Electric Vehicle (EE60082)

Lecture 5: Motor drive for EV

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Summary of resistances (recap)

- Drag resistance

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

- Rolling resistance

$$F_r = P f_r \qquad f_r = f_0 + f_s V^2$$

- Grading resistance

$$F_g = mg\sin\alpha$$

- ρ is air density,
- A_f is front area,
- C_D is drag co-efficient,
- V is vehicle velocity (in m/s)
- V_w is wind velocity (in m/s)
- P is vertical force on wheel
- f_0 and f_s are rolling resistance co-efficient
- α is slope angle of road

Example (recap)

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, ρ = 1.18 kg/m^3, g = 9.81 m/s^2

$$\frac{dV}{dt} = K_1 - K_2 V^2$$

where

$$K_1 = \frac{F_{TR}}{m} - g f_0 \,, \qquad K_2 = \frac{\rho}{2m} C_D A_F + g f_s$$

The vehicle is accelerated with constant tractive force of 500N produced by the powertrain.

- (a) find terminal velocity
- (b) calculate the time required to accelerate to 50kmh

Terminal Velocity: $V_T = \lim_{t\to\infty} v(t) = \sqrt{\frac{K_1}{K_2}}$

The time to reach a desired velocity V_f

$$t_f = \sqrt{\frac{1}{K_1 K_2}} \tanh^{-1}\left(\sqrt{\frac{K_2}{K_1}} V_f\right)$$

Limitations? (recap)

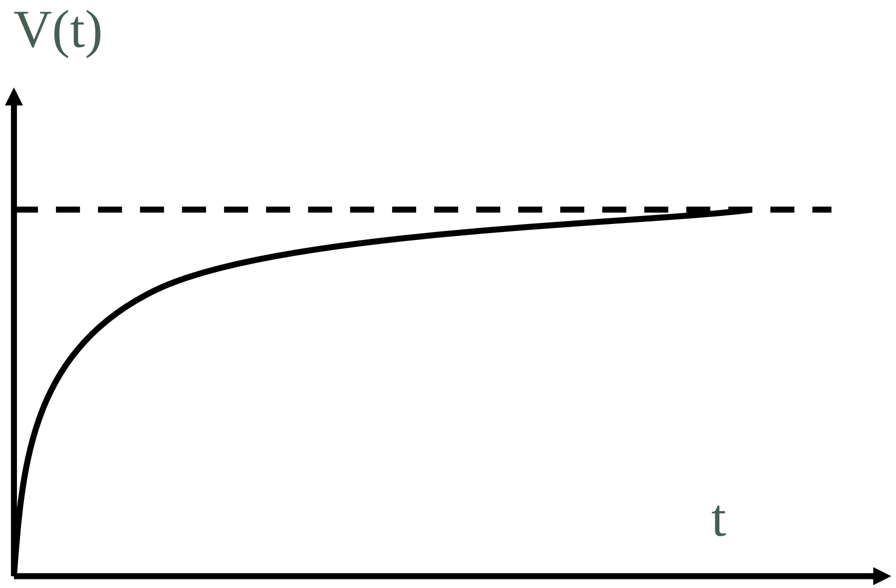
$$\frac{dV}{dt} = K_1 - K_2 V^2$$

where

$$K_1 = \frac{F_{TR}}{m} - g\,f_0\ , \qquad K_2 = \frac{\rho}{2m} C_D A_F + g\,f_s$$

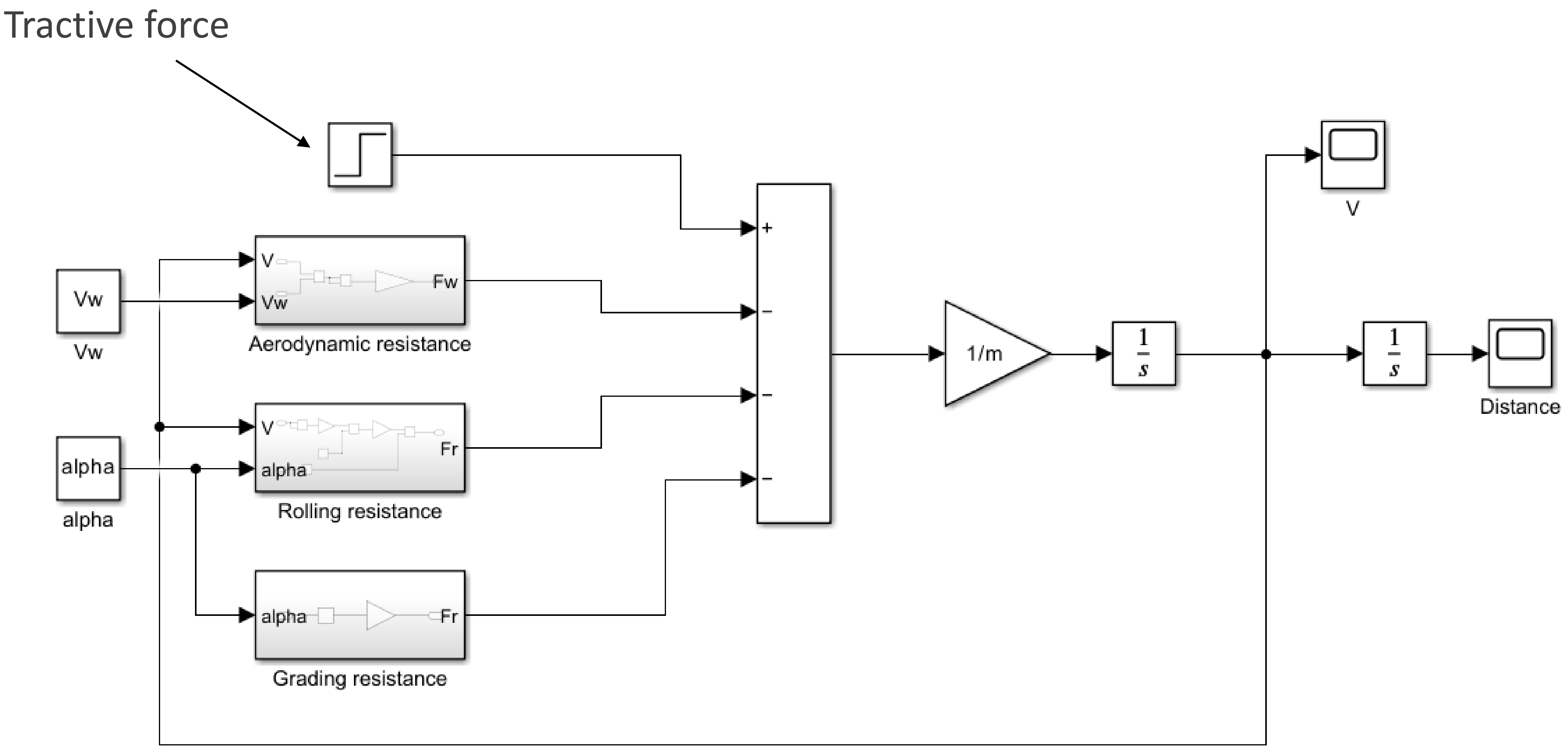
The velocity profile:

$$V(t) = \sqrt{\frac{K_1}{K_2}}\ \tanh(\sqrt{K_1 K_2}\ \ t)$$

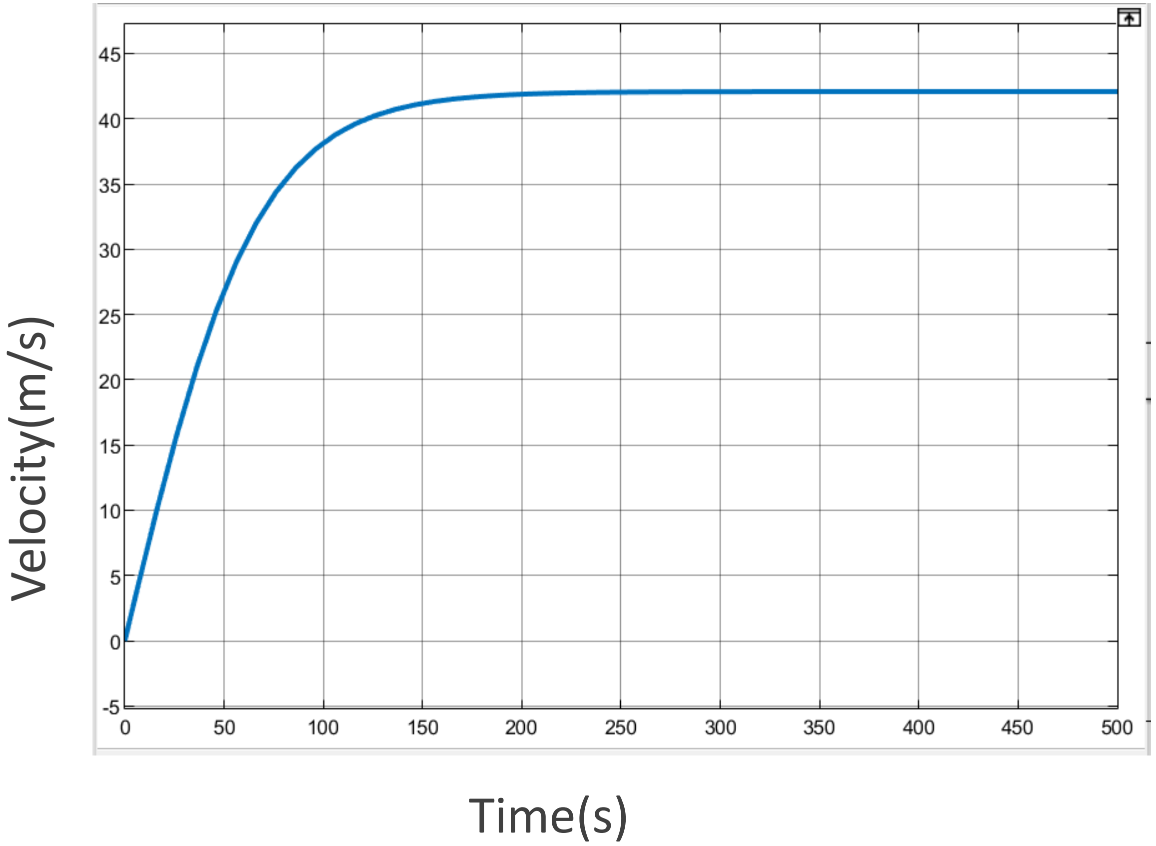


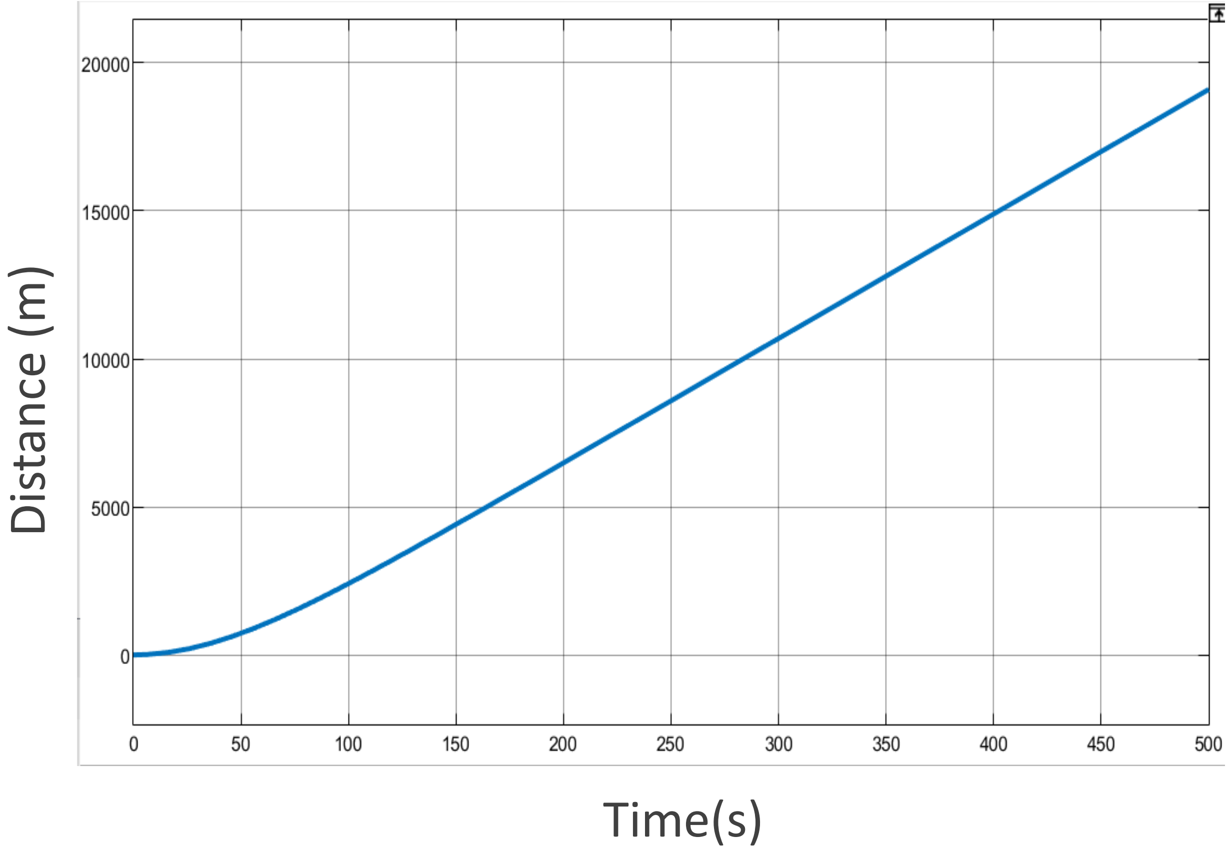
- Can we use these equations to design a car?

Simulation model (recap)

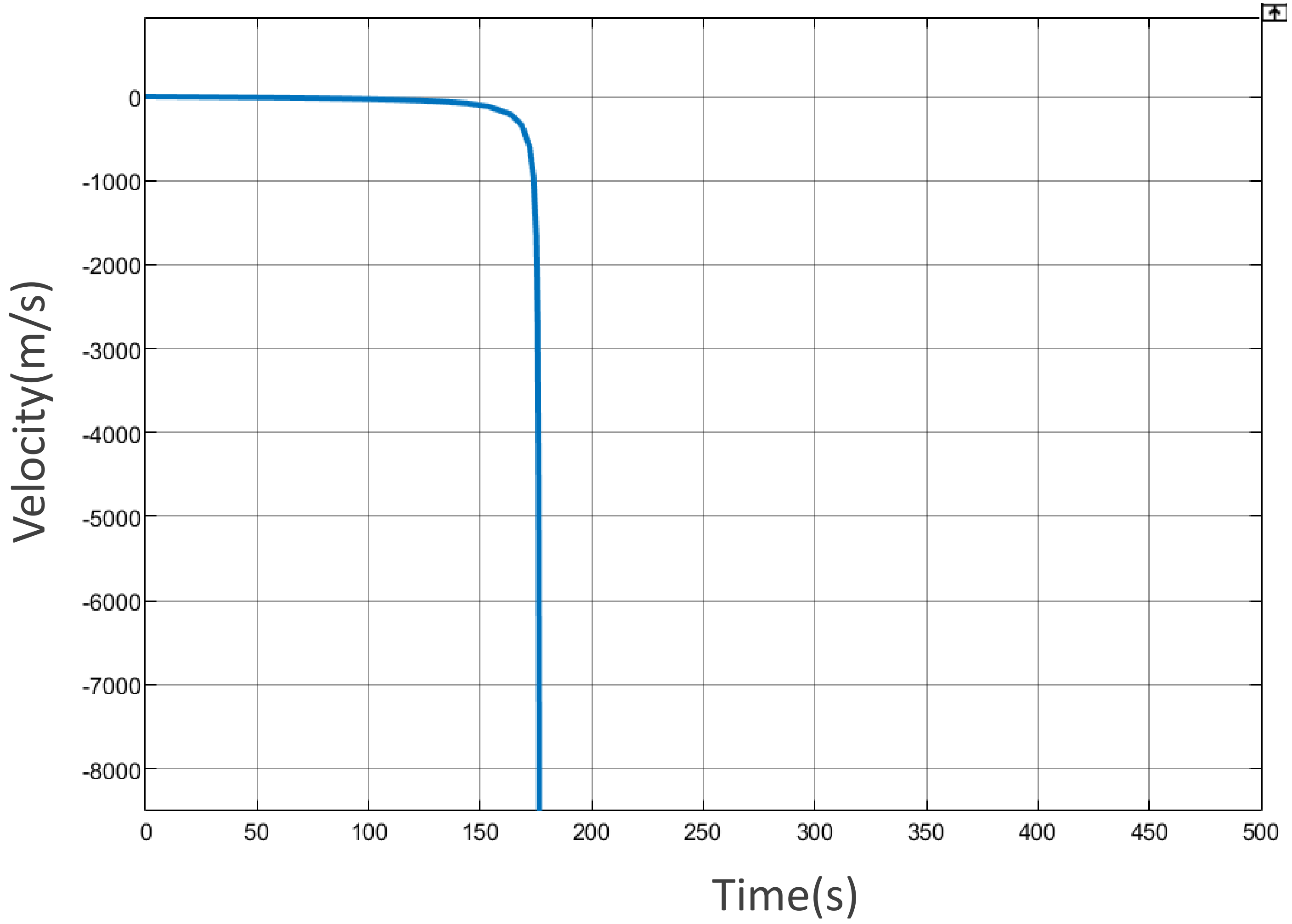


Simulation with α=0, Vw=0 (recap)

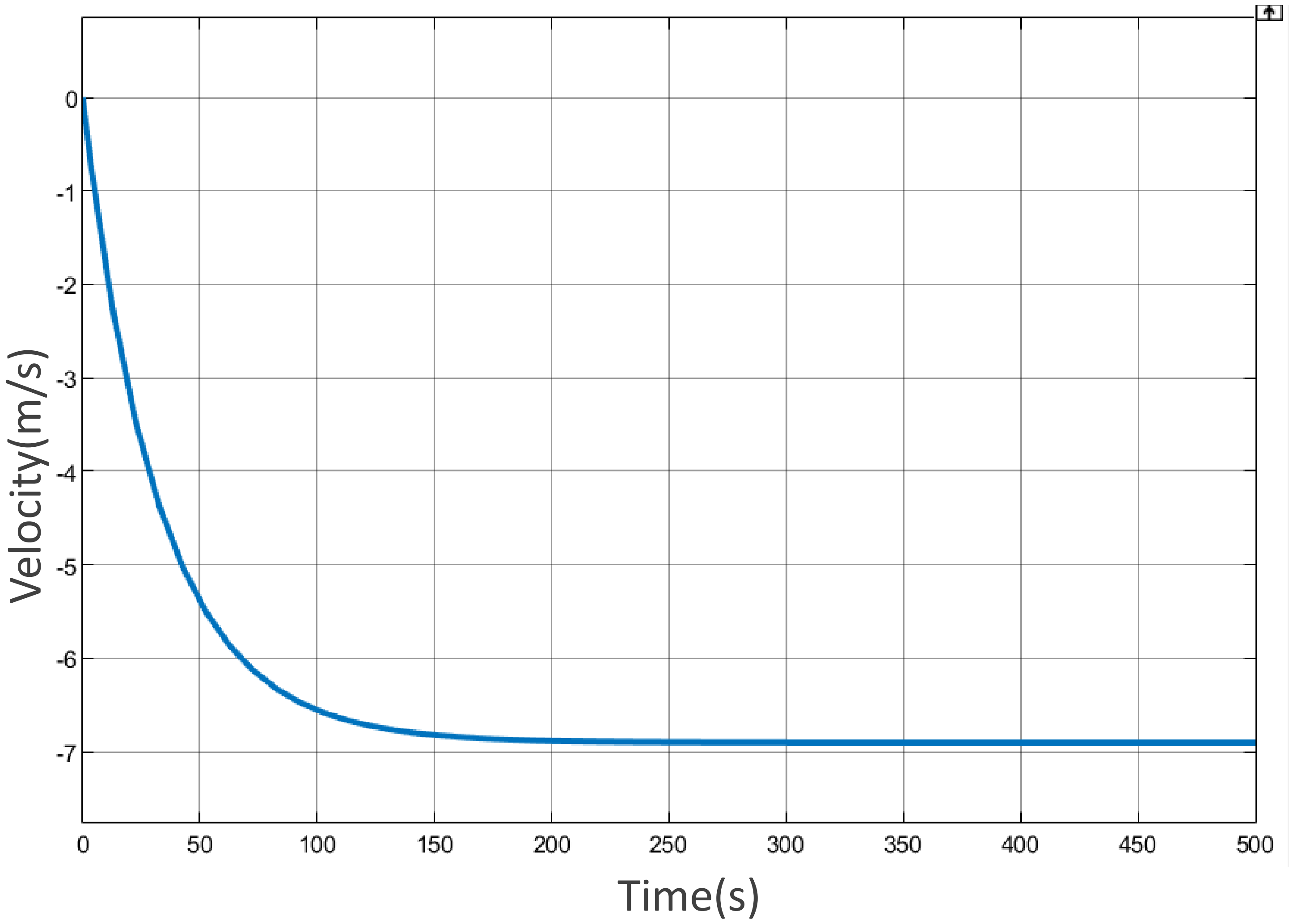




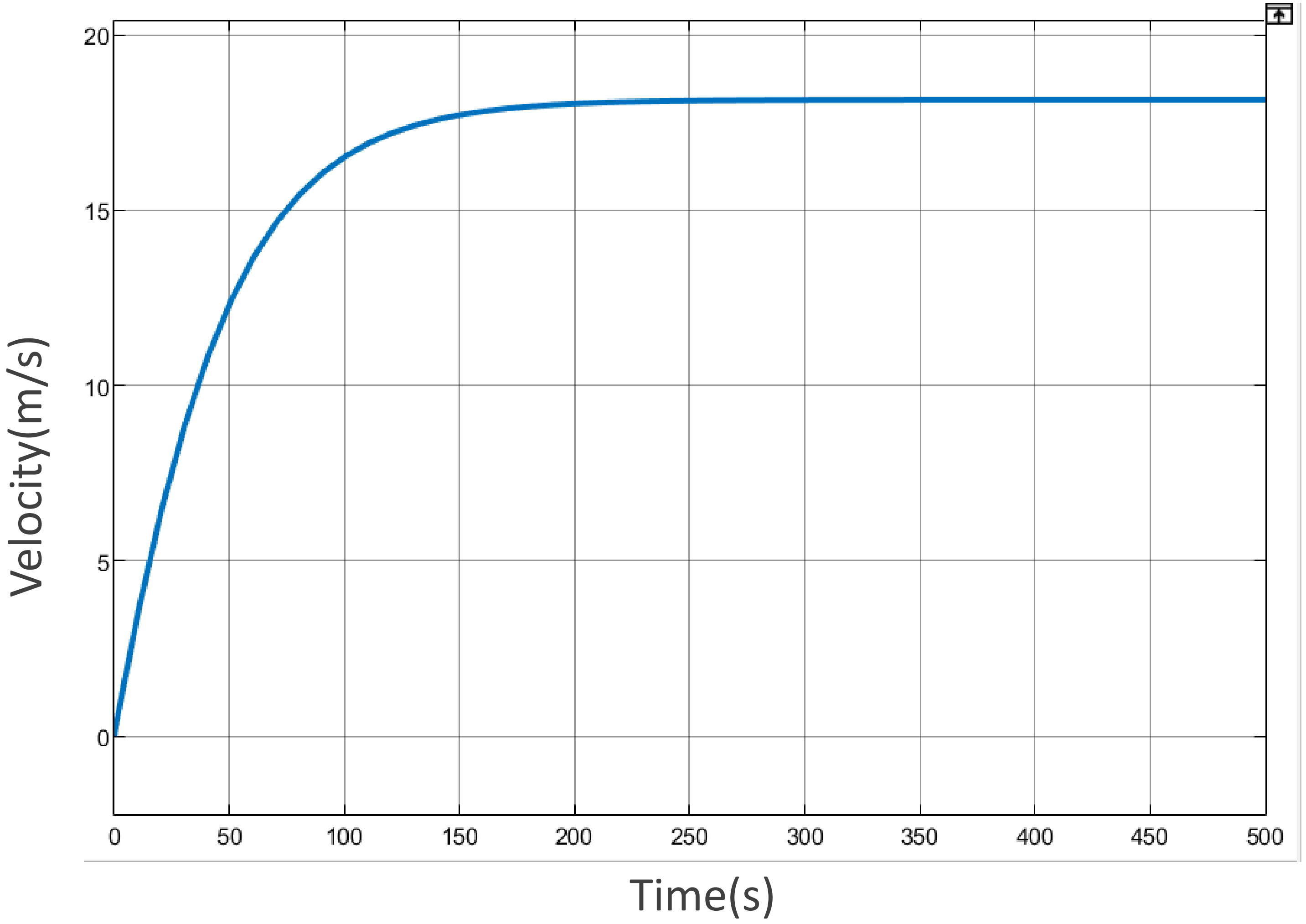
Simulation with α=5°, Vw=0 (recap)



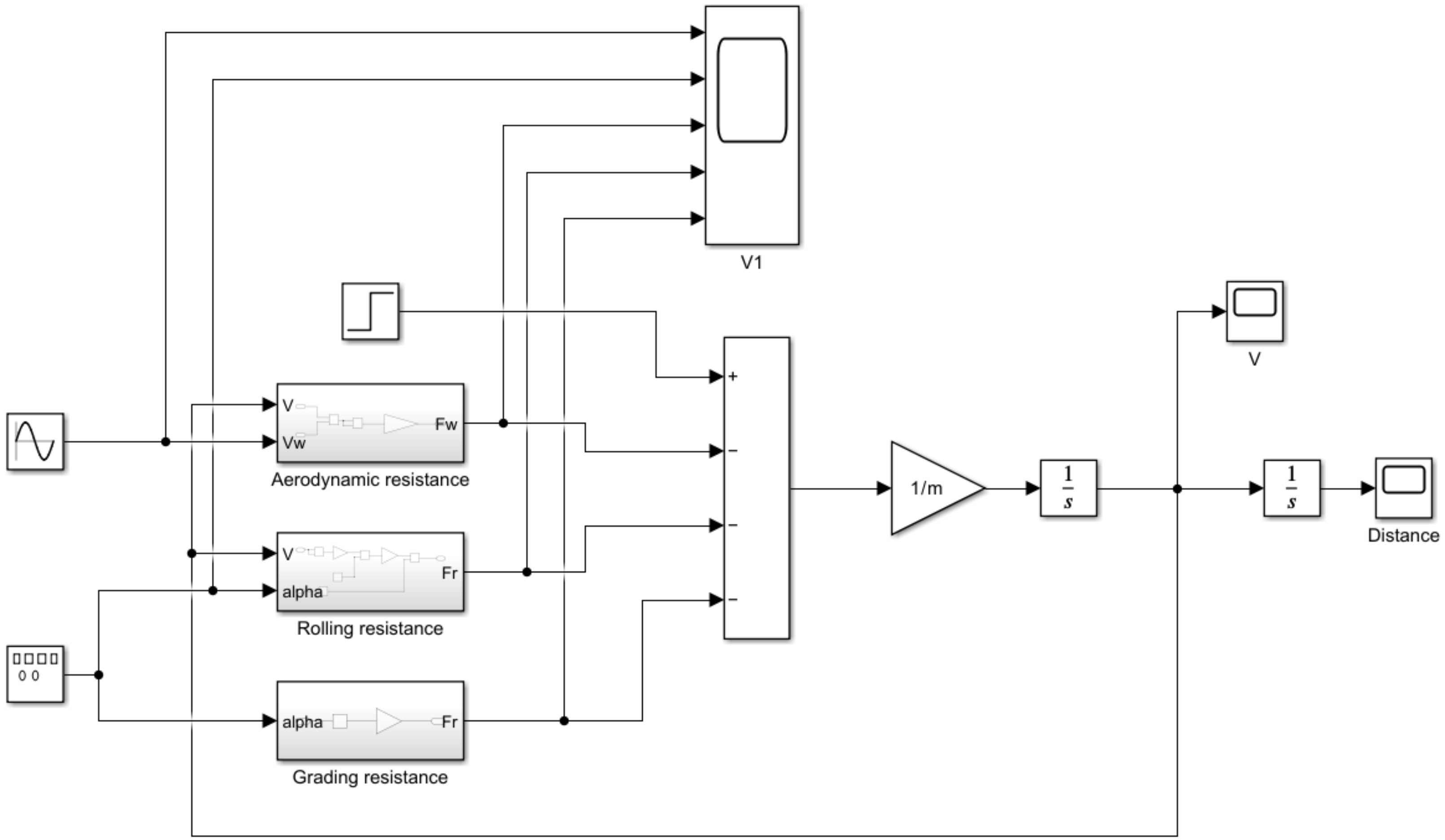
Simulation with α=0º, Vw=10m/s, Ftr=500N



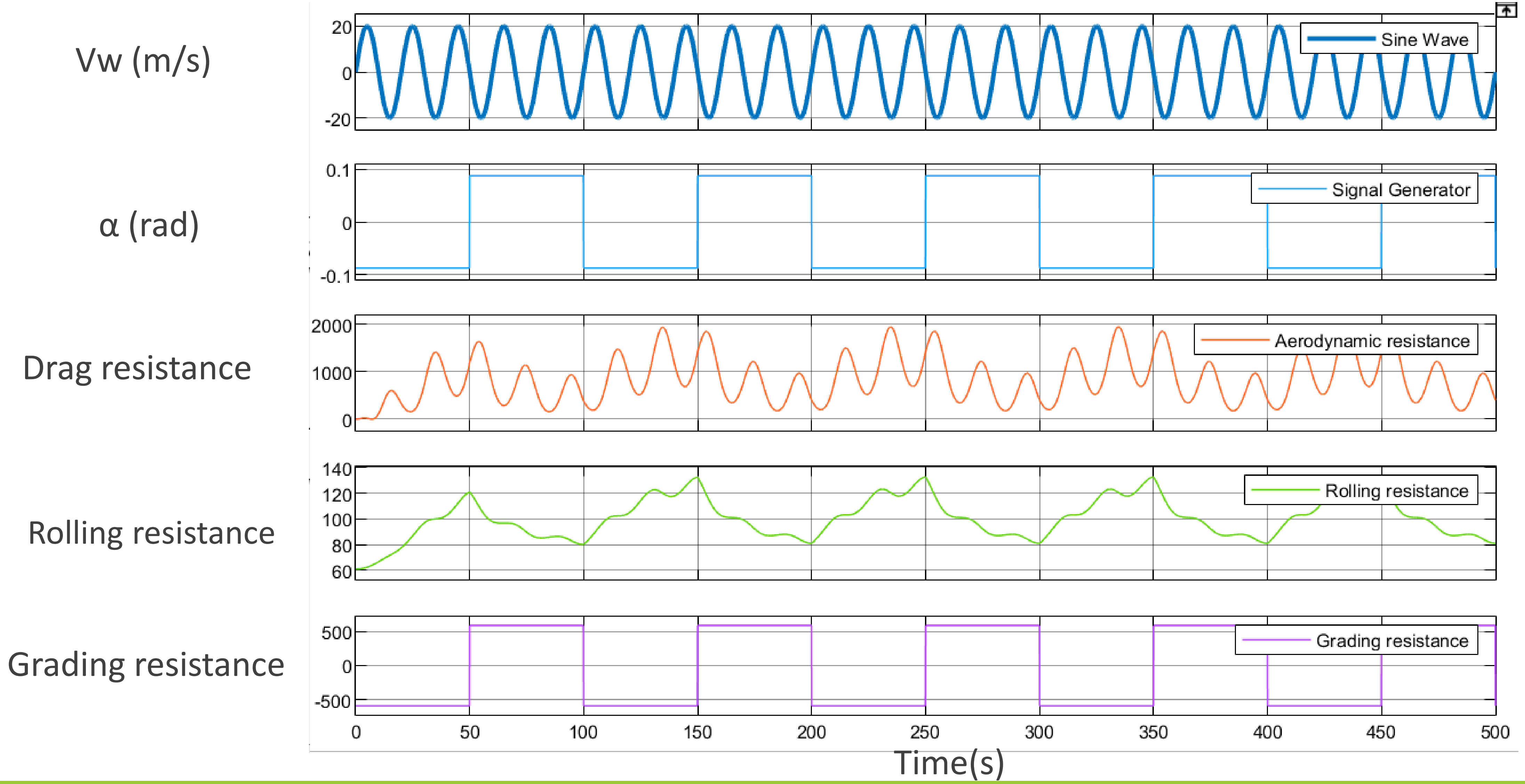
Simulation with α=5°, Vw=20m/s, Ftr=1000N



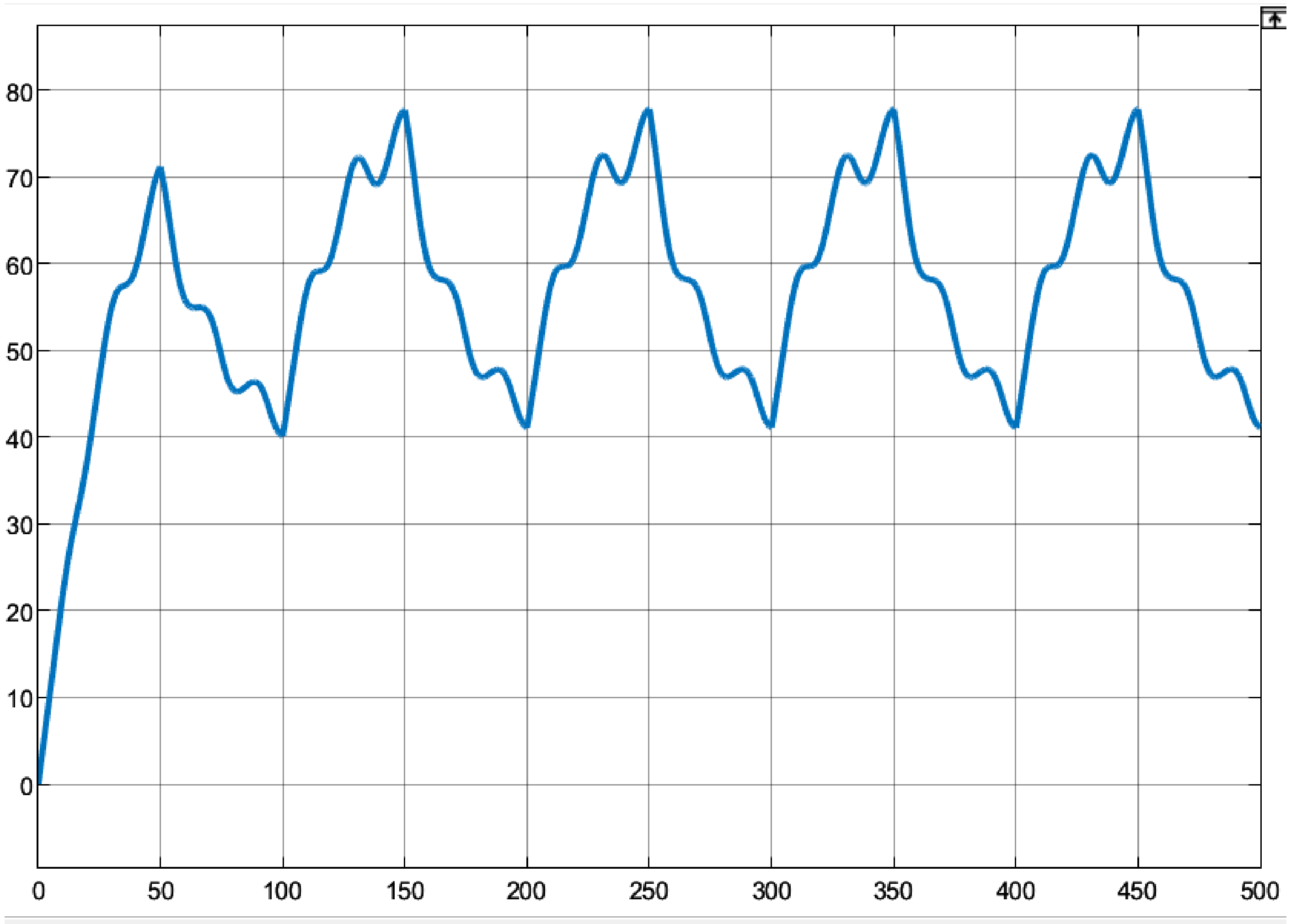
Simulation with variable Vw and α



Variable disturbances (Ftr=1000N)



Car speed



- Car speed is greatly impacted by external disturbances
- need for speed control

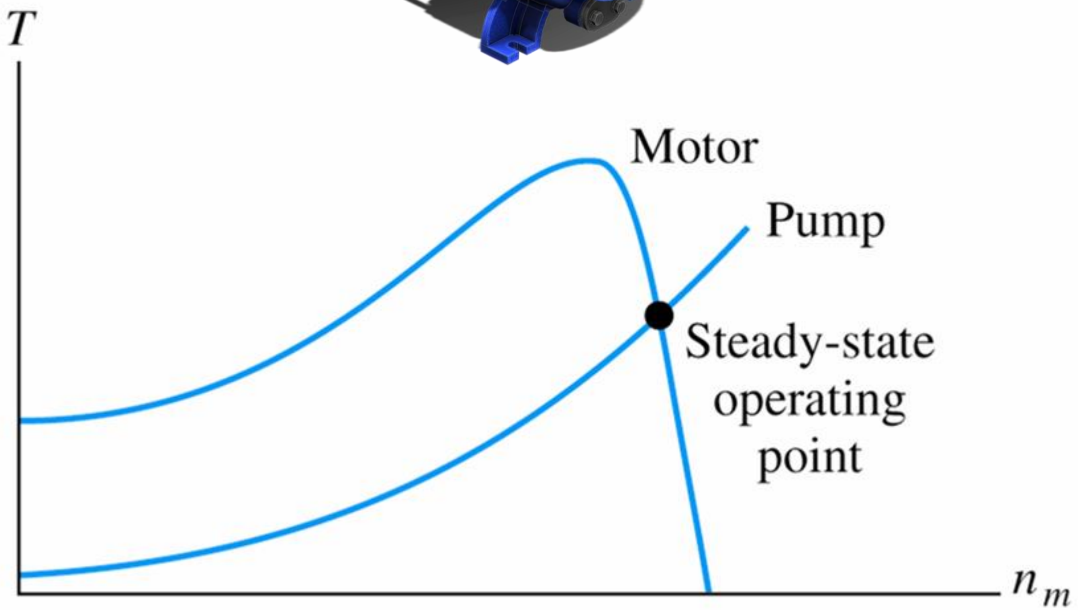
Module 2: Machine drive for EV

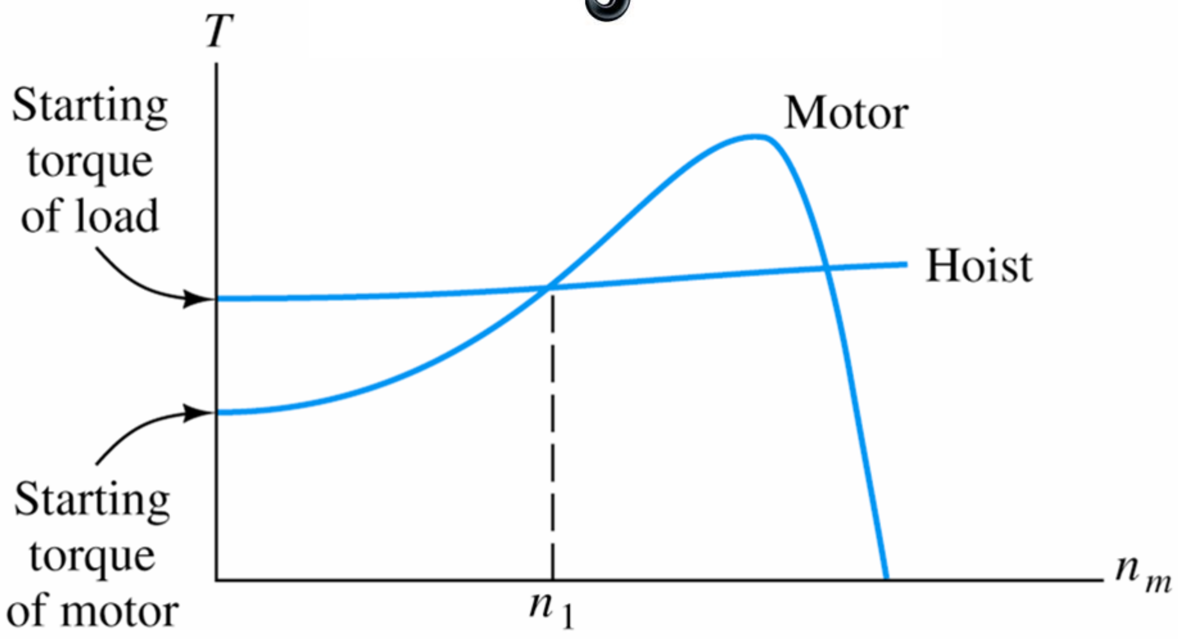
Traction motors for EV

Commonly used motors:

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

Torque-speed requirement





Torque-speed requirement for EV

High-way Drive: high speed, torque can be low;

Climbing Hills: high torque, speed can be low;

Motor speed range: wide, otherwise gear box is needed.

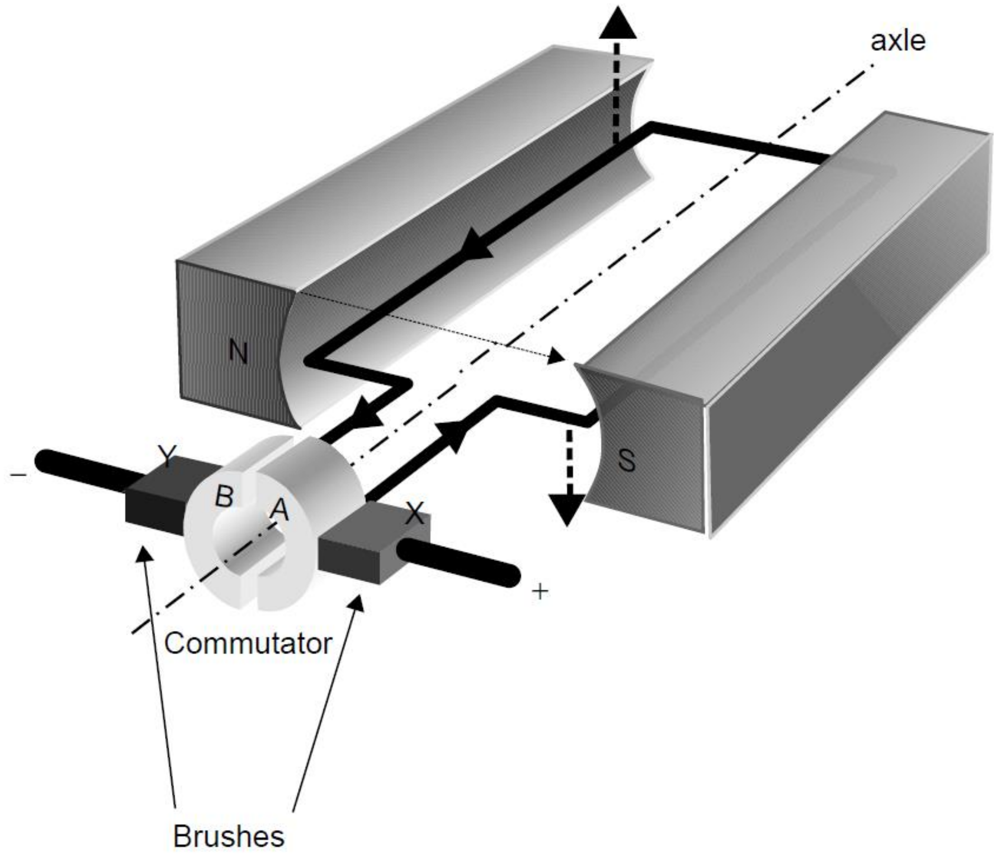
Common electrical machines-DC machine

- Force on a current carrying conductor

$$F = I \cdot L \cdot B \cdot \sin(\theta)$$

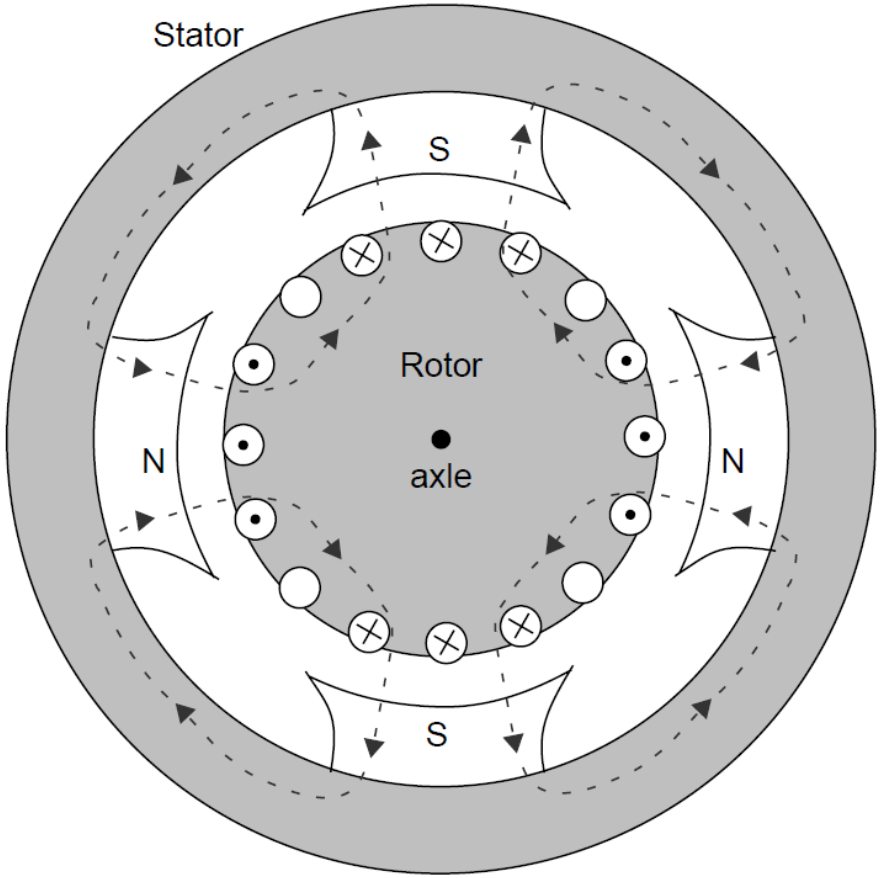
- Force on two conductors are in opposite direction
  - follows right hand rule
  - Creates torque that rotates the coil

- Commutator ensures that the coil rotates in the same direction



Common electrical machines-DC machine

- Iron core used to reduce air gap
  - To increase magnetic field
- measures to increase generated torque
  - Multiple coils
  - Each coil with multiple turns
  - Multiple magnets
  - Multi-segment commutator



Common electrical machines-DC machine

- Torque generated by one coil,

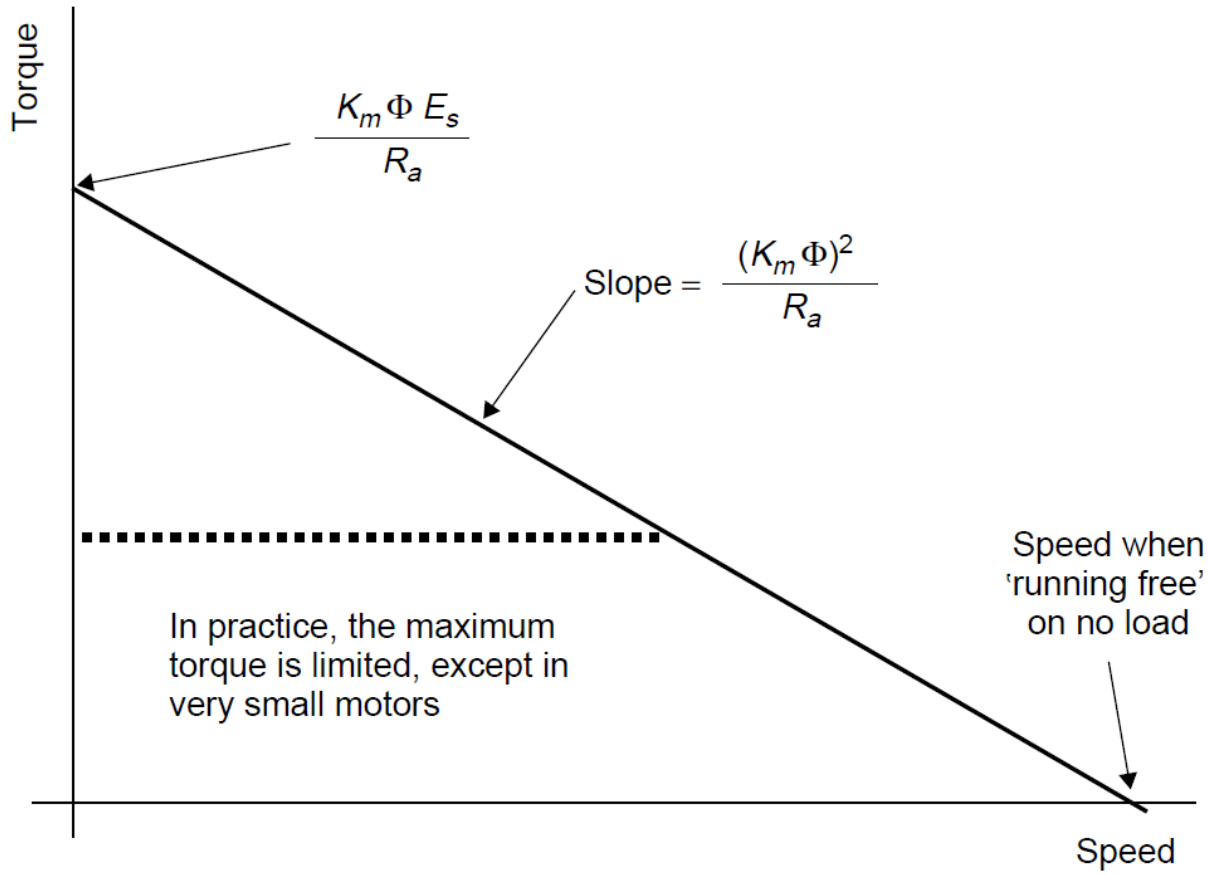
$$T = n\Phi I$$

- Overall torque $\quad T = K_m \Phi I$
- Coil current

$$I = \frac{V}{R_a} = \frac{E_s - E_b}{R_a} = \frac{E_s}{R_a} - \frac{K_m \Phi}{R_a}\omega$$

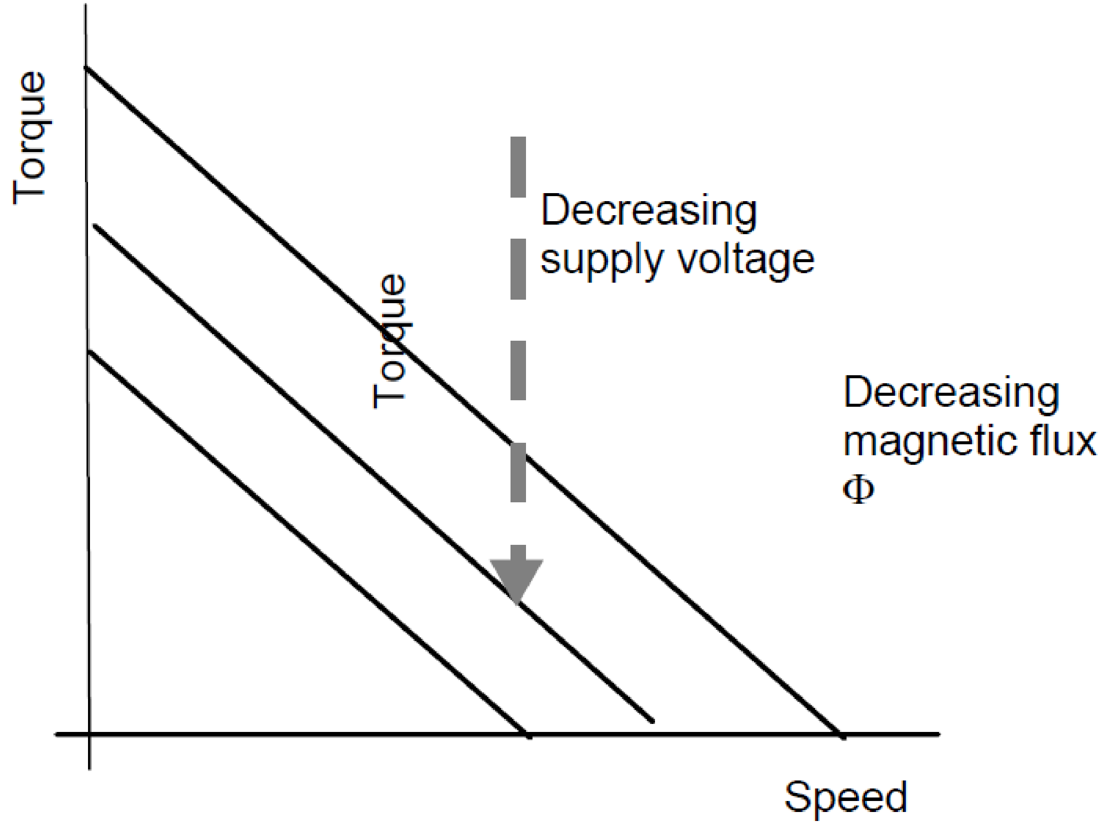
- Torque equation

$$T = \frac{K_m \Phi E_s}{R_a} - \frac{(K_m \Phi)^2}{R_a}\omega$$



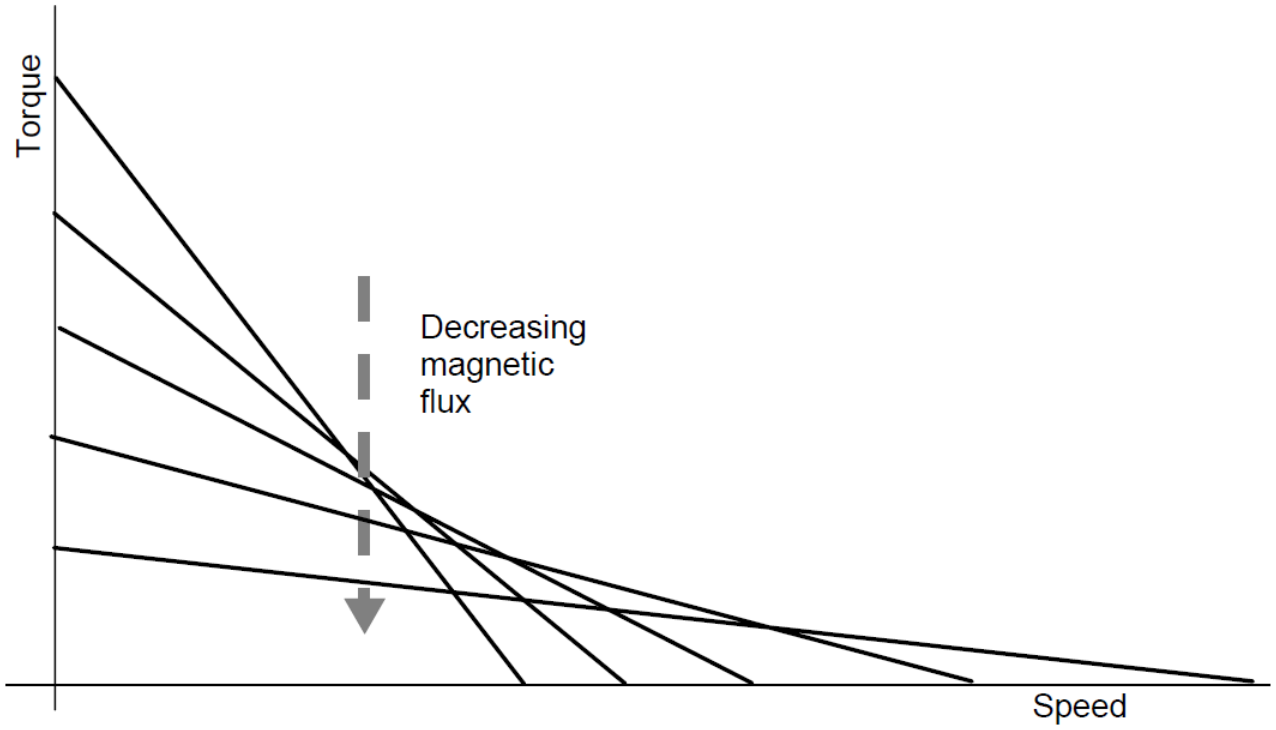
Common electrical machines-DC machine

- Control with supply:
  - supply voltage is reduced
  - maximum torque falls in proportion,
  - slope of the torque/speed graph is unchanged
  - any torque and speed can be achieved below the maximum values



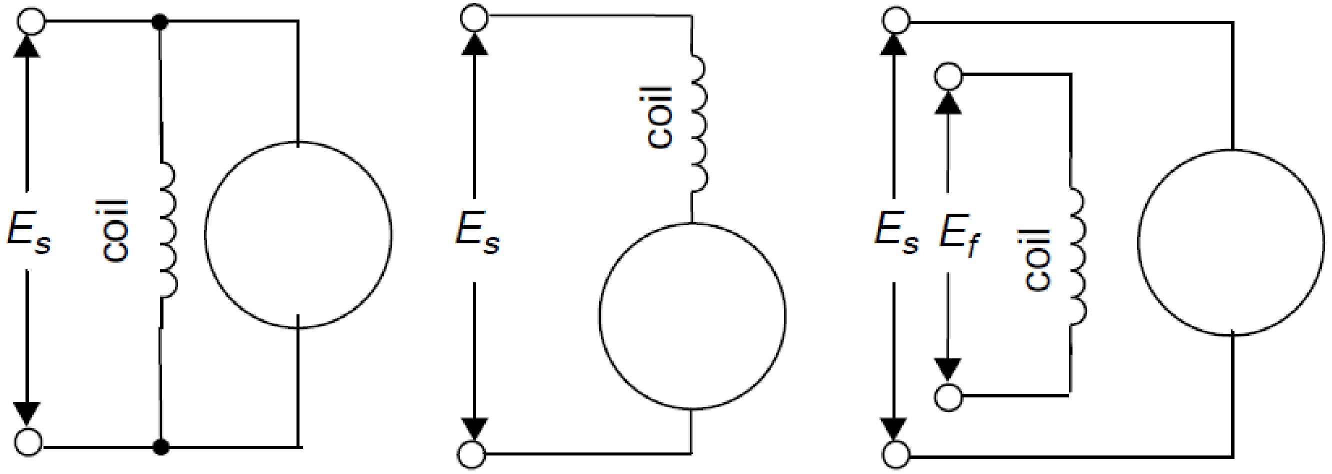
Common electrical machines-DC machine

- Control with magnetic field:
  - magnetic flux can be controlled in some DC machines
  - Magnetic field is produced by coil, not by permanent magnet
  - higher speed can be achieved during low torque operation
  - Main advantage: produce strong magnetic field at lower cost
  - Main drawback: additional losses in the field winding
    - Can be somewhat compensated by more efficient operation of motor



DC motor with field winding

- Shunt motor:
  - Hard to control
- Series motor:
  - Large initial torque
  - Not suitable for all traction application
- Separately excited motor:
  - independent field control
  - Popular for EV applicaiton



DC motor losses

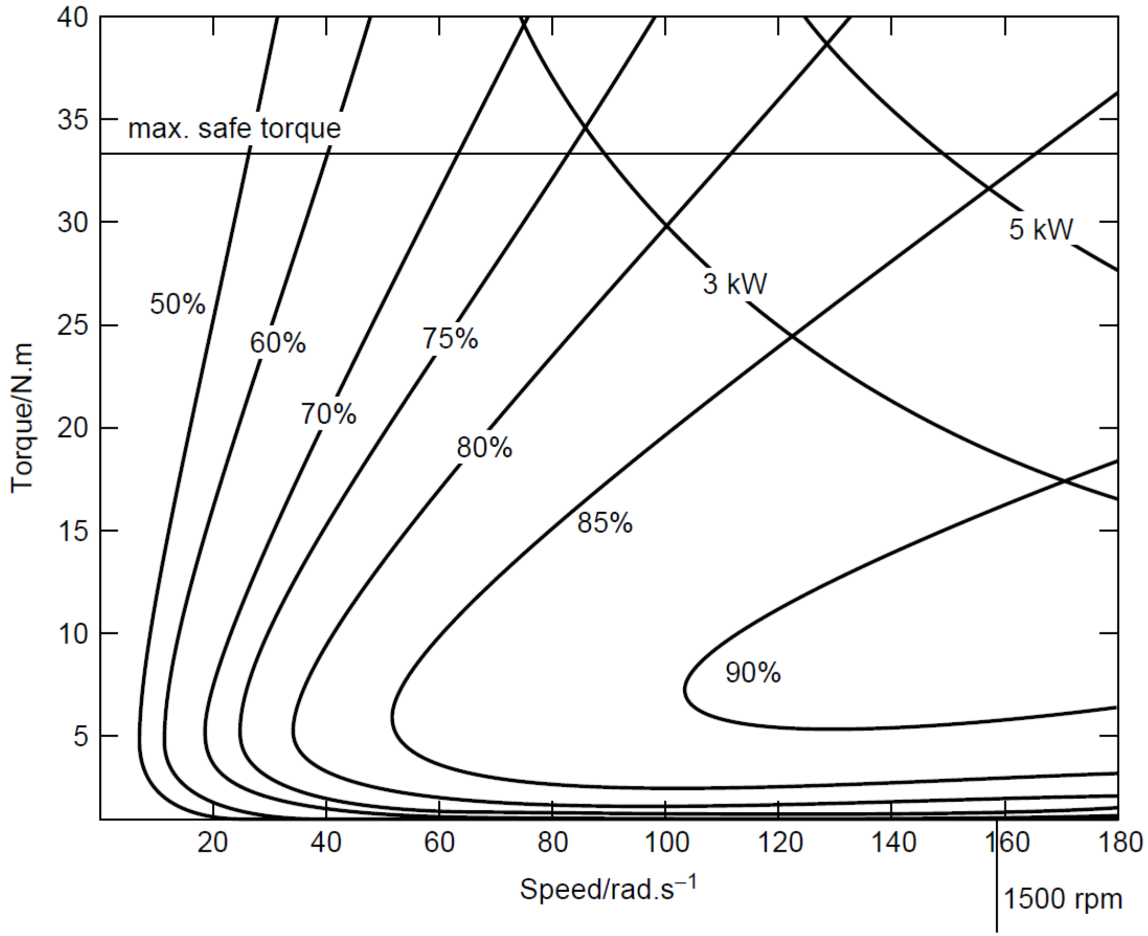
$$\text{Copper losses} = k_c T^2$$

$$\text{Iron losses} = k_i \omega$$

$$\text{friction power} = T_f \omega$$

$$\text{windage power} = k_w \omega^3$$

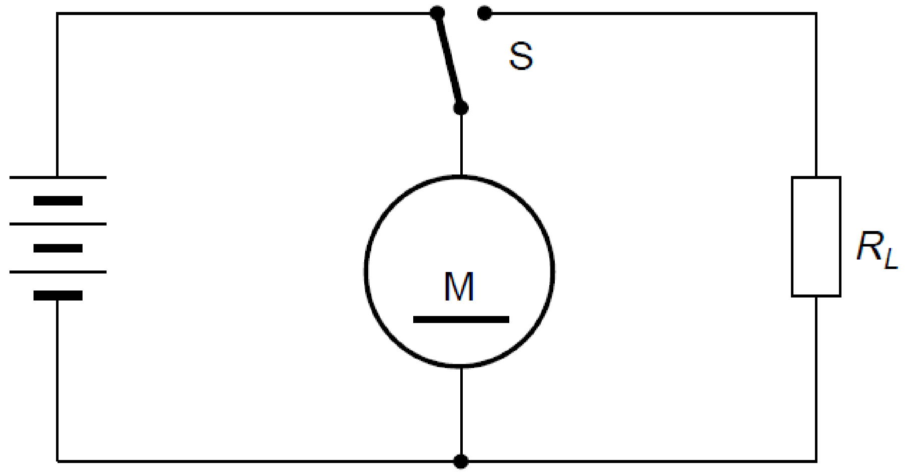
$$\text{total losses} = k_c T^2 + k_i \omega + k_w \omega^3 + C$$



Electric braking

- In braking mode, supply voltage is disconnected from motor
- as wheels are still rotating due to inertia, the motor generates back emf

$$I = \frac{K_m \Phi \omega}{R_a + R_L} \qquad T = -\frac{(K_m \Phi)^2 \omega}{R_a + R_L}$$



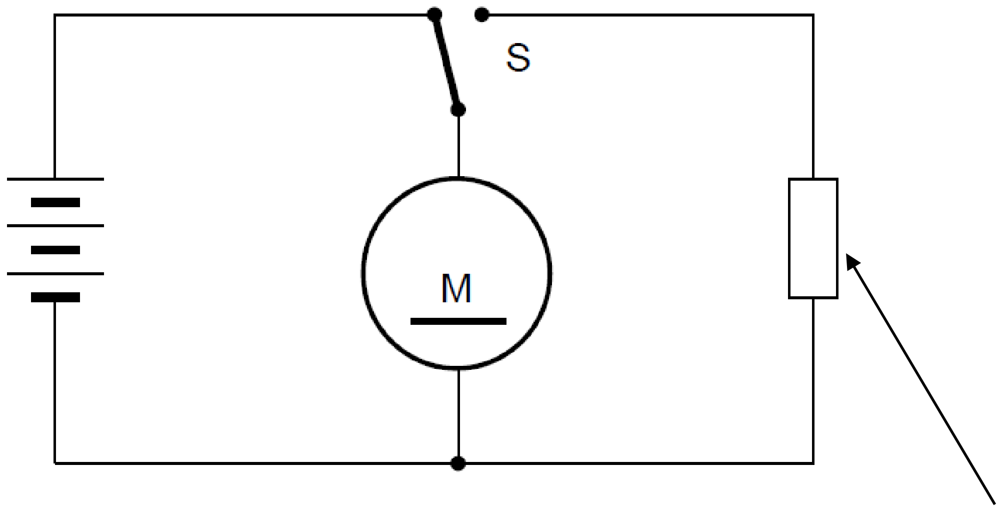
- This current flows out of motor, producing a reverse torque (braking action)
- This is called dynamic braking
- This is not regenerative braking
- Braking is wasted as heat

Electric braking - regenerative

- In braking mode, motor is connected to a low voltage battery
- Current into battery is,

$$I = \frac{V}{R} = \frac{K_m \Phi \omega - V_b}{R_a}$$

- This current flows out of motor, producing a reverse torque (braking action)
- This is called regenerative braking

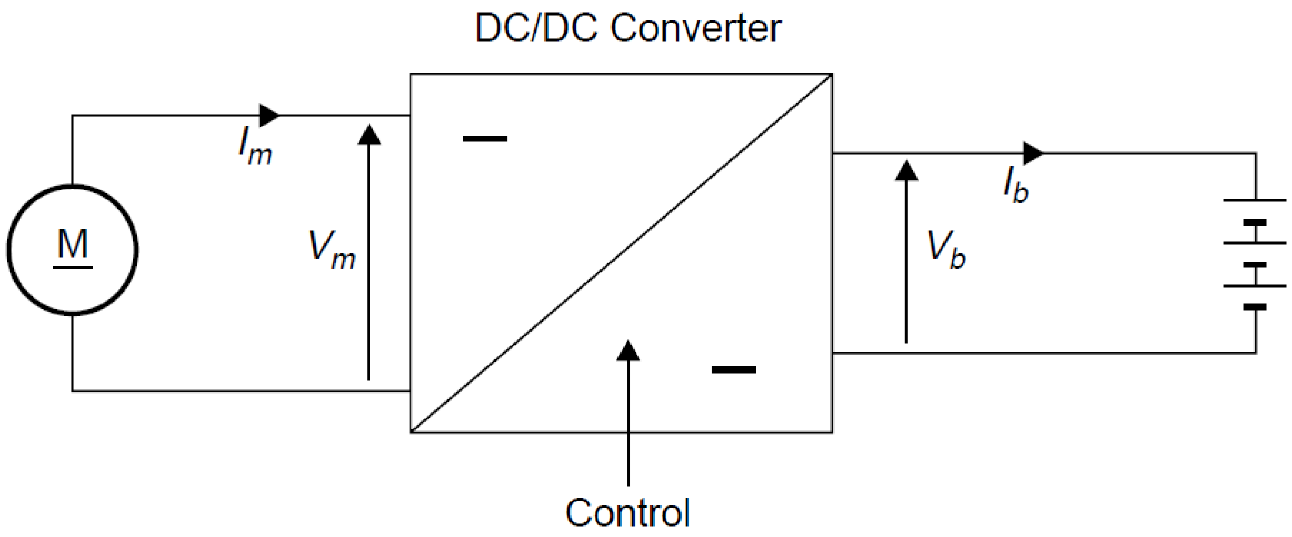


Low-voltage battery

- Large uncontrolled current
- Regeneration not possible at low speed

Electric braking - regenerative

- Energy transfer to a battery with controlled current possible with a DC-DC power converter
- Can support wide rage of battery voltage
- No need for a separate low-voltage battery
- Effective for entire range of speed
- Highly efficient energy transfer
- Fast control of braking power



Choice of converter

- basic DC-DC converters: buck, boost, buck-boost
- Ex1: motor rated voltage 550V, battery nominal voltage 400V, range of battery voltage 300V-460V
- Which converter to choose?

DC motor model

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + e_A \Rightarrow \frac{di_a}{dt} = \frac{1}{L_a}(V_a - i_a R_a - e_a)$$

$$J\frac{d\omega}{dt} = T_{em} - T_L - B\omega \Rightarrow \frac{d\omega}{dt} = \frac{1}{J}(T_{em} - T_L - B\omega)$$

L_a, armature inductance

R_a, armature resistance

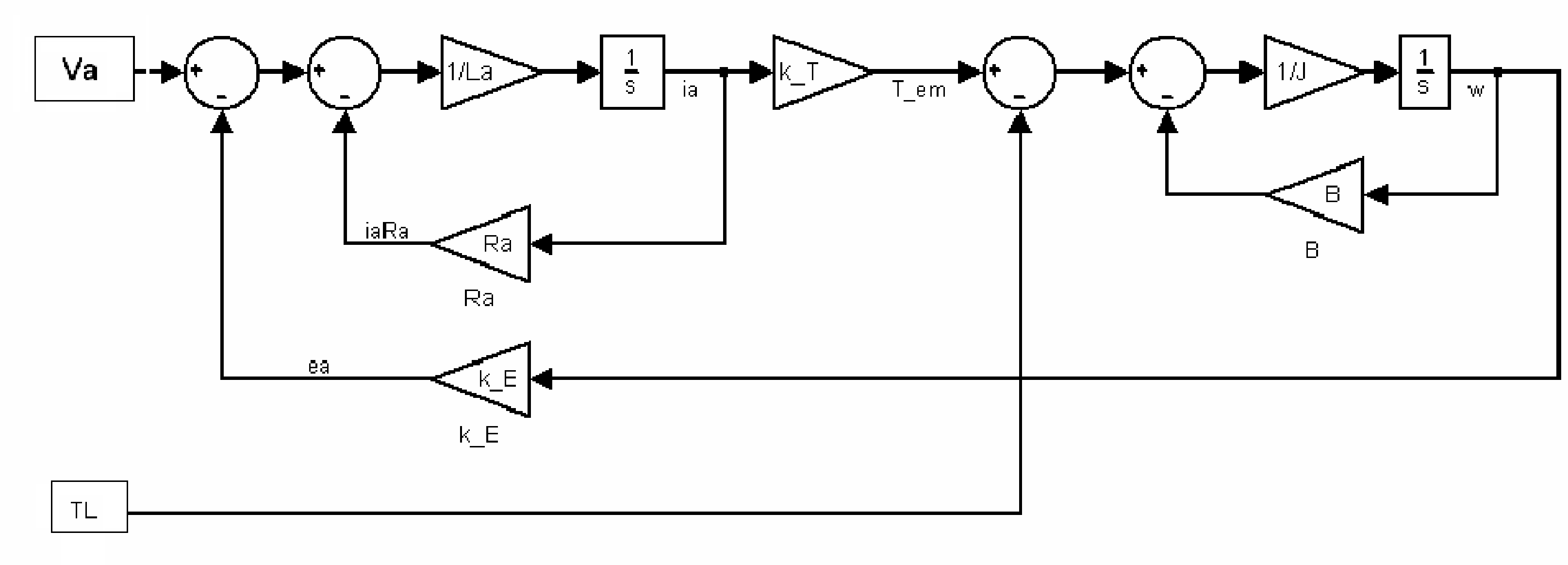
K_T, torque constant

K_E, emf constant

B, shaft damping constant

J, inertia

DC motor model



L_a, armature inductance

R_a, armature resistance

K_T, torque constant

K_E, emf constant

B, shaft damping constant

J, inertia

DC machine drawbacks

- 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

Thank you!