Electric Vehicle (EE60082)

Lecture 7: Motor drive for EV (part 3)

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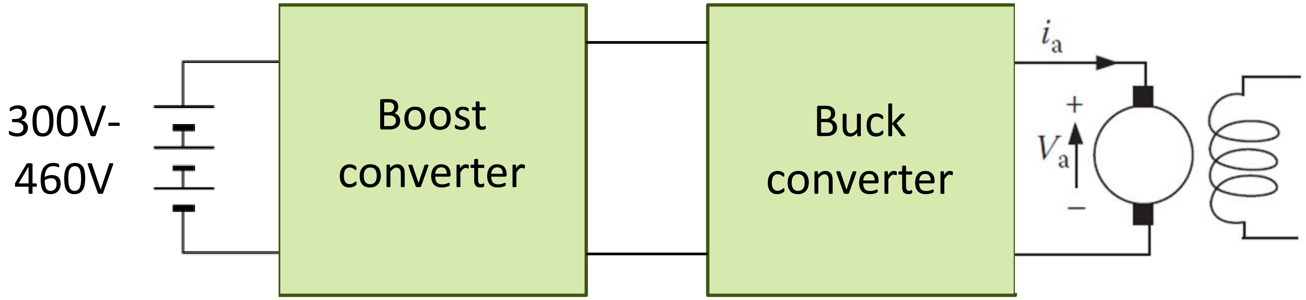
Traction motors for EV (recap)

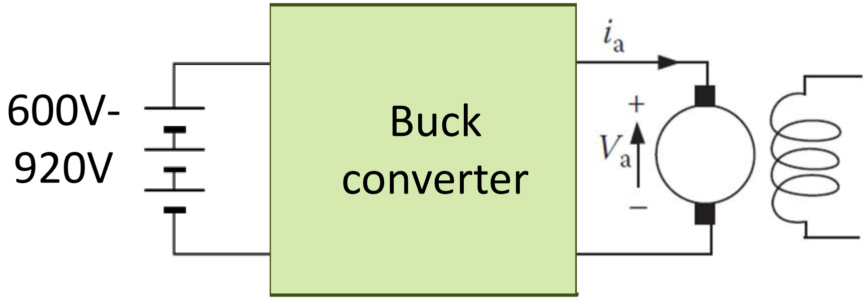
Commonly used motors:

- Brushed DC motor
- Brushless DC motor (BLDC)
- Induction motor
- Permanent magnet synchronous motor (PMSM)
- Switched reluctance motor (SRM)

DC motor drive (recap)

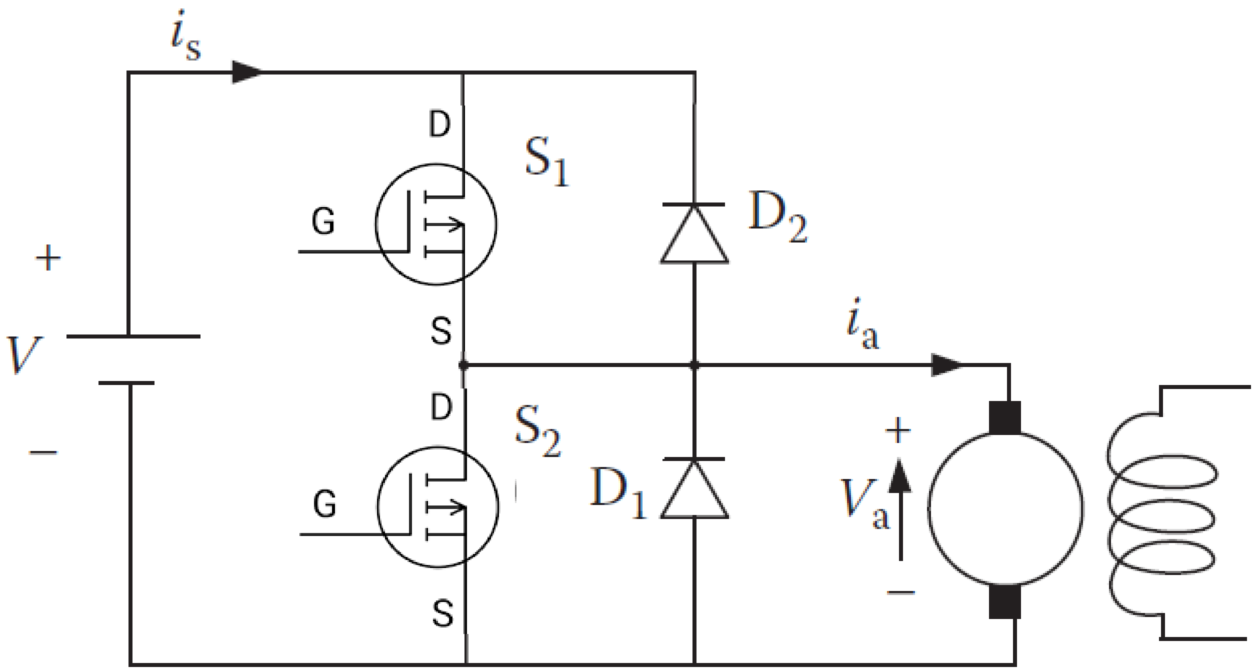


Lower battery voltage



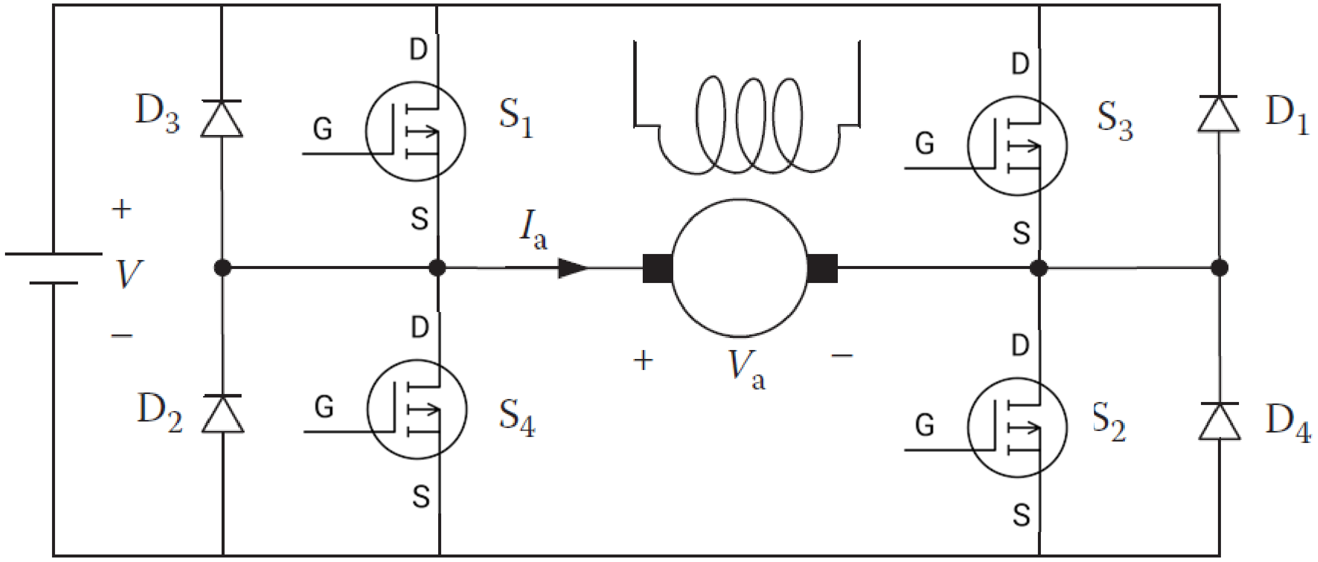
Higher battery voltage

DC motor drive – synchronous buck (recap)



- Synchronous buck
- bidirectional power flow
- Two-quadrant chopper
- Class C chopper
- How to drive in reverse?

DC motor drive – 4 quadrant chopper (recap)



- Full bridge
- bidirectional power flow
- Four-quadrant chopper
- Class E chopper
- Drive in reverse-
  - 4 quadrant chopper vs. gear box

DC machine drawbacks (recap)

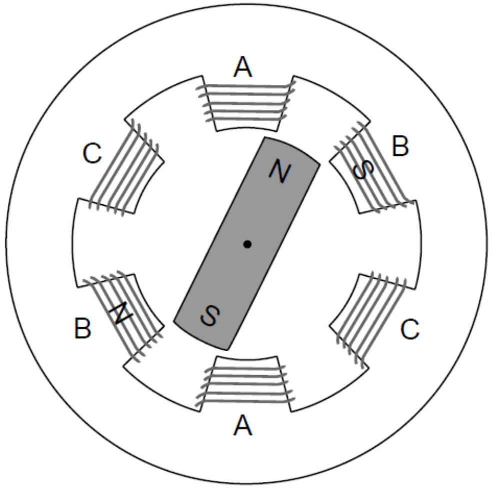
- Wear and tear of brush and commutator
  - High maintenance
  - Limited life
  - limited speed range

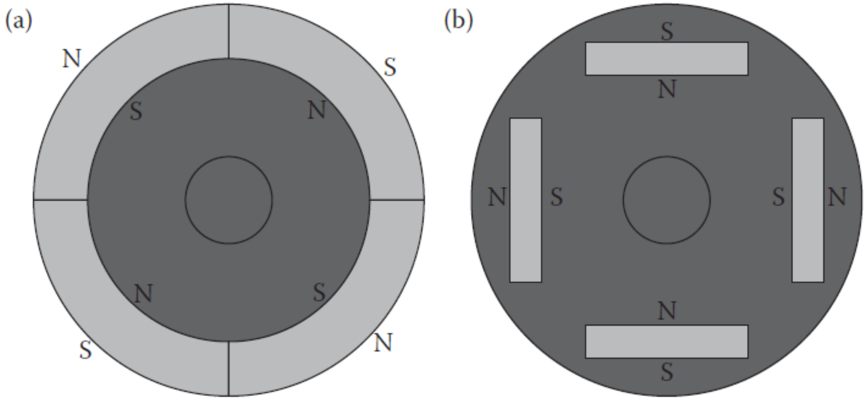
- Sparking at the commutator
  - sparking at brush contacts, especially under heavy load and high speed
  - EMI noise due to sparking
  - Potential safety hazards

- Higher weight and volume

- Lower efficiency

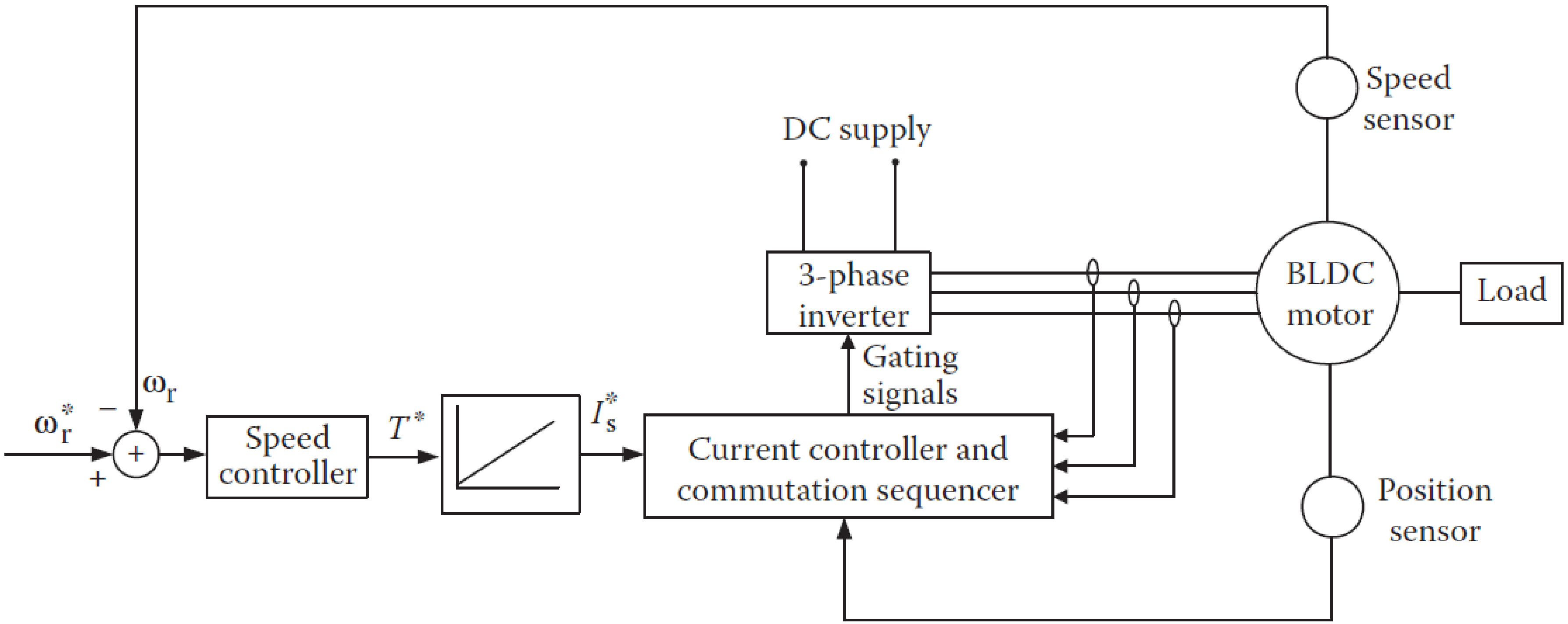
Coil arrangements in a BLDC (recap)





- Multiple coils to increase torque
- Strong magnet needed for rotor
- No current flow in rotor
- Only stator cooling required
- Two types of PM mounting
  - Surface and interior mounting

BLDC control loop (recap)



BLDC- advantages and limitations (recap)

- Advantages:
  - no brush, commutator
  - Low maintenance
  - Higher efficiency
  - ease of cooling
  - Low noise

- Drawbacks:
  - Higher cost of magnets
    - Cost and availability of rear earth elements
  - Limited high speed capability
    - limitation of magnet assembly strength
  - large fault current in case of drive failure
    - Can causse wheel block

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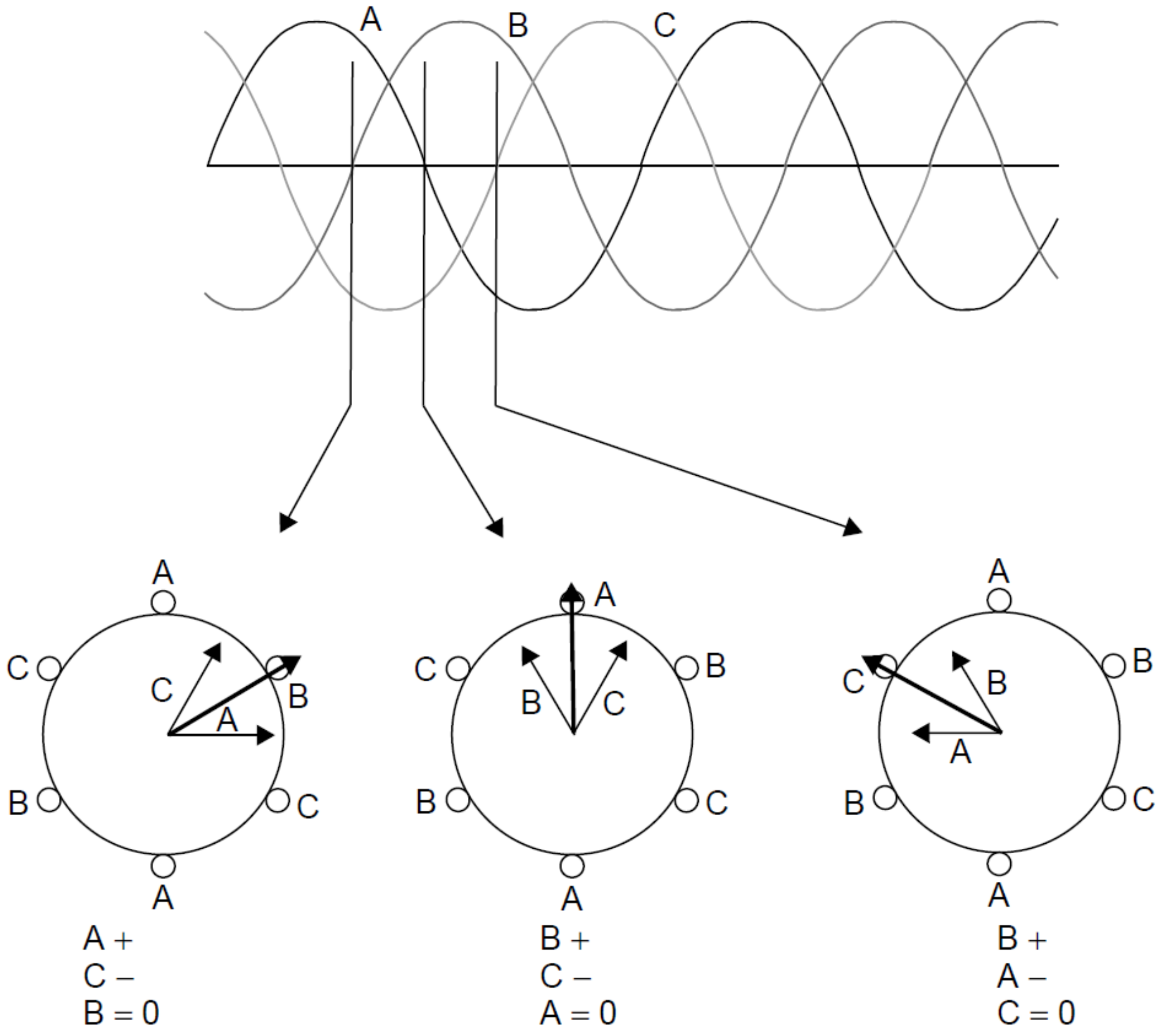
  - Limited constant power range
    - Lack of field strength control
  - Need for position sensors
    - costly
    - can lead to reliability issues

AC Machines

Rotating magnetic field



$$n_s = \frac{60f}{p}$$

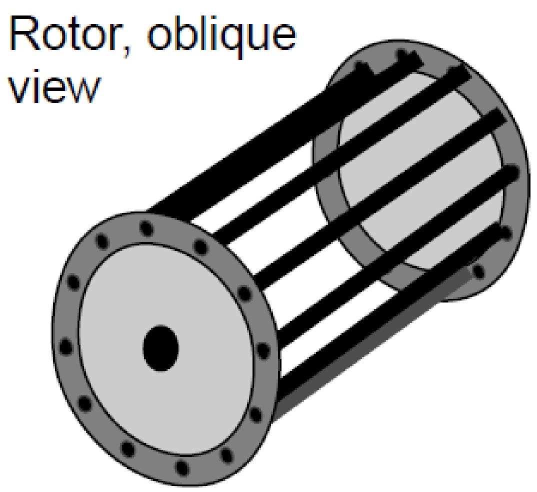
$$\omega_s = \frac{2\pi n_s}{60}$$

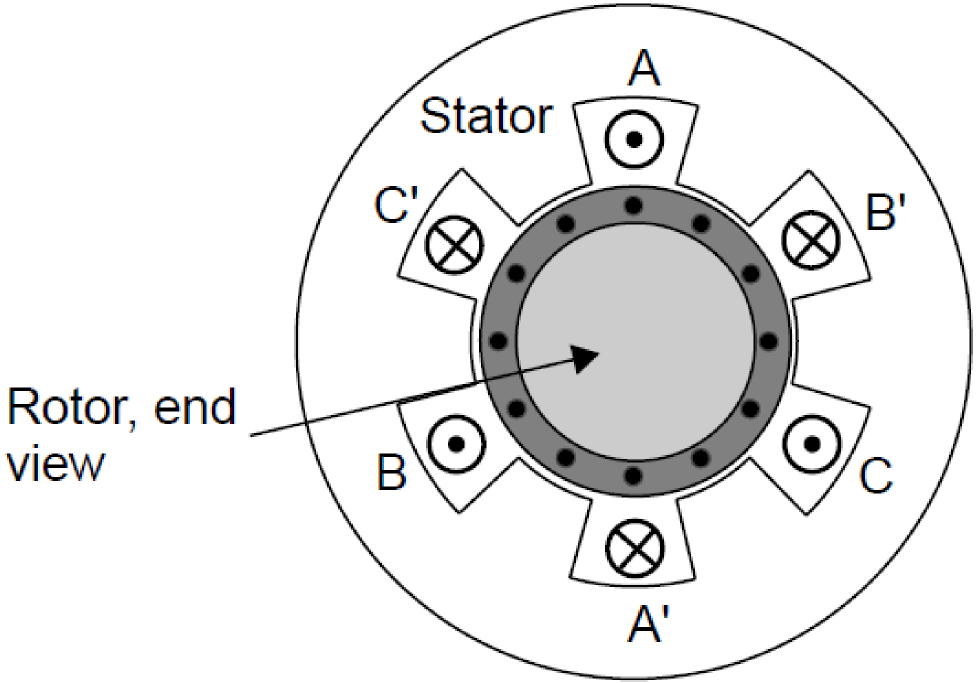
Synchronous speed

Assume the wheel radius is 0.25m. The final drive ratio is 1, i.e., gearless. f=50Hz is the rated frequency.

Pole pair	Synchronous speed (rpm)	Vehicle speed (kmph)
1	3000	282
2	1500	141
3	1000	94
4	750	70
5	600	56
6	500	47

Induction motor construction





Slip

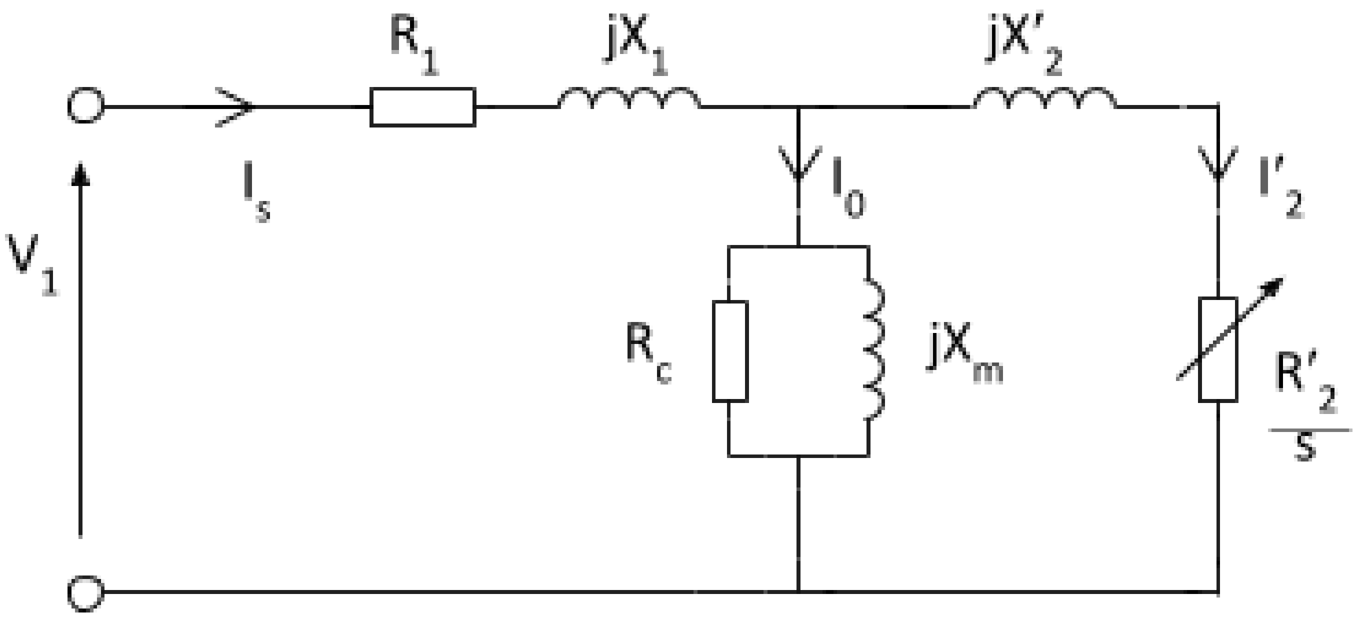
$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{n_s - n_m}{n_s}$$

$$\omega_m = (1 - s)\omega_s$$

$$n_m = (1 - s)n_s$$

$$\omega_{\text{slip}} = s\omega$$

Equivalent circuit



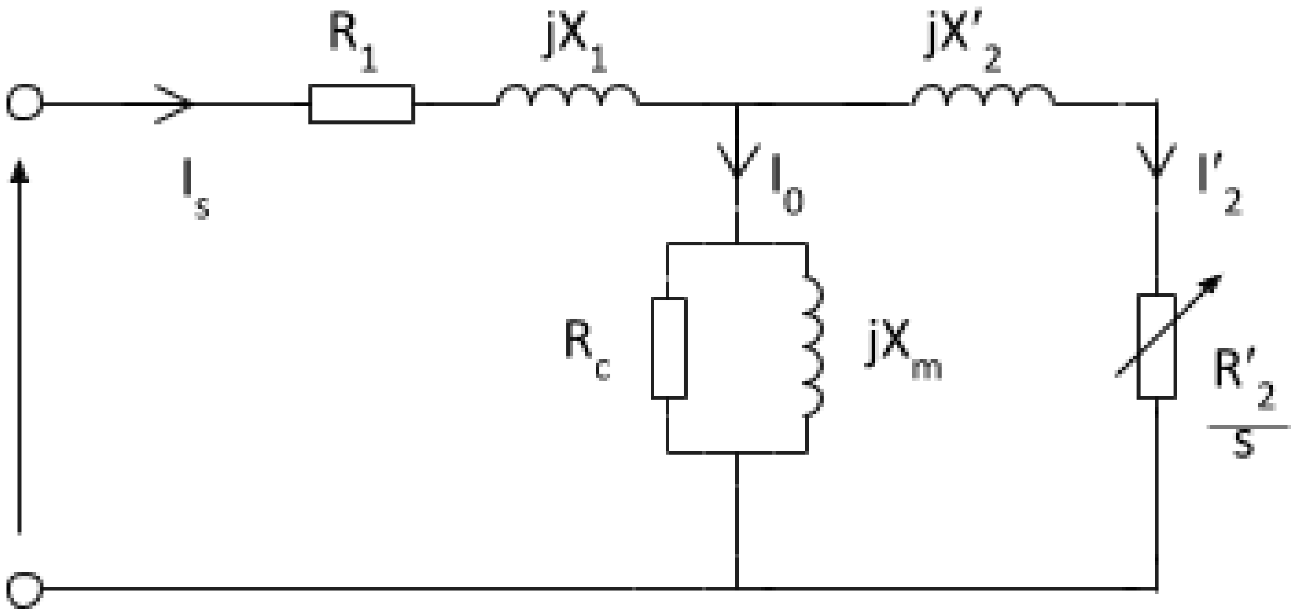
R_1 and X_1: stator leakage resistance and impedance;

R_c and X_m: core-loss resistance and mutual impedance;

R'_2 and X'_2: reflected rotor leakage resistance and impedance;

Equivalent circuit

When the load is heavy…



$$P_o = \left| \frac{V_1}{R_1 + R_2'/s + jX_1 + jX_2'} \right|^2 R_2'(1-s)/s$$

$$P_o = \frac{R_2' V_1^2}{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2} \frac{1-s}{s}$$

Torque equation

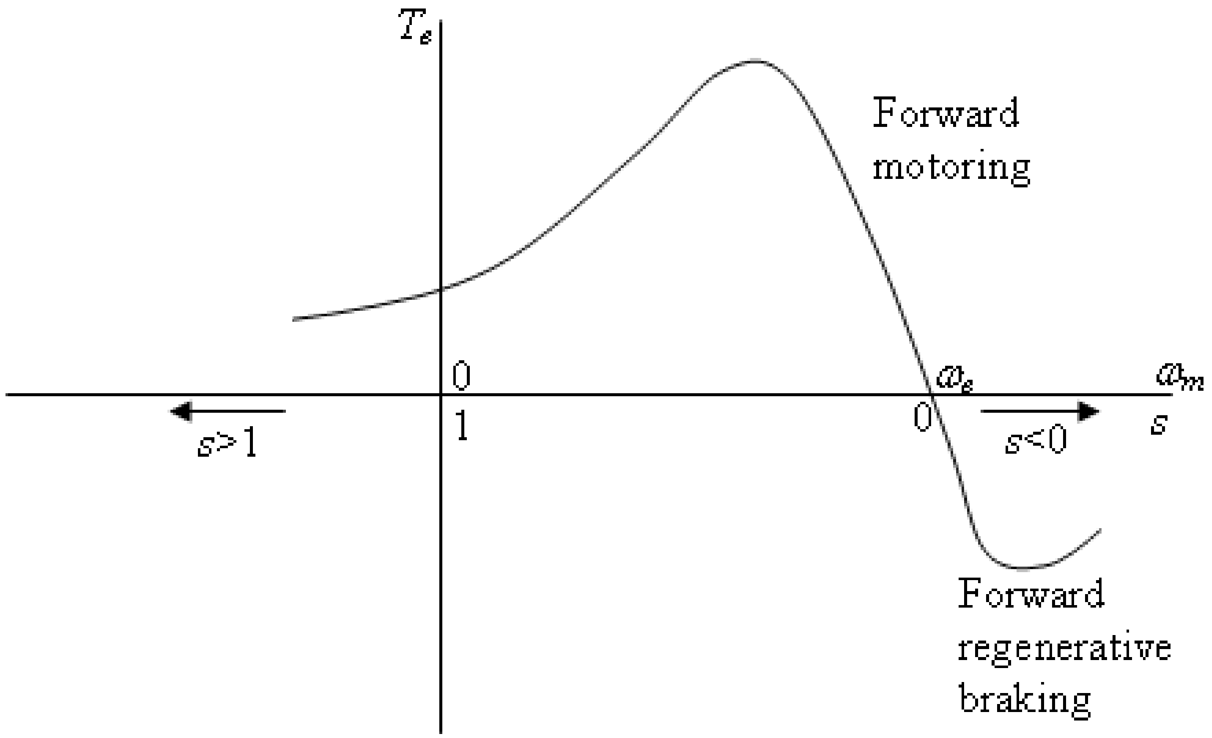
$$P_o = \frac{R_2^{'} V_1^2}{(R_1 + R_2^{'}/s)^2 + (X_1 + X_2^{'})^2} \frac{1-s}{s}$$

$$T = \frac{P_o}{\omega_m} = \frac{P_o}{(1-s)\omega_s}$$

$$T = \frac{R_2^{'} V_1^2}{(R_1 + R_2^{'}/s)^2 + (X_1 + X_2^{'})^2} \frac{1-s}{s} \frac{1}{(1-s)\omega_s}$$

$$T = \frac{R_2^{'} V_1^2}{s\{R_1^2 + (X_1 + X_2^{'})^2\} + \frac{R_2^{'2}}{s} + 2R_1 R_2^{'}} \frac{1}{\omega_s}$$

Torque-speed characteristics

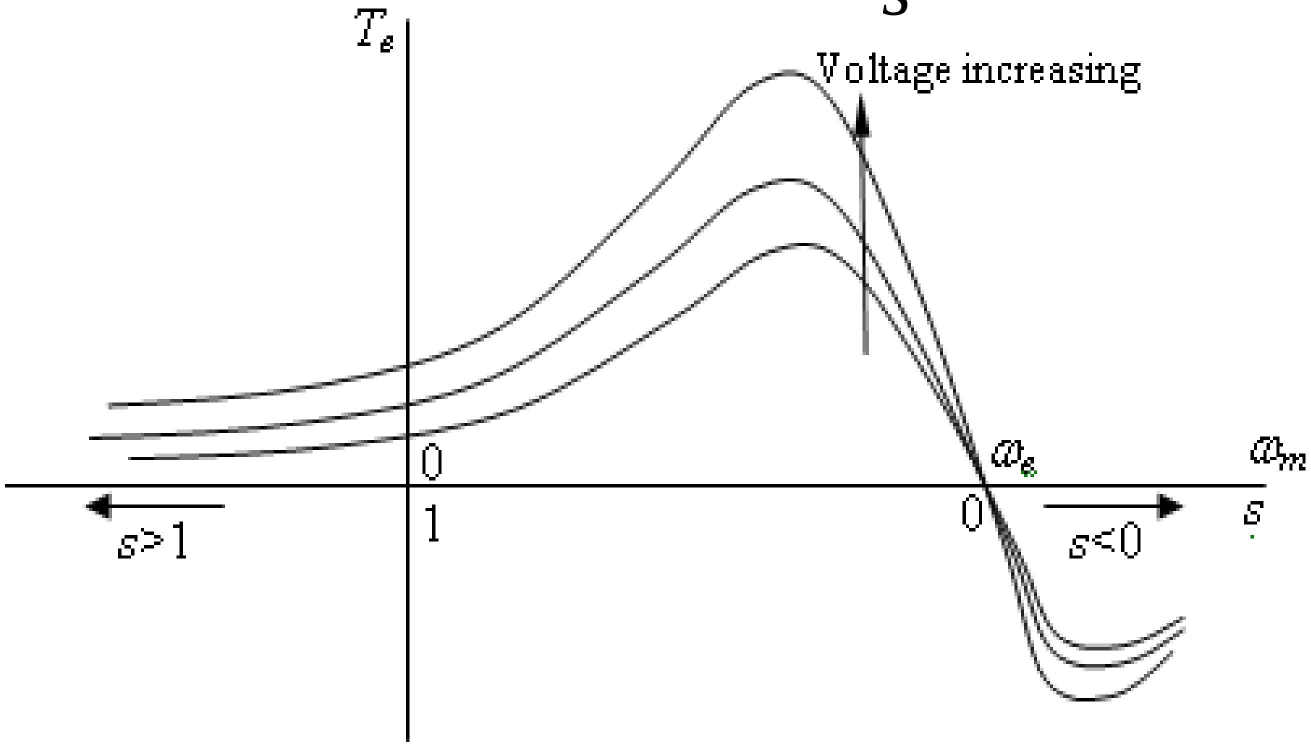


1. Motor has the maximum torque T_{max} at the fixed frequency;

2. When slip ratio is negative, the torque is negative.

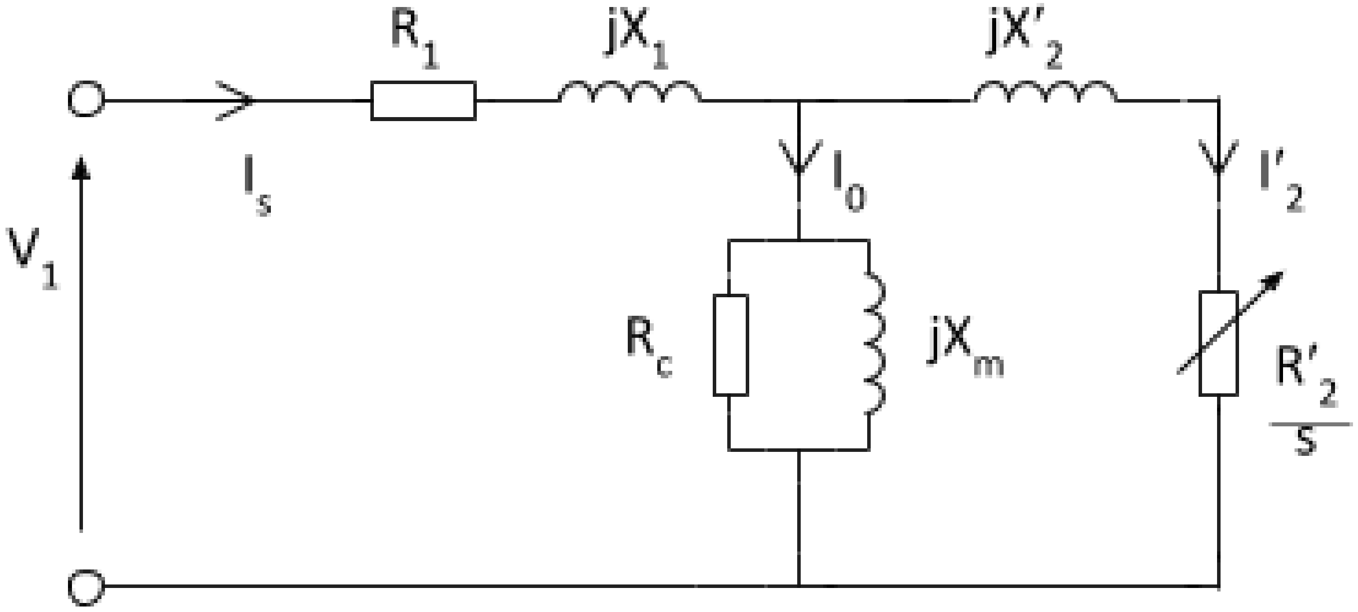
Voltage control

$$T = \frac{R_2' V_1^2}{s\{R_1^2 + (X_1 + X_2')^2\} + \frac{R_2'^2}{s} + 2R_1R_2'} \frac{1}{\omega_s}$$



V/F control

Ignore the stator loss.



$$V_1 = j\omega_s L_m I_0$$

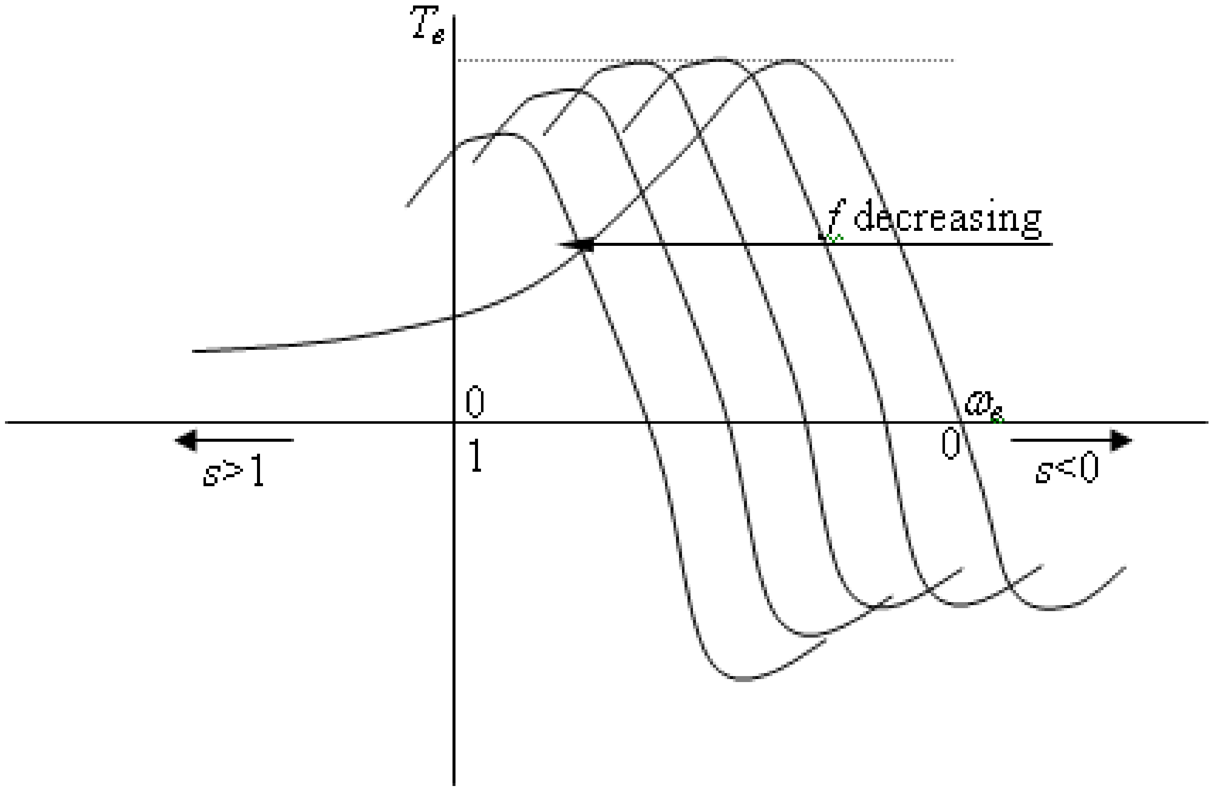
$$V_1 = j2\pi f_s \psi_m$$

$$\frac{V_1}{f_s} = j2\pi\psi_m$$

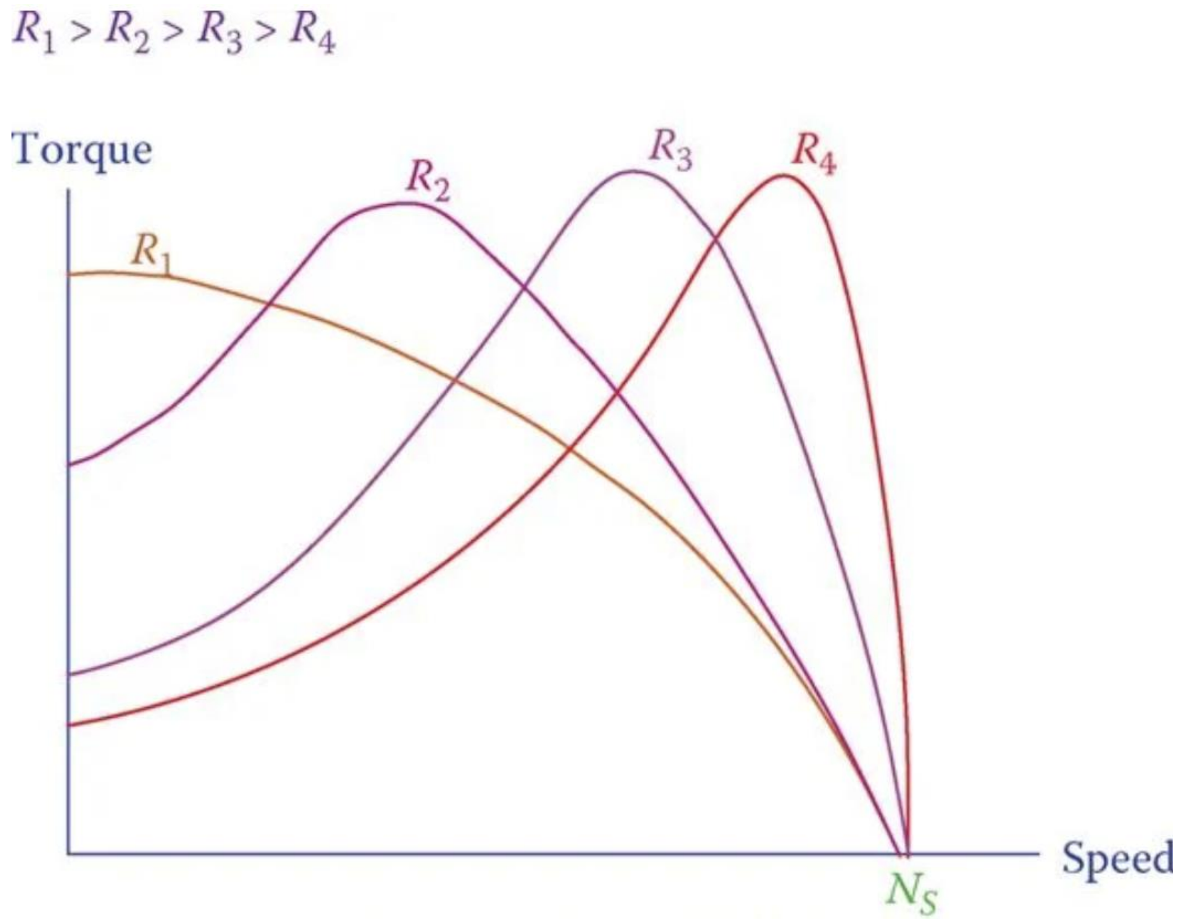
To avoid potential saturation, VVVF control is used.

Frequency control

$$T = \frac{R_2' V_1^2}{s\{R_1^2 + (X_1 + X_2')^2\} + \frac{R_2'^2}{s} + 2R_1R_2'} \frac{1}{\omega_s}$$



Design for higher starting torque



Induction motor- advantages and limitations

- Advantages:
  - Simple construction
    - harsh environments with minimal maintenance
  - no permanent magnet
    - Lower cost
    - No need for rear-earth elements
  - Self-starting
    - No special arrangement needed for starting
  - minimal noise and vibration
  - can be designed for a wide range of power outputs

- Drawbacks:
  - Losses in rotor
    - Relatively lower efficiency
    - Heating in rotor
  - Complicated torque and speed control
    - complex controller required
  - High in-rush current
    - When DOL starter used
  - Lower starting torque

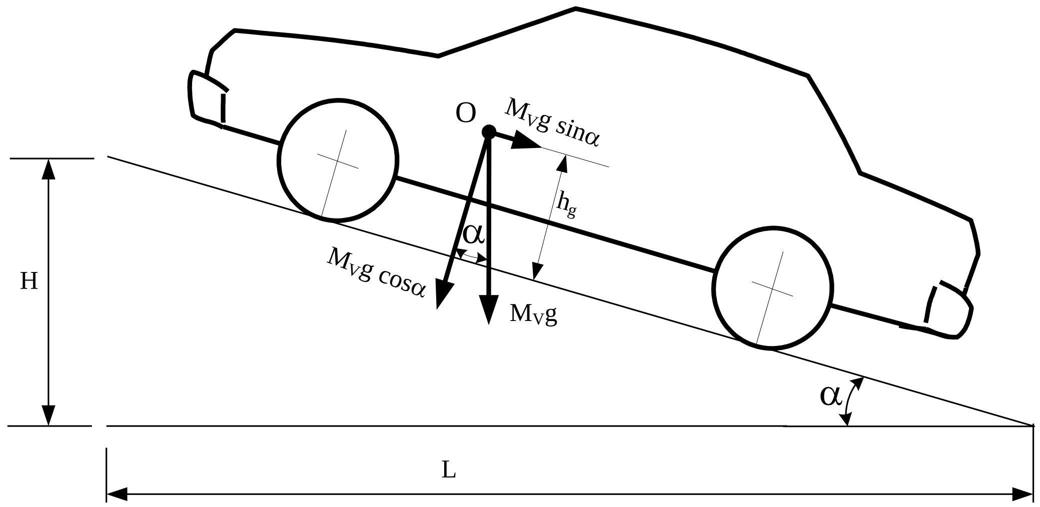
Exercise – part 1

A vehicle has following parameter values:

m=692kg, $C_D = 0.2$, $A_F = 2m^2$, $f_0 = 0.009$,

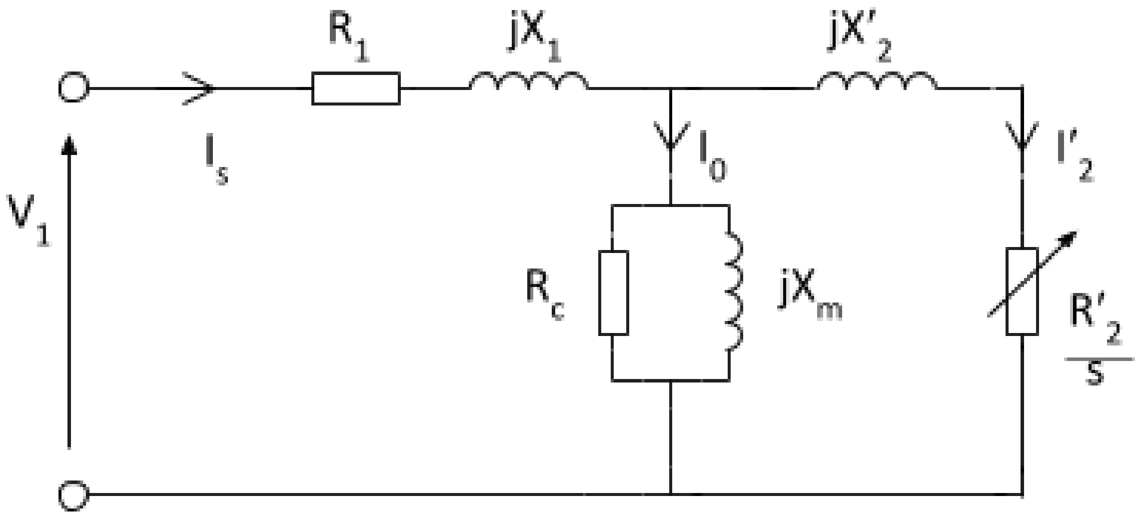
$f_s = 1.75*10^{-6}\ s^2/m^2$, $\rho = 1.18\ kg/m^3$, $g = 9.81\ m/s^2$

Wheel radius, R_w=0.25m, gear ratio=1



The vehicle is to be accelerated at 1 m/s on a slope of 5^o . What is the starting torque requirement?

Exercise - part 2



A **three-phase** induction motor has $R_1=R'_2=0.01\Omega$, $L_1=L_2'=2mH$, $L_m=200mH$, R_c is infinite. $V_1=400VAC$, $f=50Hz$, $J = 2.5\ kg.m^2$

Can this motor drive the car up the slope?

Torque required

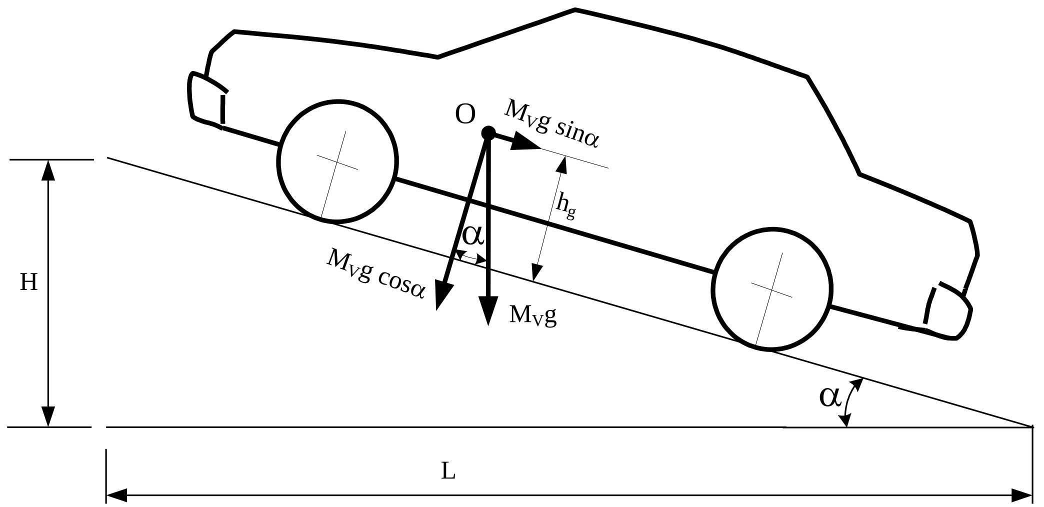
- Vehicle dynamic equation
  - $m\frac{dV}{dt} = F_{TR} - F_r - F_g - F_w$
  - Required tractive power:

$$F_{TR} = m\frac{dV}{dt} + F_r + F_g + F_w$$

$$F_r = mg\cos\alpha\,(f_0 + f_s V^2)$$

$$F_g = mg\sin\alpha$$

$$F_W = \frac{1}{2}\rho A_f C_D (V - V_W)^2$$



- Torque required, $T_L = F_{TR}R_W$

Motor dynamics

$$J\frac{d\omega}{dt} = T_{em} - T_L - B\omega$$

$$v = \omega R_w$$

Tem, electromagnetic torque

TL, Load torque

B, shaft damping constant

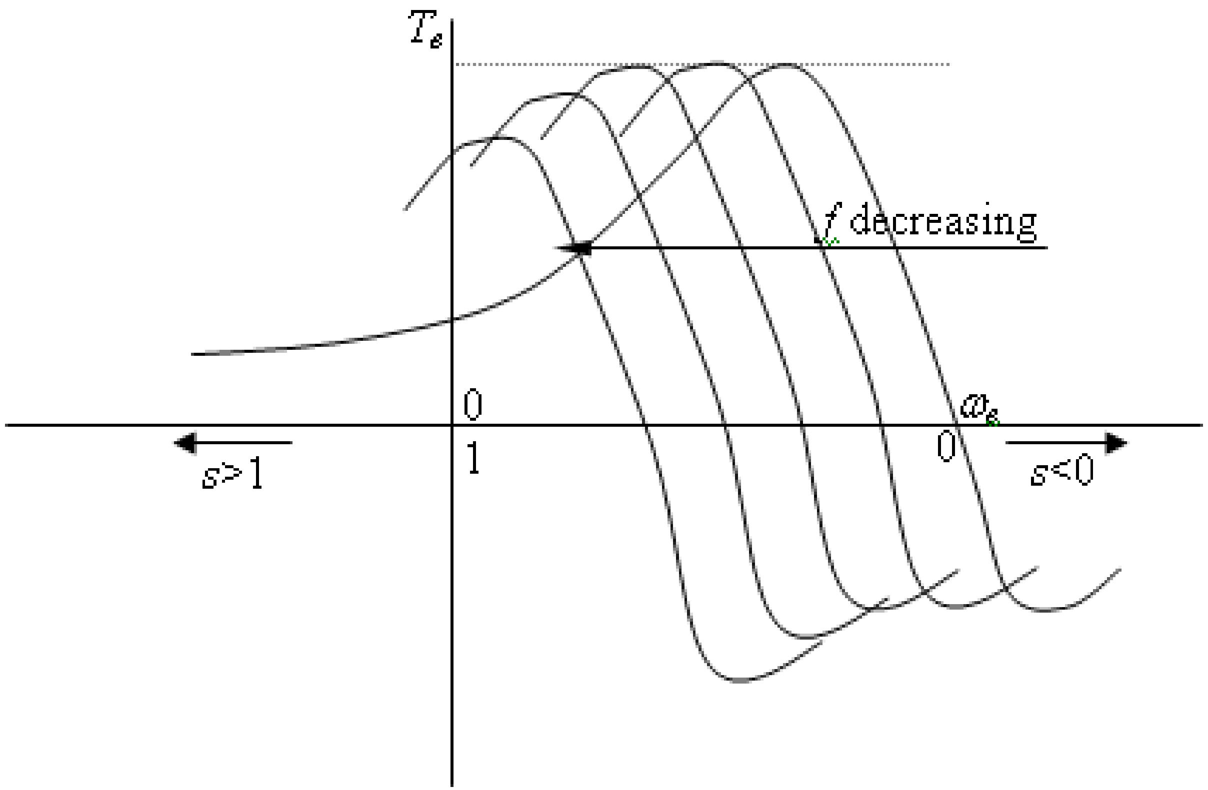
J, inertia of motor

ω, Angular speed(rad/s)

v, Vehicle speed (m/s)

Motor torque

$$T = \frac{R_2^{'} V_1^2}{s\{R_1^2 + (X_1 + X_2^{'})^2\} + \frac{R_2^{'2}}{s} + 2R_1 R_2^{'}} \frac{1}{\omega_s}$$



Thank you!