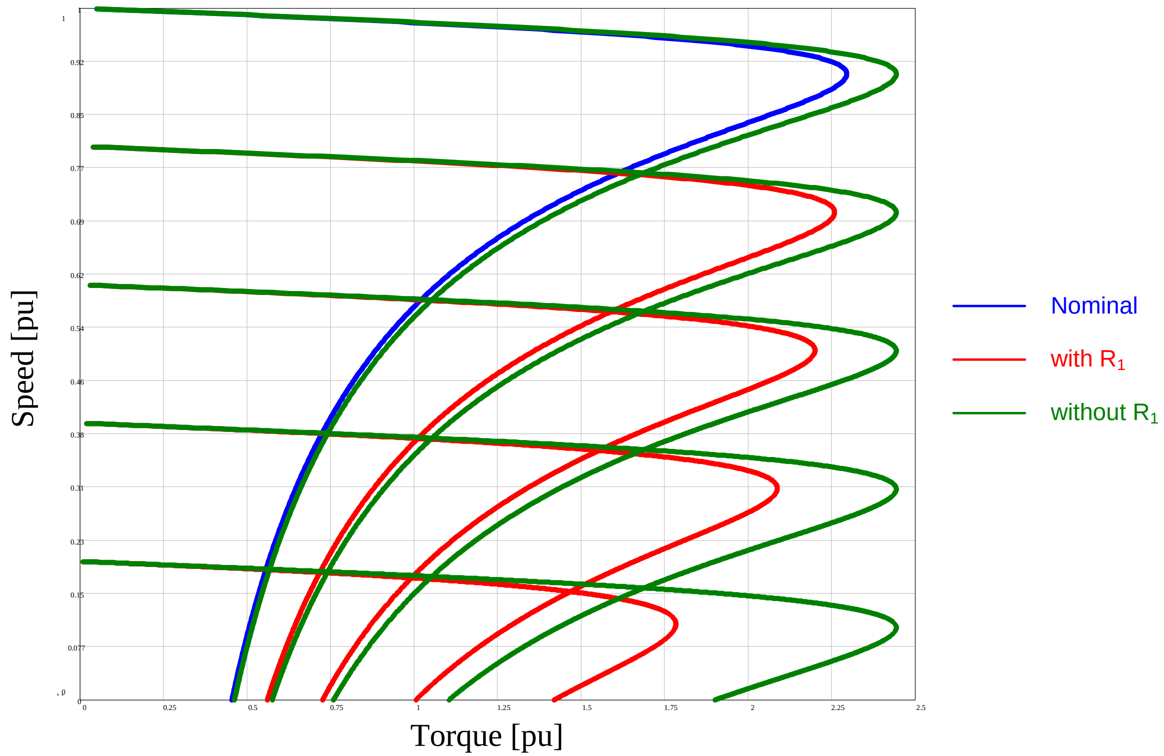
$$Z_{in}(\omega_e) = j\,\omega_e L_{ls} + j\,\omega_e L_m \,//\, \left(\frac{R_2}{s\,\omega_e}\omega_e + j\,\omega_e L_{lr}\right)$$

$$T_{em} = 3\frac{P}{2}\frac{I_2^2 R_2}{s\,\omega_e}$$

Maintain constant V/f:

- Maintains circuit (machine) impedance
- Maintains stator current
- Maintains rotor current (and thus torque)
- Maintains magnetizing current (and thus flux)

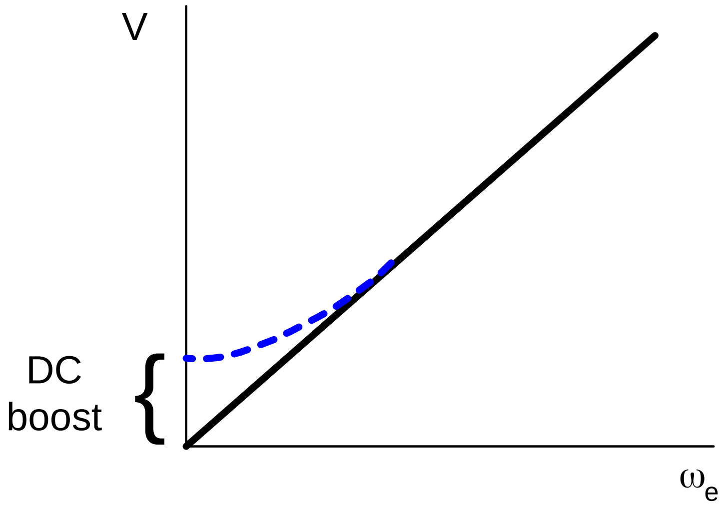
Induction Machine Control



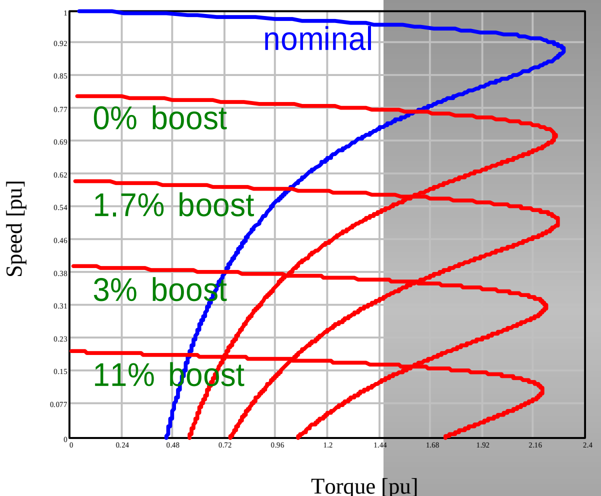
Induction Motor Speed Torque Curves with Constant V/Hz

Induction Machine Control

Stator resistance causes deviation from ideal→ use voltage boost to (partially) compensate

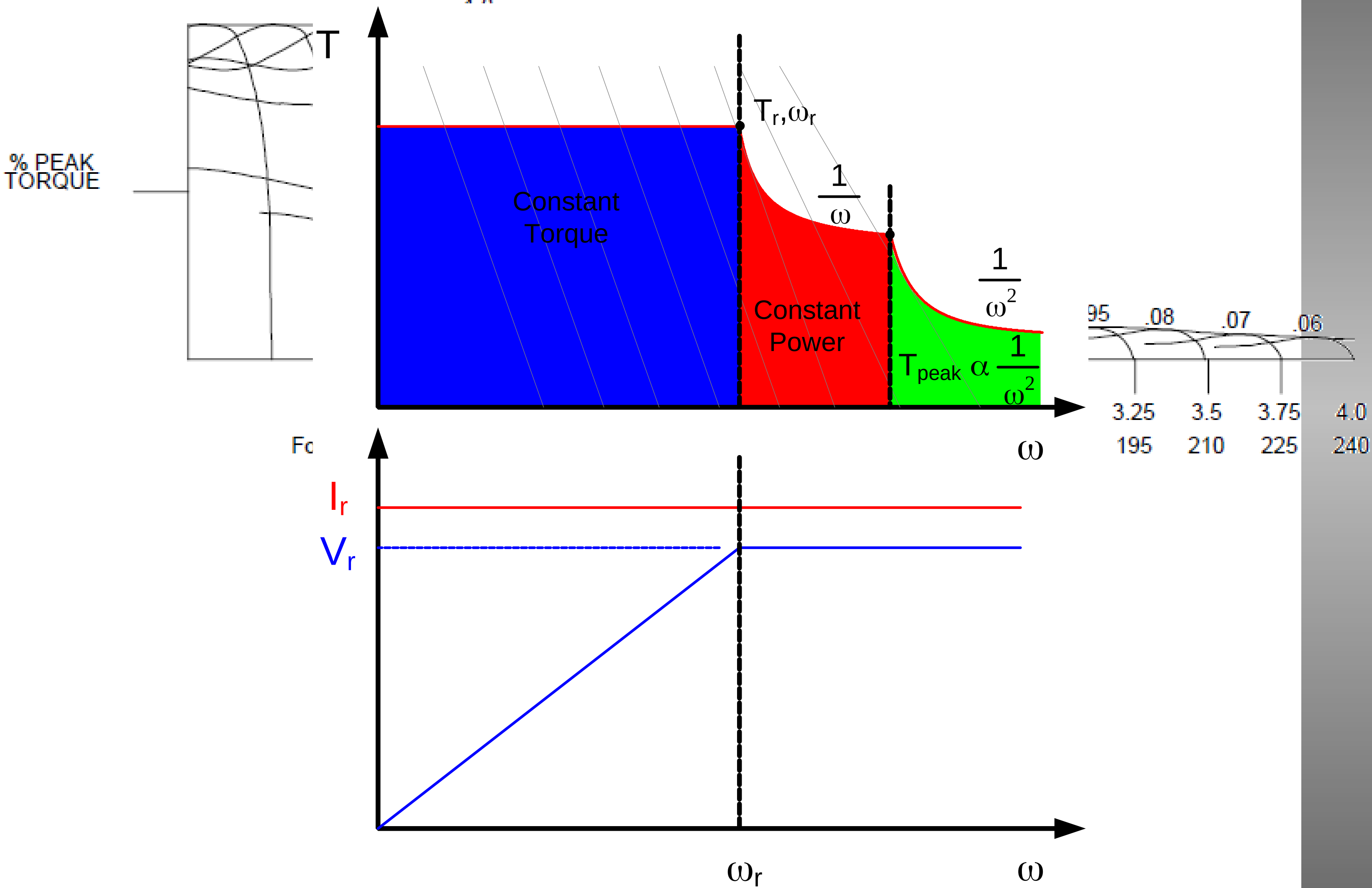


Typical Voltage Boost Strategy for V/Hz Drives

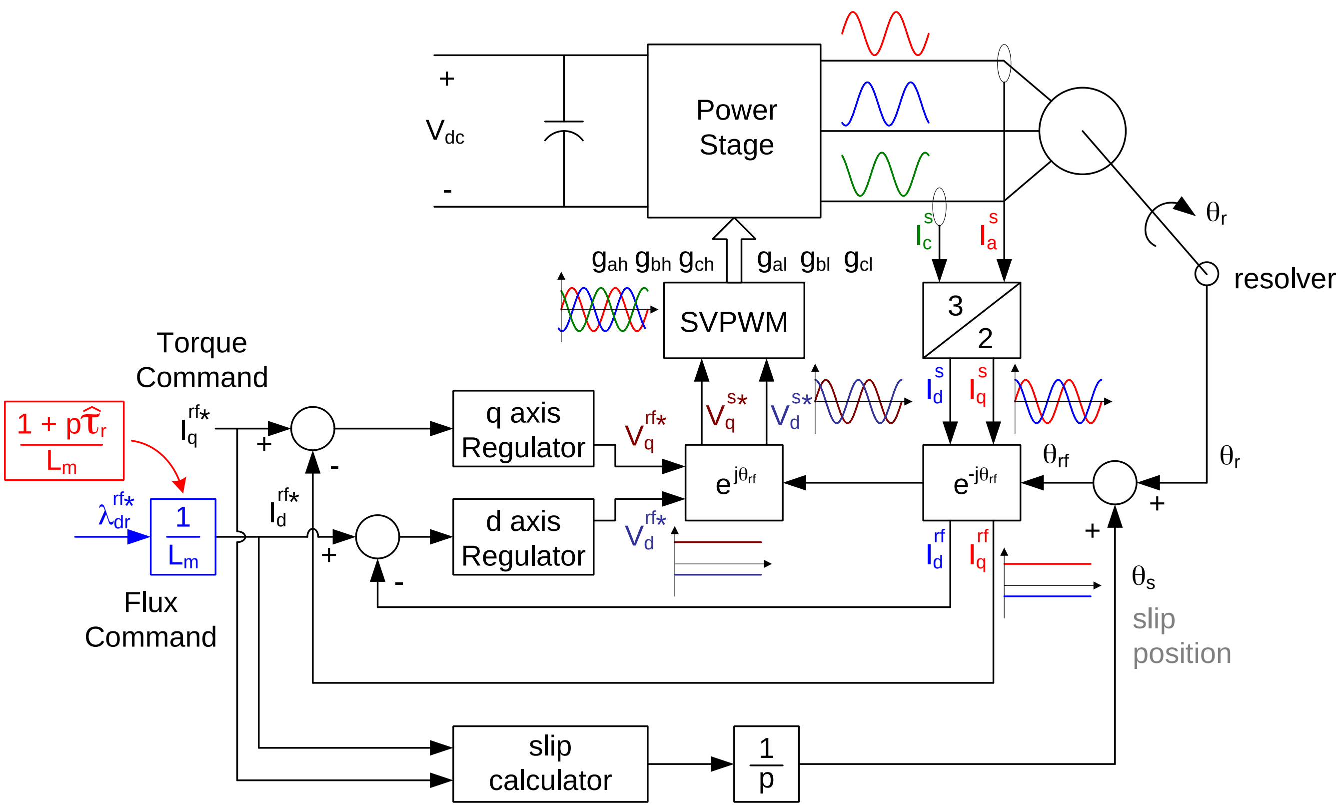


Induction Motor Speed Torque Curves with Constant V/Hz with Boost

Induction Machine Modeling

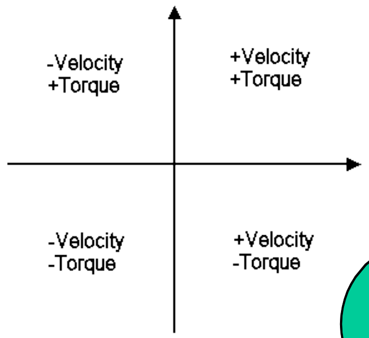


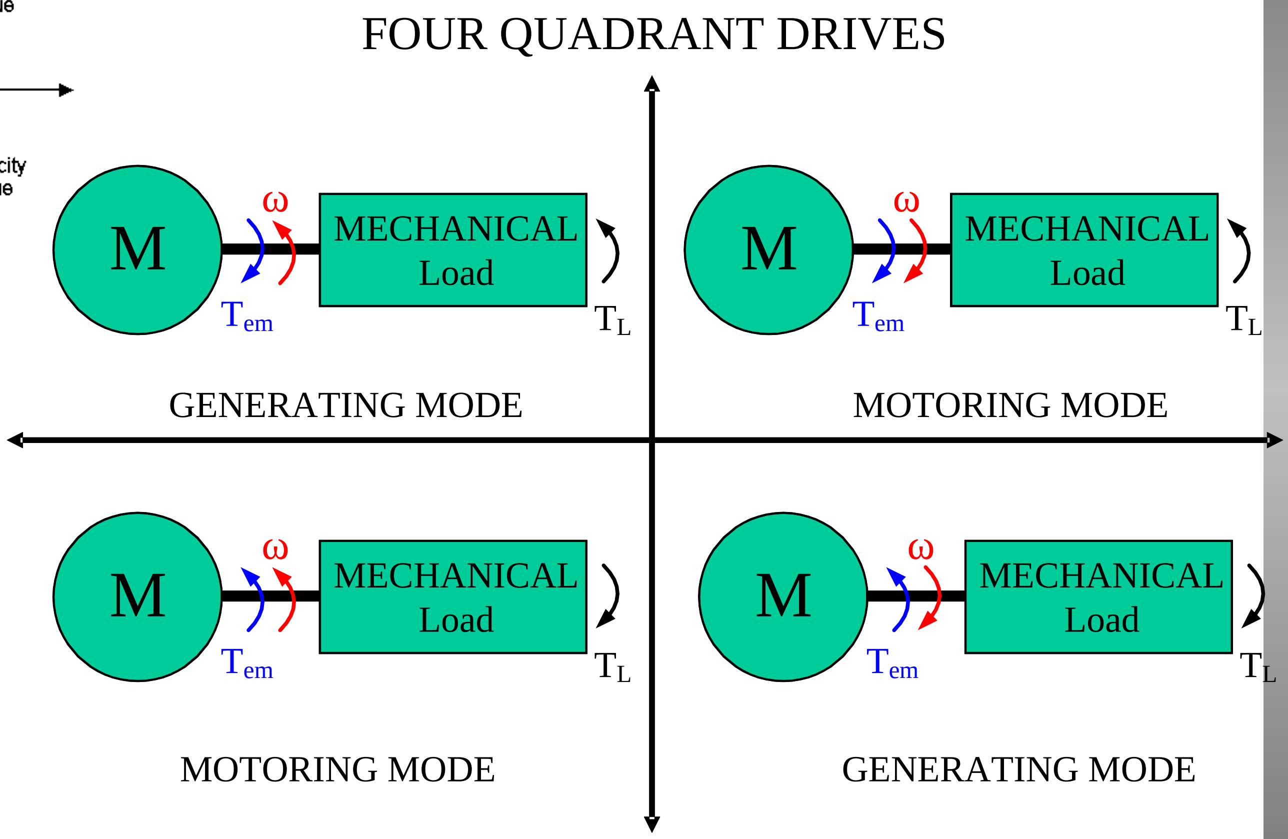
Induction Machine Control



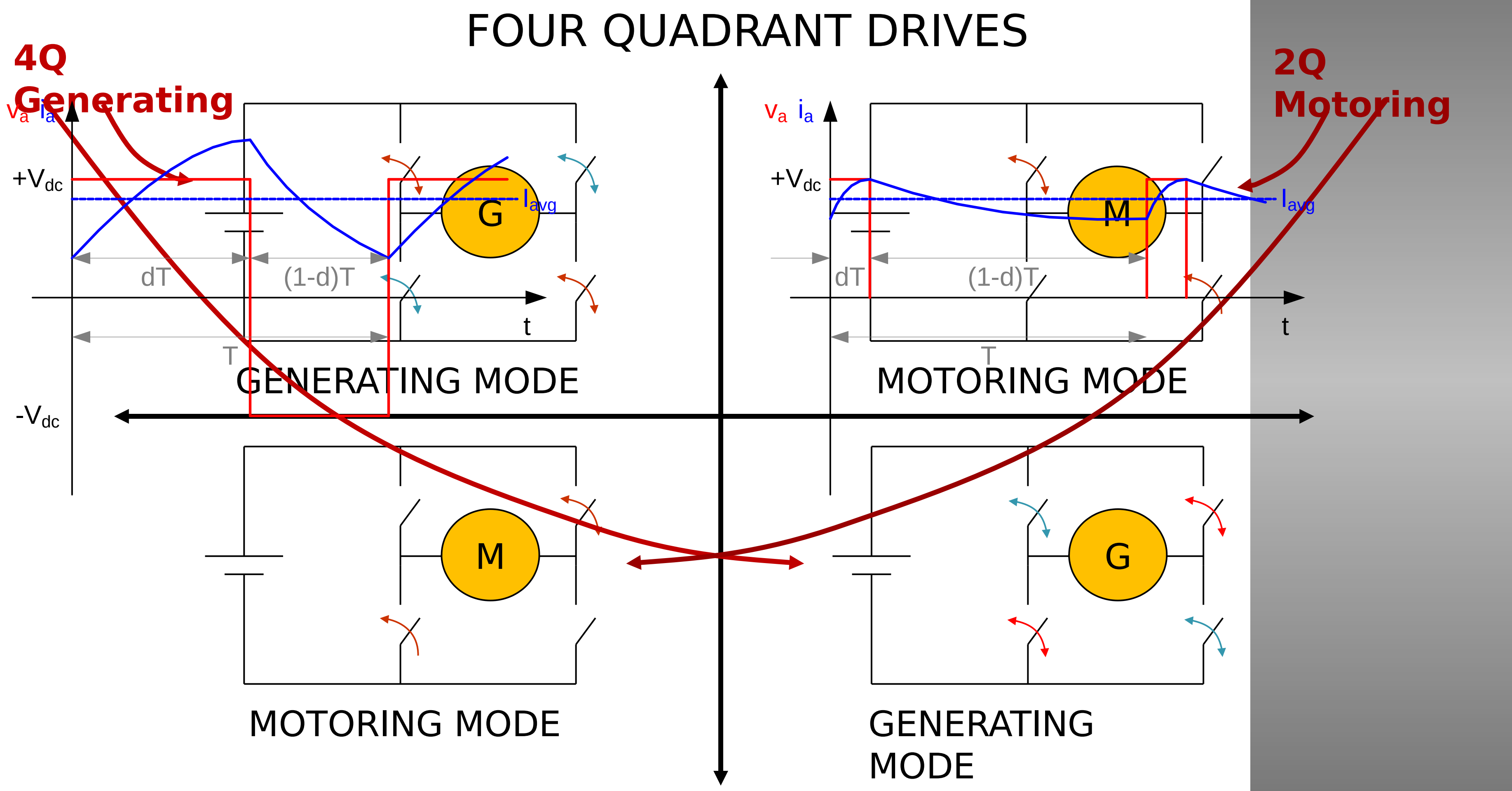
Indirect Field Orientation – Rotor Flux Orientation Induction Machine Control

Machine Control

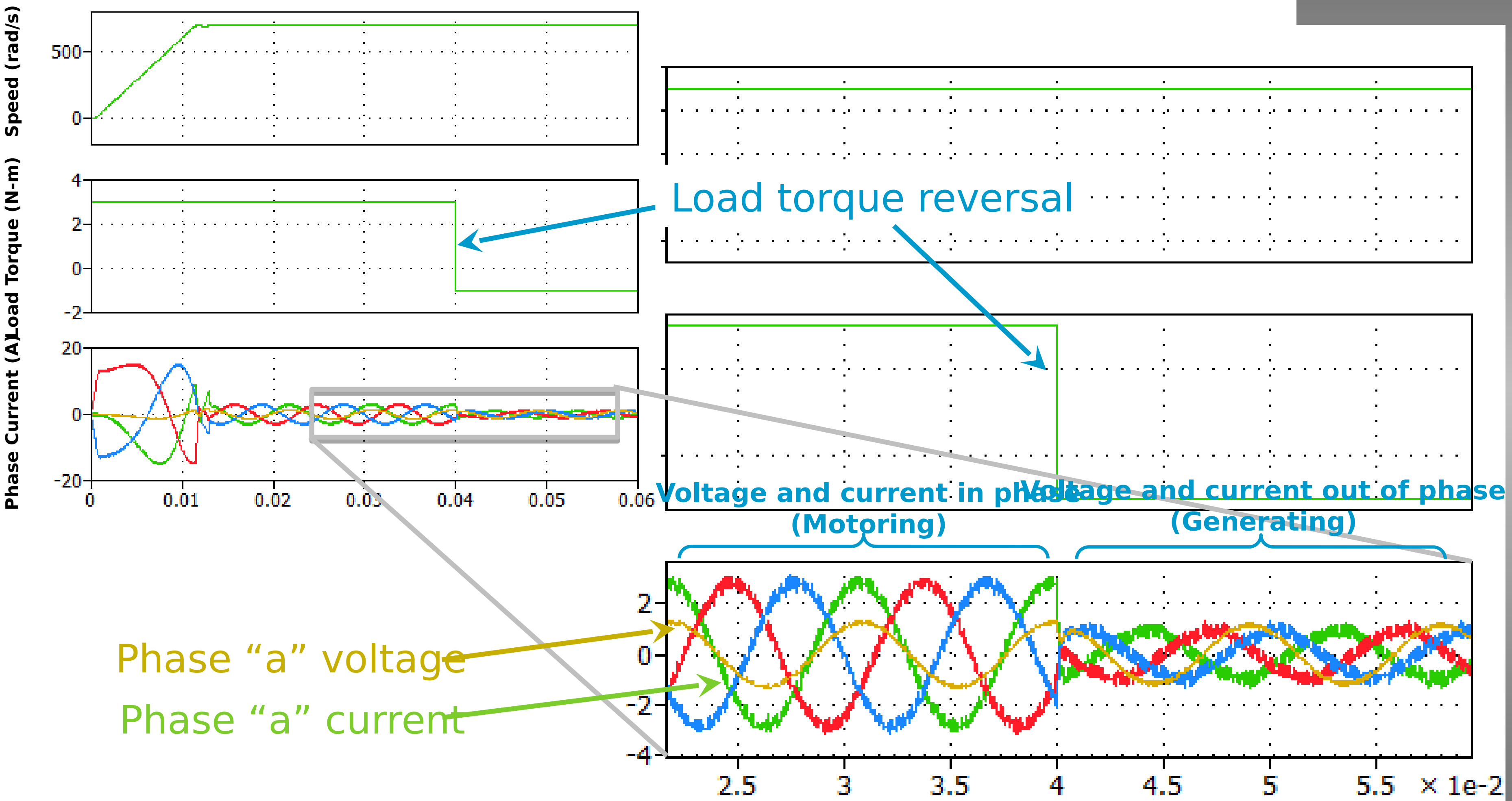




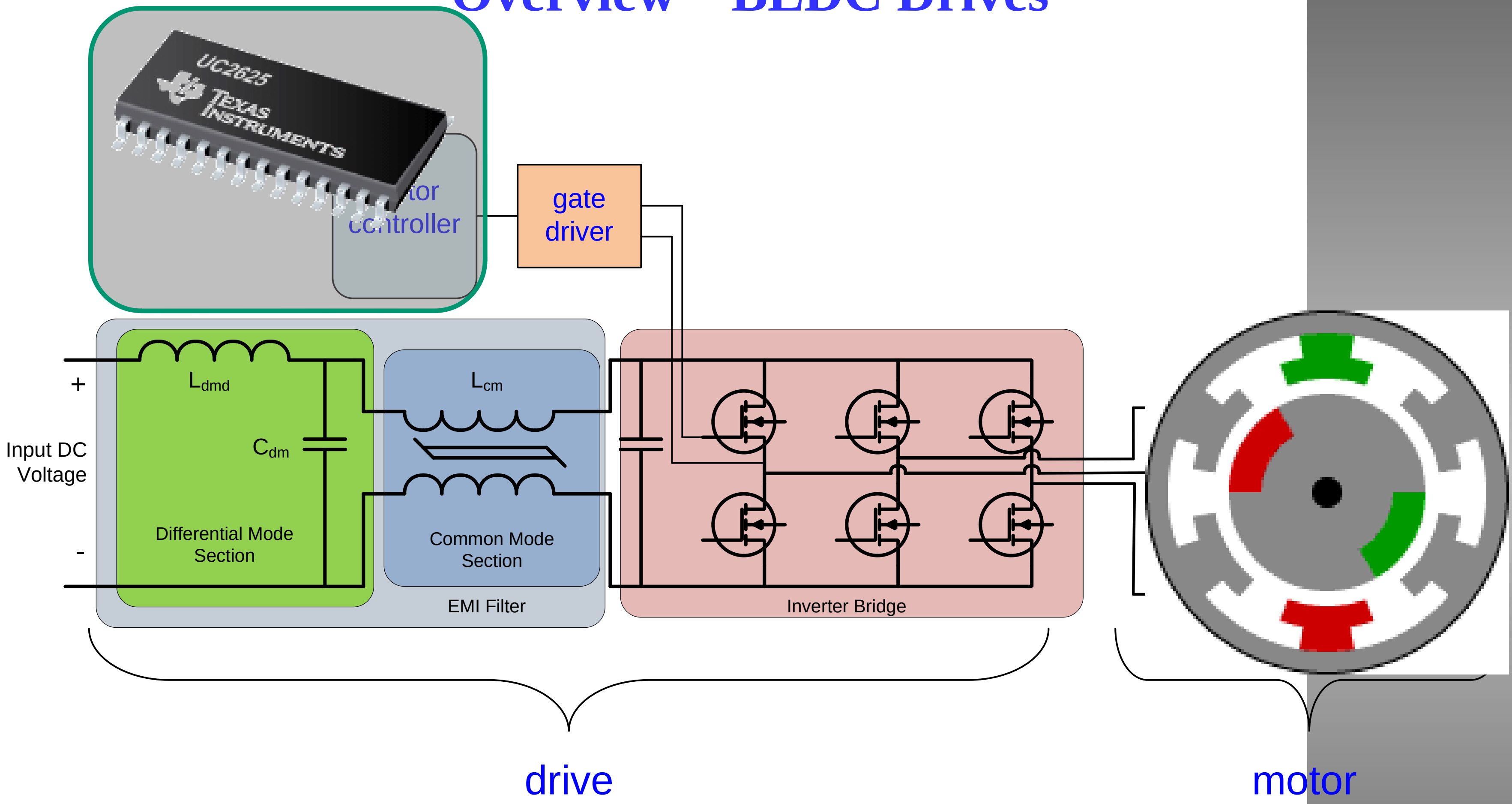
Machine Control



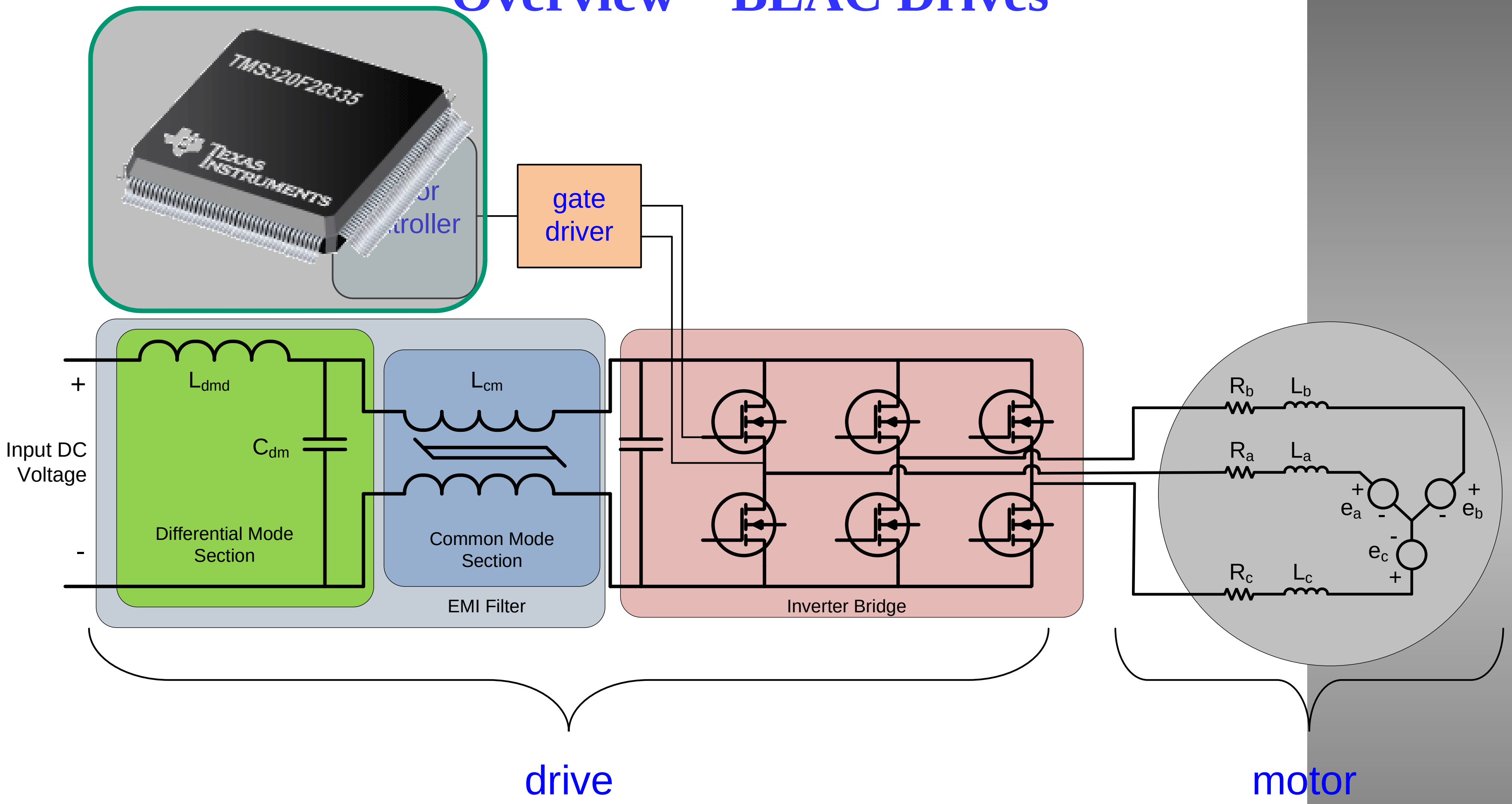
Machine Control – PMSM Simulation



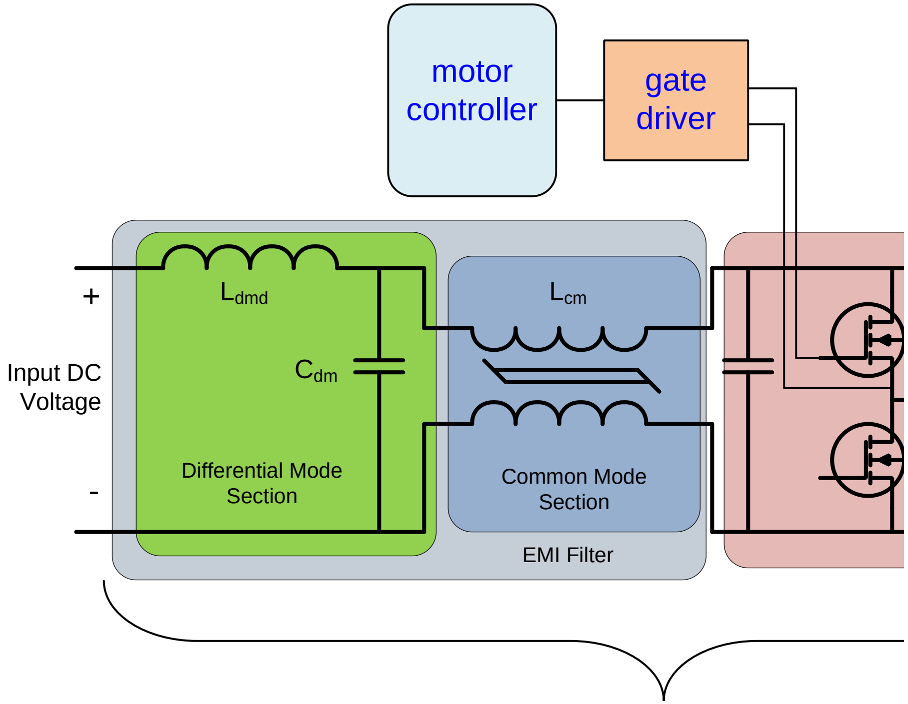
Overview – BLDC Drives



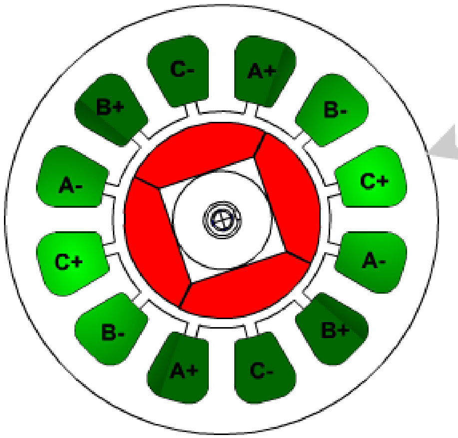
Overview – BLAC Drives



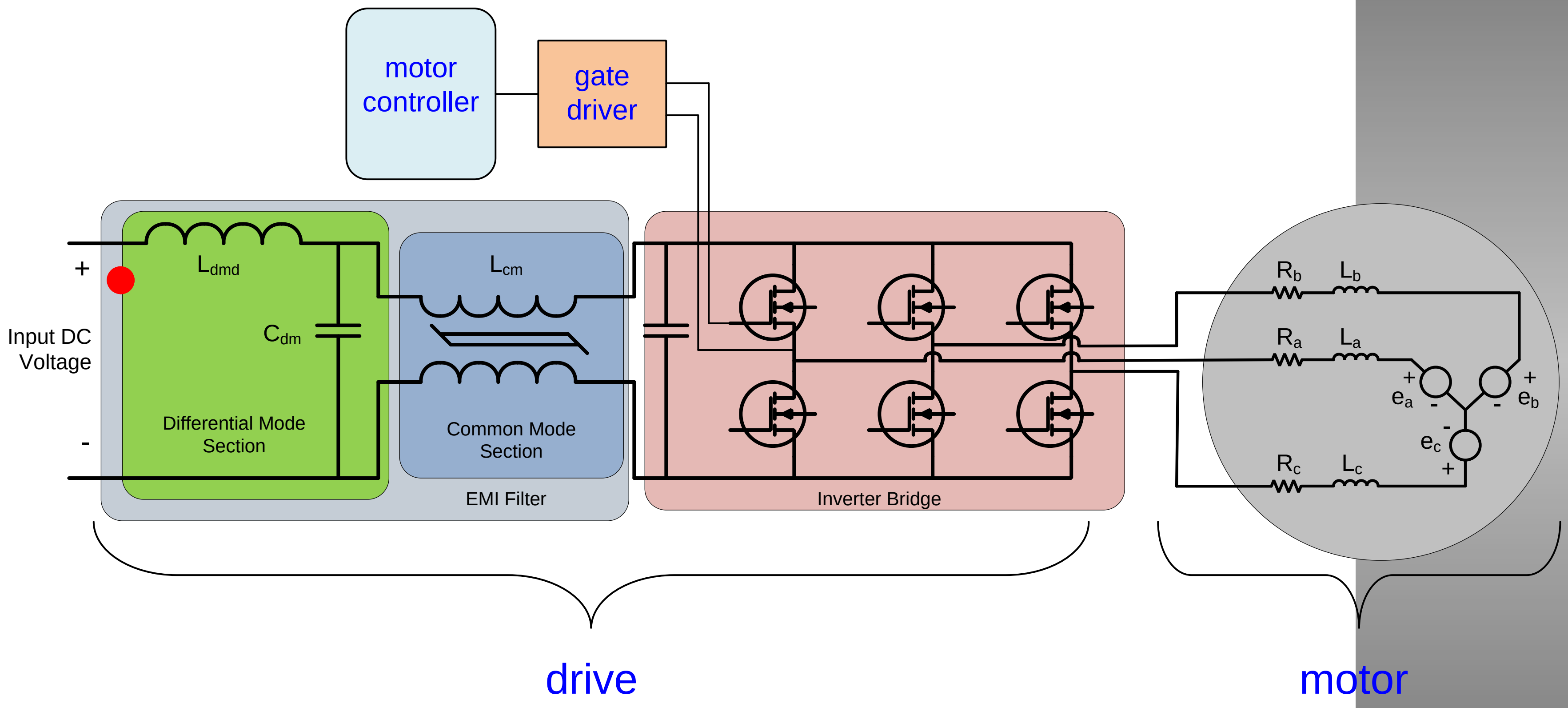
Overview – BLAC Drives



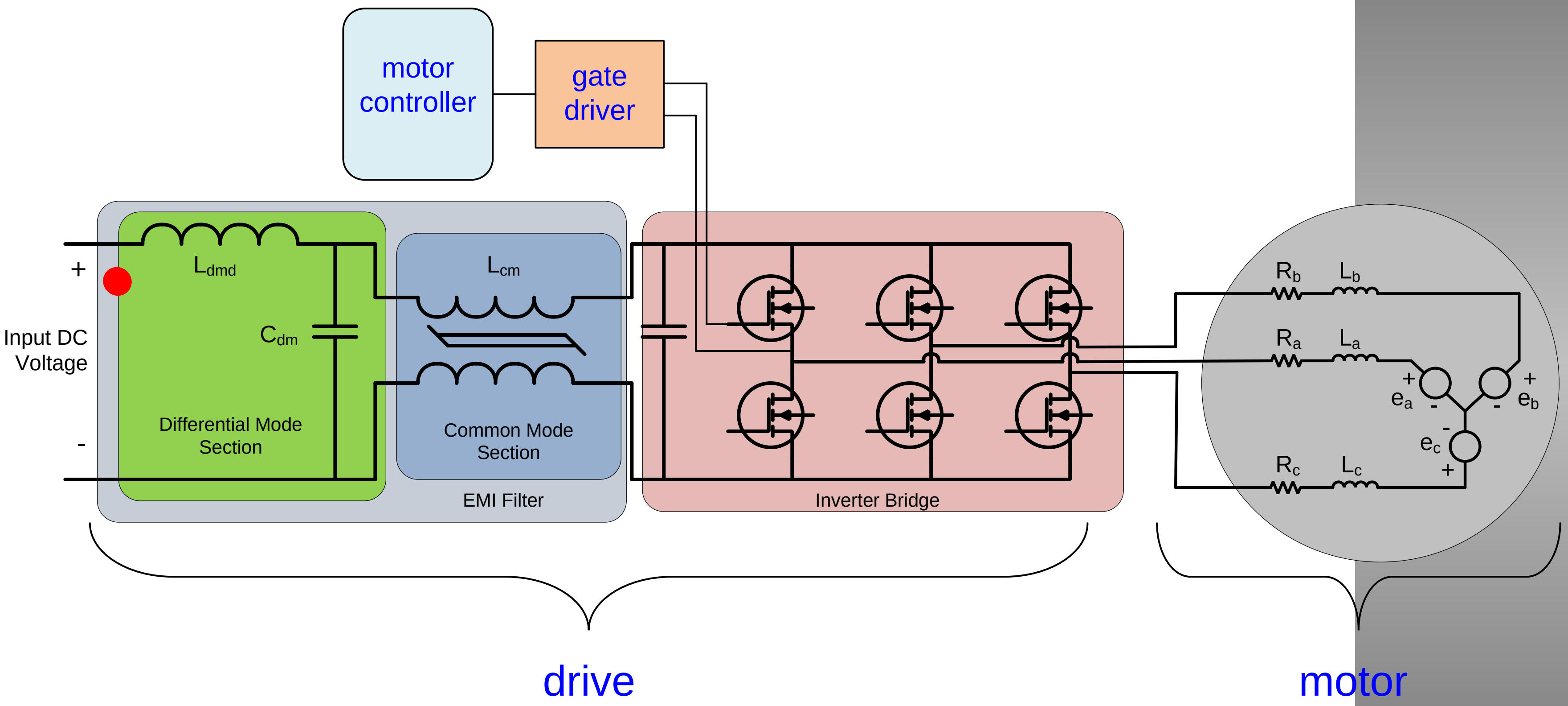
drive



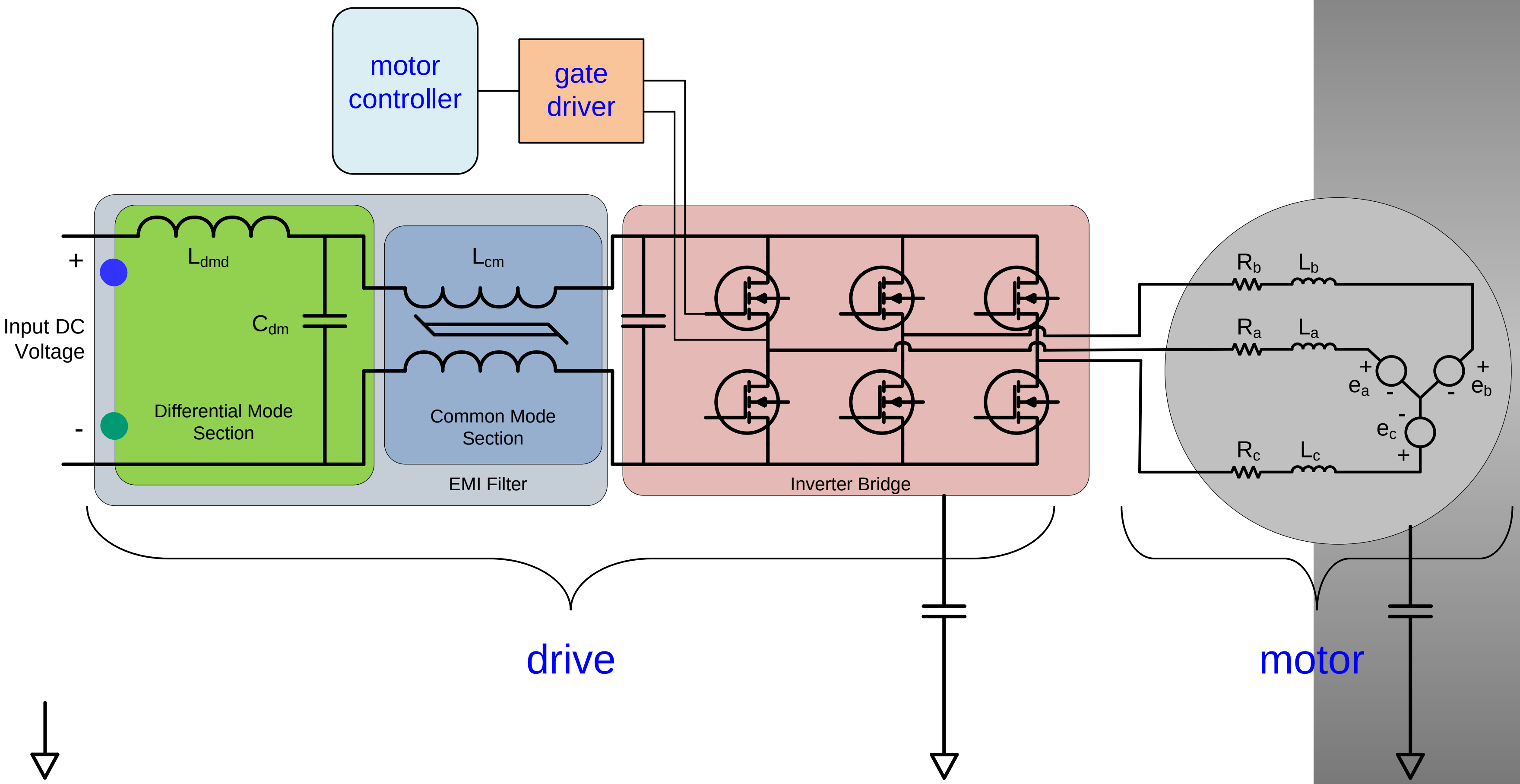
Differential Mode Currents – BLDC Motors



Differential Mode Currents – BLAC Motors

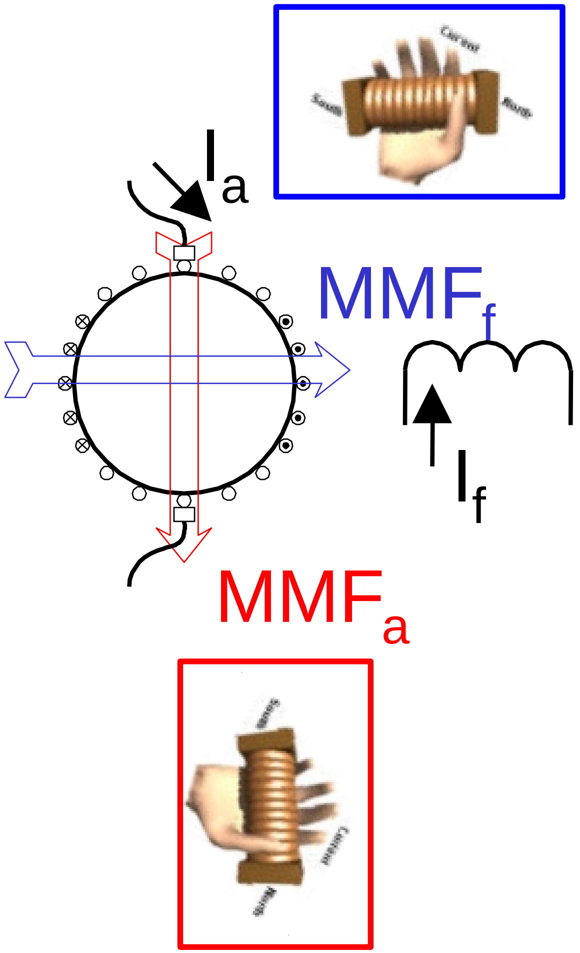


Common Mode Currents



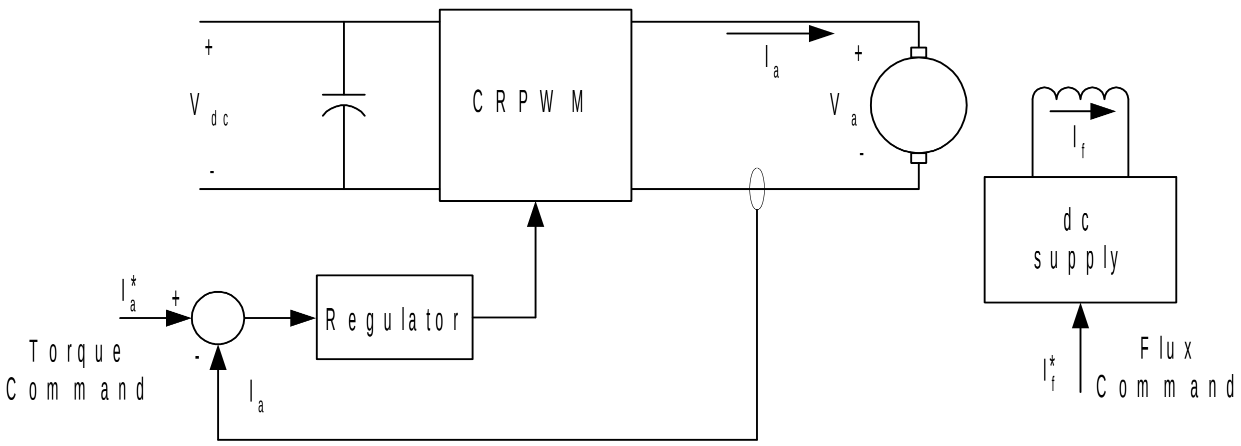
Electric Machines Control Overview

MOTOR CONTROL

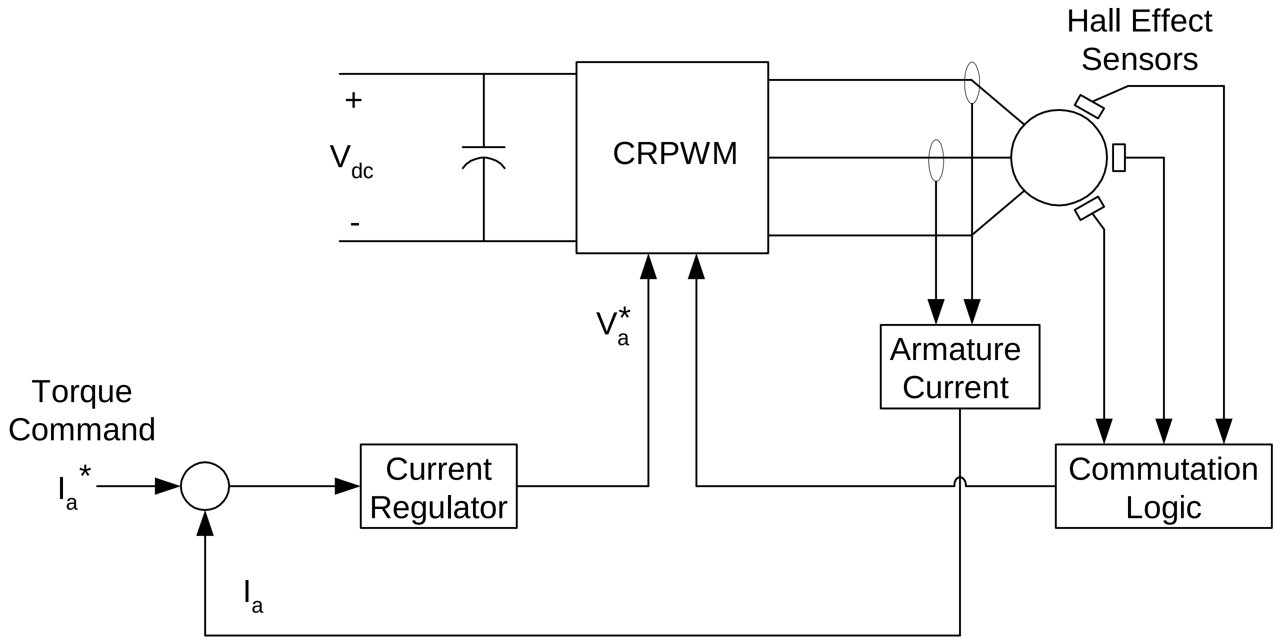


- commutator maintains orthogonality between field and armature current
- field and aramature currents independently controlled

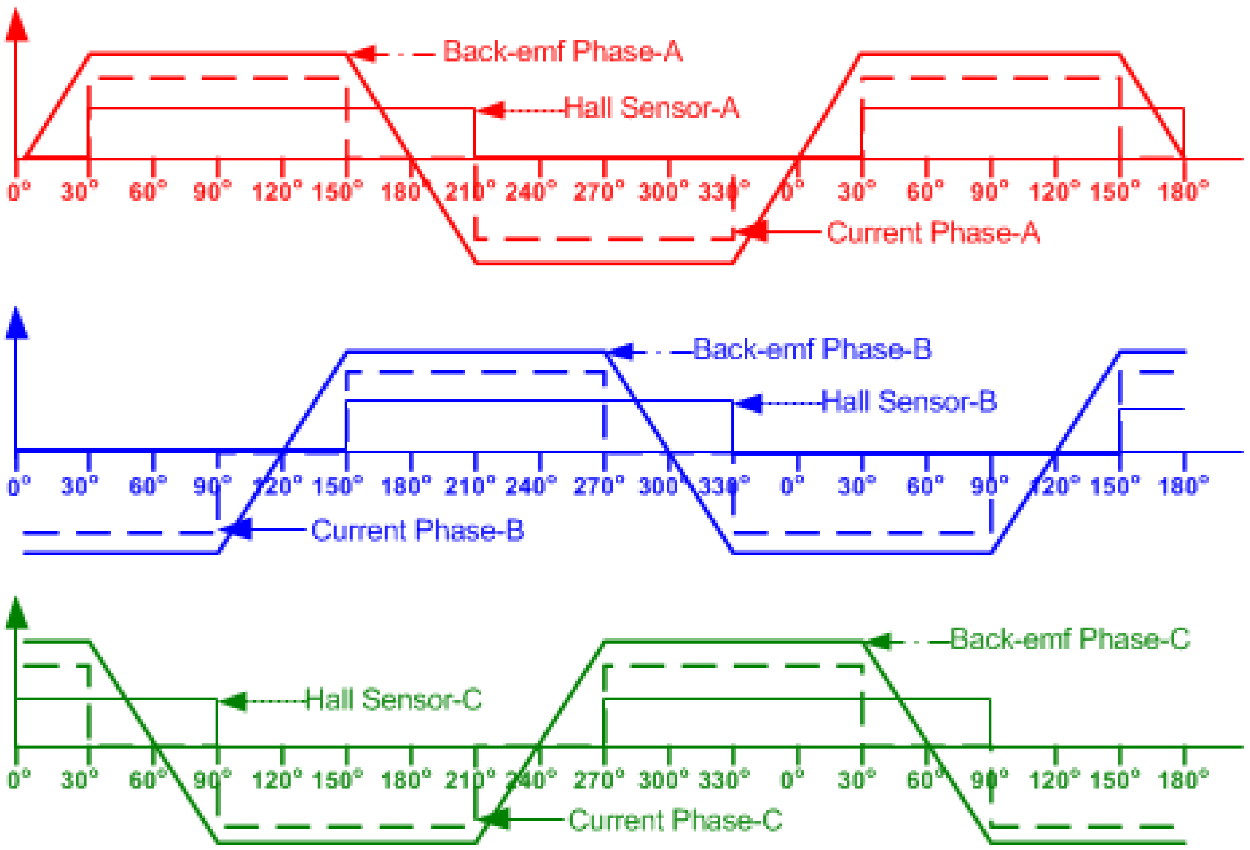
BRUSH D.C. MOTOR CONTROL



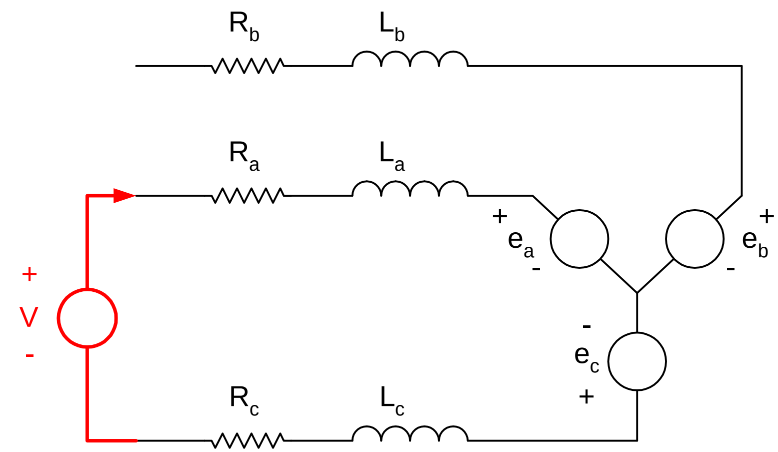
BRUSHLESS D.C. MOTOR CONTROL

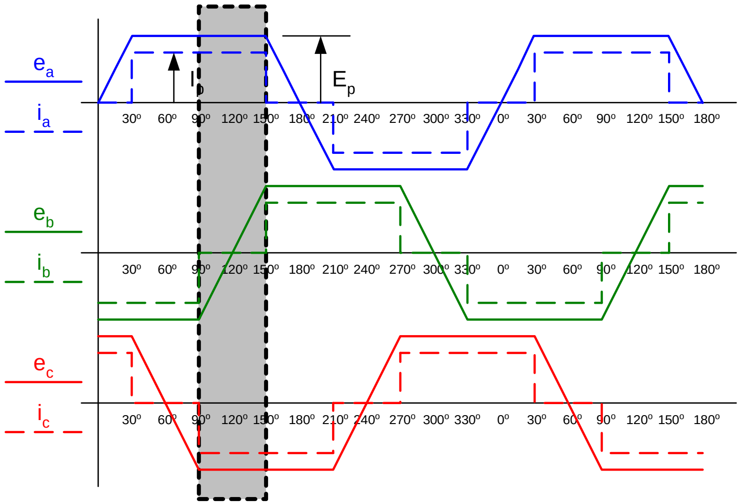


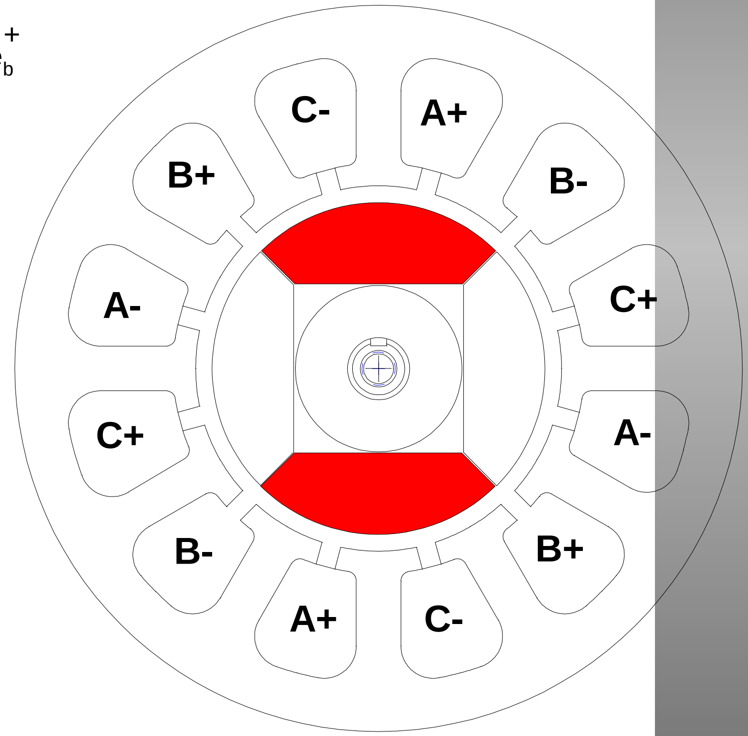
BRUSHLESS D.C. MOTOR CONTROL



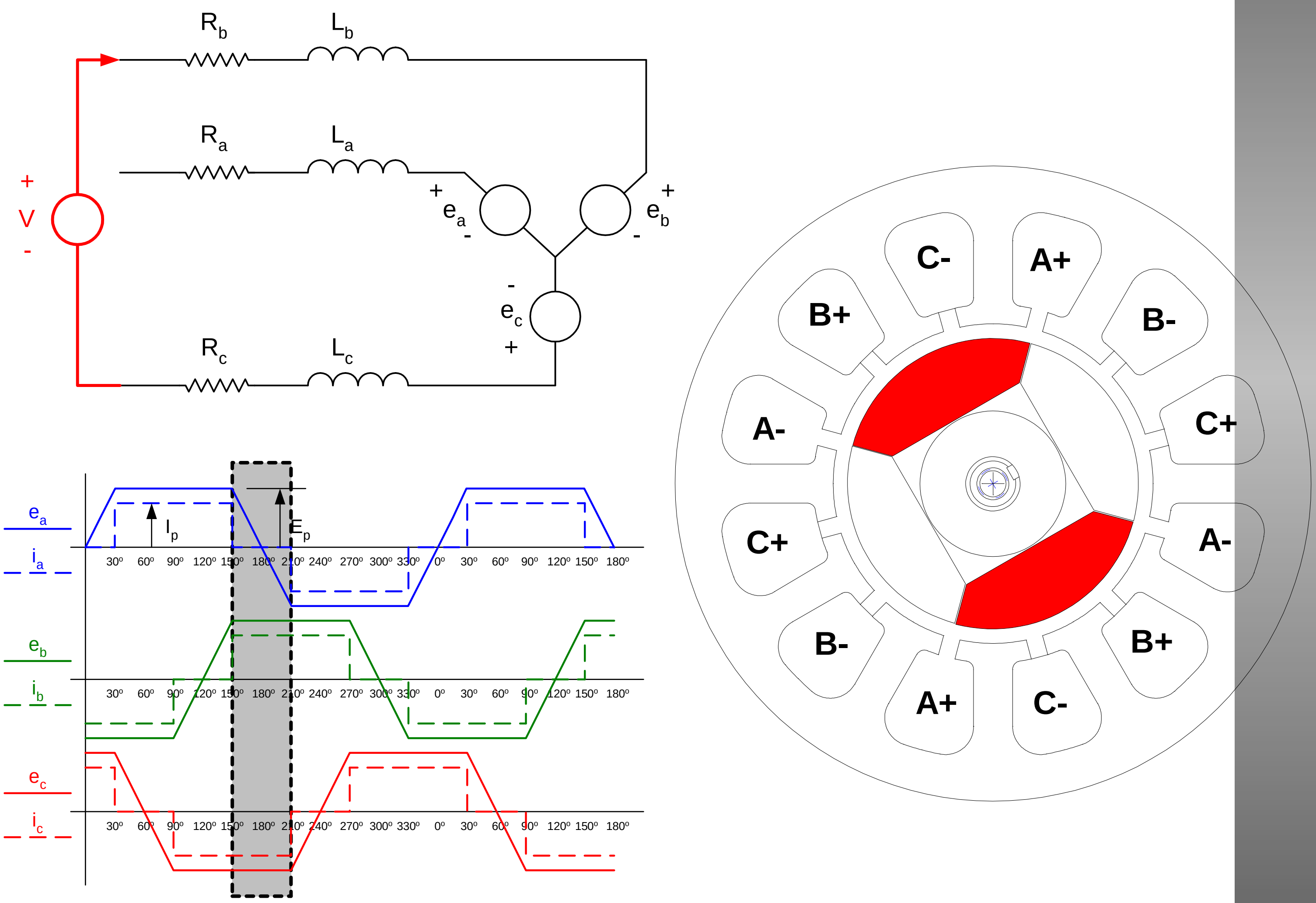
BRUSHLESS DC MACHINES







BRUSHLESS DC MACHINES



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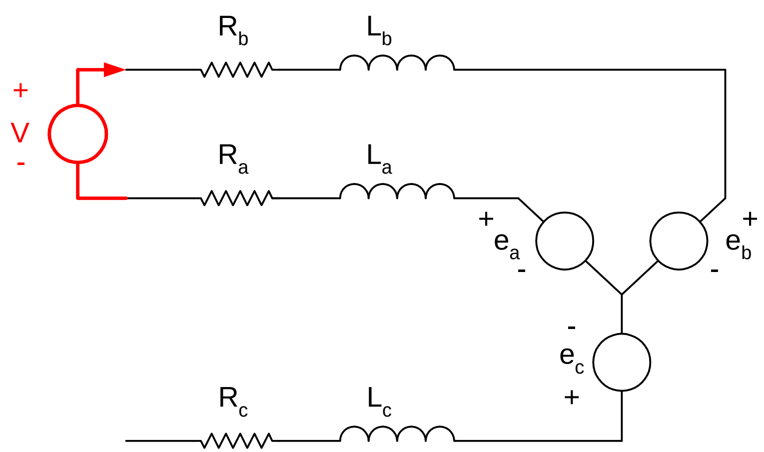

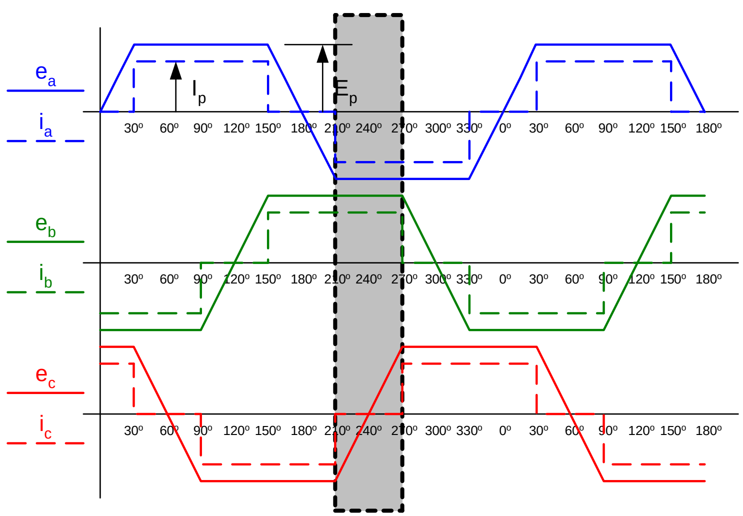

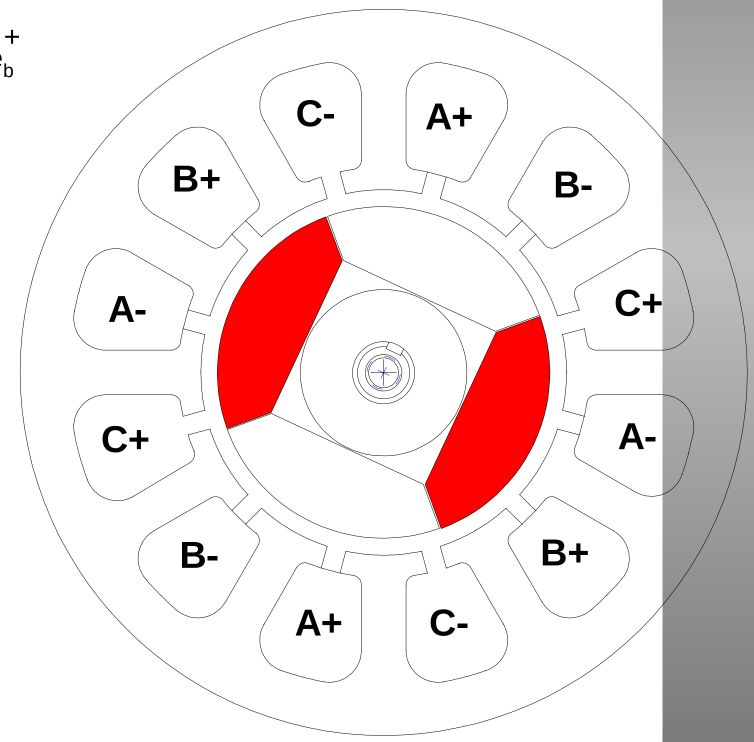

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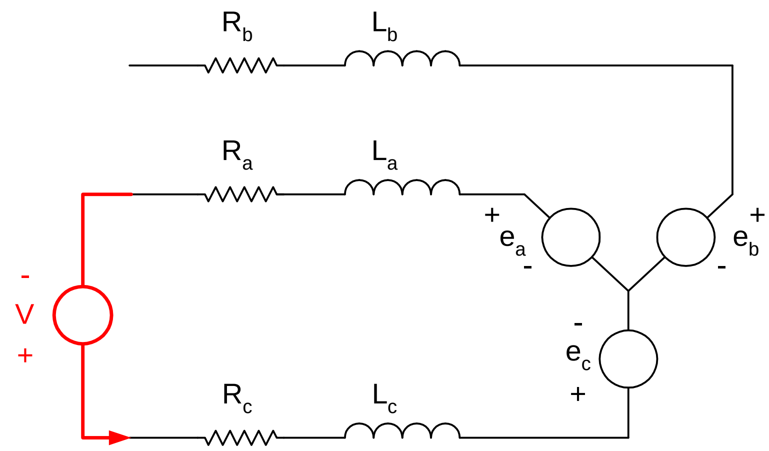

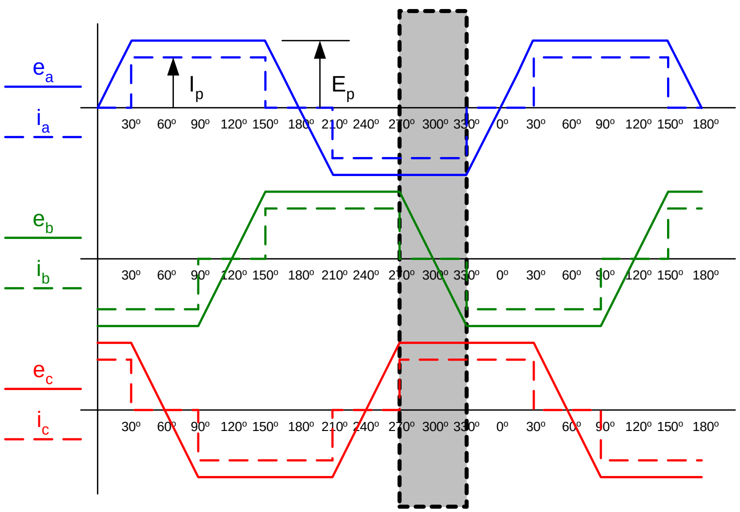

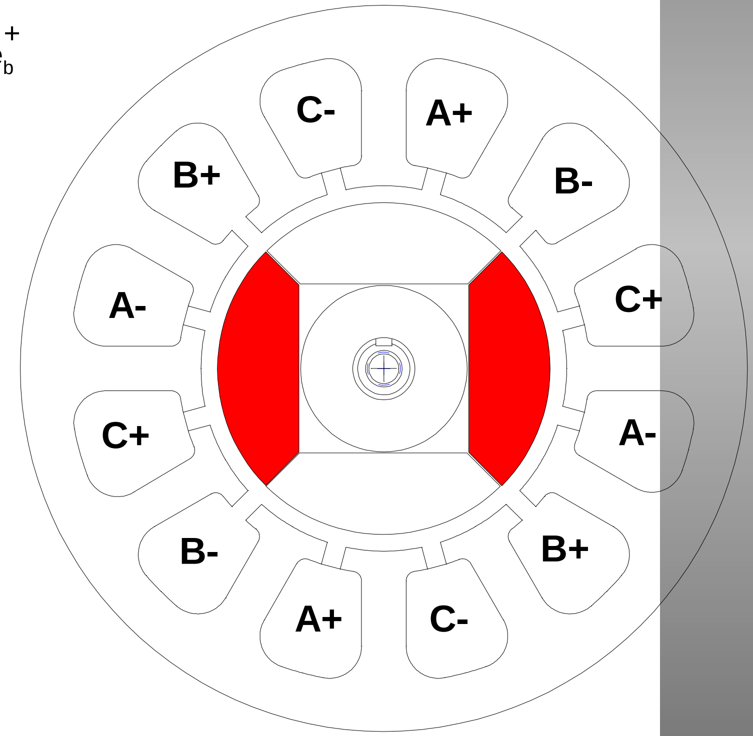

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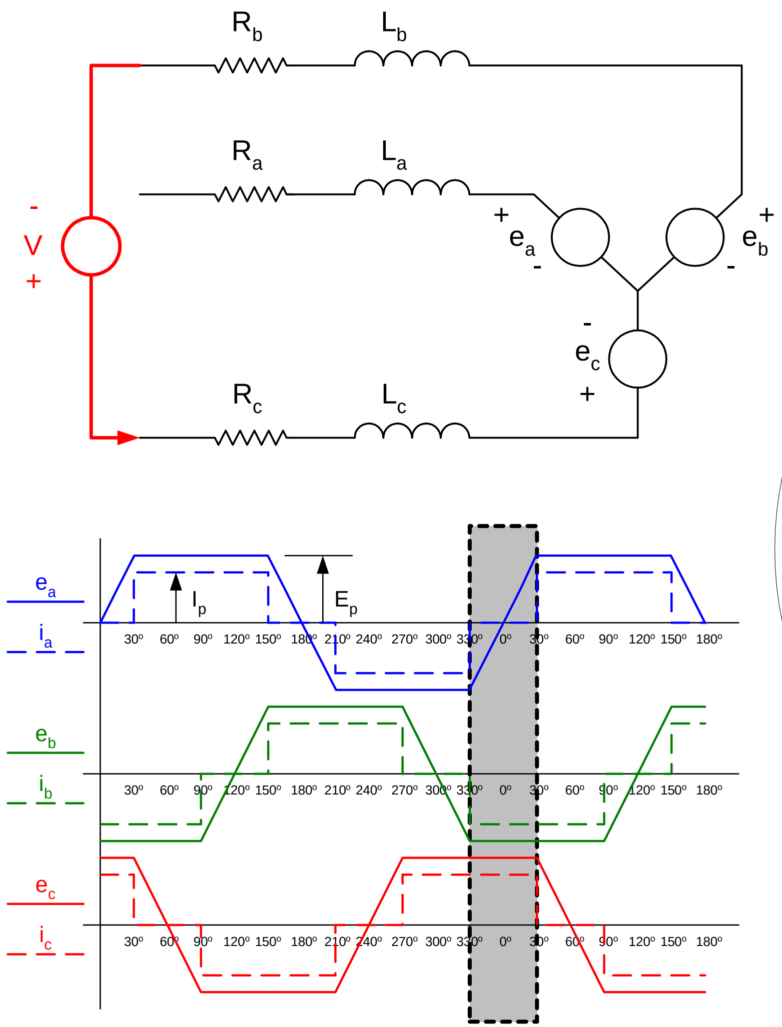

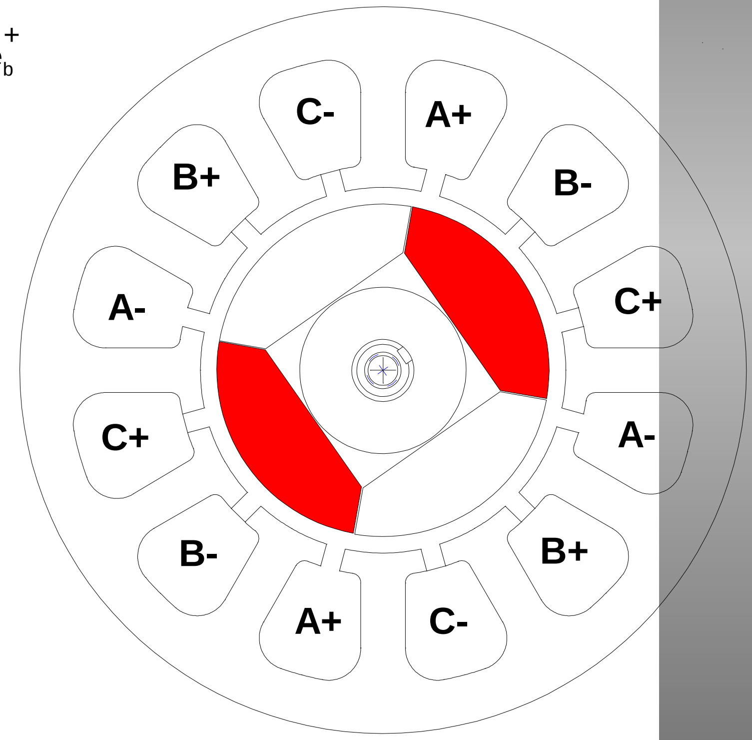

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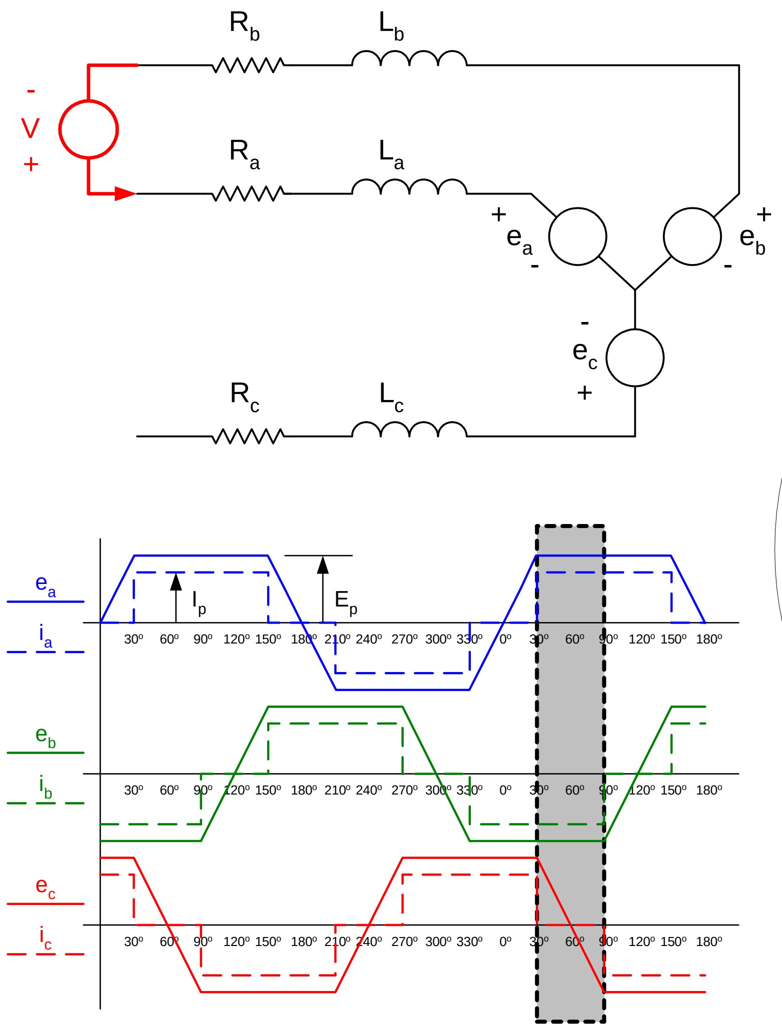

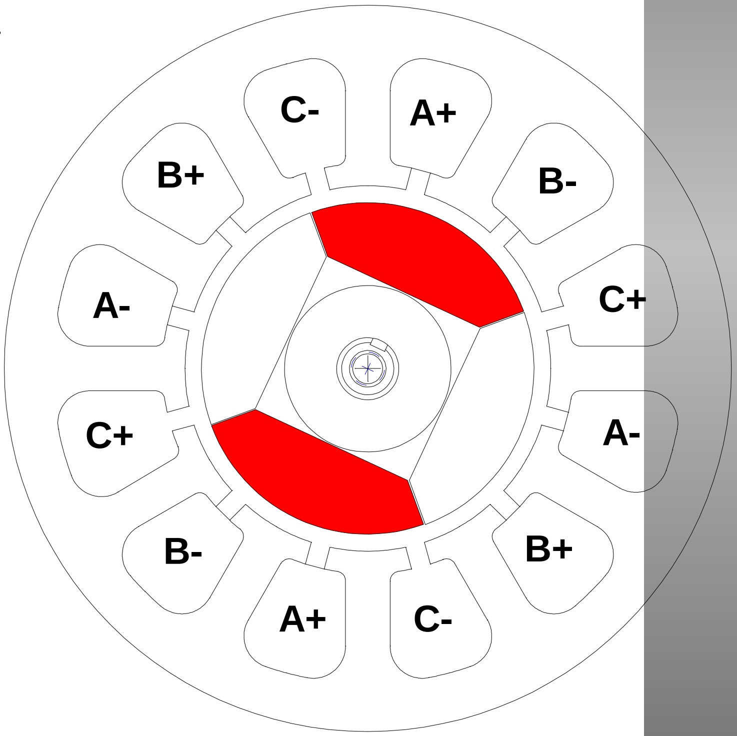

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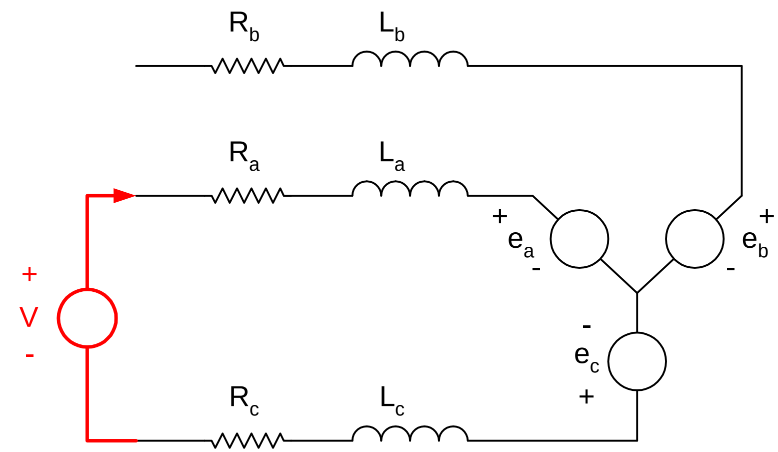
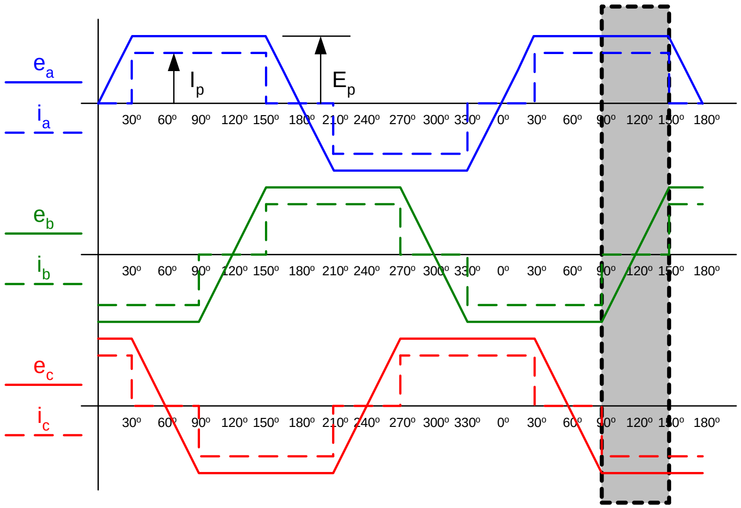
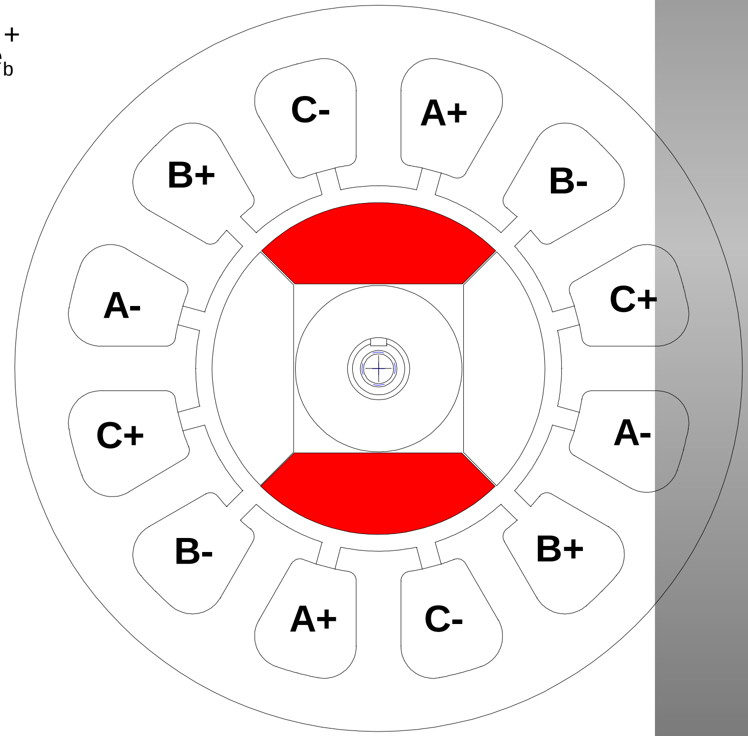
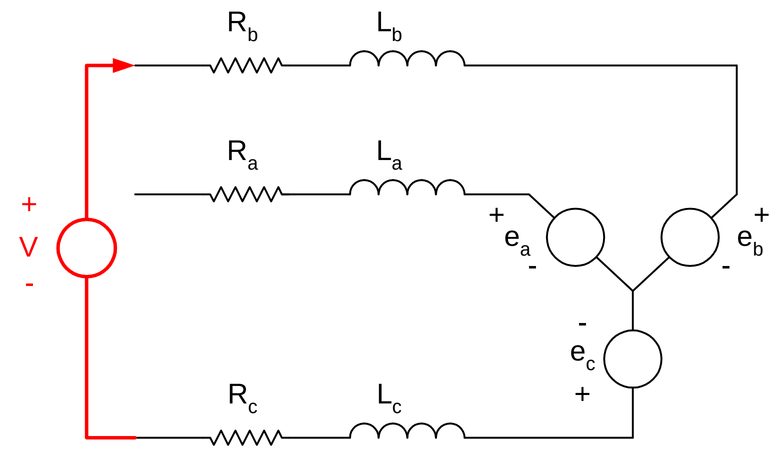
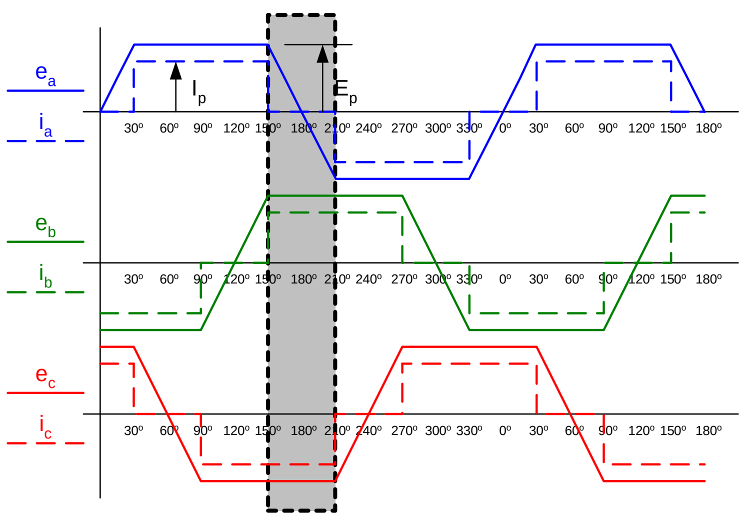


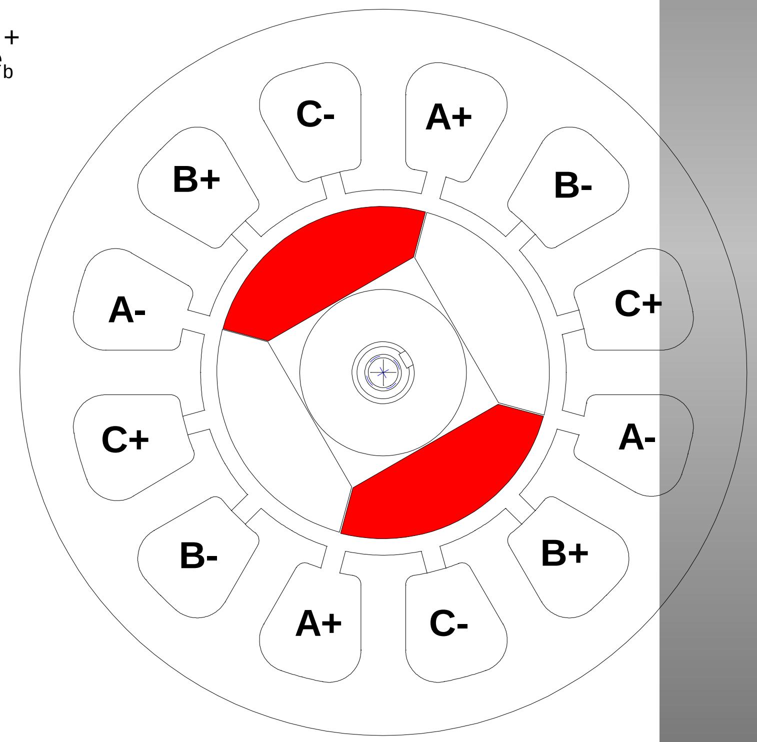




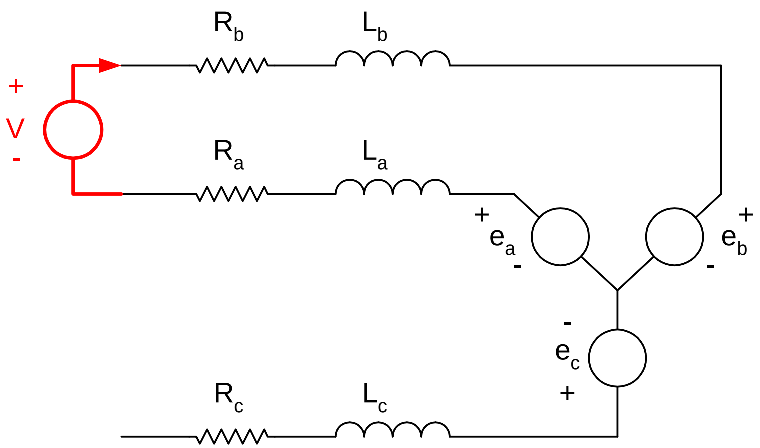
BRUSHLESS DC MACHINES

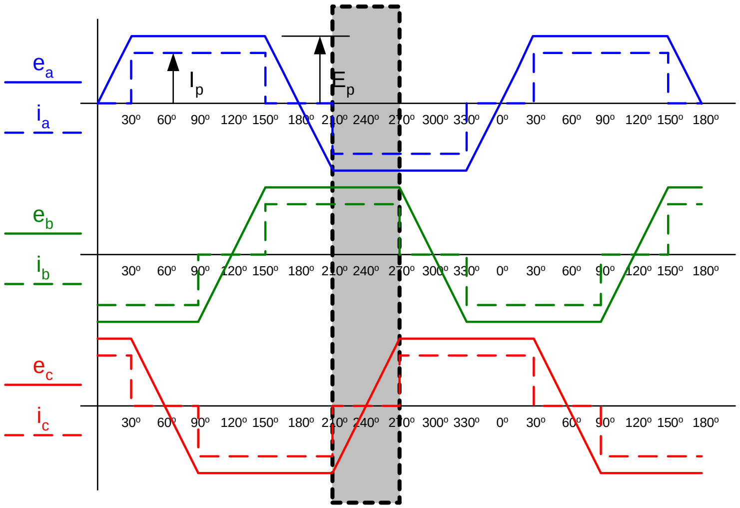


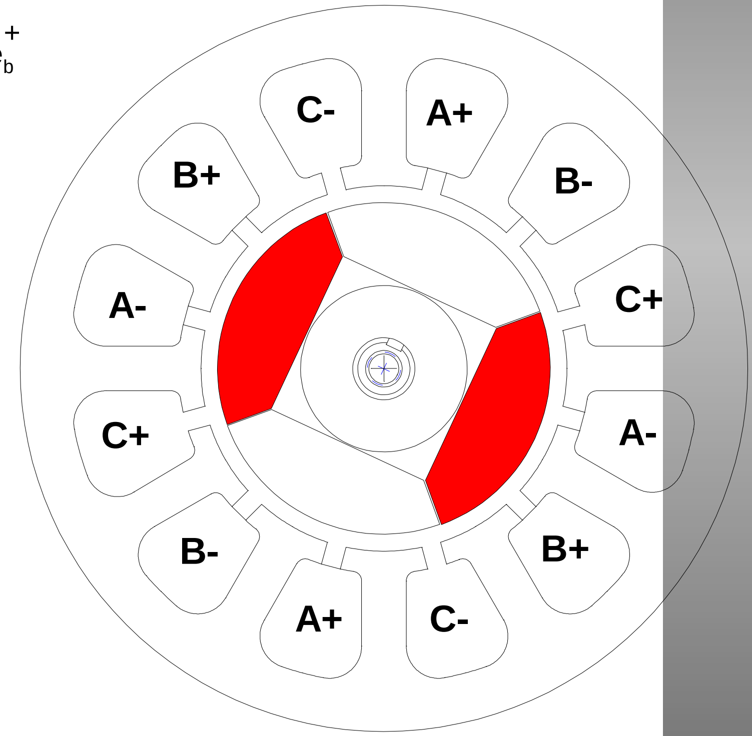




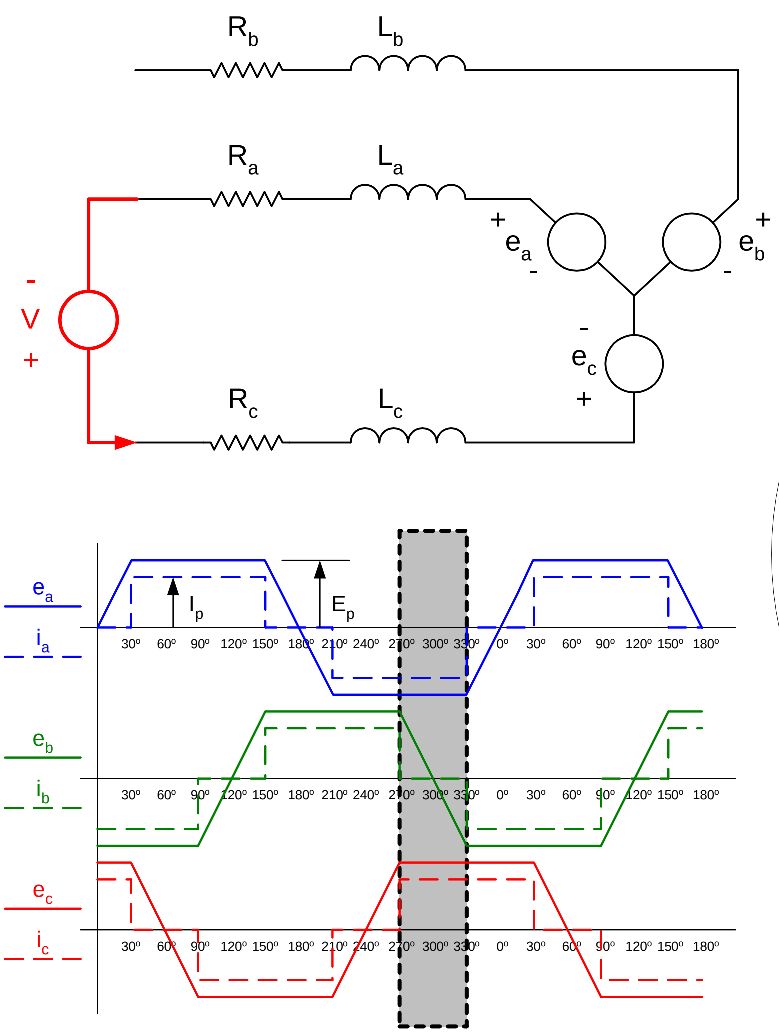
BRUSHLESS DC MACHINES

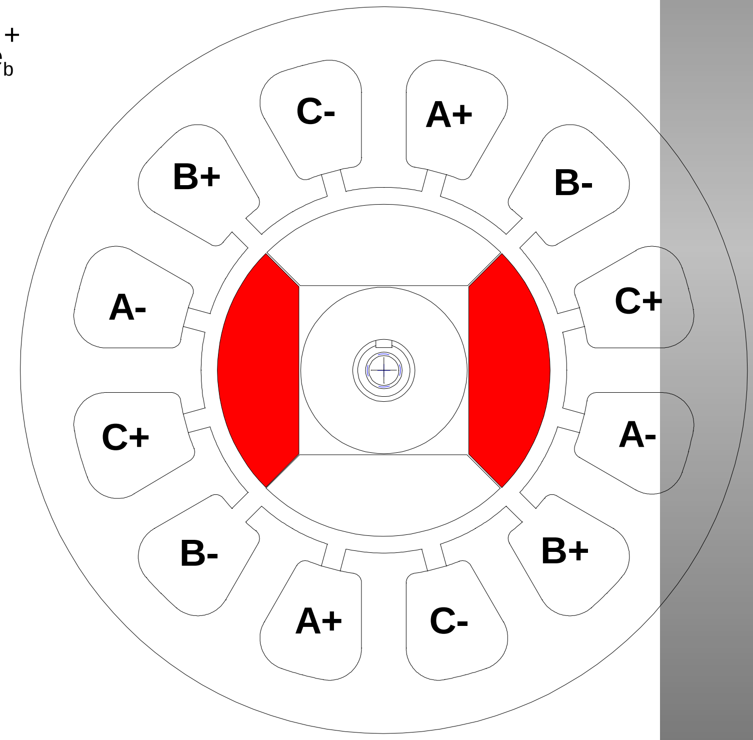






BRUSHLESS DC MACHINES





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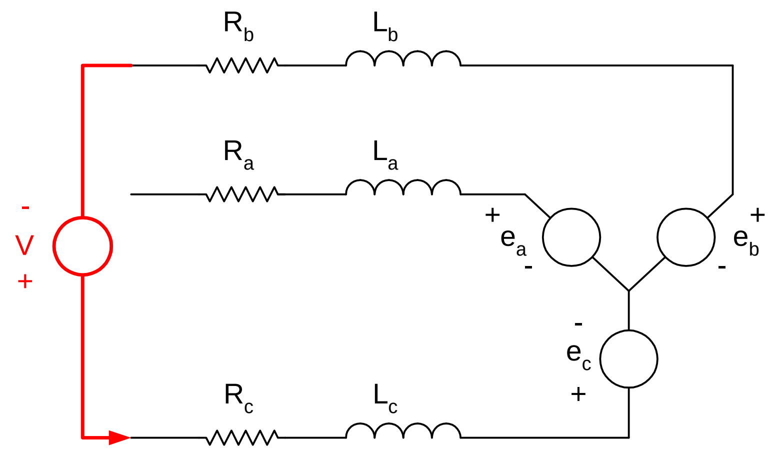

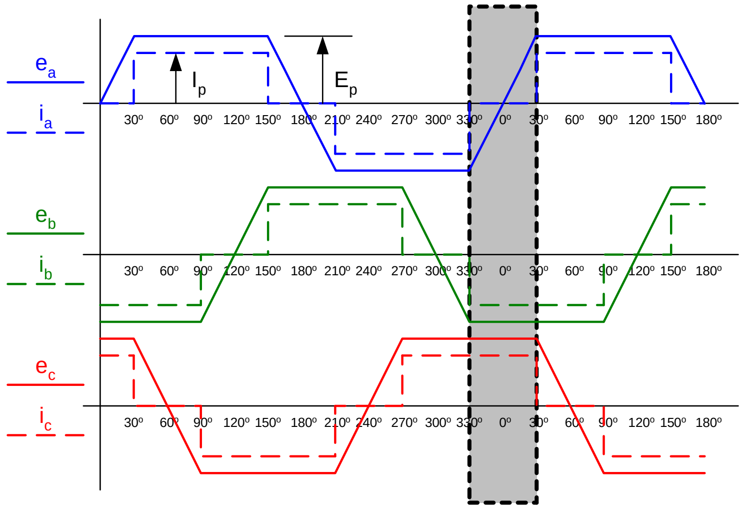

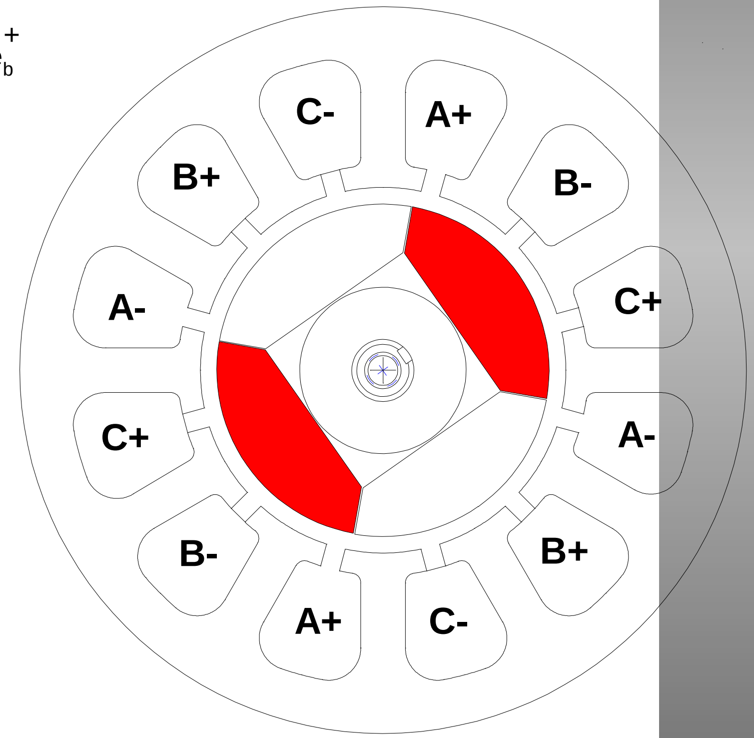

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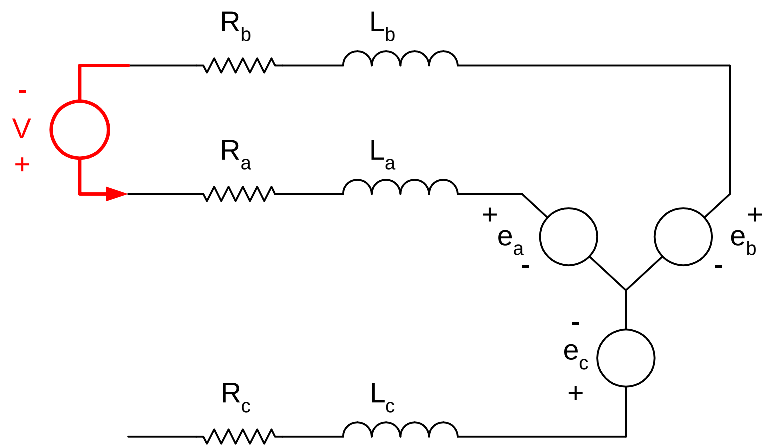
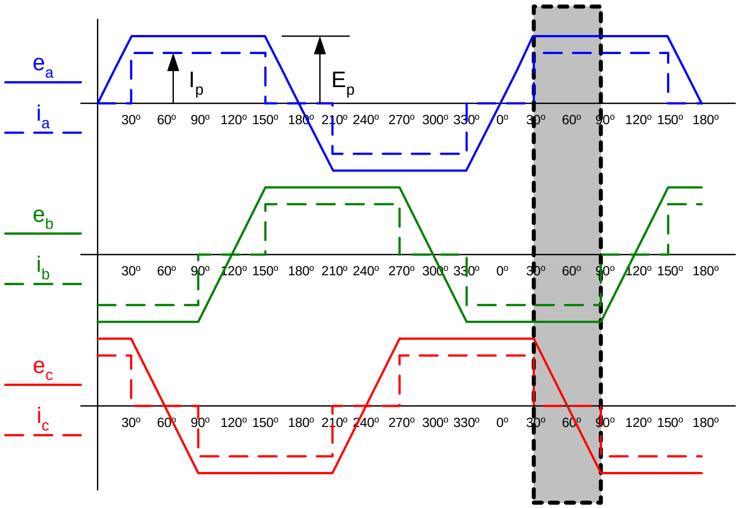
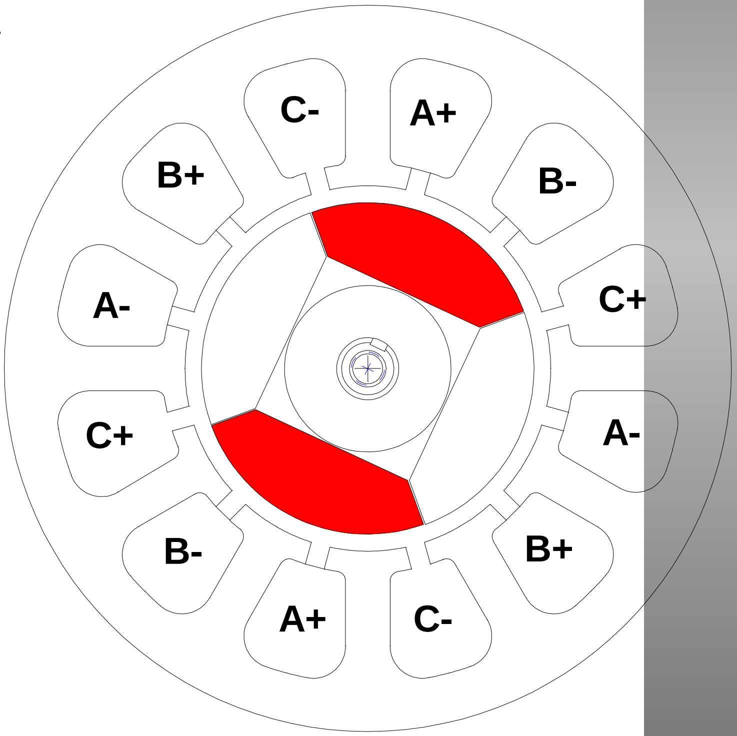
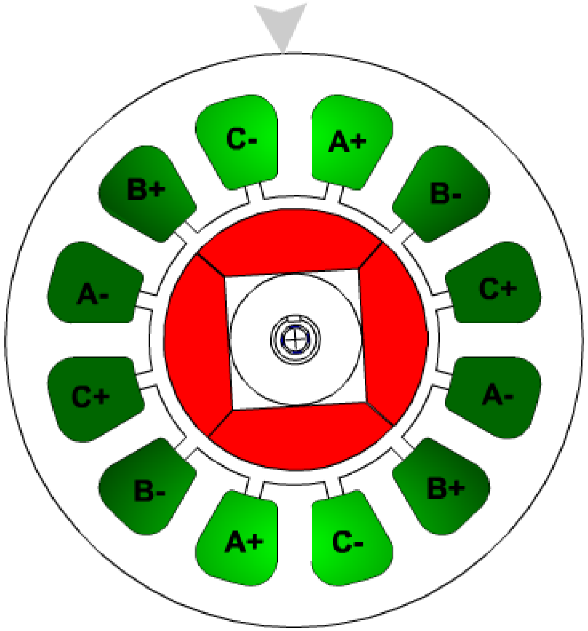




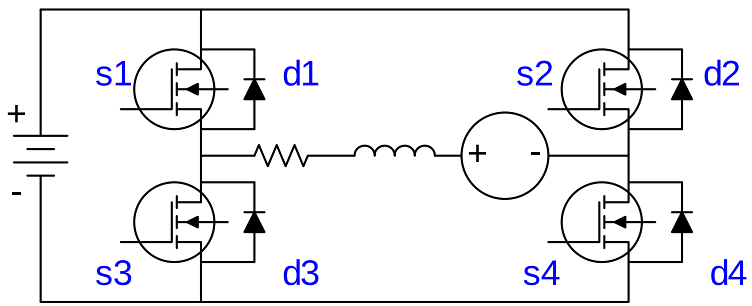


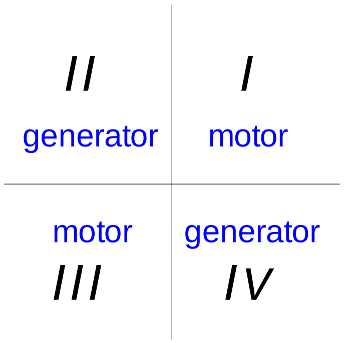
BRUSHLESS AC MACHINES

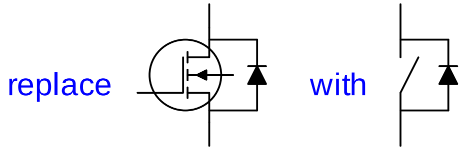


BLDC Drives

Electric Machines & Drives

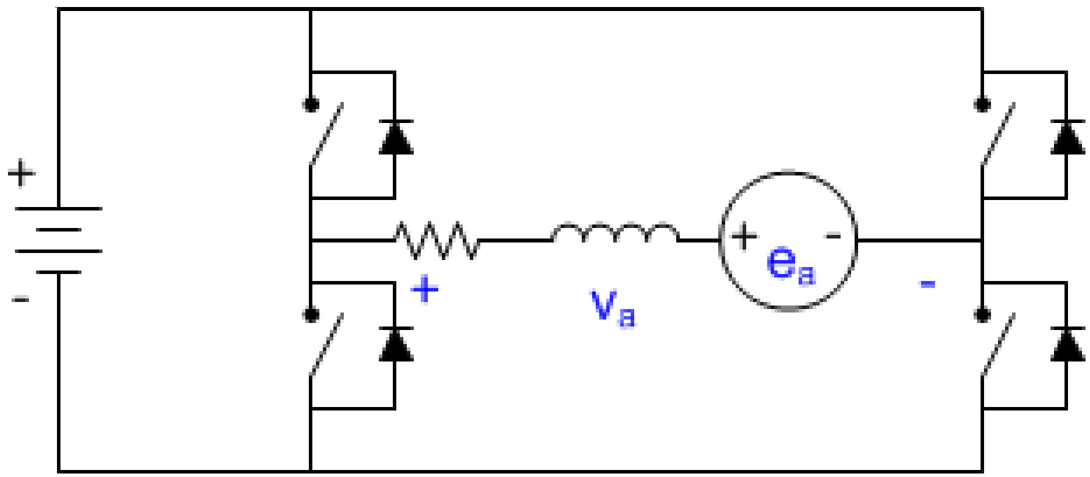




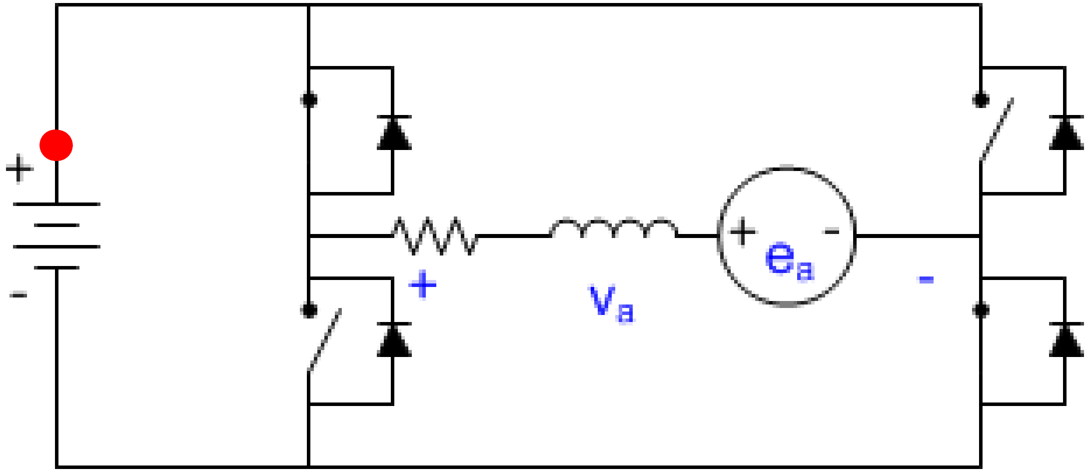


Note: There is a big difference between 2Q& 4Q drives!

Two quadrant operation in positive direction:



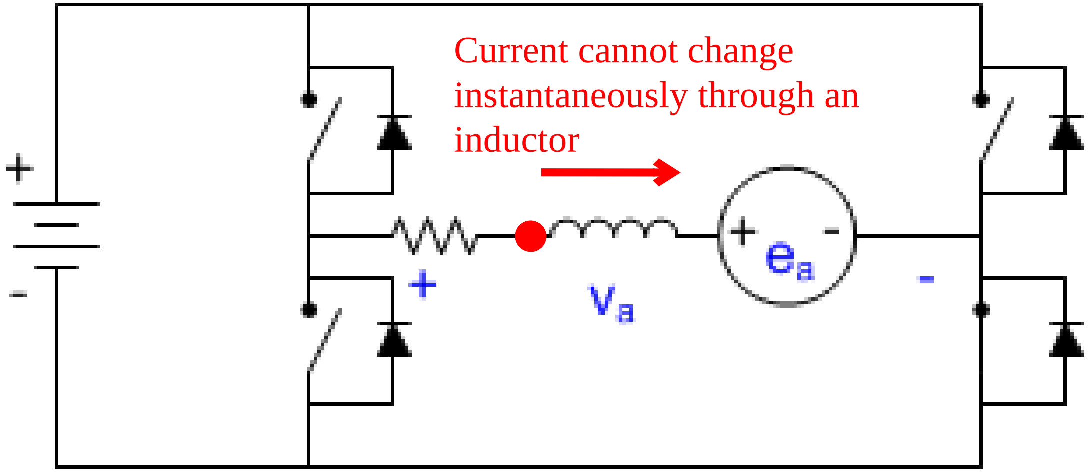
Two quadrant operation in positive direction:



With S1 and S4 on (conducting):

$v_a = +V_{dc}$

Two quadrant operation in positive direction:

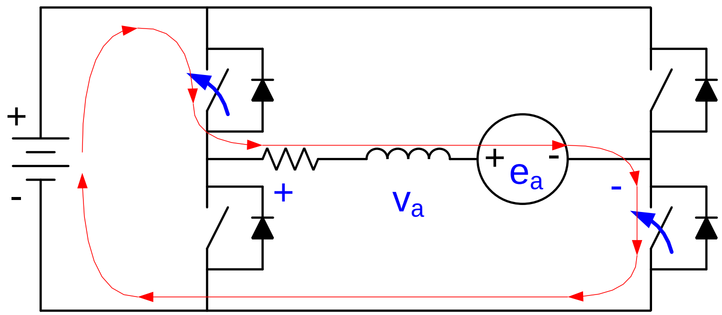


With S1 off and S4 on, D3 conducts (until current goes to zero):

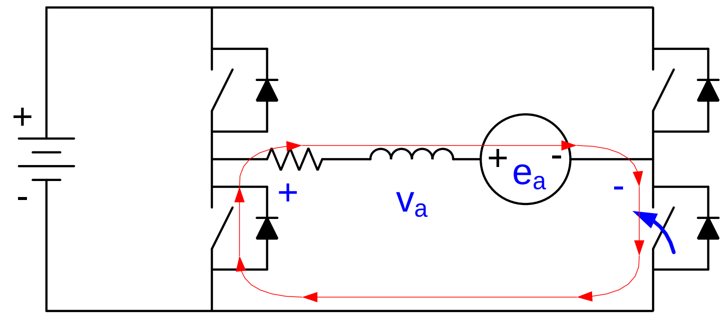
$v_a = 0$

This is known as "free-wheeling".

Two quadrant operation in positive direction:



2Q Operation with S1 and S4 On



2Q Operation with S1 Off and S4 On

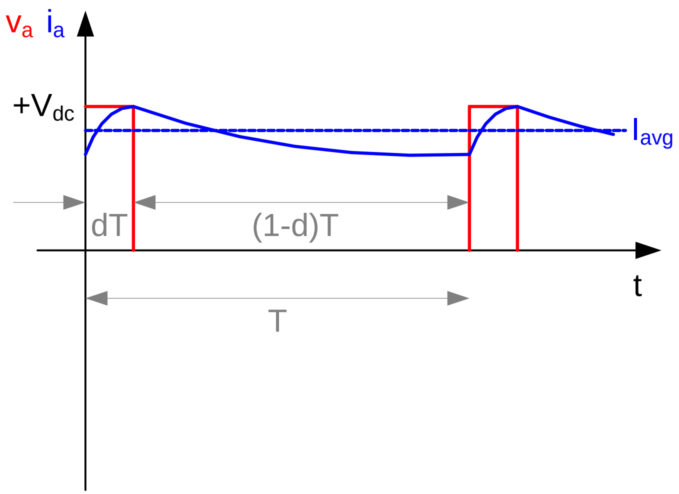
With S1 and S4 on (conducting):

$v_a = +V_{dc}$

With S1 off and S4 on, D3 conducts (until current goes to zero):

$v_a = 0$

With S4 on, S1 on for d·T, off for (1-d)·T



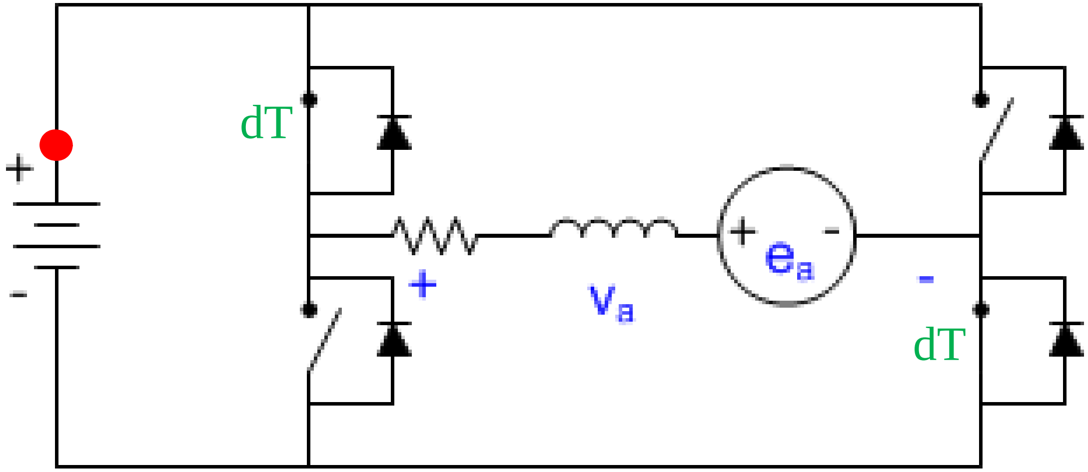
2Q Operation

$$\bar{v}_a = \frac{1}{T}\int_0^T v_a(t)dt = d \cdot V_{dc}$$

Average voltage is equal to duty cycle times dc link voltage

$$\bar{i}_a = \frac{\bar{v}_a - \bar{e}_a}{R_a}$$

Four quadrant operation in positive direction:

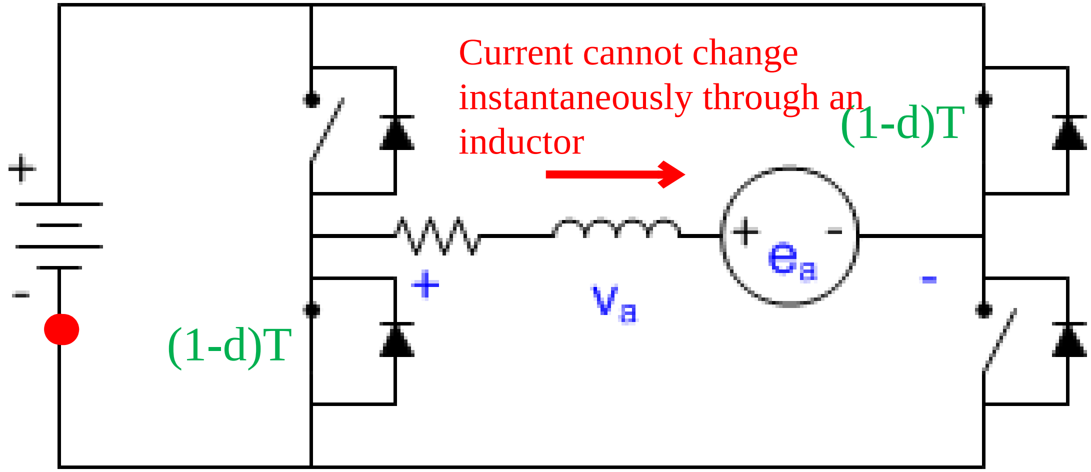


With S1 and S4 on (conducting):

$v_a = +V_{dc}$

Same as two quadrant case.

Four quadrant operation in positive direction:

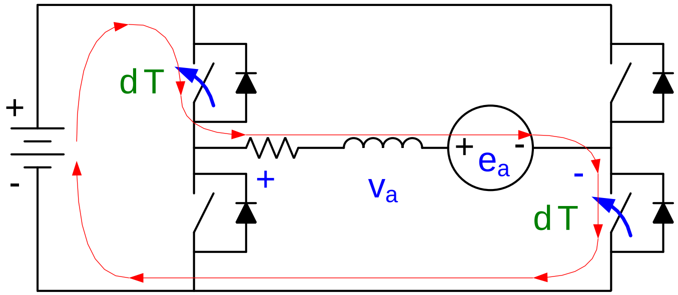


With S2 and S3 on (conducting):

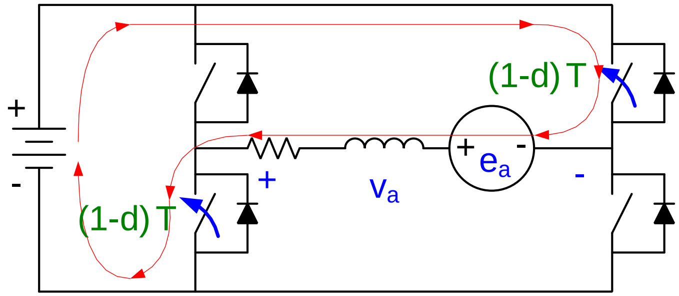
$v_a = -V_{dc}$

With S1 and S4 open, current has to "free-wheel" through diodes

Four quadrant operation in positive direction:



4Q Operation with S1 and S4 On



4Q Operation with S2 and S3 On

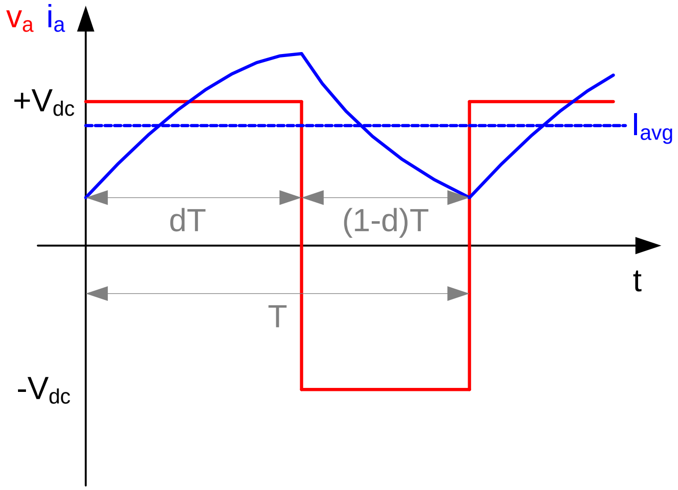
With S1 and S4 on (conducting):

$v_a = +V_{dc}$

With S2 on and S3 on (conducting):

$v_a = -V_{dc}$

Four quadrant operation in positive direction:



4Q Operation

$$\overline{v}_a = \frac{1}{T}\int_0^T v_a(t)dt$$

$$= \frac{1}{T}[d\cdot T\cdot V_{dc} + (1 - d)\cdot T\cdot(-V_{dc})]$$

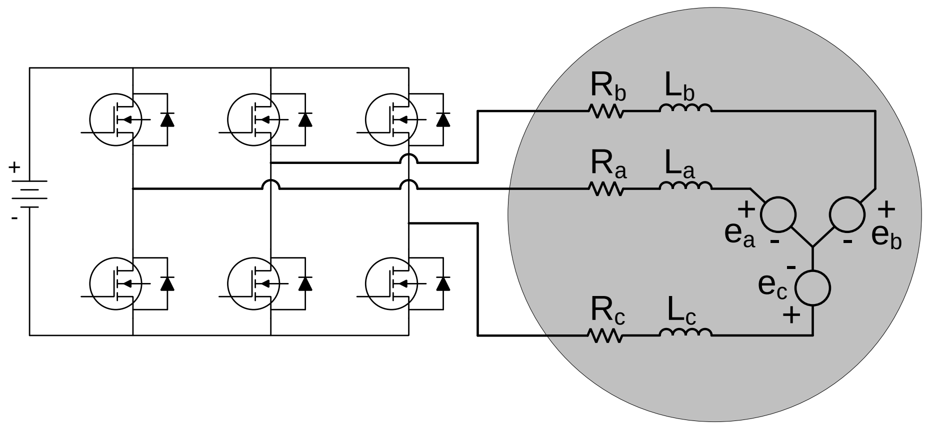
$$= (2d - 1)\cdot V_{dc}$$

$$\overline{i}_a = \frac{\overline{v}_a - \overline{e}_a}{R_a}$$

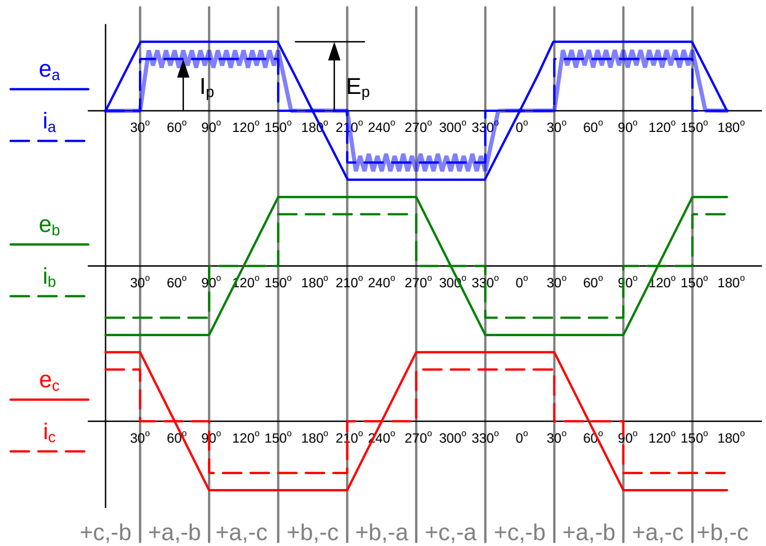
Average voltage is biased:
50% = 0 average voltage
100% = V_{dc}
0% = $-V_{dc}$

This allows bi-directional voltage control.

Brushless DC (BLDC) Drives:



BLDC Drive (Motor and Inverter)

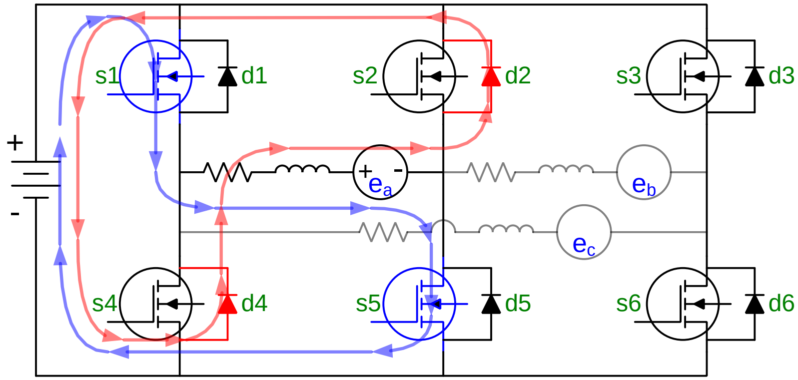


Trapezoidal Back EMF Waveforms

A note on BLDC control chips:

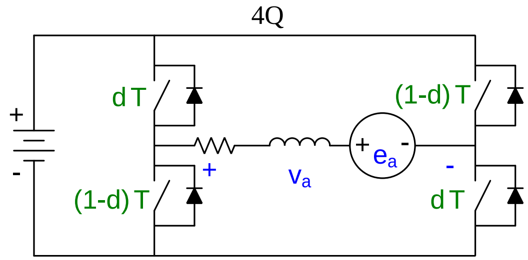
2Q operation is normal
4Q operation is not a true 4Q, but rather a "quasi" 4Q control

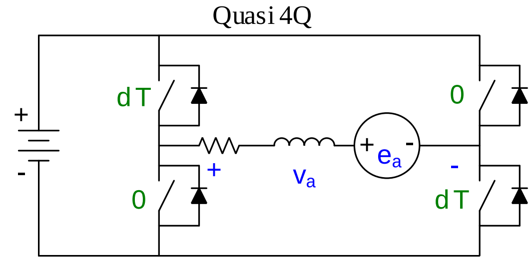
Quasi 4Q operation of a BLDC Motor

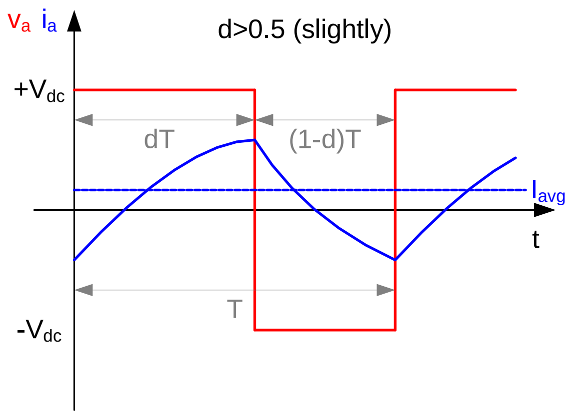


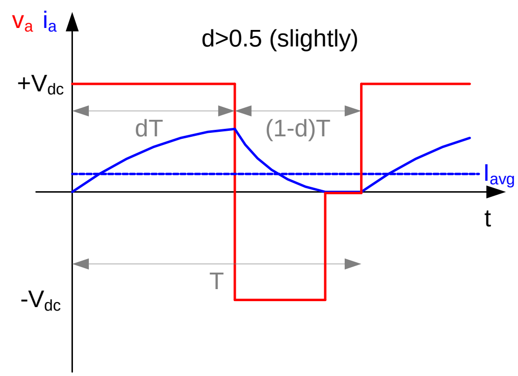
Quasi 4Q Operation of a BLDC Motor

Only PWM S1 and S5 (not S2 and S4). Current freewheels through D2 and D4. Better (lower) switching losses. This introduces duty cycle vs. applied voltage nonlinearity near zero voltage.

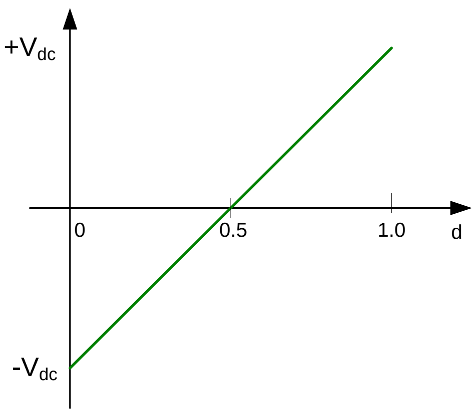


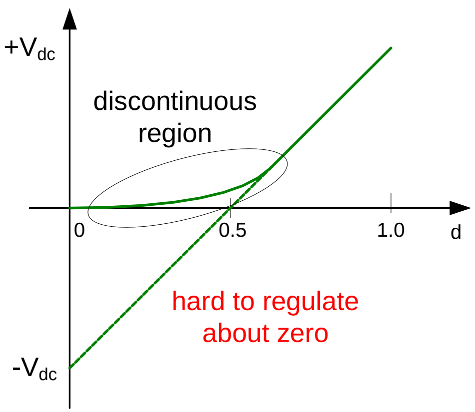






Note: Need D.O.R. (direction of rotation) delay with 2Q and quasi 4Q controllers.

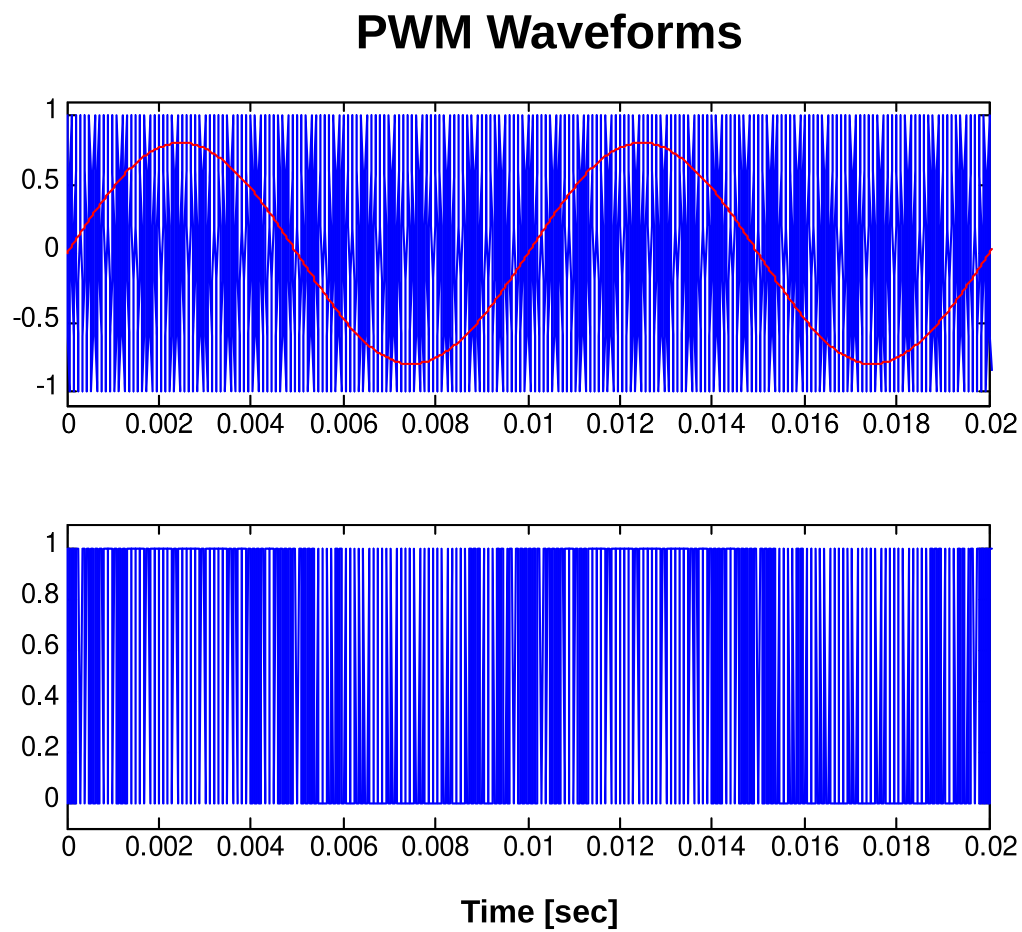




Pulse Width Modulation

Pulse Width Modulation

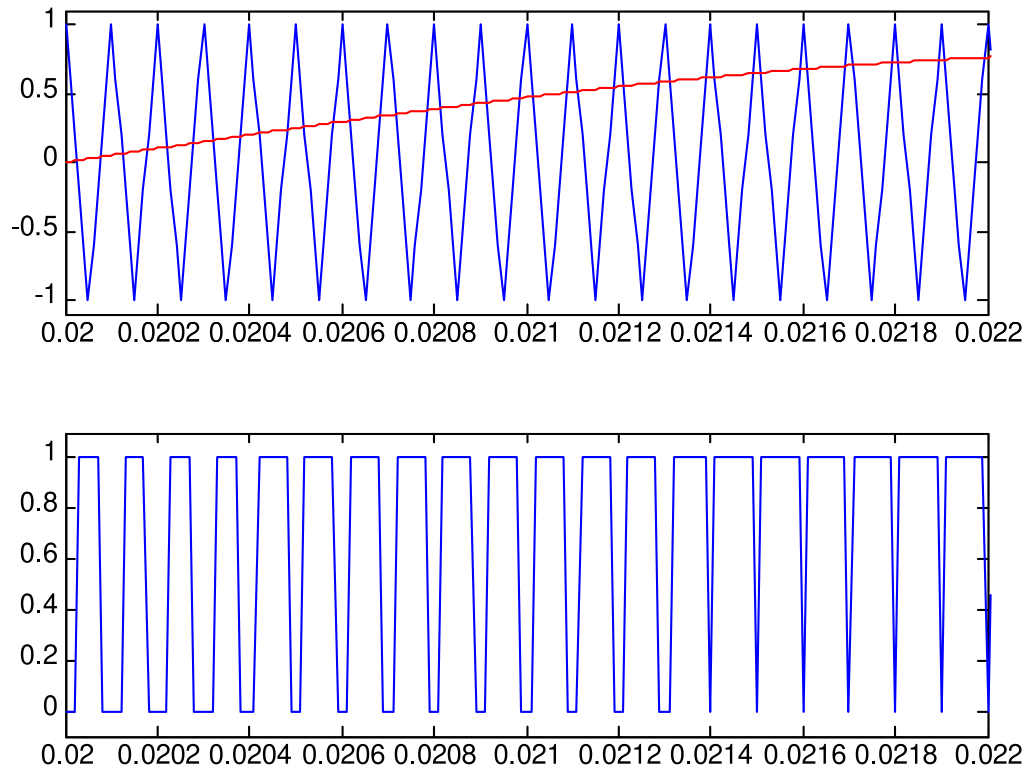
f_s – 10 kHz
f_o – 100 Hz
m = 0.8



Pulse Width Modulation

f_s – 10 kHz
f_o – 100 Hz
m = 0.8

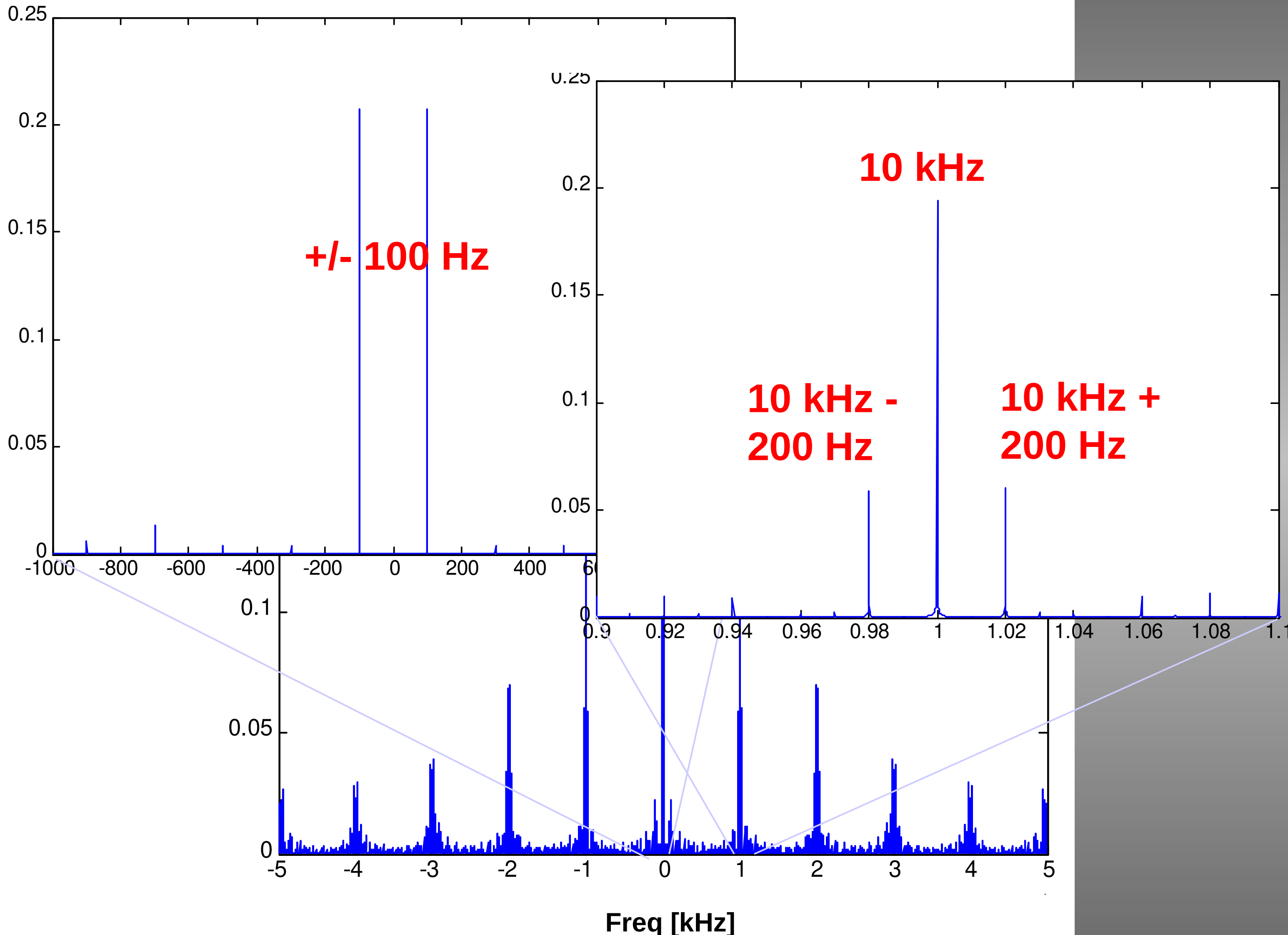
PWM Waveforms



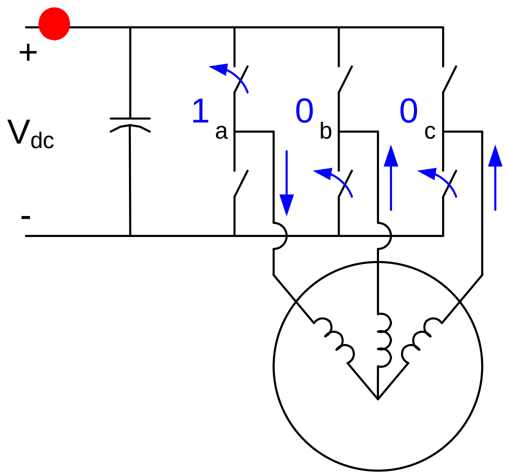
Time [sec]

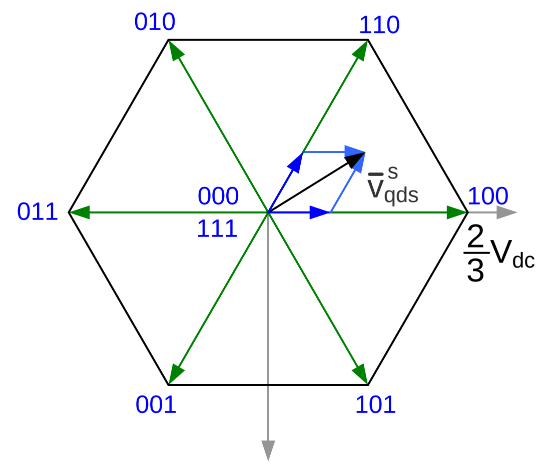
Electric Machines & Drives

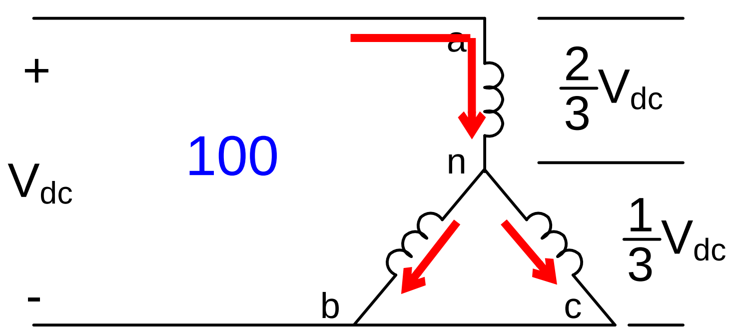
f_s – 10 kHz
f_o – 100 Hz
m = 0.8

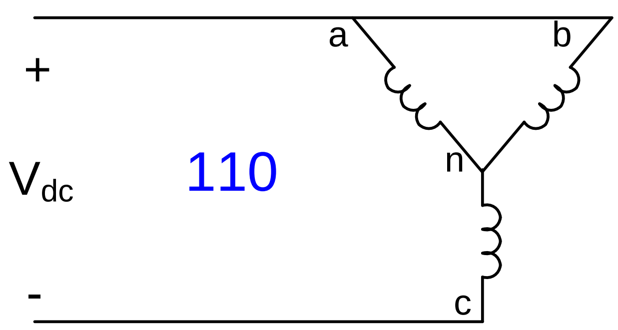


Space Vector Pulse Width Modulation



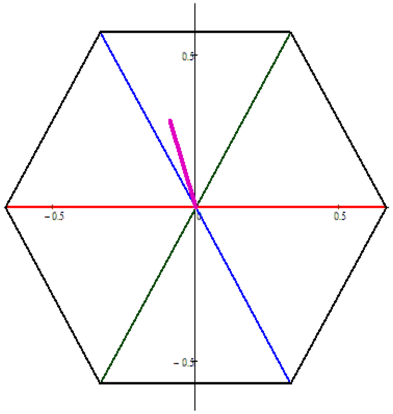


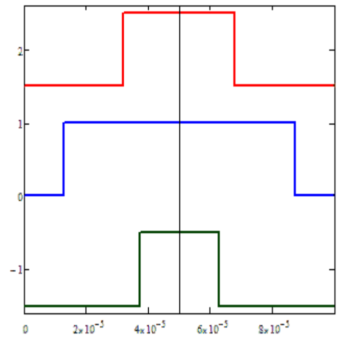


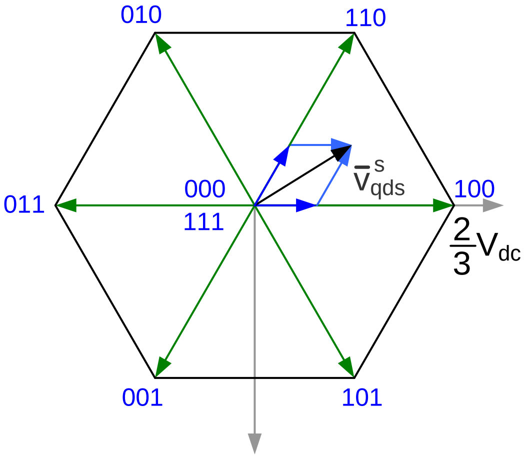


First Two States of Space Vector PWM

Space Vector Pulse Width Modulation

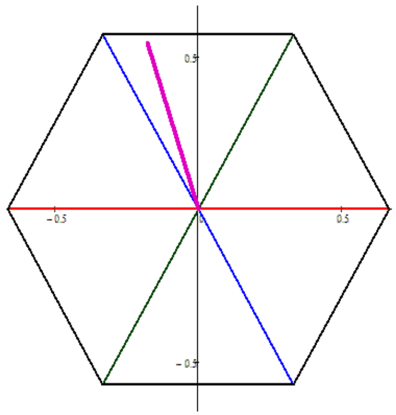


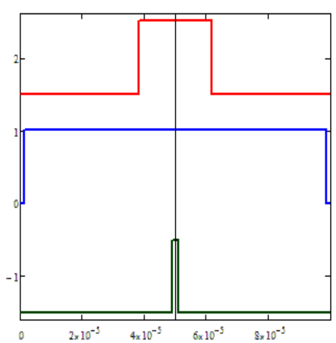


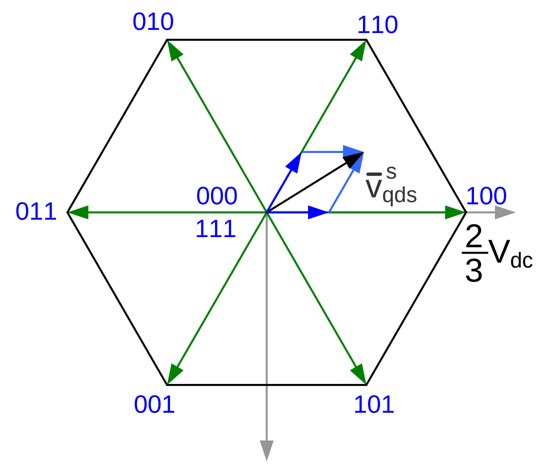


$$|\overline{\mathbf{V}}| = \mathbf{0.3}$$

Space Vector Pulse Width Modulation

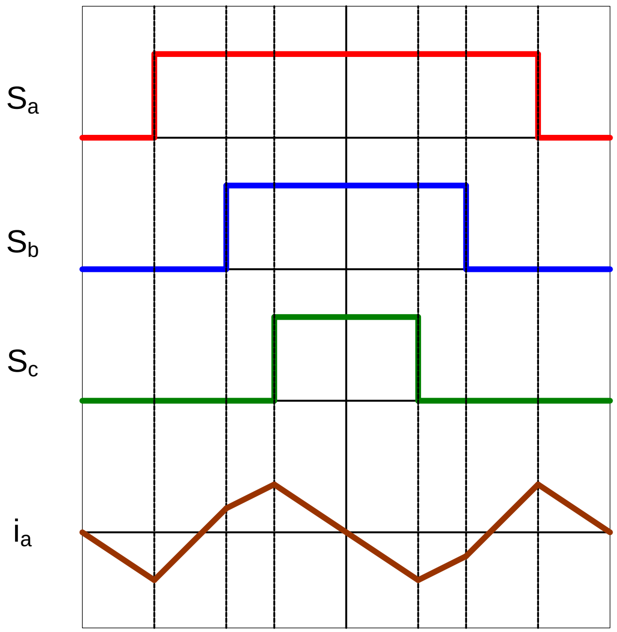


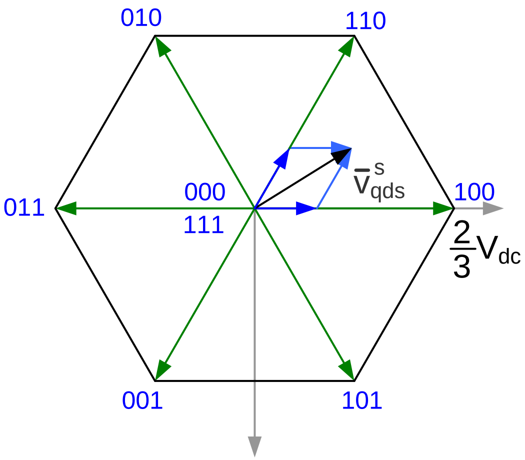




$$\left|\overline{\boldsymbol{V}}\right| = \mathbf{0.577}$$

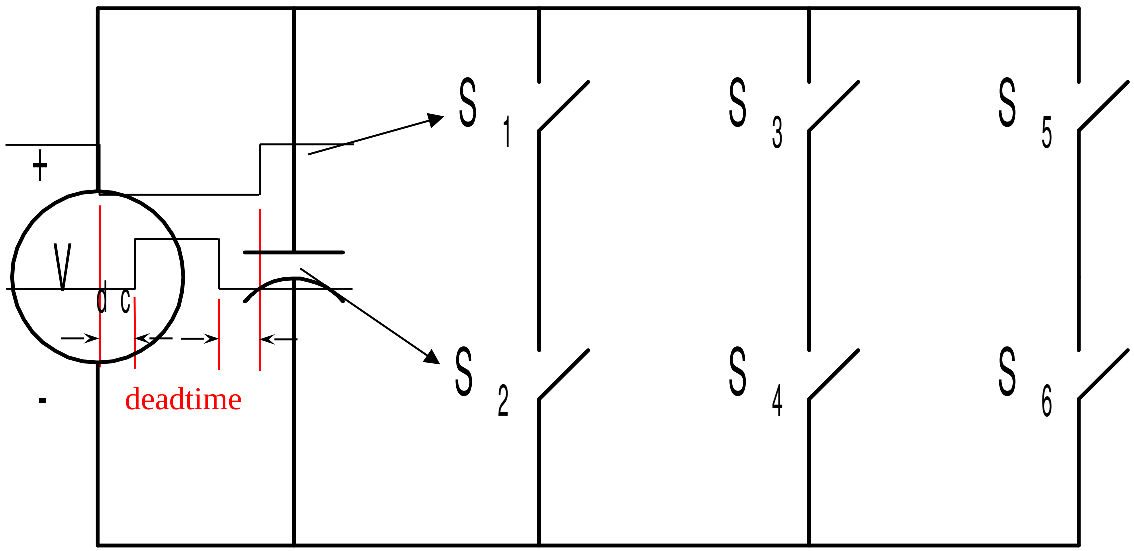
Space Vector Pulse Width Modulation



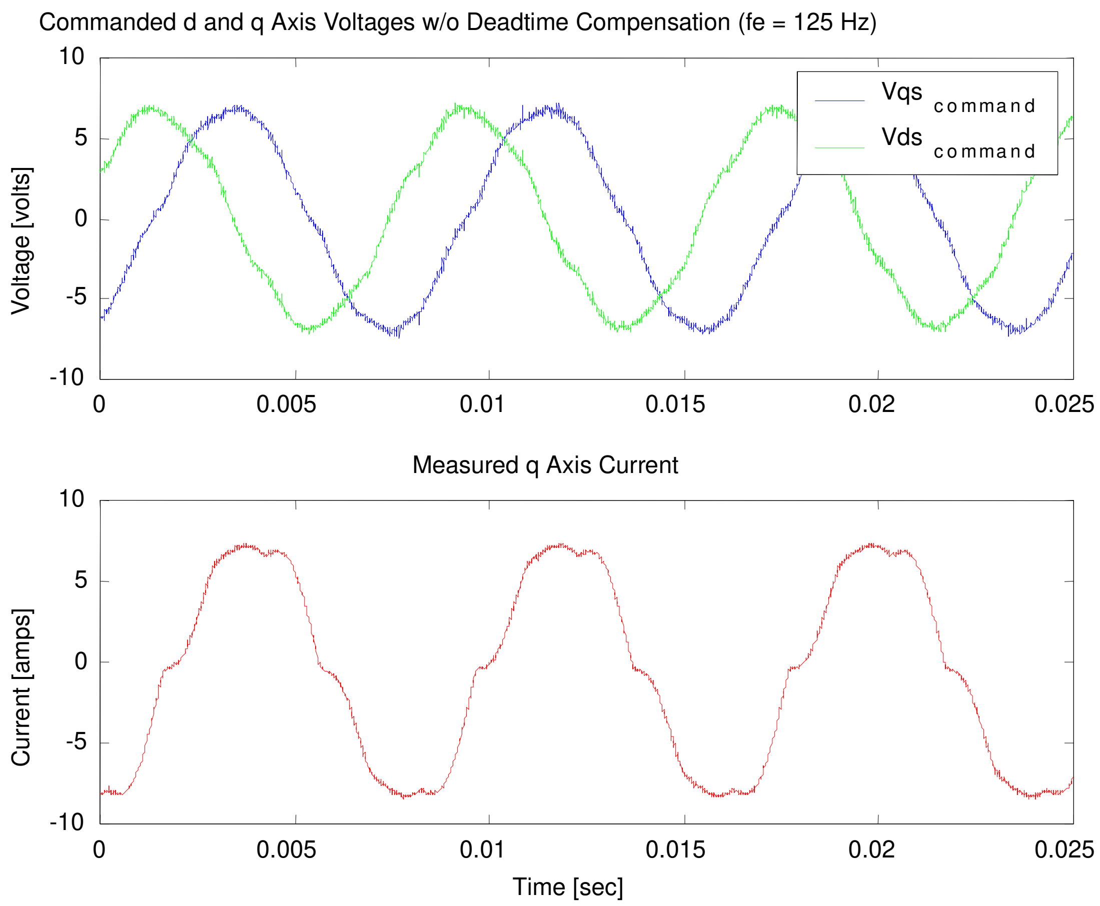


Switching States and Phase Current Ripple in Space Vector PWM Quadrant 1

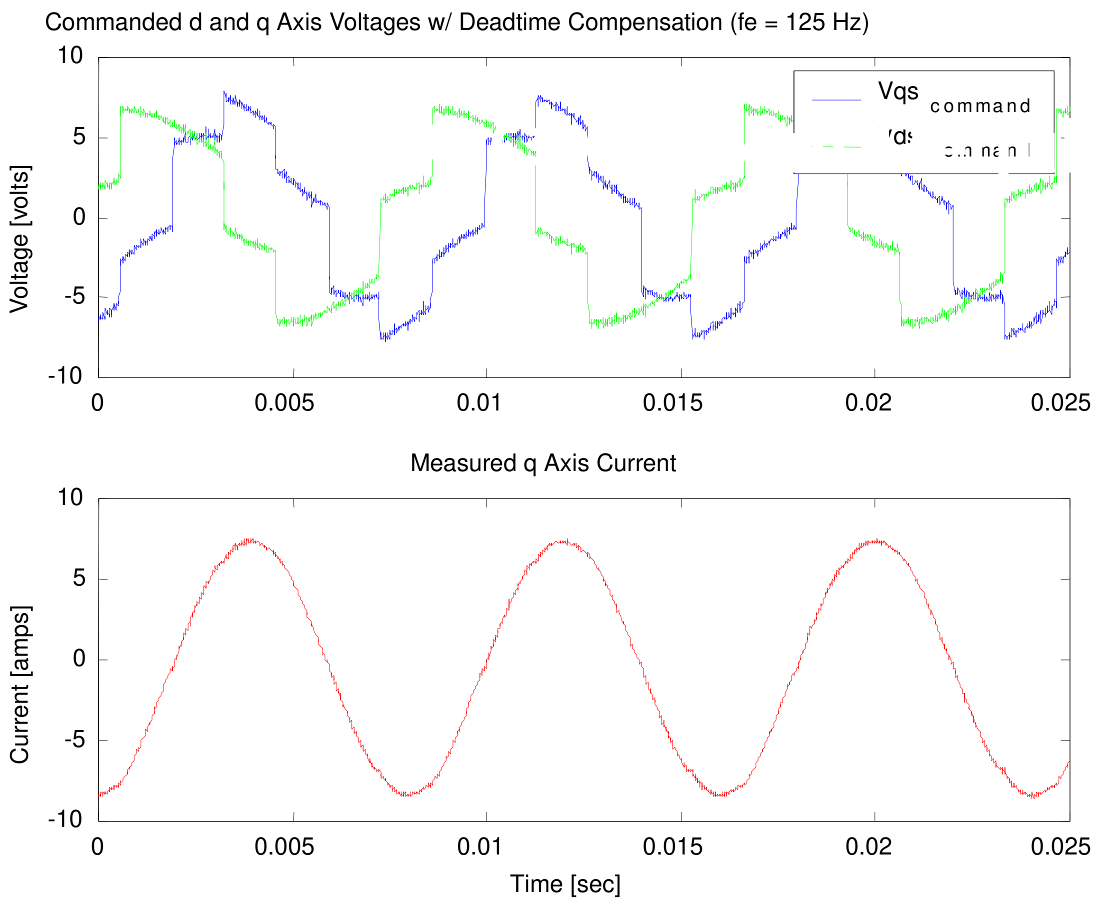
A.C. Current Regulation



In an A.C. drive, all three phases are used simultaneously. Therefore, deadtime must be inserted between upper and lower switches to prevent shoot through.

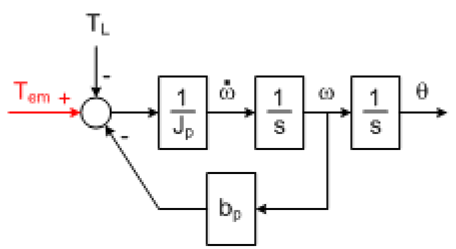

Commanded d and q Axis Voltages w/o Deadtime Compensation (fe = 125 Hz)
Vqs command
Vds command
Voltage [volts]
10
5
0
-5
-10
0
0.005
0.01
0.015
0.02
0.025
Measured q Axis Current
Current [amps]
Time [sec]

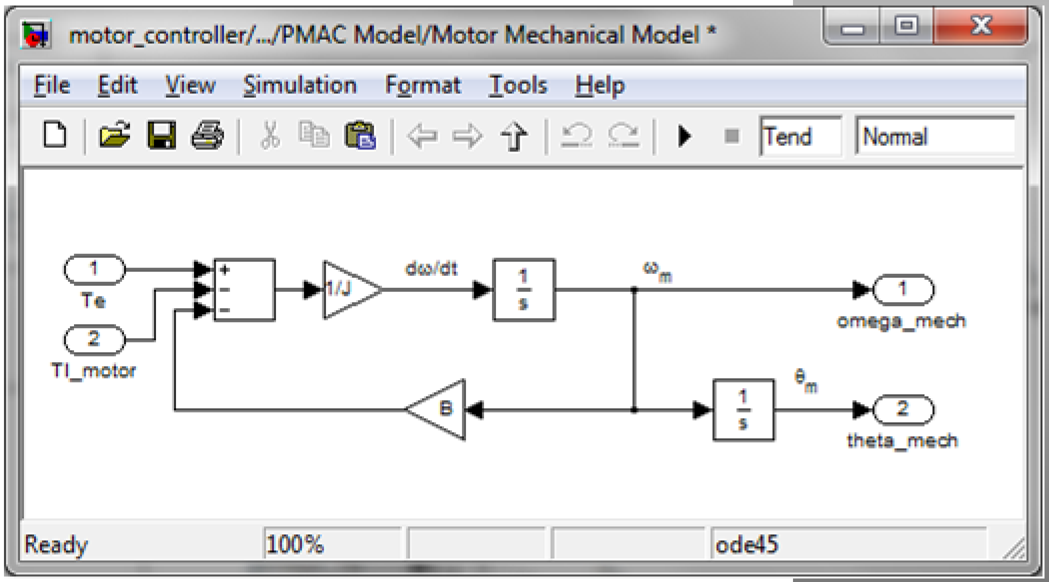
Electric Machines & Drives



Motor Simulation Model (continued)

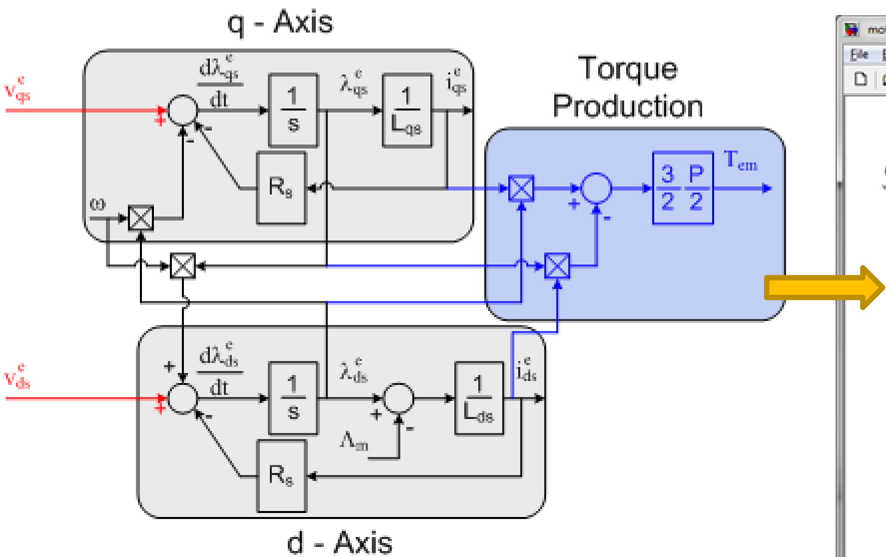
- Mechanical portion of motor
  - Simple 2nd order system
  - Viscous damping
  - Inertia
  - Load torque (can be linear or nonlinear)

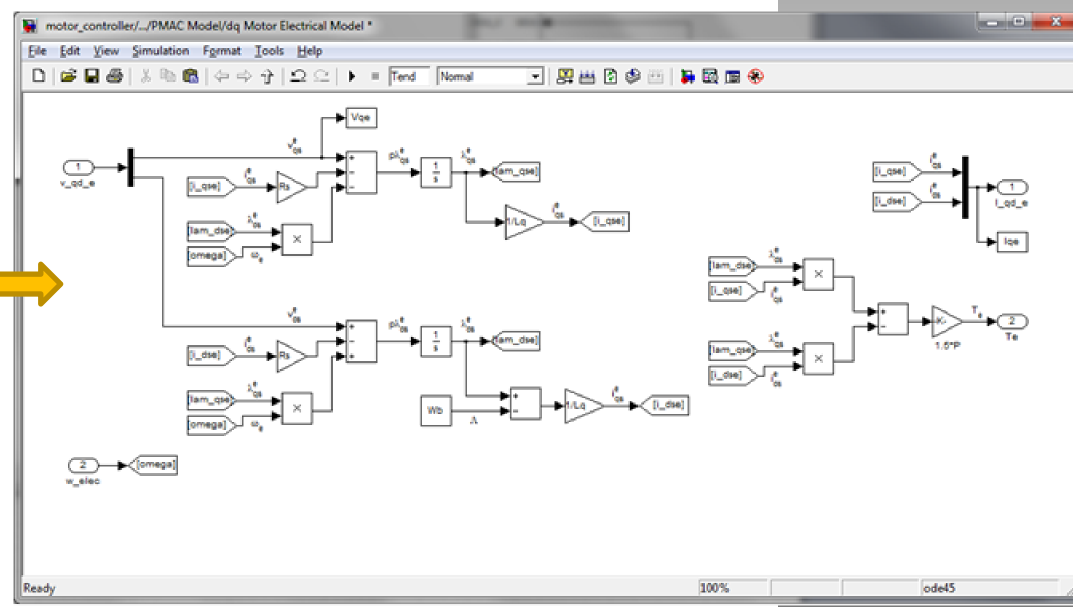




Motor Simulation Model (continued)

- Electrical portion of motor
  - For surface PM Machine, Electrical Model is simple 2nd order cross-coupled system
  - Calculation of currents from flux linkages increases model speed/accuracy



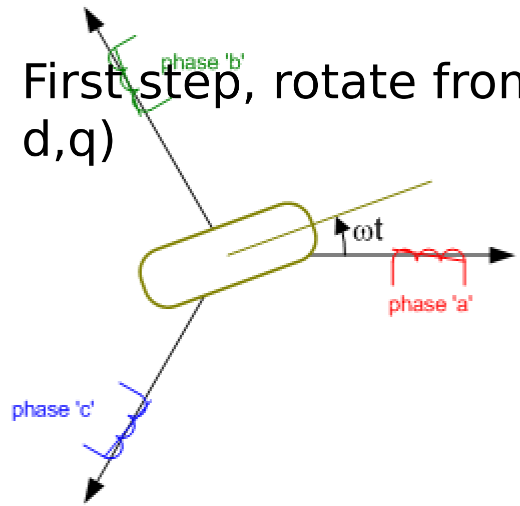


Motor Simulation Model (continued)

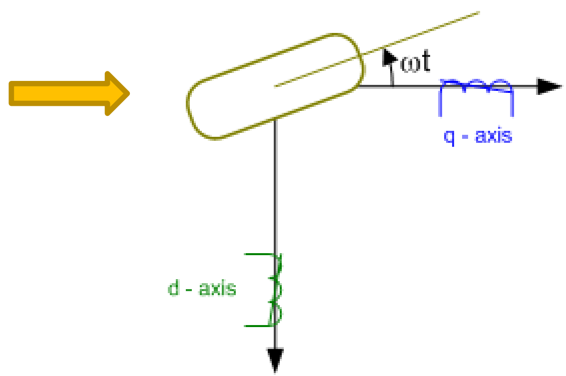
- Current (Torque) Regulation – Field Oriented Control (FOC)
  - FOC aligns (orients) d-axis with rotor flux and q-axis with torque producing current
  - FOC aligns and rotates reference frame with rotor flux (PM)
  - This transforms steady state time varying functions (sine waves) to dc quantities
- First step, rotate from 3 phases (physical a,b,c) to 2 phases (orthogonal d,q)

Forward Transformation:

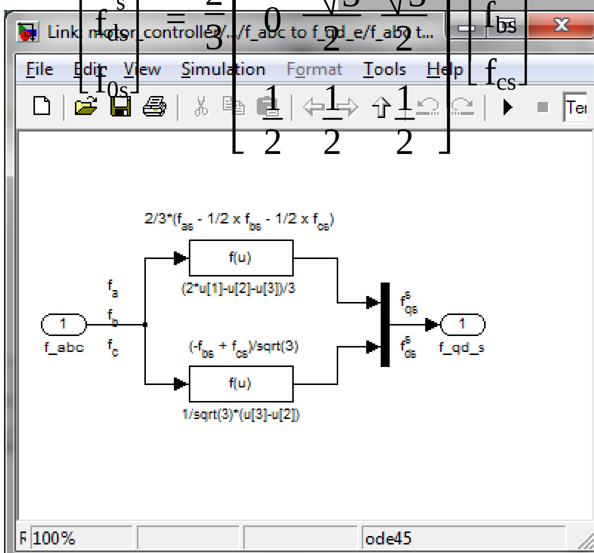
$$\begin{bmatrix} f_{qs}^{s} \\ f_{ds}^{s} \\ f_{0s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix}$$



3 phase stationary a,b,c reference frame



2 phase stationary d,q reference frame



Motor Simulation Model (continued)

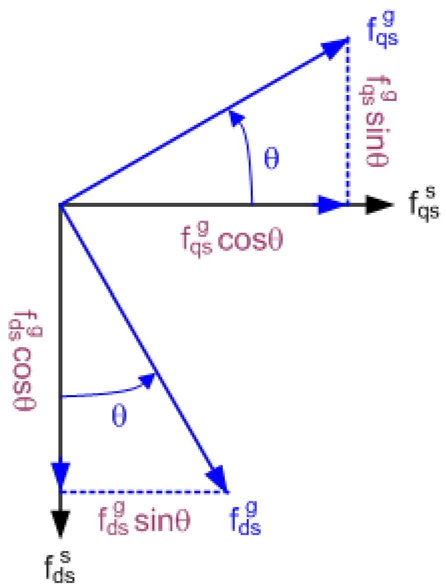
- Current (Torque) Regulation – Field Oriented Control (FOC)

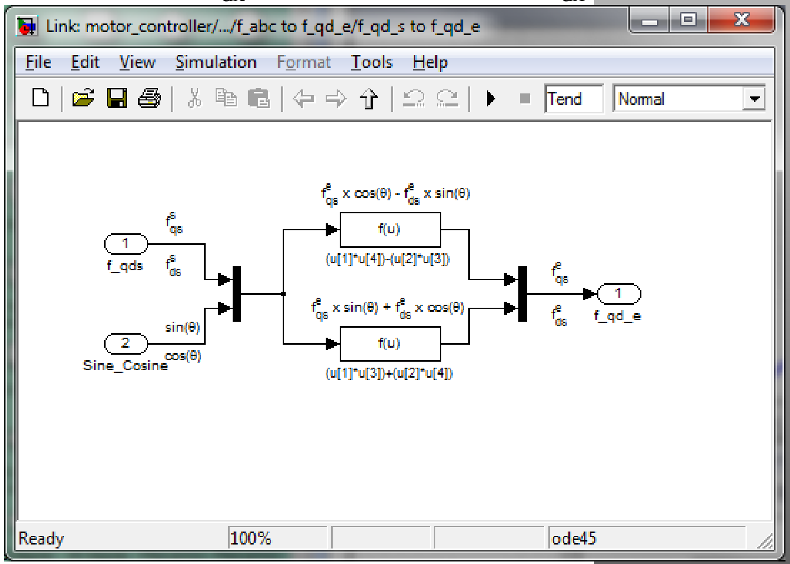
  - Next, rotate from the stationary dq reference frame to general rotating dq reference frame (for FOC, rotate to the rotor flux reference frame)

Stationary to Rotationg

$$\overline{f}_{qdx}^{\,g} = e^{-j\theta}\,\overline{f}_{qdx}^{\,s}$$

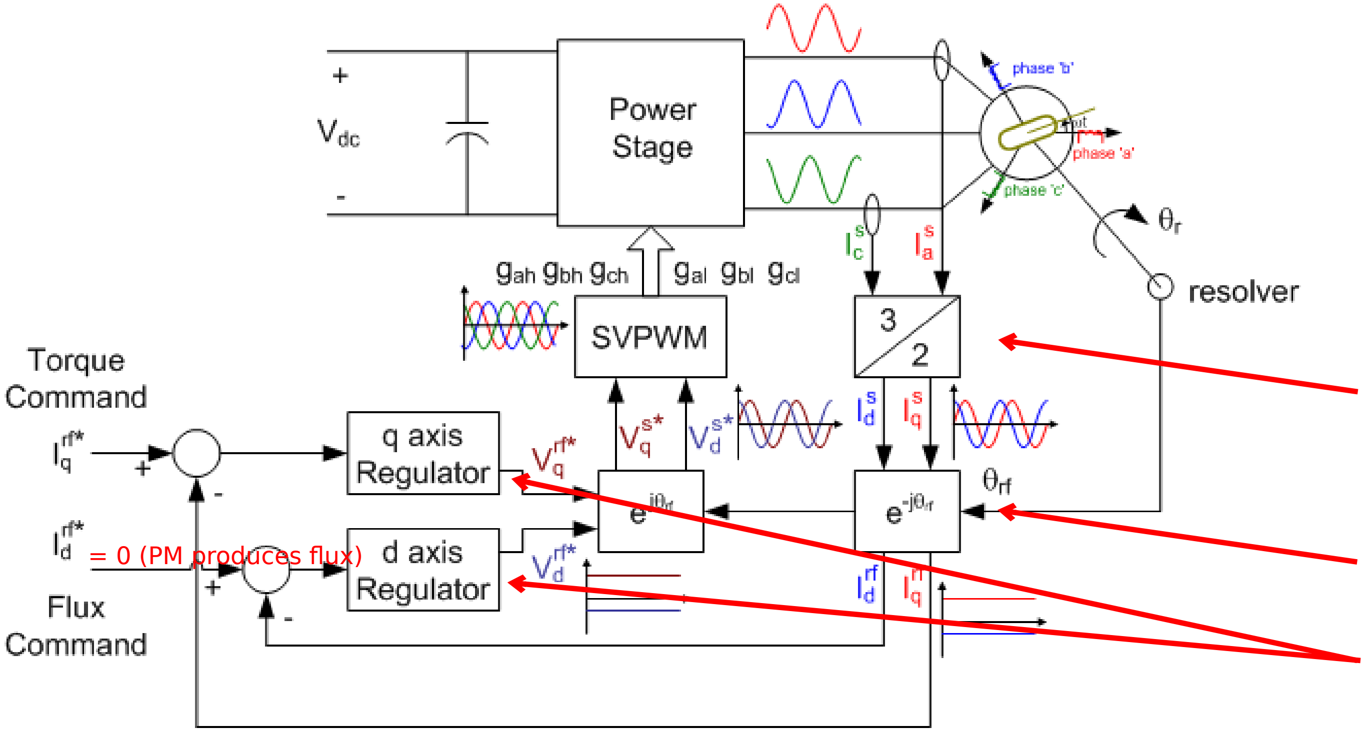
$$\begin{bmatrix} f_{qx}^{g} \\ f_{dx}^{g} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} f_{qx}^{s} \\ f_{dx}^{s} \end{bmatrix}$$





Motor Simulation Model (continued)

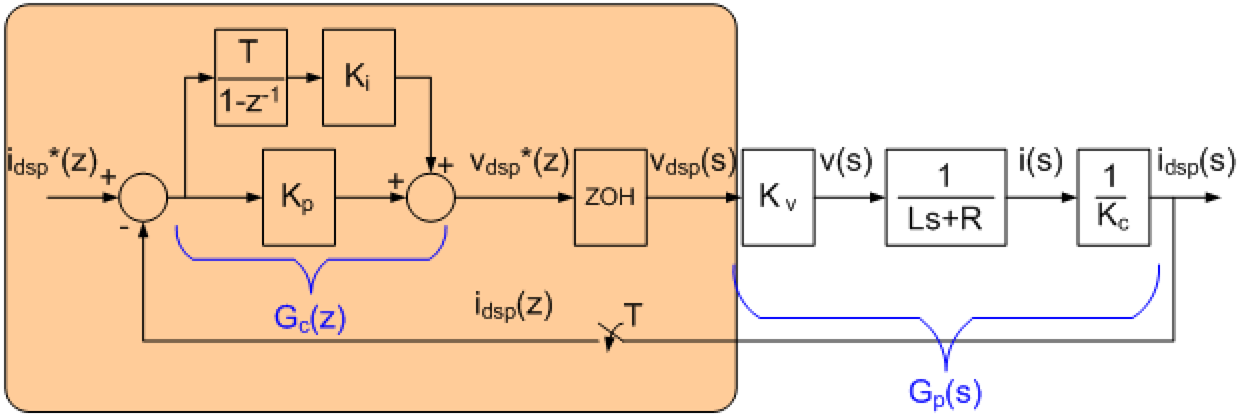
- Current (Torque) Regulation – Field Oriented Control (FOC)
- Next, use Proportional plus Integral (PI) control on both d and q axis currents. The d axis current command represents flux produced by the stator. This is set to zero unless we're trying to field weaken. The q axis current represents the torque producing current and is used to

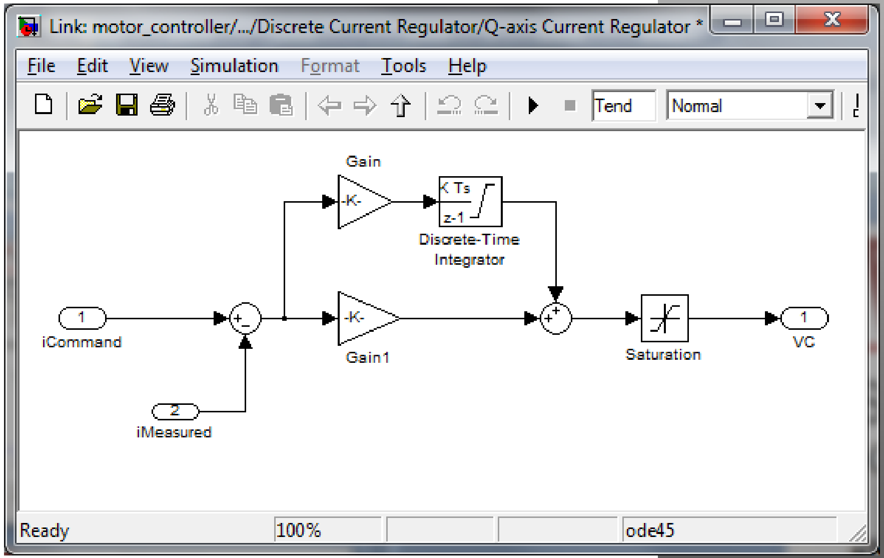


- 3 phase to 2 phase transformation
- dq stationary to dq rotating reference frame
- PI current regulators

Motor Simulation Model (continued)

- Current (Torque) Regulation – Field Oriented Control (FOC)
- Digital PI Loop





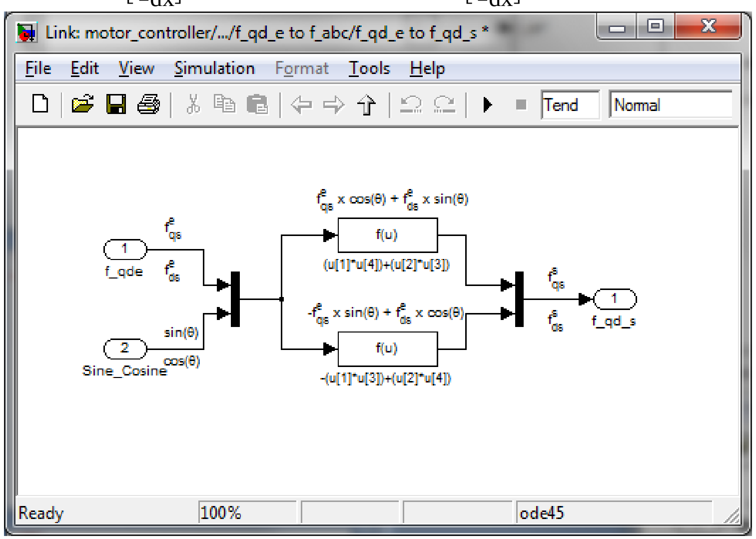
Motor Simulation Model (continued)

- Current (Torque) Regulation – Field Oriented Control (FOC)
- After deriving voltage commands, transform back into stationary reference frame to be applied to model (this assumes an ideal voltage regulator – neglects high order harmonics of PWM)

Rotating to Stationary

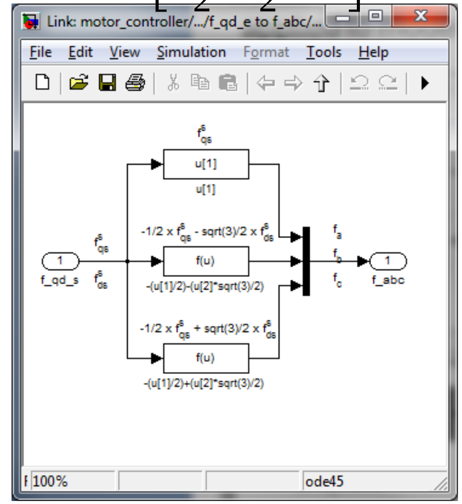
$$\overline{f}^{\,s}_{qdx} = e^{j\theta}\,\overline{f}^{\,g}_{qdx}$$

$$\begin{bmatrix} f^{s}_{qx} \\ f^{s}_{dx} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} f^{g}_{qx} \\ f^{g}_{dx} \end{bmatrix}$$

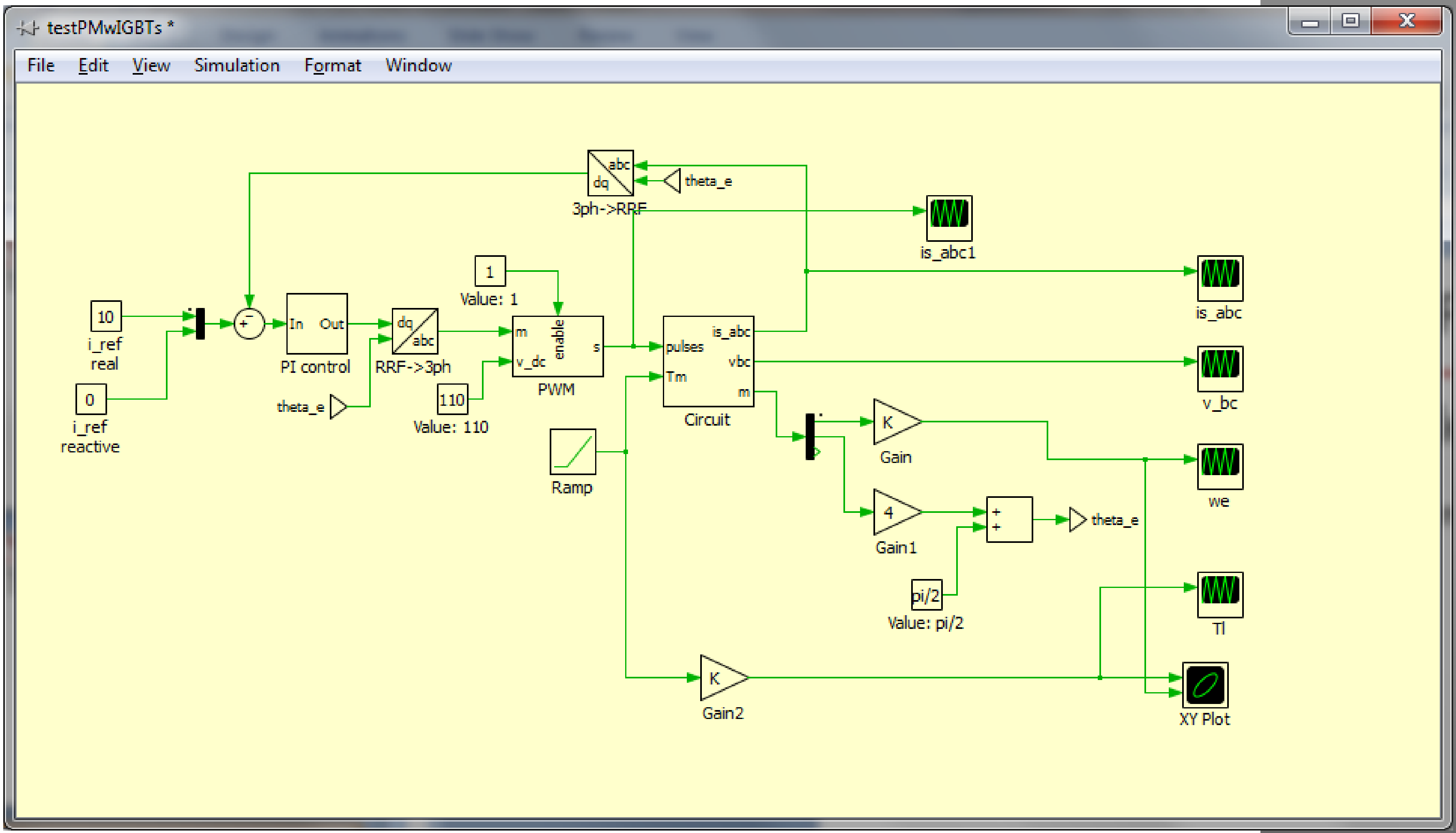


Inverse Transformation:

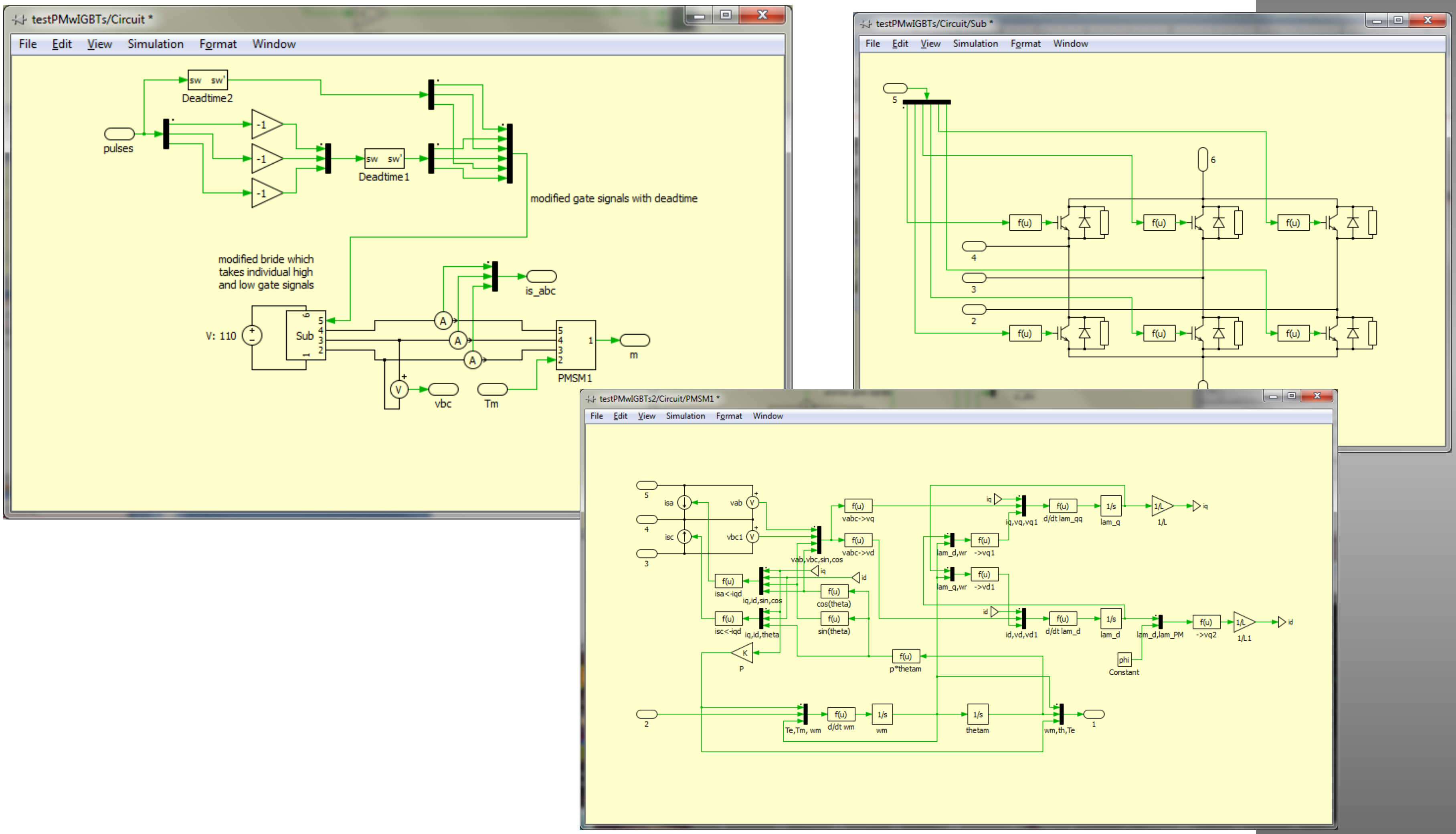
$$\begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} & 1 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} & 1 \end{bmatrix} \begin{bmatrix} f^{s}_{qs} \\ f^{s}_{ds} \\ f_{0s} \end{bmatrix}$$



Motor Simulation Model (with Plecs)

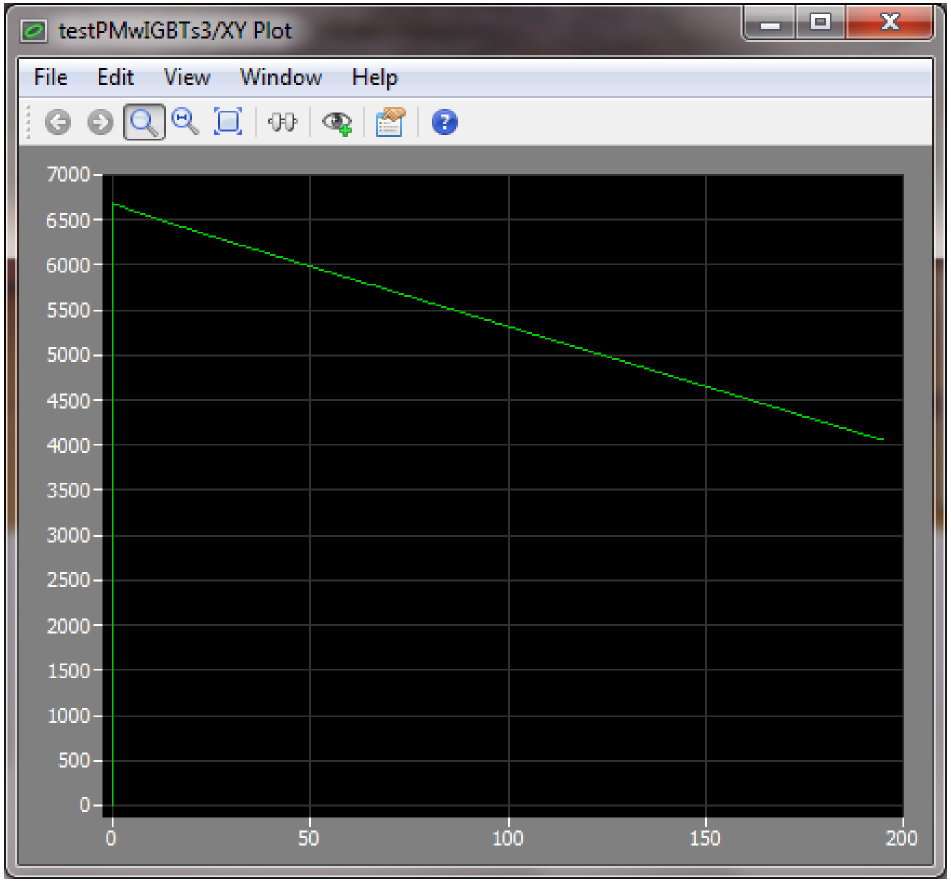


Motor Simulation Model (with Plecs)



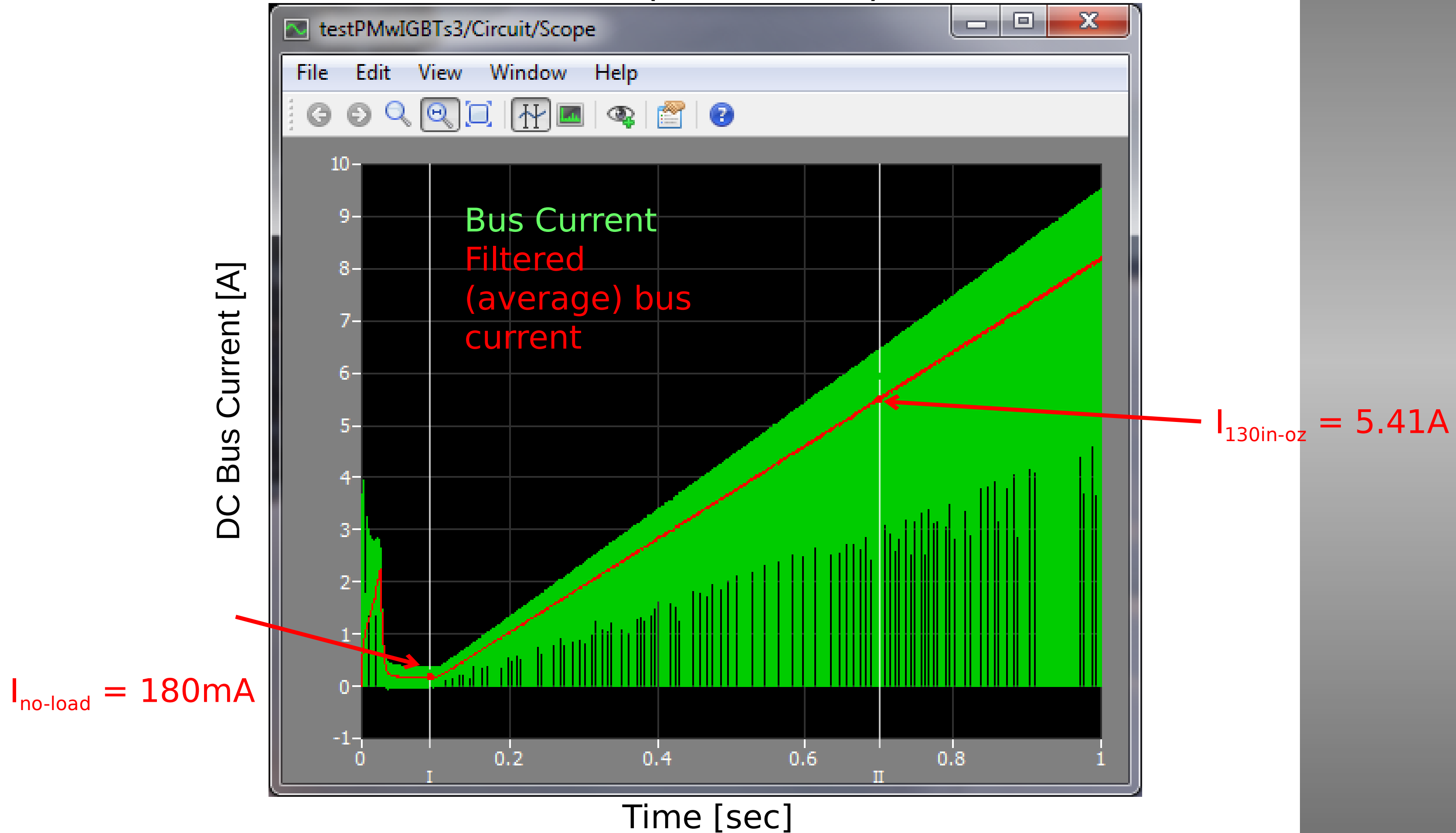
Motor Simulation Model (with Plecs) – Speed vs. Torque Curve

Speed [rpm]

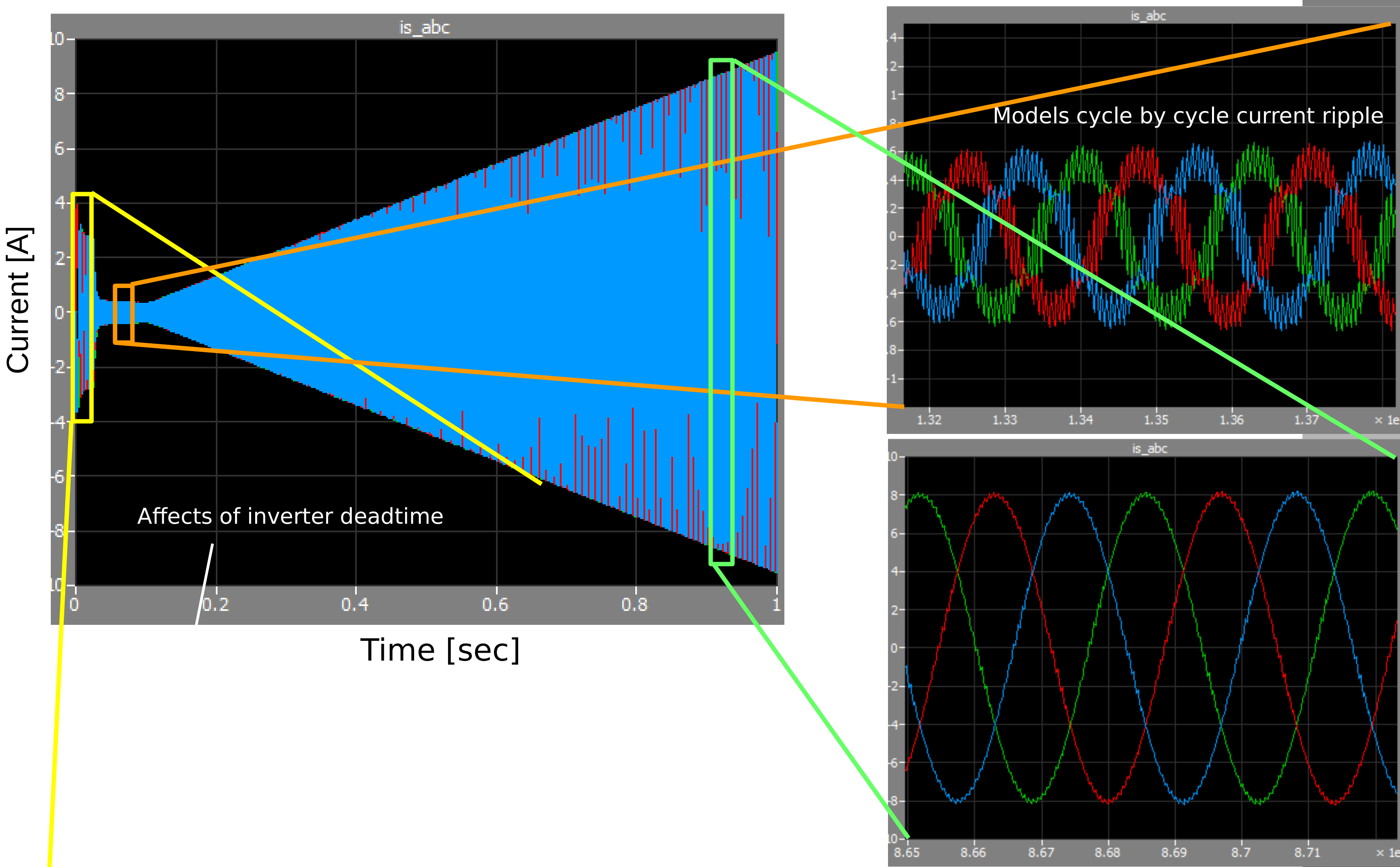


Torque [in-oz]

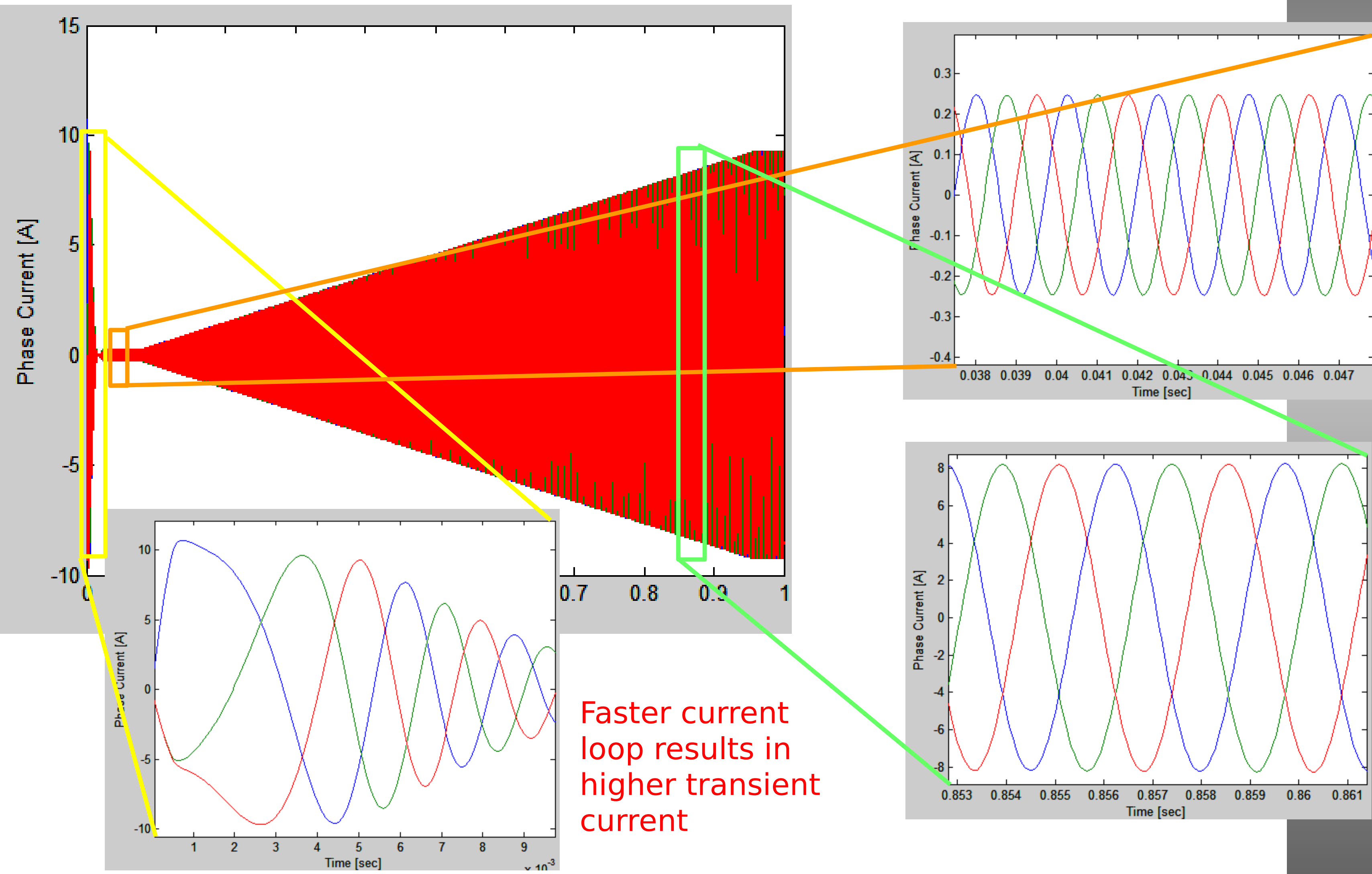
Motor Simulation Model (with Plecs) – Bus Current



Motor Simulation Model (with Plecs) – Phase Currents



Motor Simulation Model (with Simulink) – Phase Currents



Faster current loop results in higher transient current