ECE 398GG – ELECTRICAL VEHICLES

8. Key Considerations in EV Design and Operations

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Electric Motors

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Basic Principles of, and Design Considerations in, EV Electric Motors and Generators: concepts of electromechanical energy conversion – energy, co-energy, force and torque; review of low-frequency electromagnetics (EM) and EM force calculations of shear stress, machine power density and efficiency; generator application requirements on torque–speed curve, constant power speed range; comparative assessment and equivalent circuits of motor types – induction, surface and internal permanent magnet, switched and synchronous reluctance

- Overview
- Requirements
- Technology Options
- Design Considerations
- Control
- Example

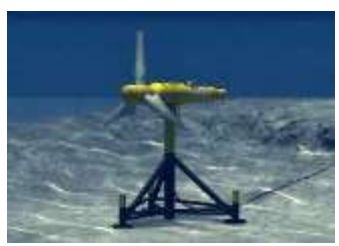
Electric Machine Applications





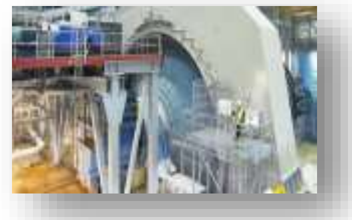

Transportation

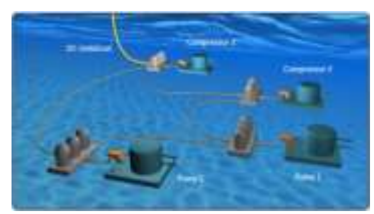




Renewable Energy



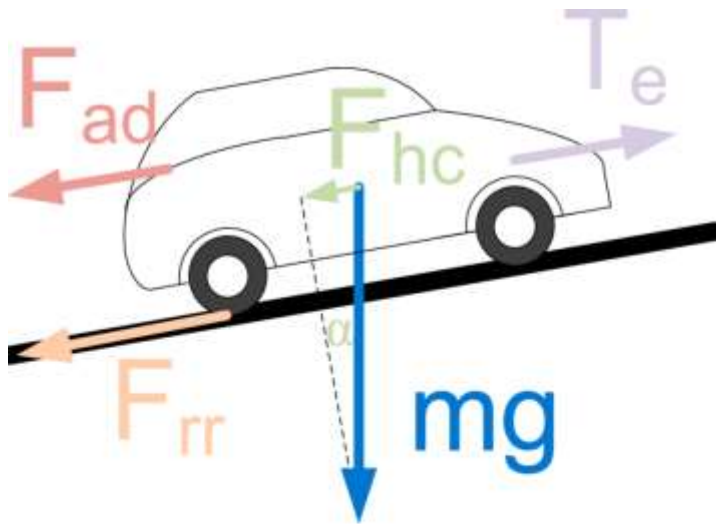


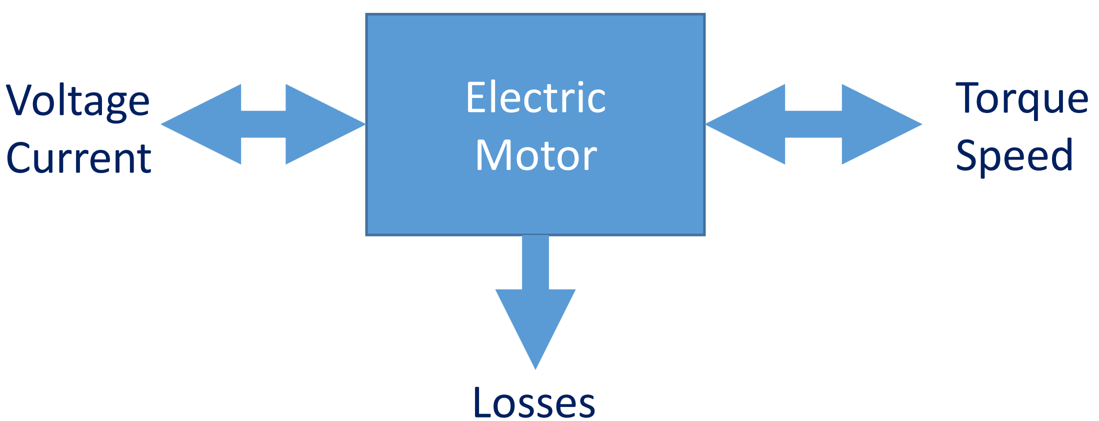
Industry



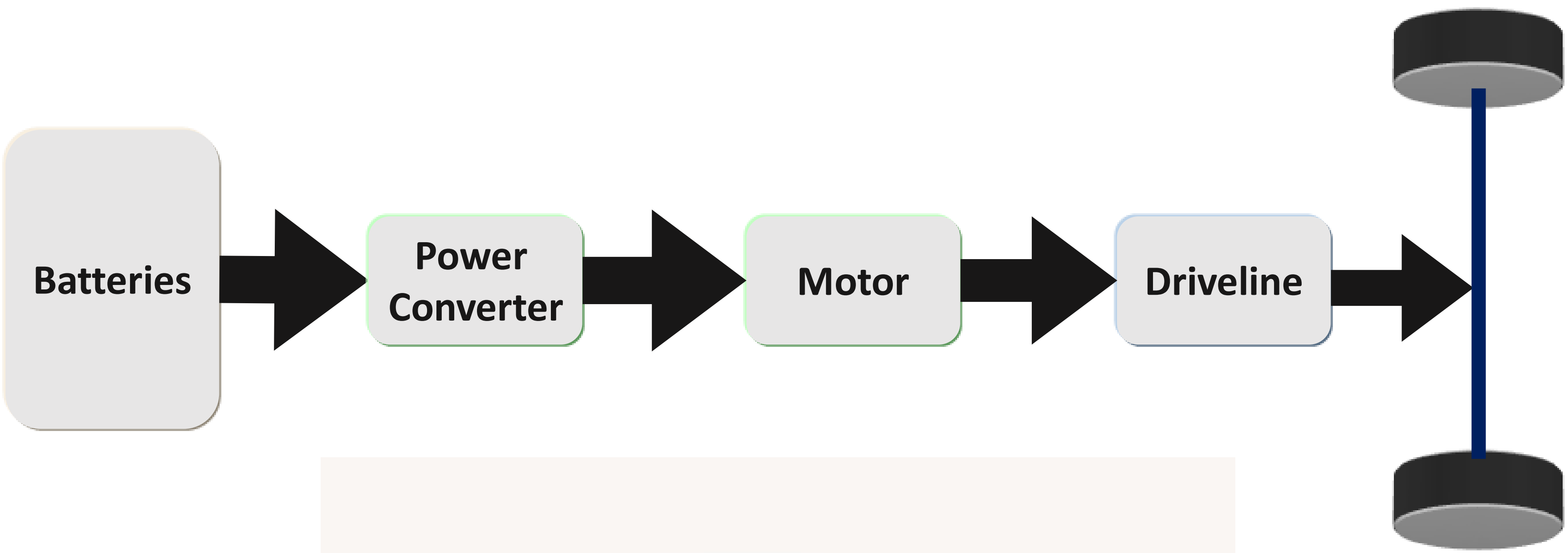
Medicine



<u>“Loads”</u>
Aerodynamic drag
Rolling friction
Hill climbing
Acceleration

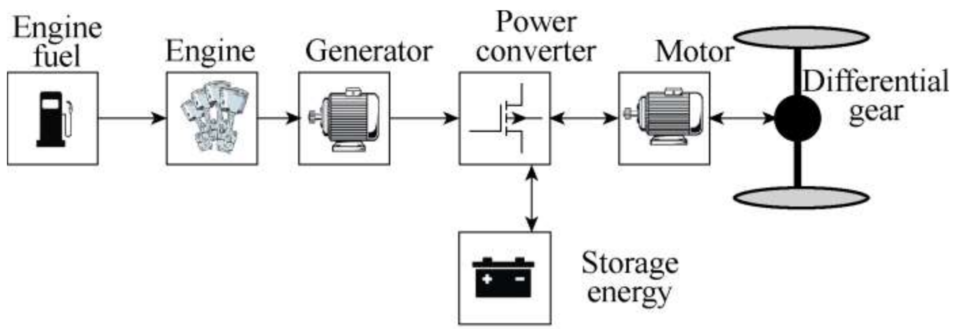


EV Powertrain



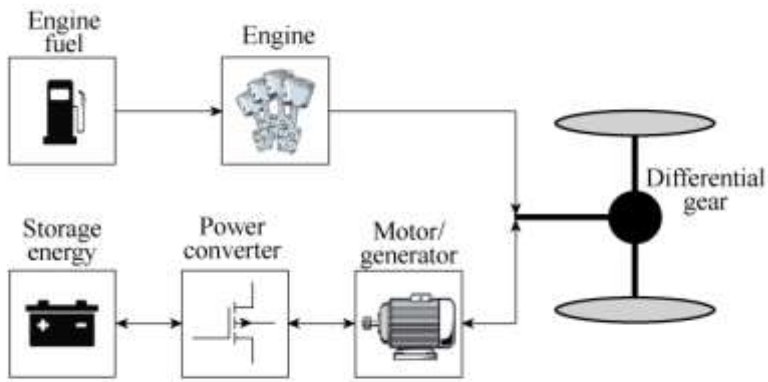
Hybrids

Series-HEV



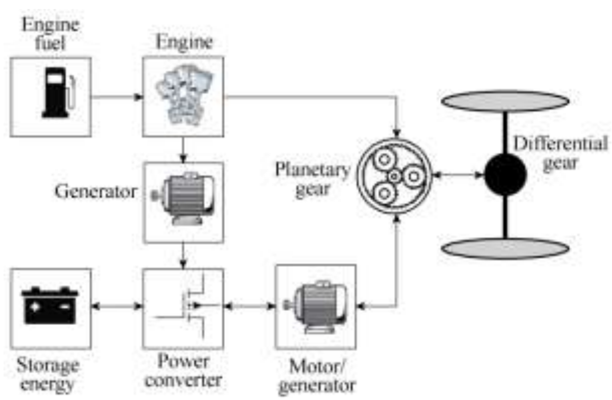
Mercedes Citaro bus,
MAN-Lions City Hybrid bus
TEMSA Avenue Hybrid bus

Parallel-HEV



Honda insight
Ford Escape Hybrid SUV
Lexus Hybrid SUV
Mercedes Citaro bus,
MAN-Lions City Hybrid bus
TEMSA Avenue Hybrid bus

Series-Parallel HEV



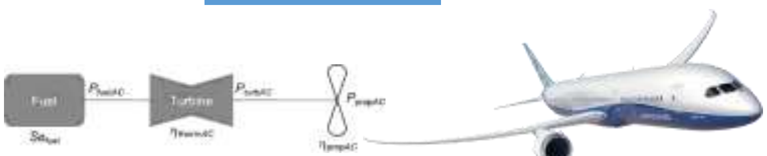
Nissan, Fiat, Toyota Prius

Drivetrain Integration

In-wheel motor assembly - Protean

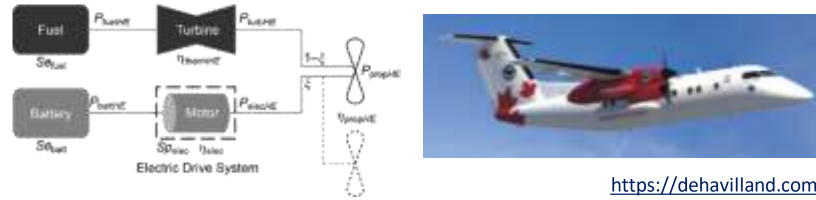
Electrified Aircraft

Conventional



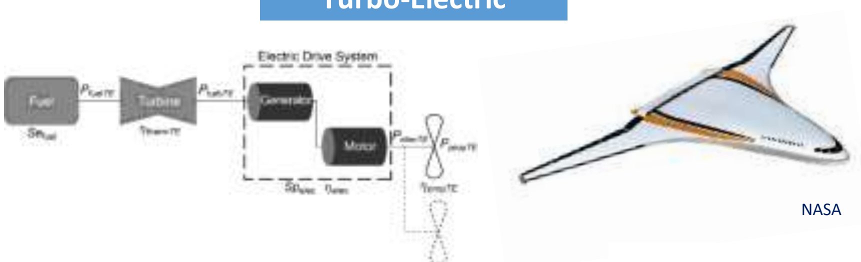
Boeing

Parallel Hybrid



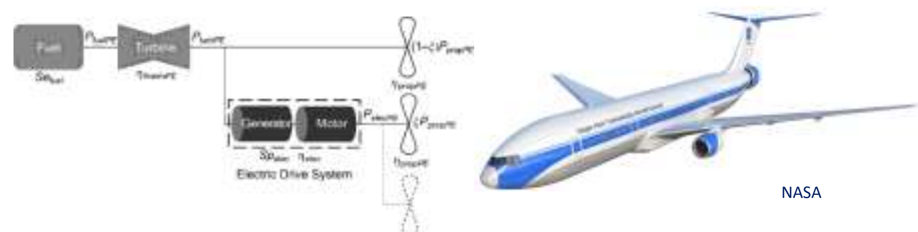
https://dehavilland.com/

Turbo-Electric



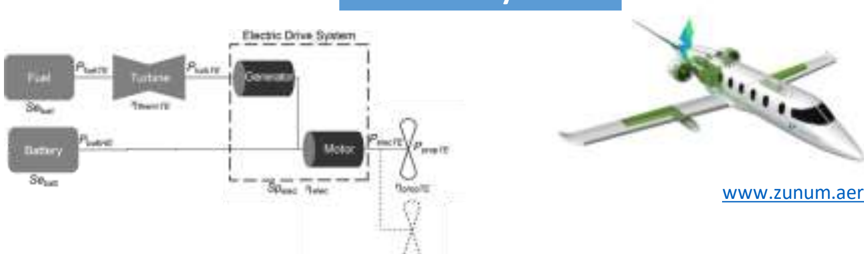
NASA

Partial Turboelectric



NASA

Series Hybrid



www.zunum.aero/

Electric

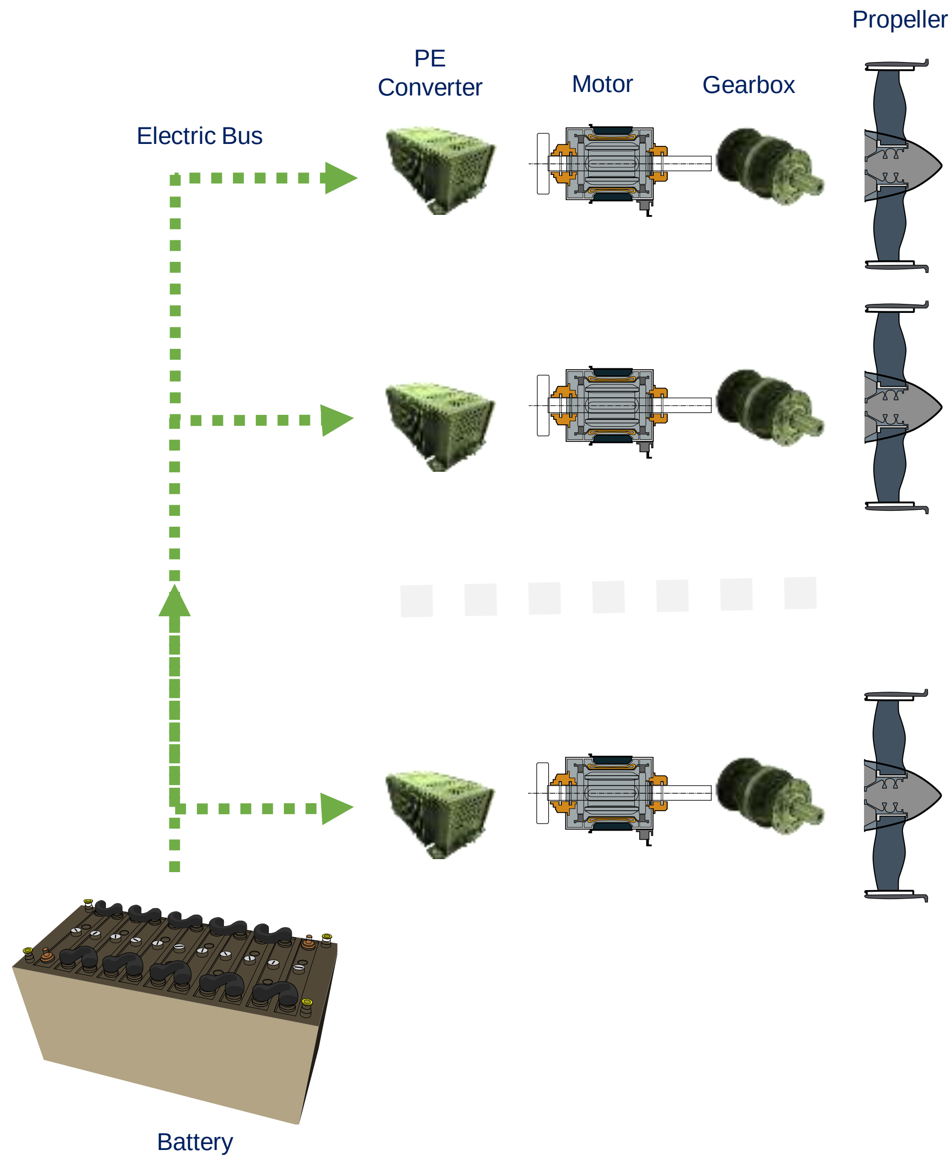
Or hydrogen fuel cells

Airbus

Distributed Propulsion

Boeing 737

Electric Aircraft Concept (CHEETA)



Electromechanics - Fields

Use EM fields to couple electrical with mechanical

EM fields defined in terms of forces

- Charge in Electric Field
- Current in magnetic field

The force **F** acting on a particle of electric charge q with instantaneous velocity **v**, due to an external electric field **E** and magnetic field **B**,

$$\mathbf{F} = q\ [\mathbf{E} + \mathbf{v} \times \mathbf{B})]$$

$q\mathbf{E}$ is the "**electric force**"

$q\mathbf{v} \times \mathbf{B}$ is the "**magnetic force**"

Electric versus magnetic

$$\sigma_{ij} \equiv \epsilon_0 \left(E_i E_j - \frac{1}{2}\delta_{ij} E^2 \right) + \frac{1}{\mu_0} \left(B_i B_j - \frac{1}{2}\delta_{ij} B^2 \right).$$

Permittivity of air, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m

Breakdown in air, $E_{max} \approx 3 \times 10^6$ V/m

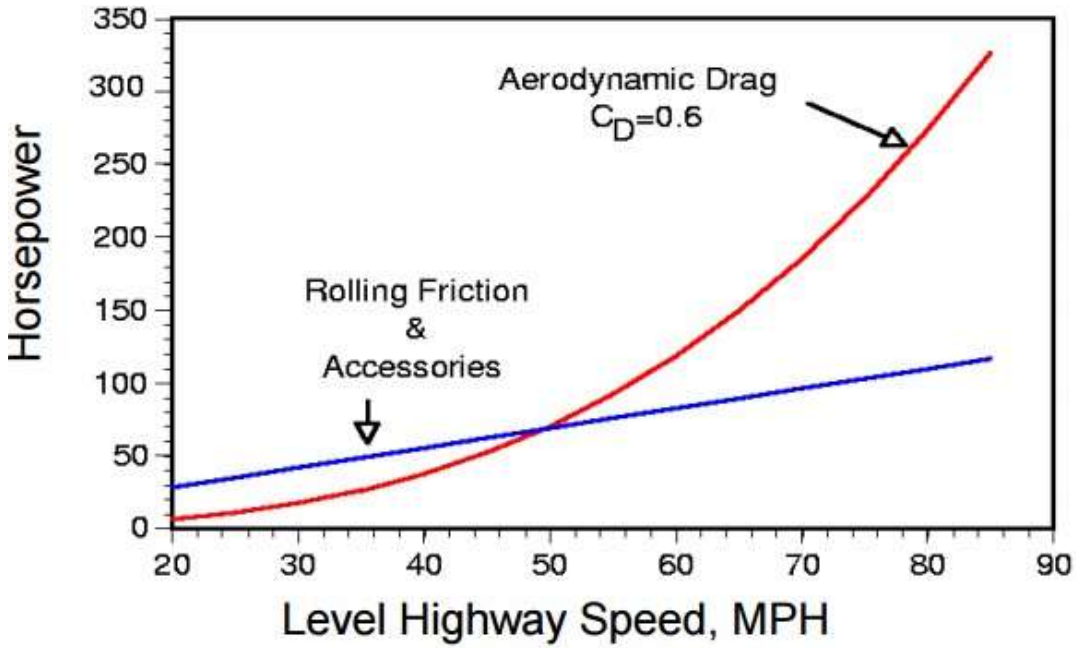
Force density ~ 10^0 N/m2

Permeability in air, $\mu_0 = 4\pi \times 10^{-7}$ H/m $\approx 1.257 \times 10^{-6}$ H/m or N/A^2

With ferromagnetic steel, practical flux density of ~1T

Force density ~ 10^5 N/m2

Torque Requirement



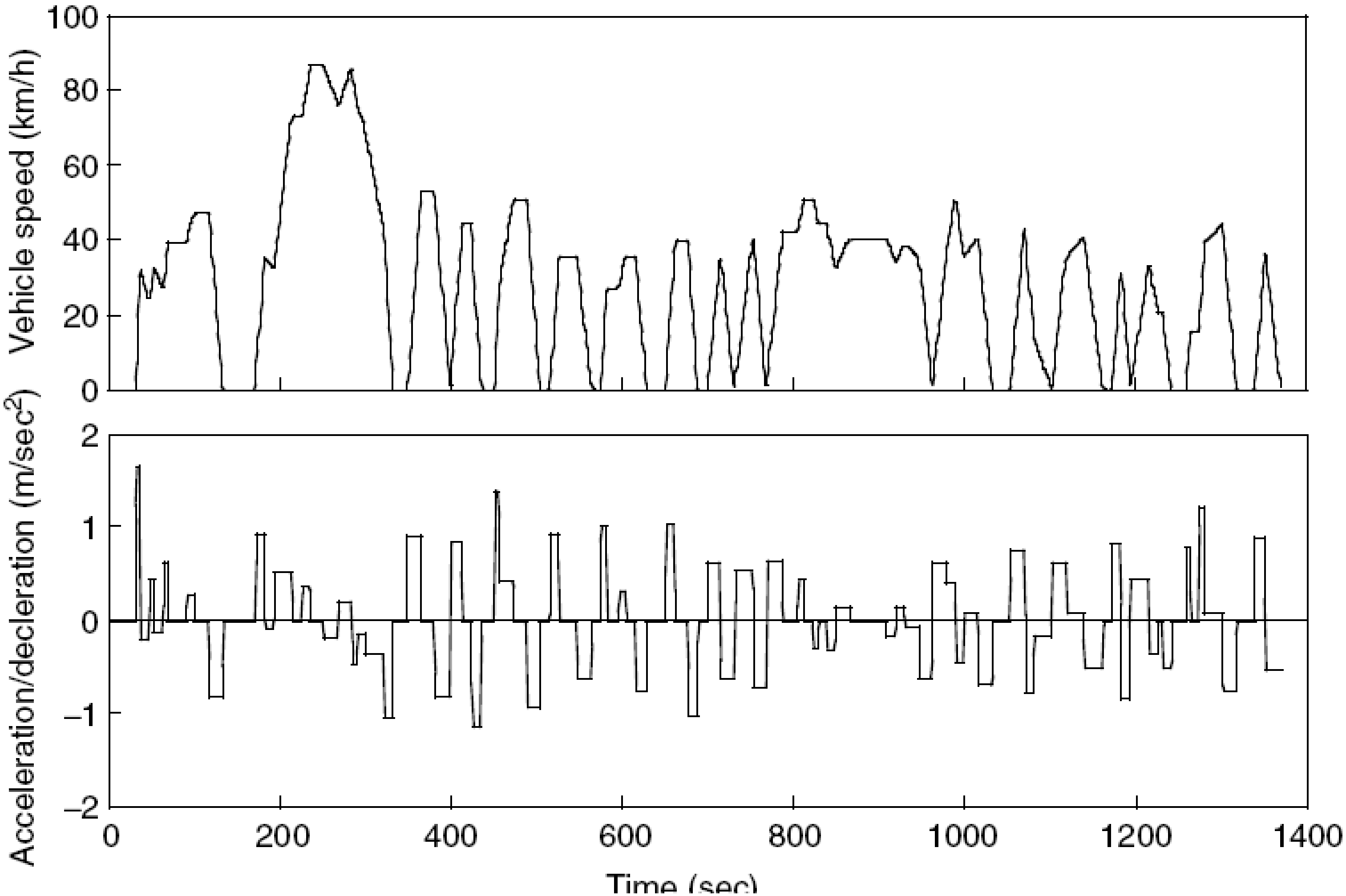
Class 8 truck
http://roperld.com/

$$F_{wheels} = F_{accel} + F_{aero} + F_{rr} + F_g$$

$$P_{wheels} = F_{wheels} V_{vehicle}$$

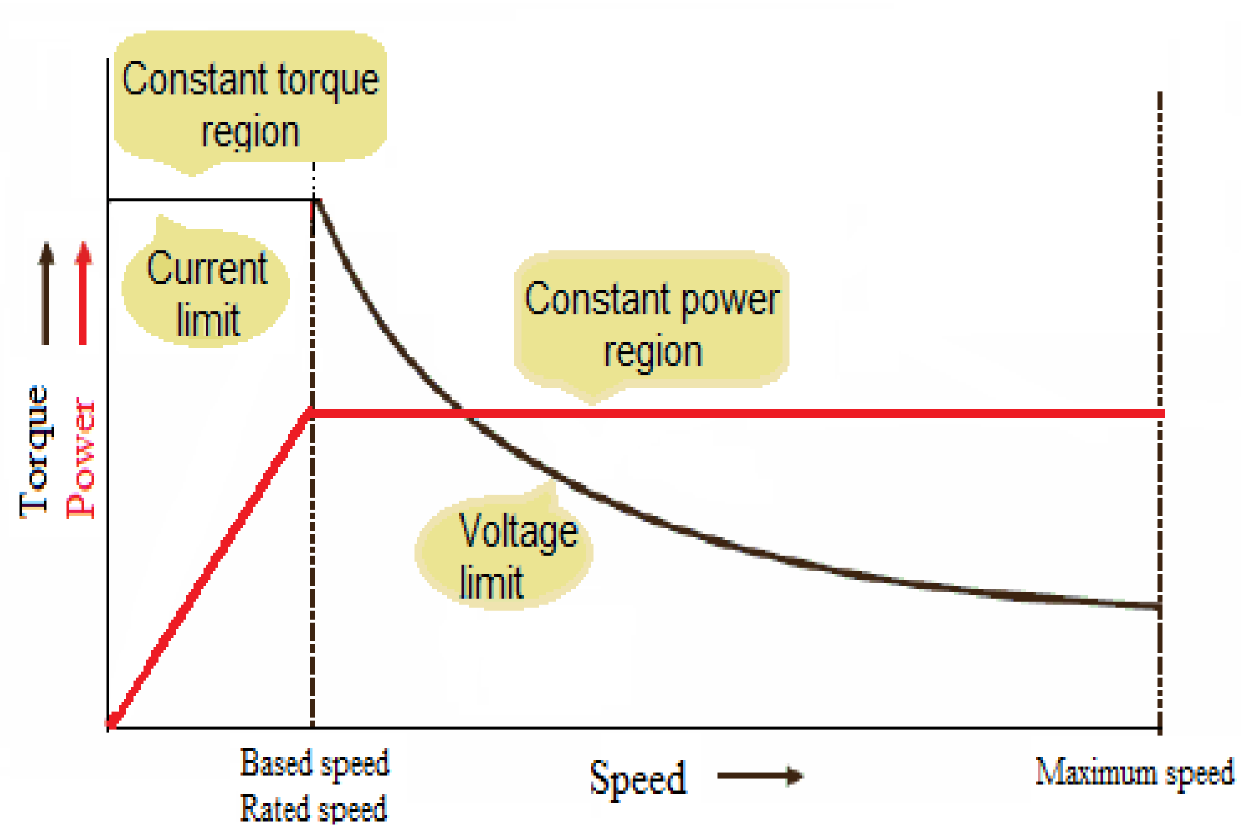
$$T_{wheels} = \frac{F_{wheels} V_{vehicle}}{2\pi N_{wheel} / 60}$$

Drive cycle

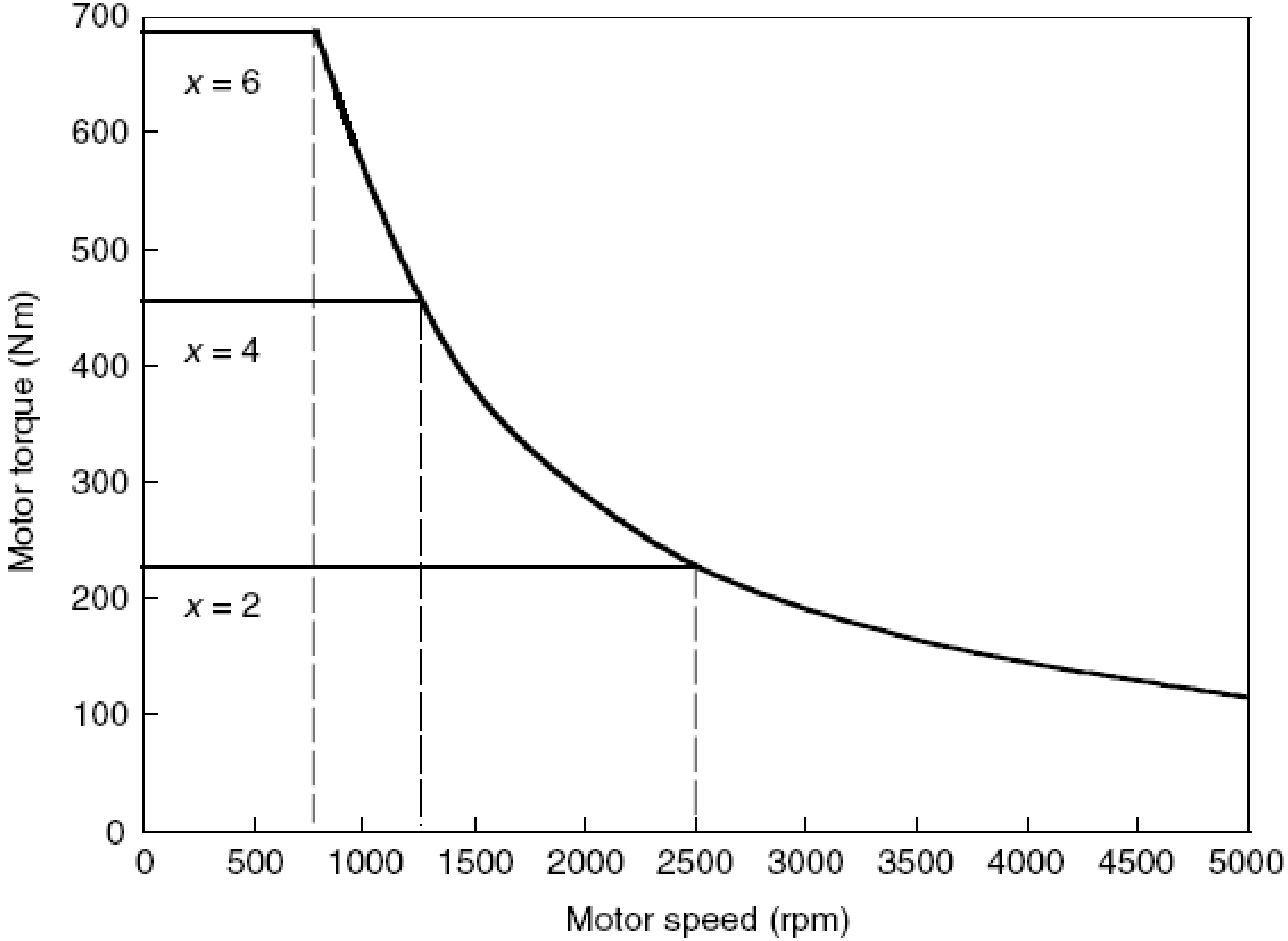


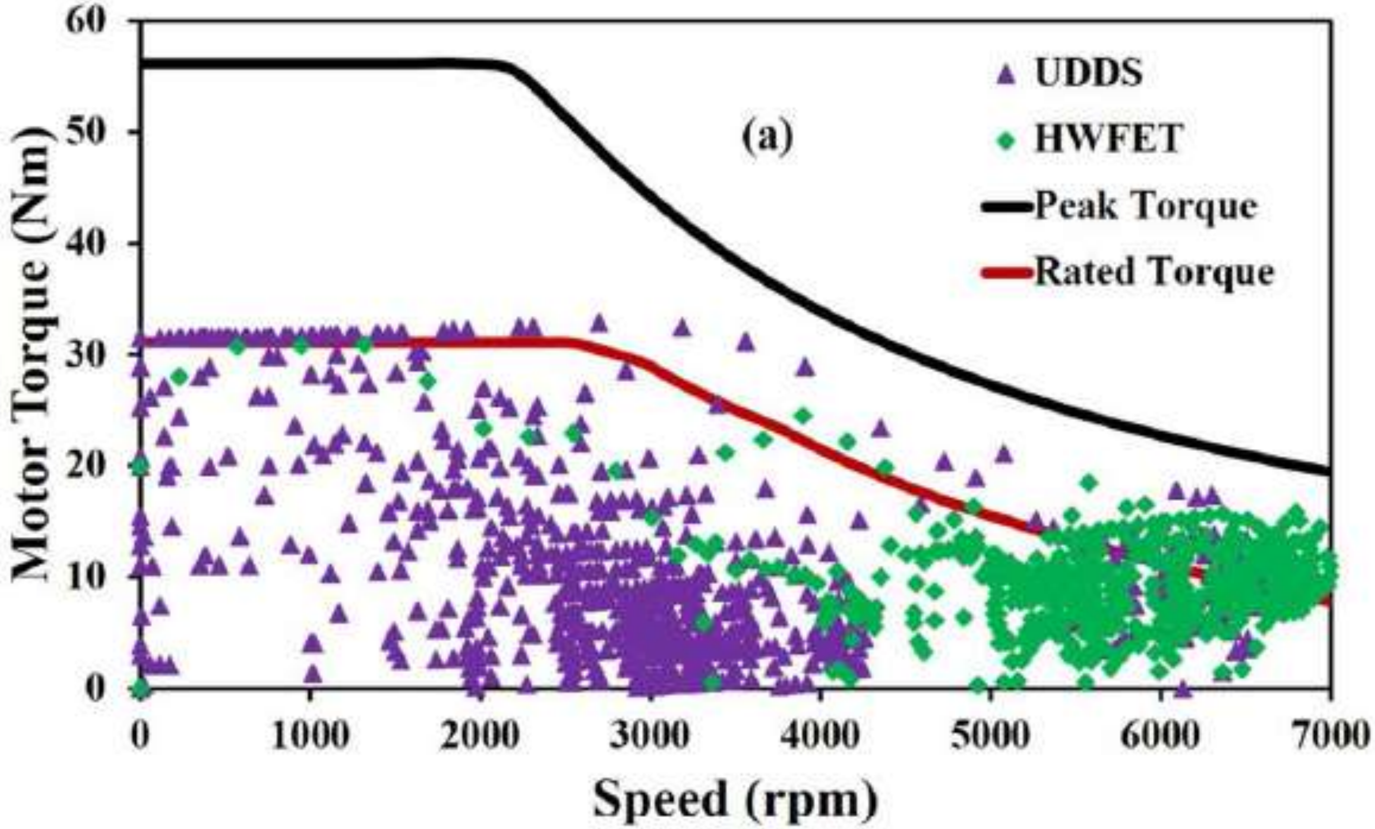
100
80
60
40
20
0
Vehicle speed (km/h)
2
1
0
–1
–2
Acceleration/decleration (m/sec^2)
0
200
400
600
800
1000
1200
1400
Time (sec)

Torque/Power vs speed capability of motors



Speed ratio & Speed–torque profile of a 60 kW electric motor





Huynh, Thanh, and Min-Fu Hsieh. "Performance analysis of permanent magnet motors for electric vehicles (EV) traction considering driving cycles." Energies 11.6 (2018): 1385.

Losses

- Copper losses

$$P_{Cu} = RI^2$$

- Iron Losses

$$P_{Fe} = \left(c_{hyst} f + c_{eddy} f^2\right) B^2 + c_{excess} \left(fB\right)^{1.5}$$

- Mechanical Losses

- Stray losses

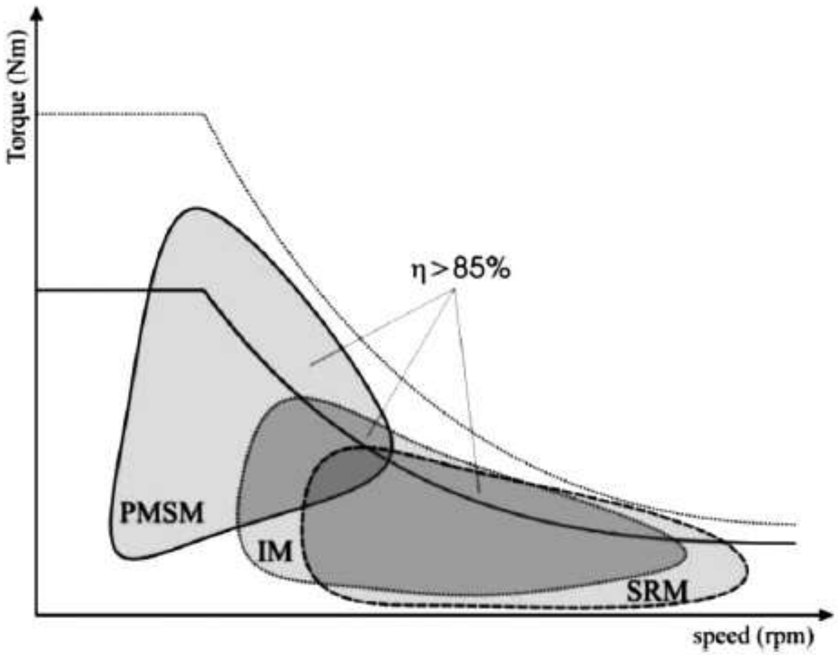


Fig. 2. Efficiency map of different electrical machines [19]

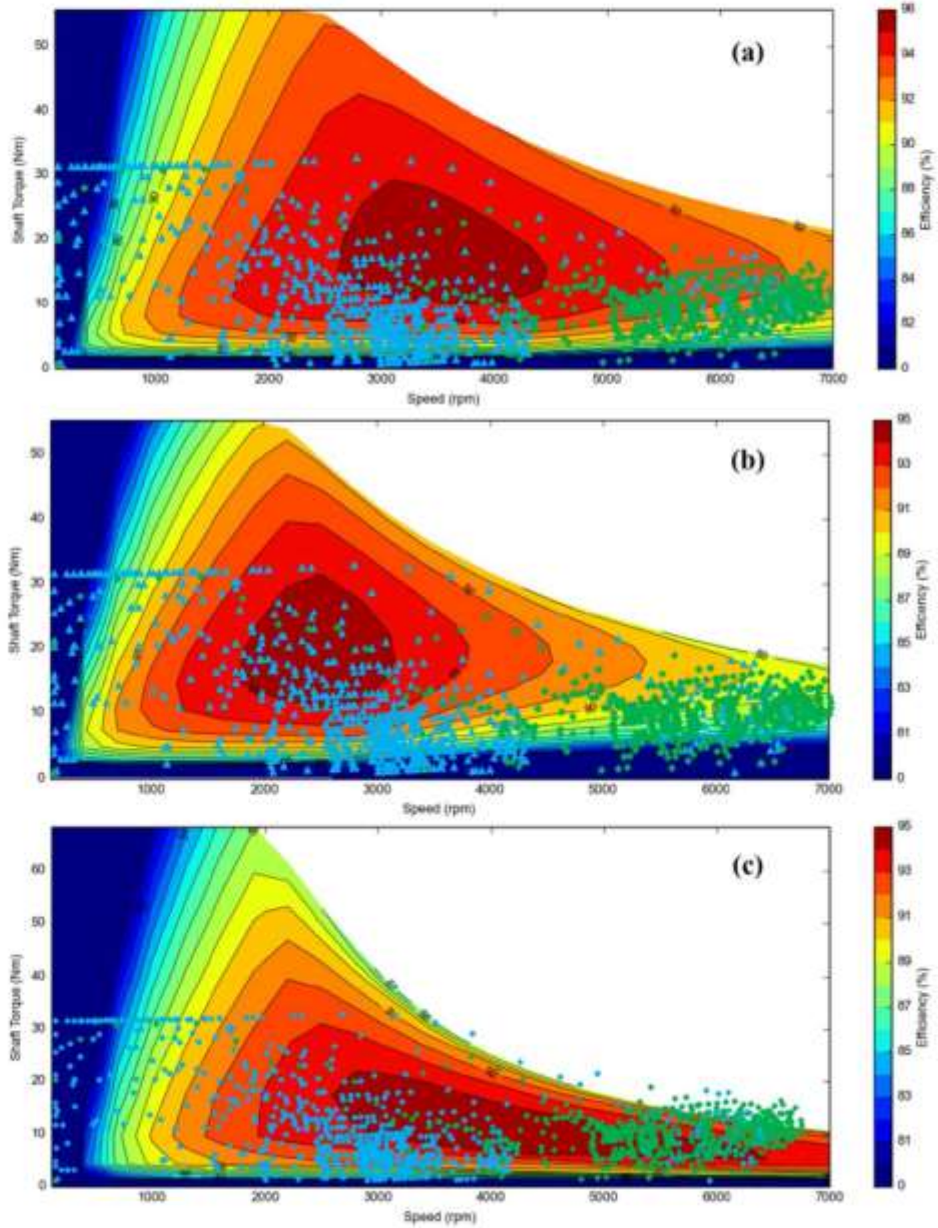
[19] Lipo TA (2007), *Introduction to AC machine design*. Madison WI, University of Wisconsin.

Efficiency maps

(a) double layers magnet IPMSM

(b) v-shaped magnets IPMSM

(c) PMa-SynRM.

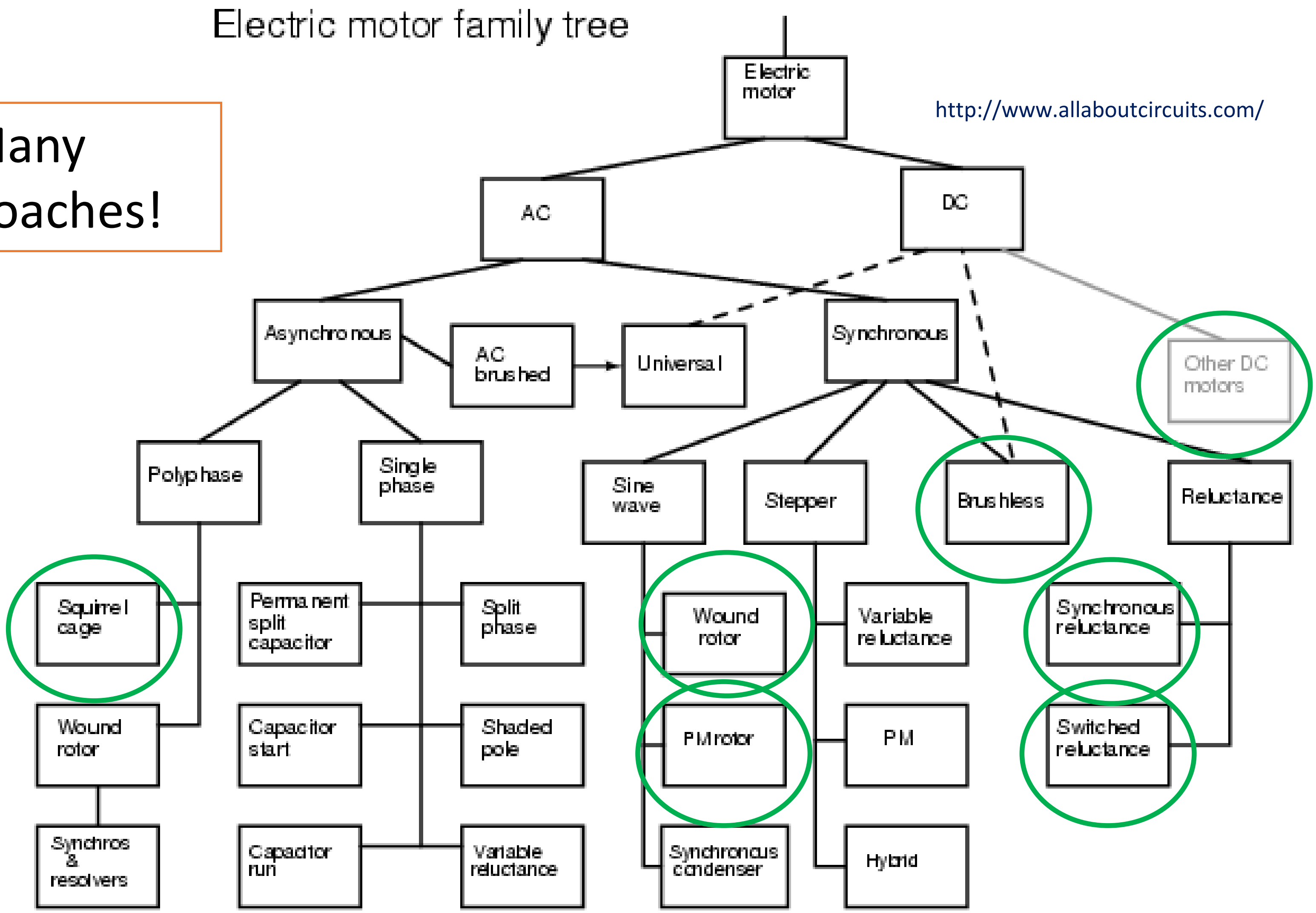


Traction Motor Requirements

- High torque/power over wide speed range -
  High torque at low speeds for starting and climbing, as well as high power at high speed for cruising.
- High efficiency over broad speed and torque
- Easy to control
- Light weight and low moment of inertia - high power density.
- Capable of regenerative braking.
- Suppression of electromagnetic interface (EMI) of motor controllers
- High reliability and fault tolerance
- Low noise and vibration
- Low cost

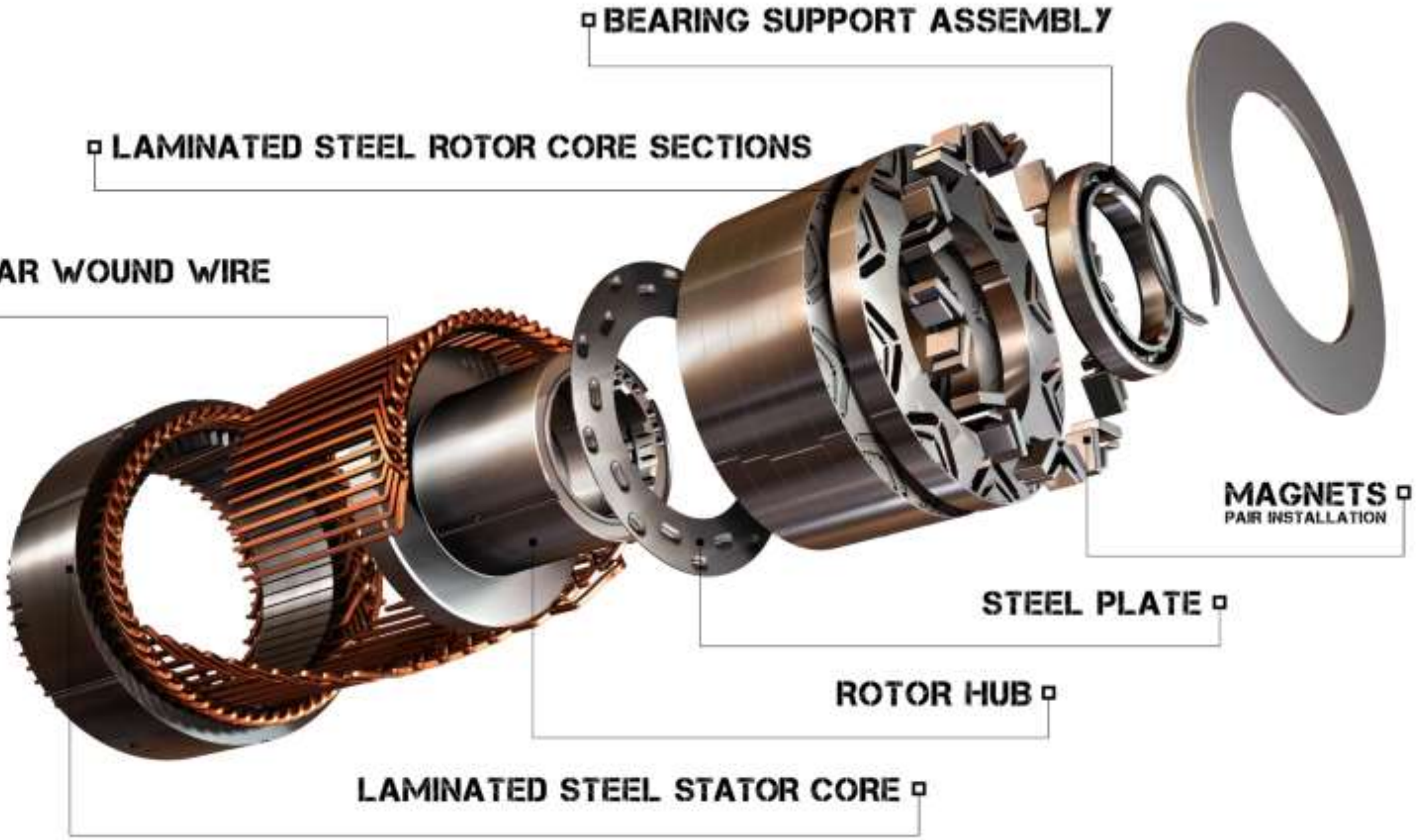
Types of Machines

Many Approaches!



https://youtu.be/dQKL1apu6LI

General Motors
Permanent Magnet Electric Motor

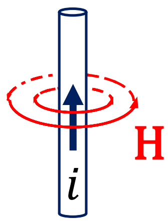


General Motors Induction Motor

Reluctance machines

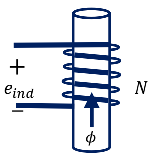
Principles of Magnetic Fields

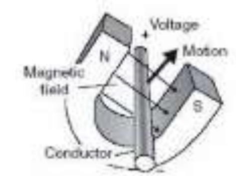
1. Ampere's Law: a current-carrying conductor produces a magnetic field surrounding it



$$\oint_C \mathbf{H} \cdot d\mathbf{l} = \boldsymbol{N} i$$

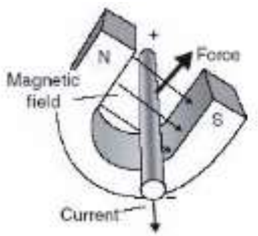
2. Faraday's Law: the induced voltage in a circuit is proportional to the rate of change over time of the magnetic flux through that circuit





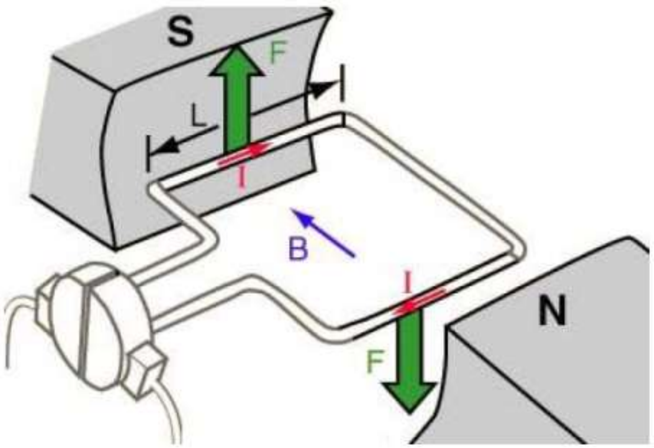
$$e_{ind} = \frac{d\lambda}{dt} = N \frac{d\phi}{dt}$$

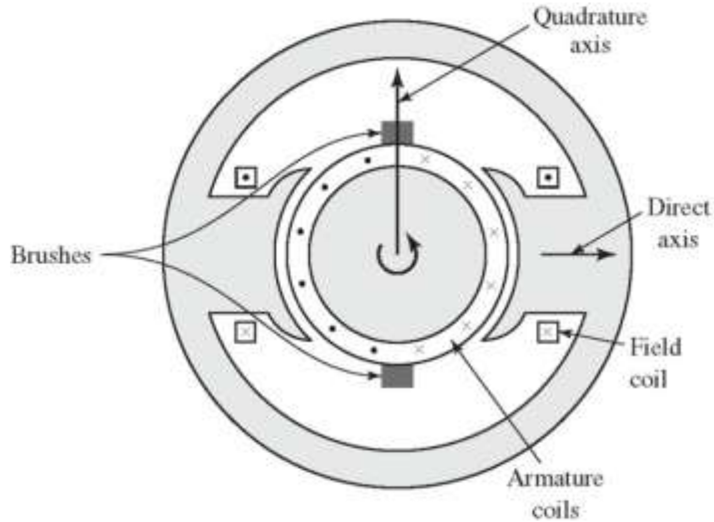
1. A current-carrying conductor in a magnetic field has a force induced on it (due to Lorentz Force)
   - *Basis for motor action*

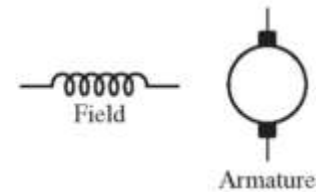


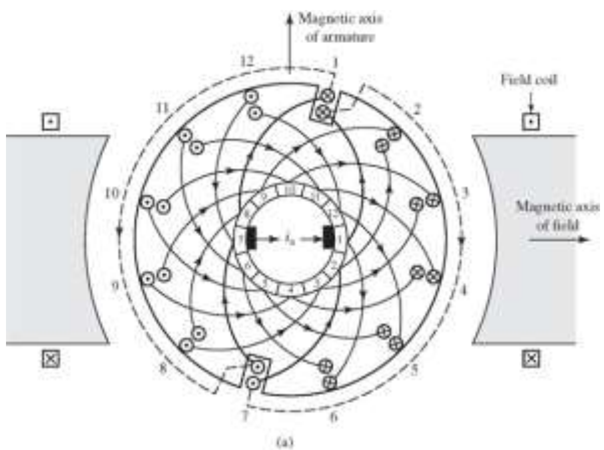
G. Masters, *Renewable and Efficient Electric Power Systems, 2nd Ed.*, Wiley IEEE Press, 2013.

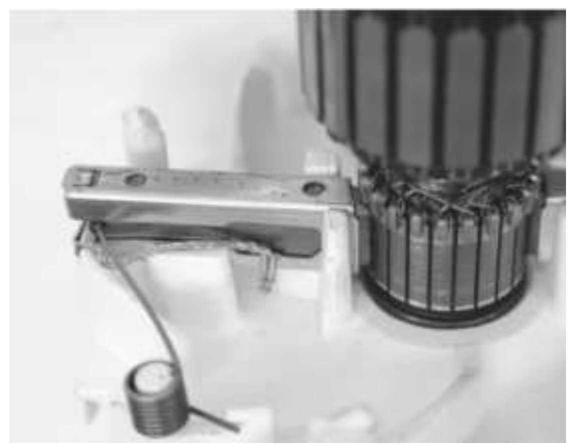
DC Machines


S
F
L
I
B
I
N
F

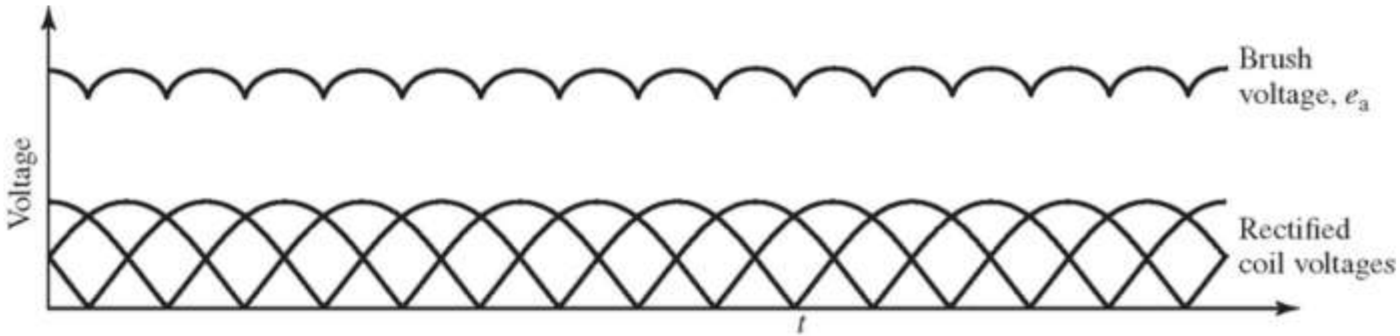

Quadrature axis
Brushes
Direct axis
Field coil
Armature coils

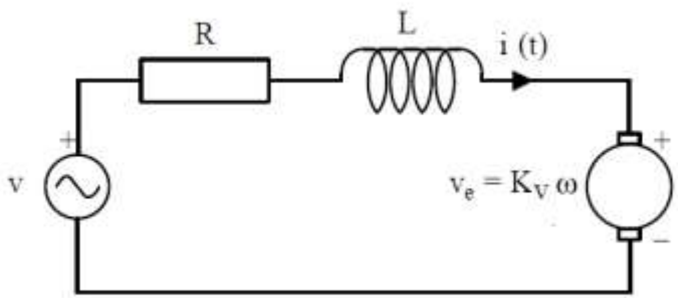

Field
Armature


Magnetic axis of armature
Field coil
Magnetic axis of field
(a)



Equivalent Circuit





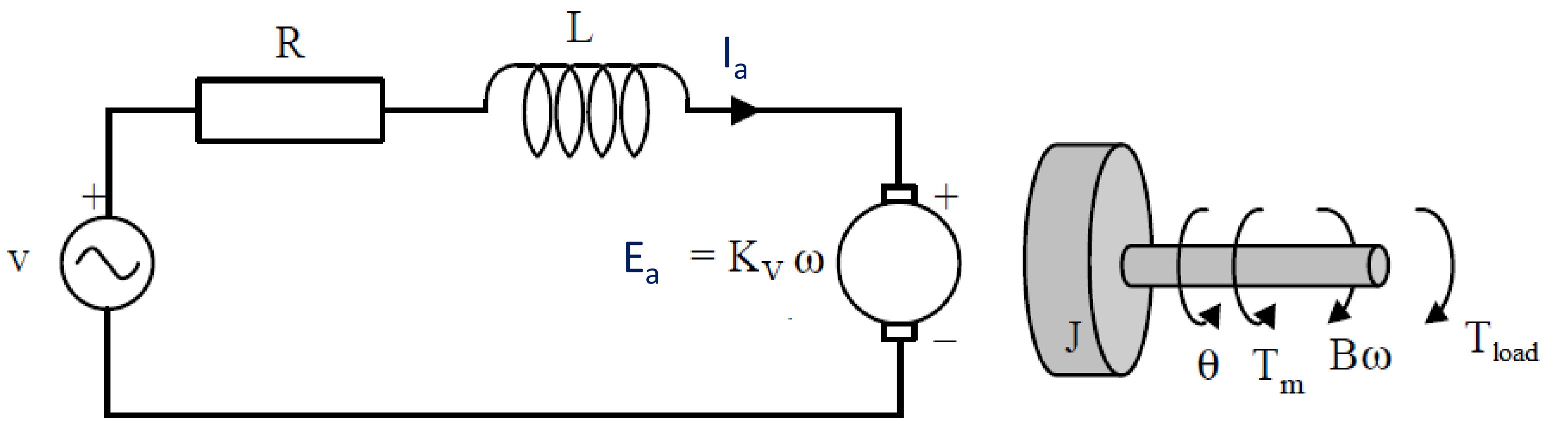
$$e_a = K_a\,\phi_d\,\omega_m$$

$$e_a\,i_a = T_e\,\omega_m$$

$$T_e = K_a\phi_d i_a = K_a\phi_d\,(v_a - K_a\phi_d\omega_m)/R_a$$

$$\omega_m = \frac{(v_a - i_a R_a)}{K_a\phi_d} = \frac{(v_a - \frac{T_e}{K_a\phi_d}R_a)}{K_a\phi_d}$$

Control



Speed control:

- Flux control or voltage control

$$E_a = V - I_a R_a = K_a \phi_d \omega$$

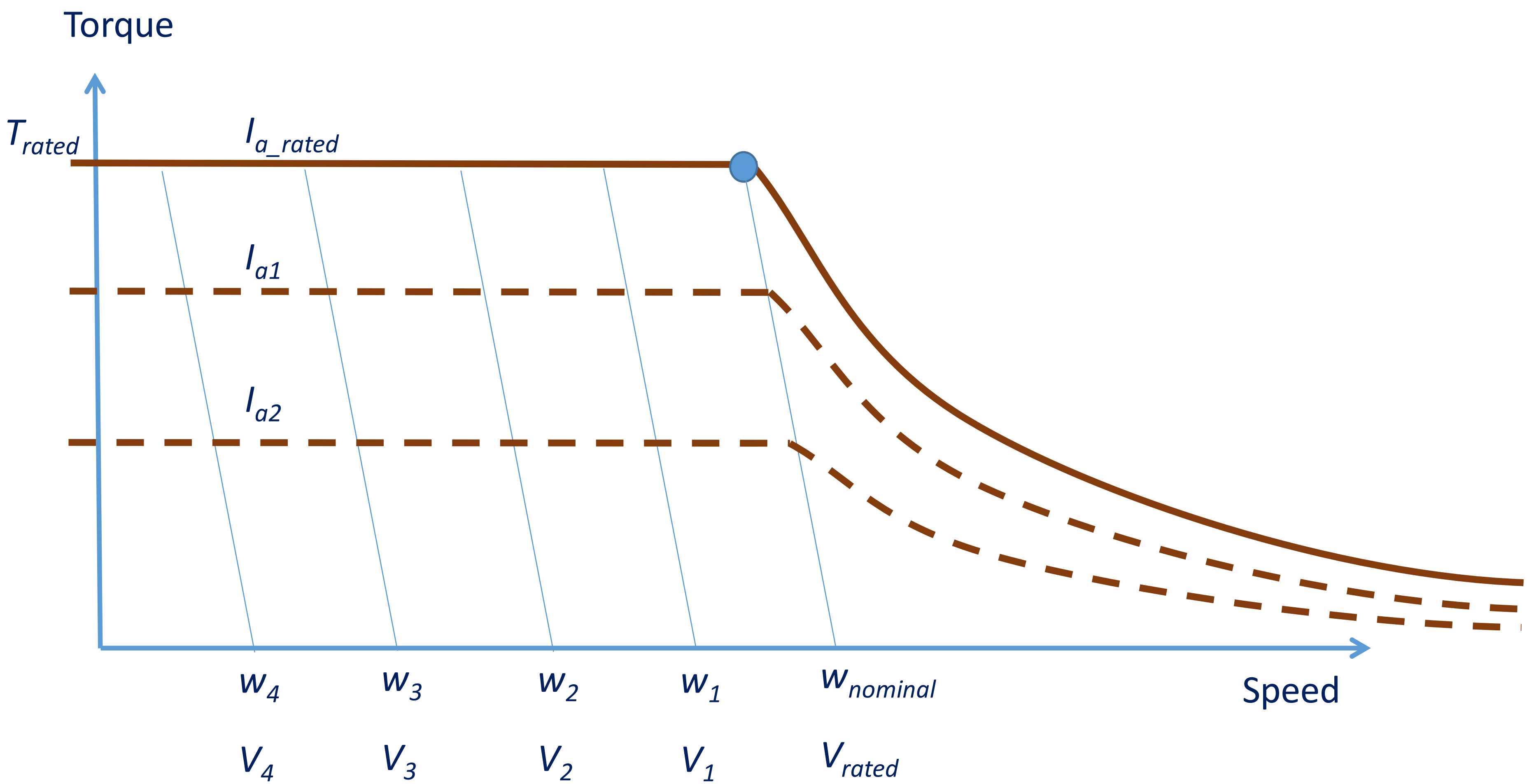
$$\Rightarrow \omega = (V - I_a R_a)/K_a \phi_d$$

Torque Control:

- Armature current (Ia)

$$P_{mech} = E_a I_a = K_a \phi_d \omega I_a$$

$$\Rightarrow \text{Torque} = P_{mech}/\omega = K_a \phi_d I_a$$



Torque
T_{rated}
I_{a_rated}
I_{a1}
I_{a2}
w_4
w_3
w_2
w_1
$w_{nominal}$
Speed
V_4
V_3
V_2
V_1
V_{rated}