Power Electronics

Introduction to Motor Drives

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Chapter 12

Introduction to Motor Drives

Chapter 12 Introduction to Motor Drives 367

- Motor drives are one of the most important applications of power electronics

12-1 INTRODUCTION

- Motor drives are used in a very wide power range, from a few watts to many thousands of kilowatts, in applications ranging from very precise, high-performance position controlled drives in robotics to variable-speed drives for adjusting flow rates in pumps. In all drives where the speed and position are controlled, a power electronic converter is needed as an interface between the input power and the motor.
- A general block diagram for the control of motor drives is shown in Fig. 12-1. The process determines the requirements on the motor drive; for example, a servo-quality drive (called the servo drive) is needed in robotics, whereas only an adjustable-speed drive may be required in an air conditioning system, as explained further.

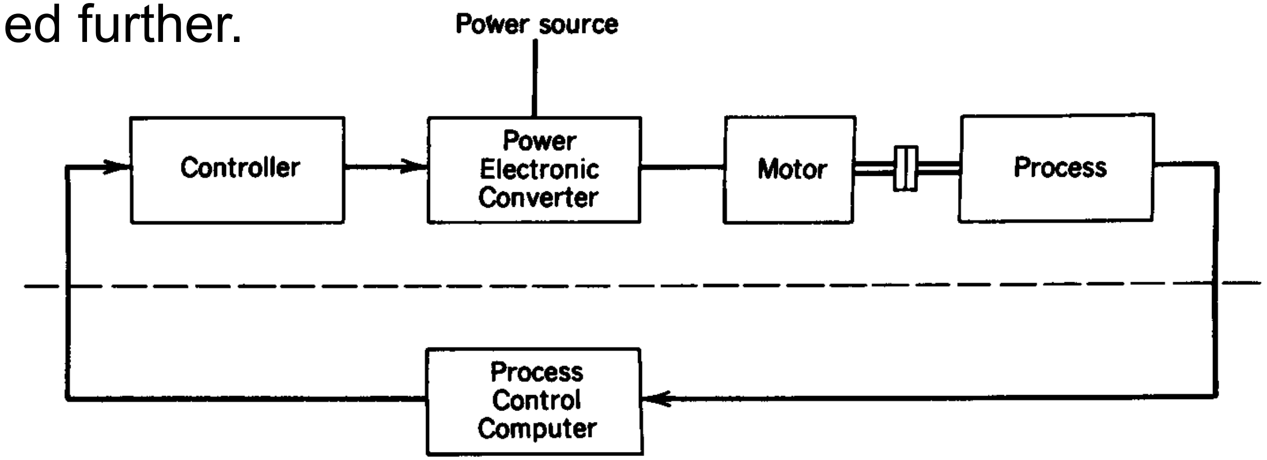


Figure 12-1 Control of motor drives.

12-1 INTRODUCTION

- In servo applications of motor drives, the response time and the accuracy with which the motor follows the speed and position commands are extremely important. These servo systems, using one of these motor drives, require speed or position feedback for a precise control, as shown in Fig. 12-2.
- In addition, if an ac motor drive is used, the controller must incorporate sophistication, such as field-oriented control, to make the ac motor (through the power electronic converter) meet the servo drive requirements.

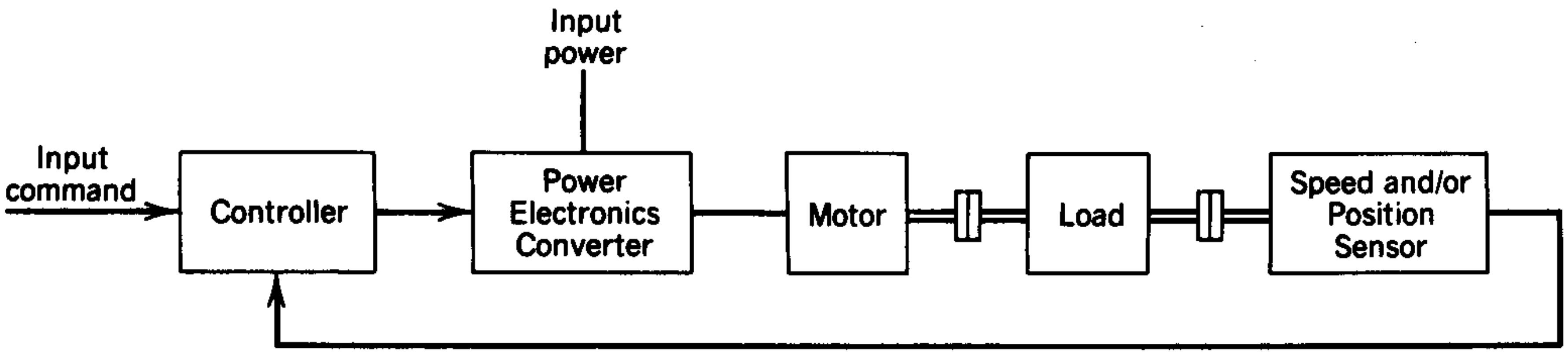


Figure 12-2 Servo drives.

12-1 INTRODUCTION

- However, in a large number of applications, the accuracy and the response time of the motor to follow the speed command is not critical. As shown in Fig. 12-1, there is a feedback loop to control the process, outside of the motor drive.
- Because of the large time constants associated with the process-control feedback loop, the motor drive's accuracy and the time of response to speed commands are not critical.
- An example of such an adjustable-speed drive is shown in Fig. 12-3 for an air conditioning system.

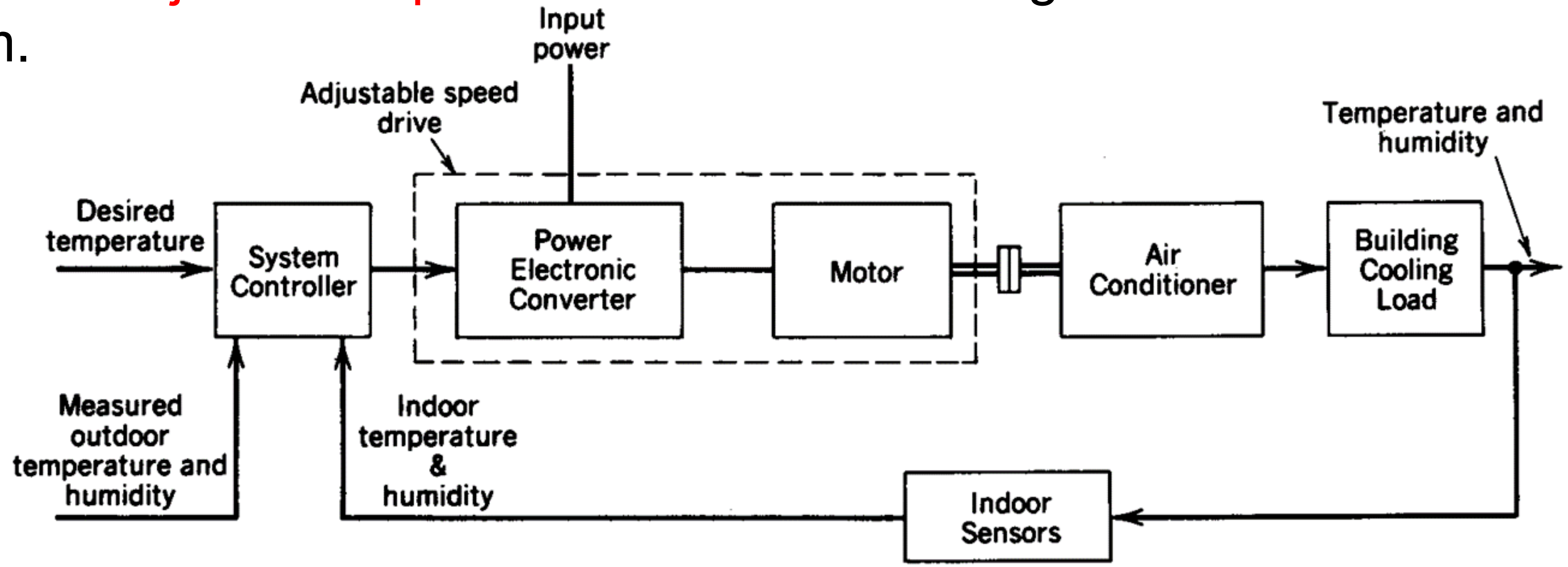


Figure 12-3 Adjustable-speed drive in an air conditioning system.

12-2 CRITERIA FOR SELECTING DRIVE COMPONENTS

- 12-2-1 MATCH BETWEEN THE MOTOR AND THE LOAD
- 12-2-2 THERMAL CONSIDERATIONS IN SELECTING THE MOTOR
- 12-2-3 MATCH BETWEEN THE MOTOR AND THE POWER ELECTRONIC CONVERTER
  - 12-2-3-1 Current Rating
  - 12-2-3-2 Voltage Rating
  - 12-2-3-3 Switching Frequency and the Motor Inductance
- 12-2-4 SELECTION OF SPEED AND POSITION SENSORS
- 12-2-5 SERVO DRIVE CONTROL AND CURRENT LIMITING
- 12-2-6 CURRENT LIMITING IN ADJUSTABLE-SPEED DRIVES

12-2-1 MATCH BETWEEN THE MOTOR AND THE LOAD

- Prior to selecting the drive components, the load parameters and requirements such as the load inertia, maximum speed, speed range, and direction of motion must be available. The motion profile as a function of time, for example as shown in Fig. 12-4a, must also be specified.
- By means of modeling the mechanical system, it is possible to obtain a load- torque profile. Assuming a primarily inertial load with a negligible damping, the torque profile, corresponding to the speed profile in Fig. 12-4a, is shown in Fig. 12-4b. The torque required by the load peaks during the acceleration and deceleration.

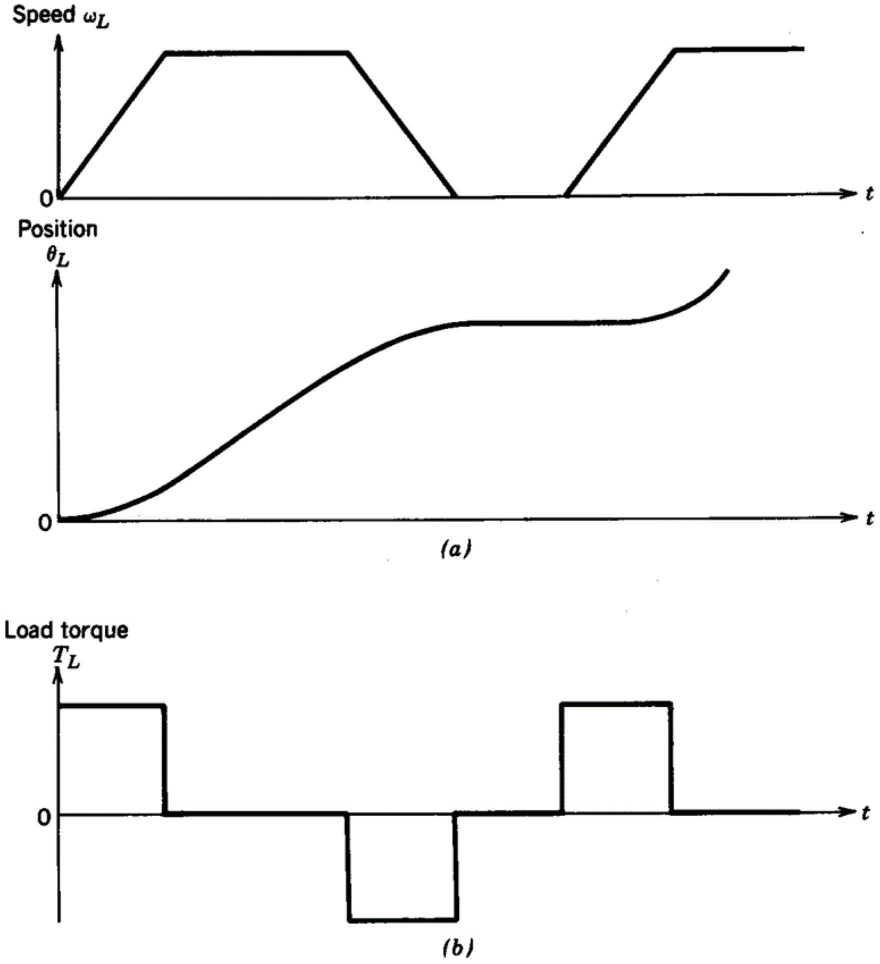


Figure 12-4 Load profile: (*a*) load–motion profile; (*b*) load–torque profile (assuming a purely inertial load).

Matlab/Simulink/Simscape Simulations

Description

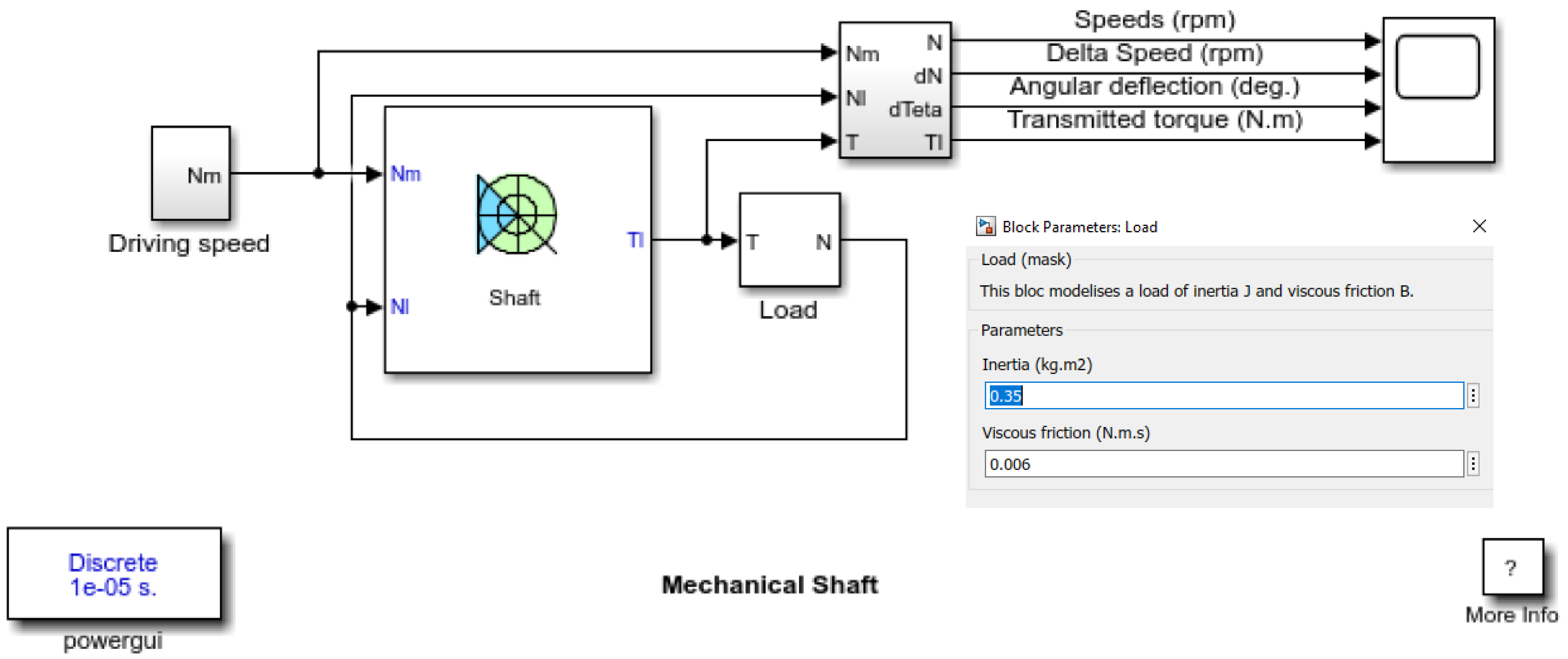
The model outputs the transmitted torque through the shaft regarding the speed difference between the driving side and the loaded side of the shaft.

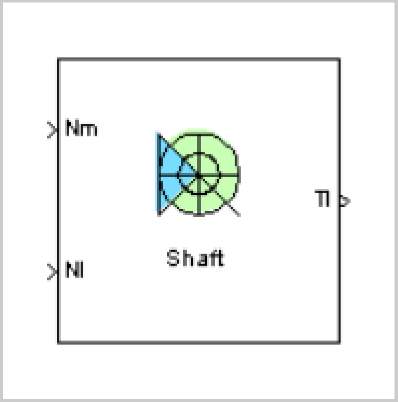
The shaft has a stiffness of 17190 N.m and an internal damping factor of 600 N.m.s. This shaft is designed to have 0.1 degree of angular deflection for a 30 N.m load torque.

The shaft is driven by a variable speed source and is connected to a load. The load has an inertia of 0.35 kg.m2 and a viscous friction term of 0.006 N.m.s

\Part2\Ch12-Intro to Motor Drives\SimScape\shaft_example.slx

Matlab/Simulink/Simscape Simulations – shaft_example.slx





Symbols used:

D_o = Outside diamater of rubber bushing, (mm, in)

D_i = Inside diamater of rubber bushing, (mm, in)

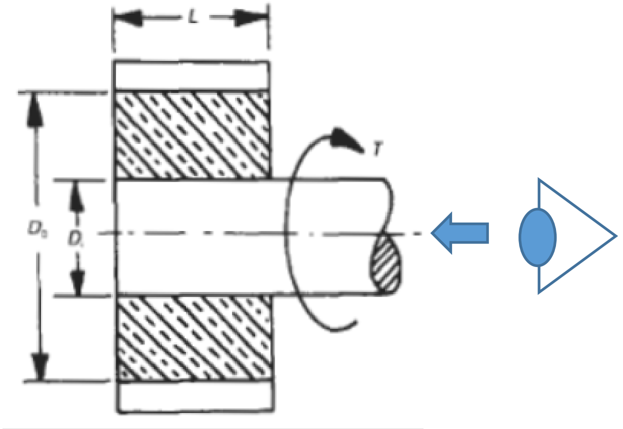
P = Loading Force, (N, lbs)

L = Rubber thickness, (mm, in)

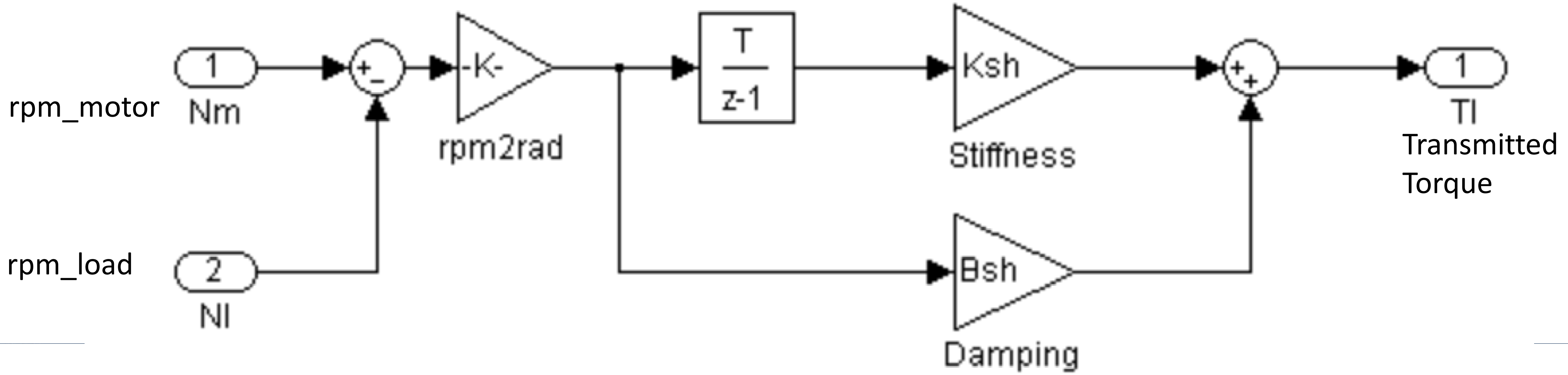
T = Torque (N-mm, lb-in)

θ = Angle of Twist Radians

G = Shear modulus



Simulink Schematic

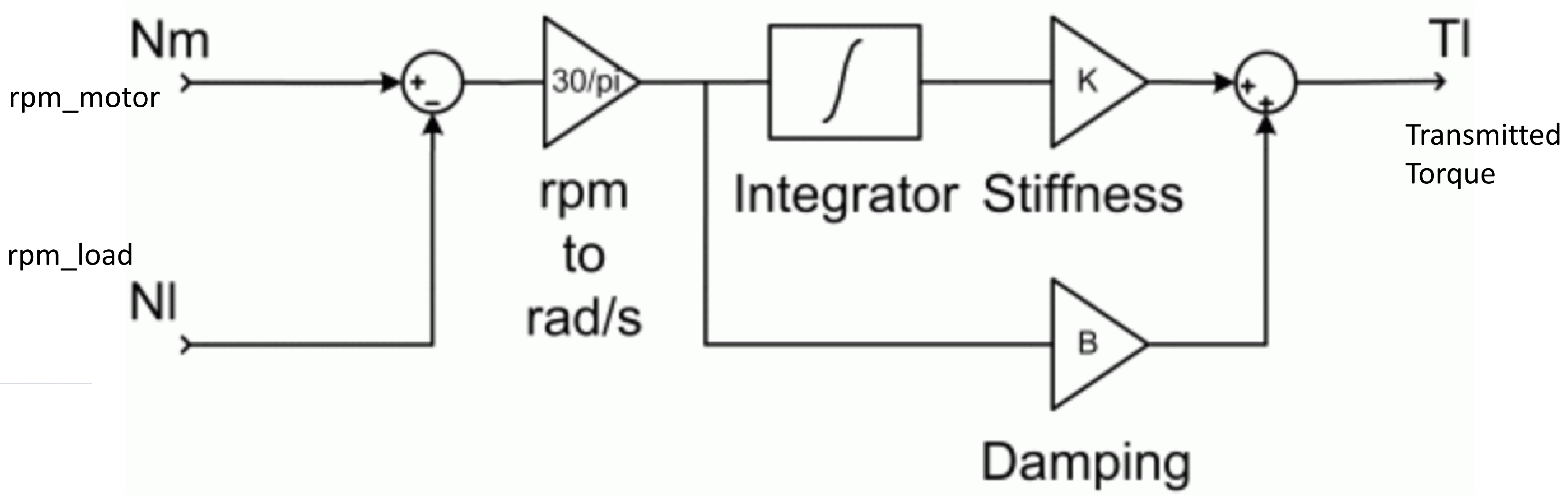


The transmitted torque T_l is given by the following equation:

$$T_l = K \int (\omega_m - \omega_l)\, dt + B(\omega_m - \omega_l),$$

where *K* (N.m) is the shaft stiffness, *B* (N.m.s) is the internal damping, and ω_m and ω_l are the speeds (rad/s) of the driving side and the loaded side, respectively. The following figure shows the internal schematic of the model. In this model the speeds are converted from rpm to rad/s.

Mechanical Shaft Model Schematic



Matlab/Simulink/Simscape Simulations

Simulation

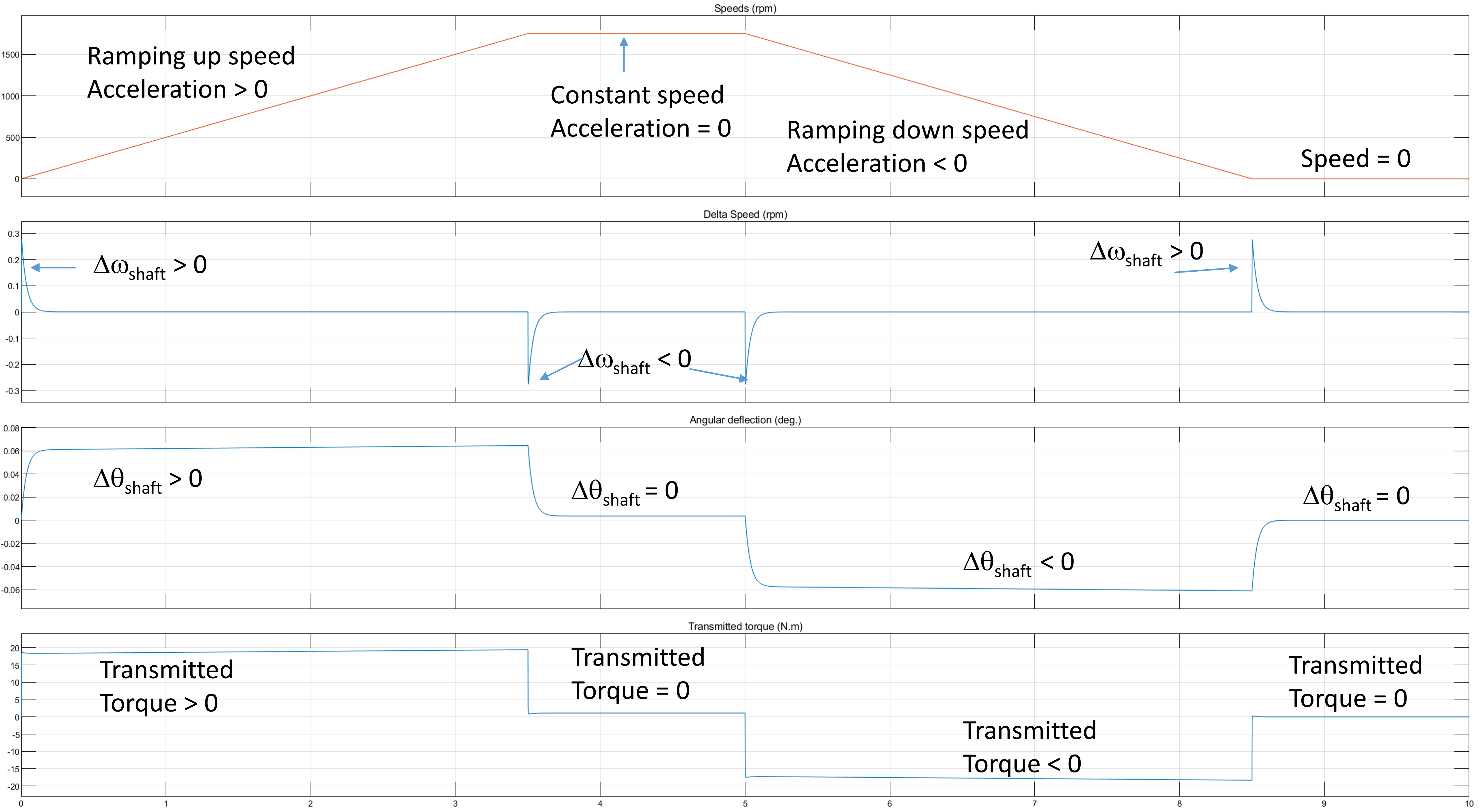
Start the simulation. You can observe the driving and the load speeds, the speed difference, the angular deflection and the transmitted torque values on the scope.

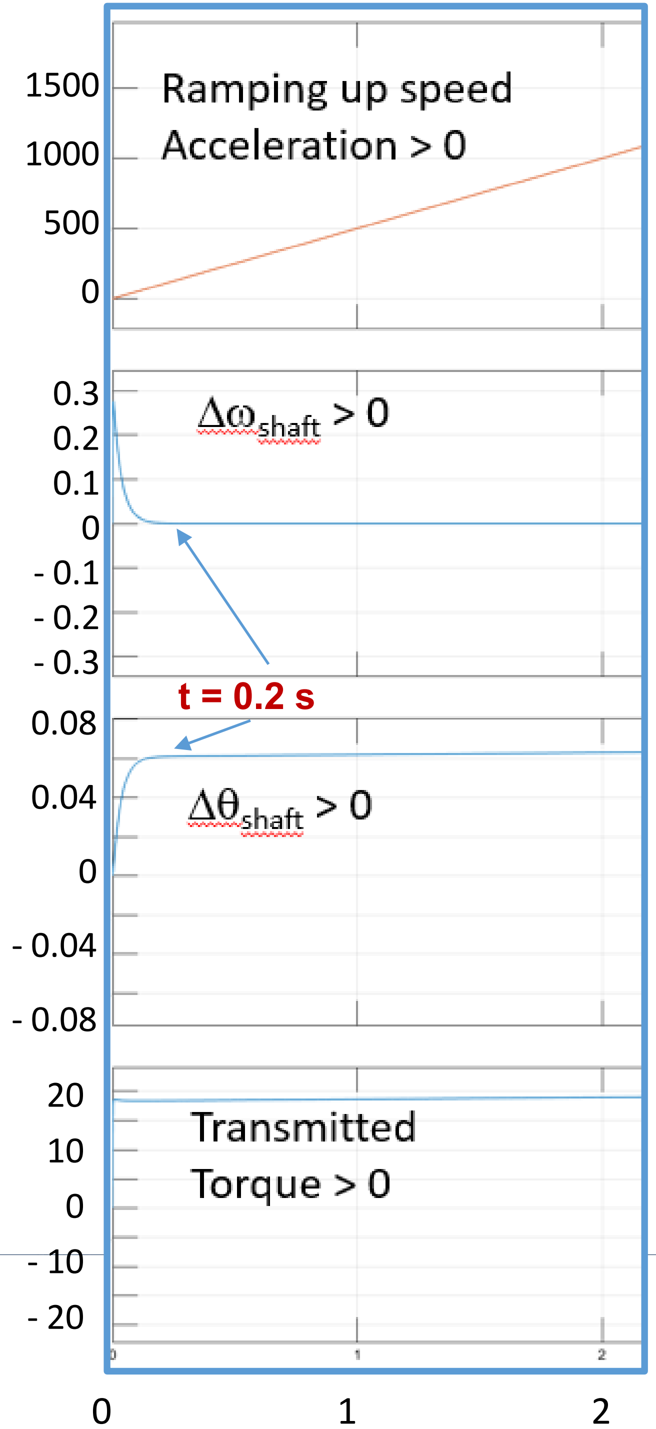
At t = 0 s, the driving speed starts climbing to 1750 rpm with a 500 rpm/s acceleration ramp. The angular deflection jumps to about 0.06 degree and the shaft transmits about 18.5 Nm to the load in order to accelerate it. At t = 0.2 s, the driving and load speeds tend to equalize. During the acceleration phase, the angular deflection increases slowly in order to transmit a higher torque to compensate the viscous friction increase.

At t = 3.5 s, the driving speed settles at 1750 rpm. This reduces the angular deflection and also the transmitted torque which settles around 1.1 Nm to compensate the viscous friction of the load.

At t = 5 s, the driving speed lowers towards 0 rpm with a -500 rpm/s deceleration ramp. The angular deflection becomes negative and thus the transmitted torque in order to decelerate the load. During the deceleration phase, the angular deflection increases in order to transmit a higher deceleration torque to compensate the reduction of viscous friction.

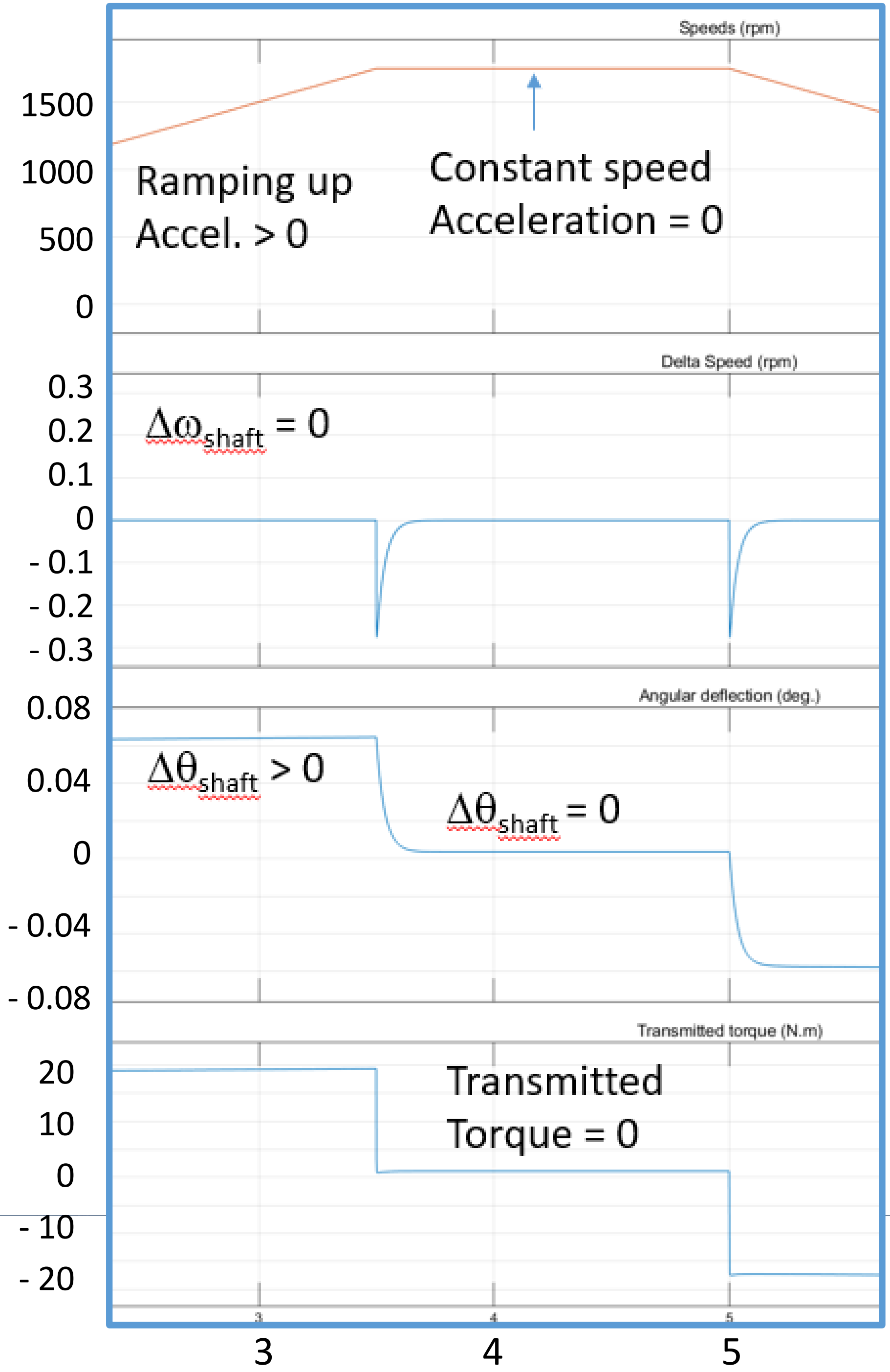
At t = 8.5 s, the driving speed stabilizes at 0 rpm. This causes the angular deflection to reduce to 0 degree, the transmitted torque becomes nul and the load stops.


Speeds (rpm)
Ramping up speed
Acceleration > 0
Constant speed
Acceleration = 0
Ramping down speed
Acceleration < 0
Speed = 0
Delta Speed (rpm)
$\Delta\omega_{shaft} > 0$
$\Delta\omega_{shaft} < 0$
$\Delta\omega_{shaft} > 0$
Angular deflection (deg.)
$\Delta\theta_{shaft} > 0$
$\Delta\theta_{shaft} = 0$
$\Delta\theta_{shaft} < 0$
$\Delta\theta_{shaft} = 0$
Transmitted torque (N.m)
Transmitted Torque > 0
Transmitted Torque = 0
Transmitted Torque < 0
Transmitted Torque = 0



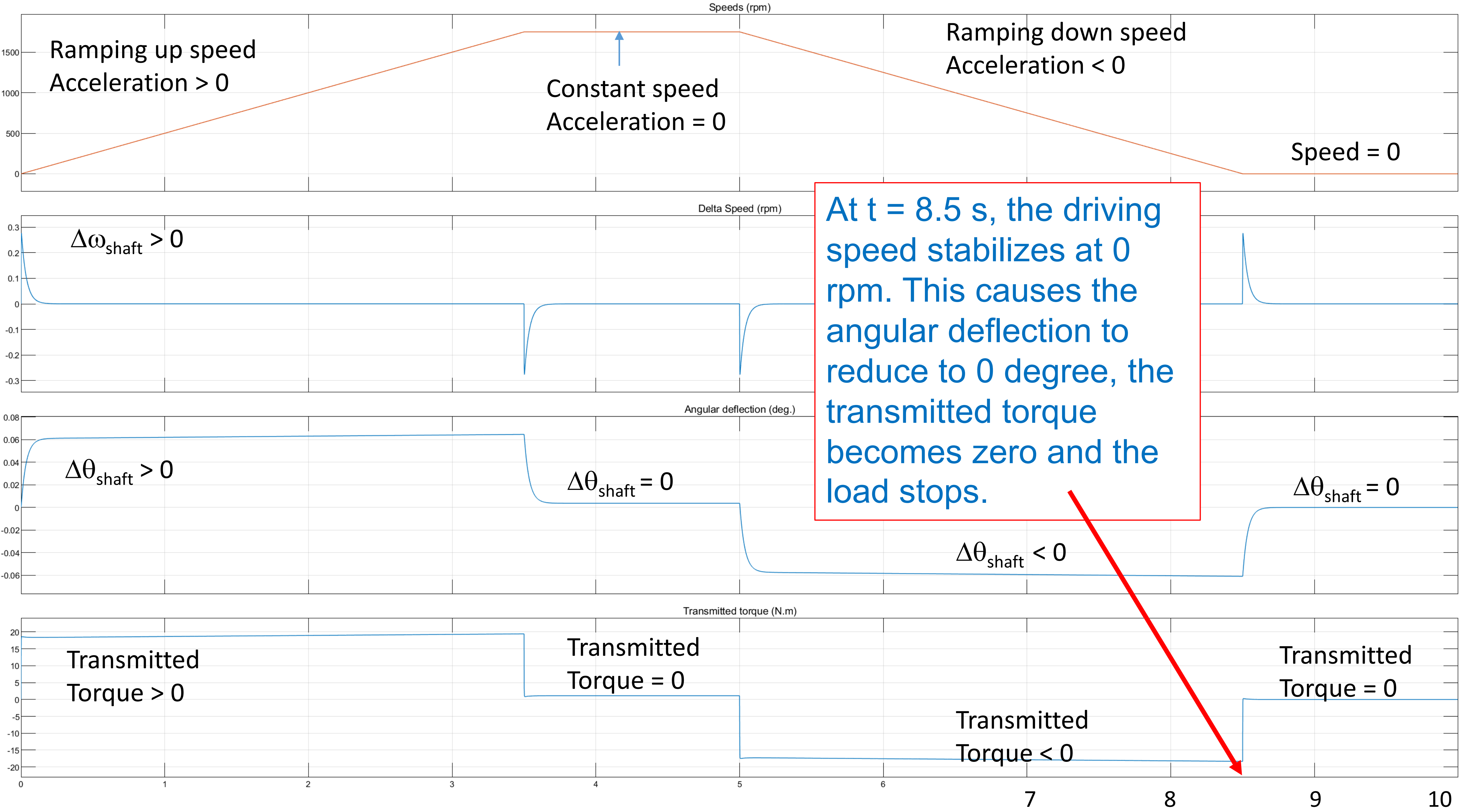
Start the simulation. You can observe the driving and the load speeds, the speed difference, the angular deflection and the transmitted torque values on the scope.

- At t = 0 s, the driving speed starts climbing to 1750 rpm with a 500 rpm/s acceleration ramp. The angular deflection jumps to about 0.06 degree and the shaft transmits about 18.5 Nm to the load in order to accelerate it.
- At t = 0.2 s, the driving and load speeds tend to equalize. During the acceleration phase, the angular deflection increases slowly in order to transmit a higher torque to compensate the viscous friction increase.

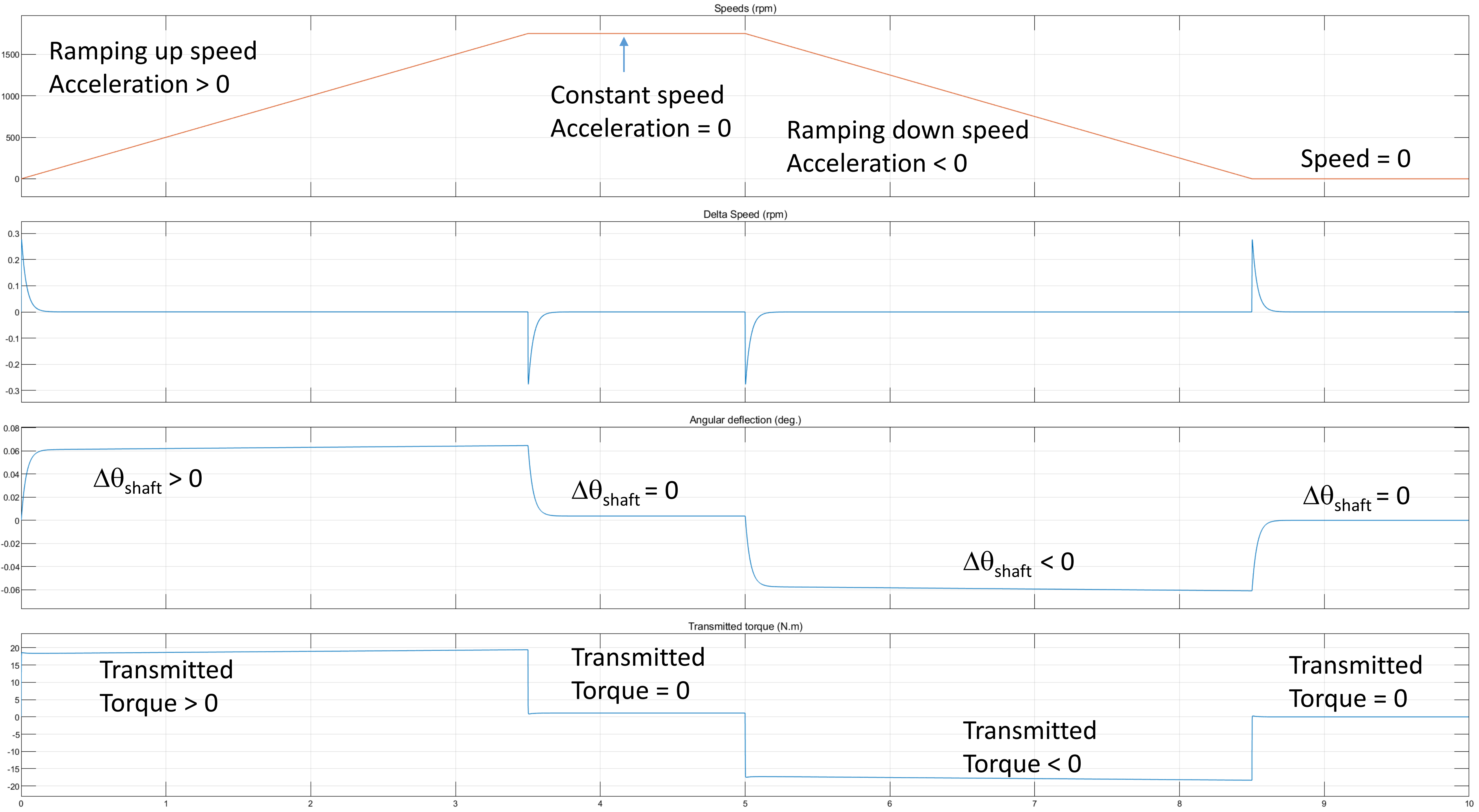


- At t = 3.5 s:
  - driving speed settles at 1750 rpm.
  - reduced the angular deflection
  - the transmitted torque settled around 1.1 Nm to compensate the viscous friction of the load.

- At t = 5 s:
  - the driving speed lowers towards 0 rpm with a -500 rpm/s deceleration ramp.
  - the angular deflection becomes negative and thus the transmitted torque in order to decelerate the load.



Speeds (rpm)
Ramping up speed
Acceleration > 0
Constant speed
Acceleration = 0
Ramping down speed
Acceleration < 0
Speed = 0
Delta Speed (rpm)
$\Delta\omega_{shaft} > 0$
At t = 8.5 s, the driving speed stabilizes at 0 rpm. This causes the angular deflection to reduce to 0 degree, the transmitted torque becomes zero and the load stops.
Angular deflection (deg.)
$\Delta\theta_{shaft} > 0$
$\Delta\theta_{shaft} = 0$
$\Delta\theta_{shaft} < 0$
$\Delta\theta_{shaft} = 0$
Transmitted torque (N.m)
Transmitted
Torque > 0
Transmitted
Torque = 0
Transmitted
Torque < 0
Transmitted
Torque = 0



Speeds (rpm)
Ramping up speed
Acceleration > 0
Constant speed
Acceleration = 0
Ramping down speed
Acceleration < 0
Speed = 0
Delta Speed (rpm)
Angular deflection (deg.)
$\Delta\theta_{shaft} > 0$
$\Delta\theta_{shaft} = 0$
$\Delta\theta_{shaft} < 0$
$\Delta\theta_{shaft} = 0$
Transmitted torque (N.m)
Transmitted
Torque > 0
Transmitted
Torque = 0
Transmitted
Torque < 0
Transmitted
Torque = 0

12-2-1 MATCH BETWEEN THE MOTOR AND THE LOAD

- One way to drive a rotating load is to couple it directly to the motor. In such a direct coupling, the problems and the losses associated with a gearing mechanism are avoided. But the motor must be able to provide peak torques at specified speeds.
- The other option for a rotating load is to use a gearing mechanism. A coupling mechanism such as rack-and-pinion, belt-and-pulley, or feed-screw must be used to couple a load with a linear motion to a rotating motor.
- A gear and a feed-screw drive are shown in Figs. 12-5a and 12-5b, respectively.

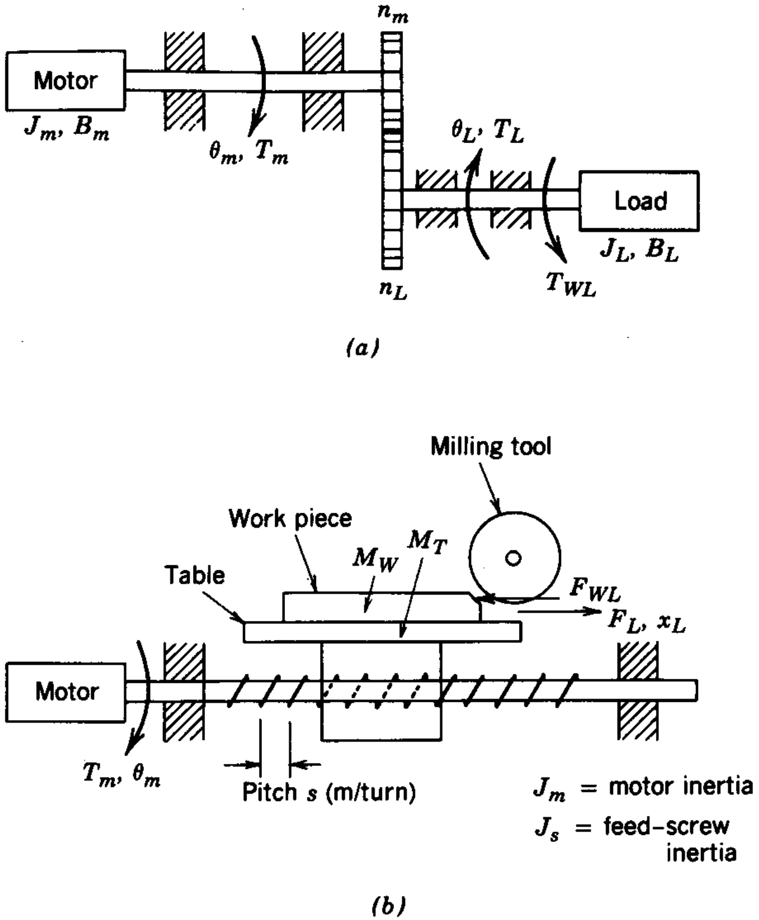
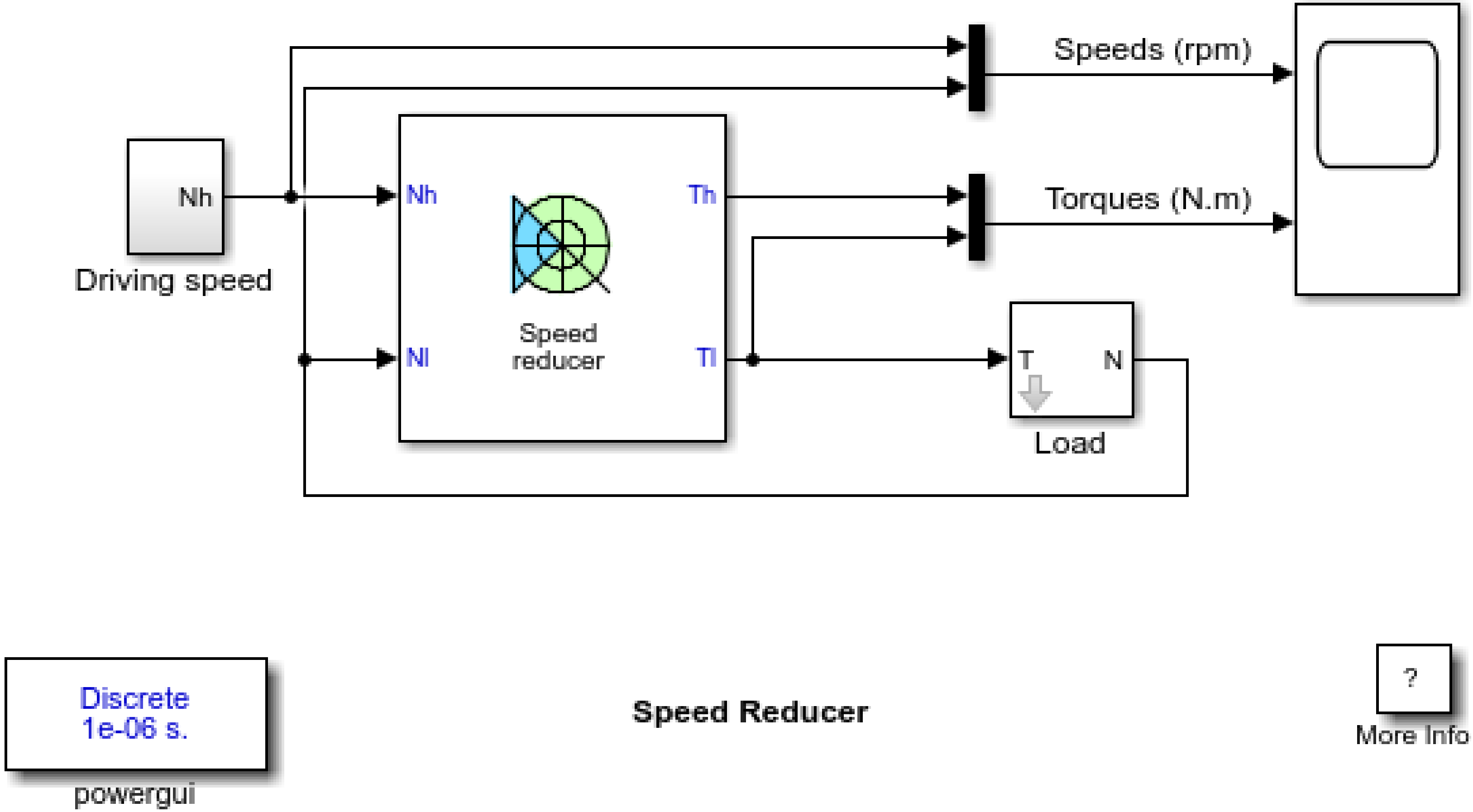


Figure 12-5 Coupling mechanisms: (*a*) gear; (*b*) feed screw.

Matlab/Simulink/Simscape Simulations – reducer_example.slx

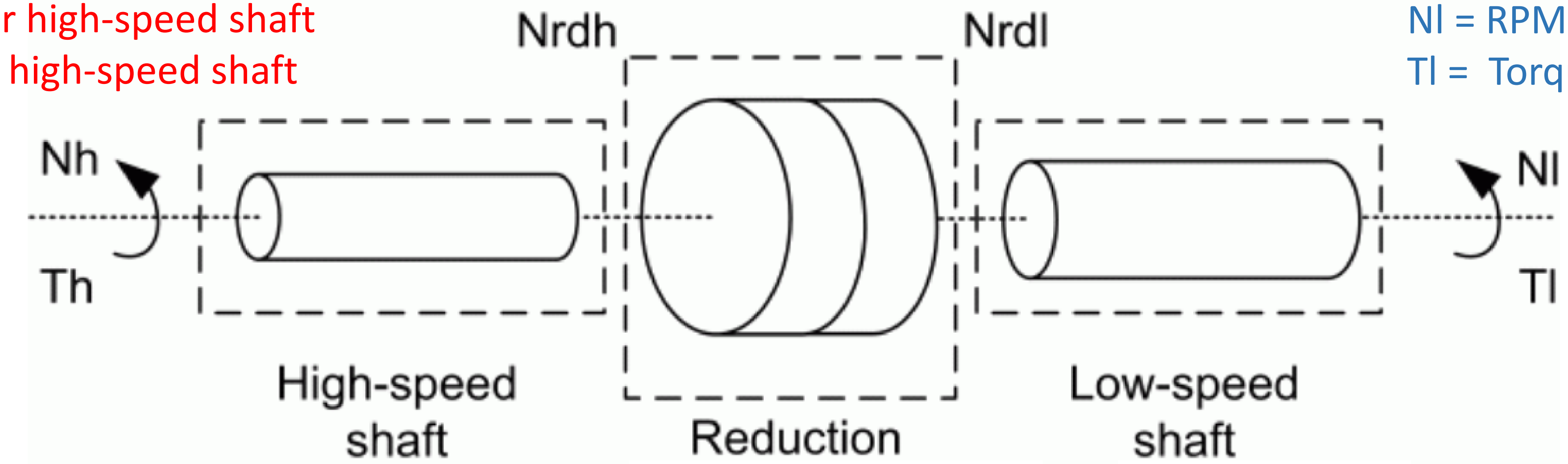


Nh = RPM for high-speed shaft

Th = Torque high-speed shaft

Nl = RPM for low-speed shaft

Tl = Torque low-speed shaft



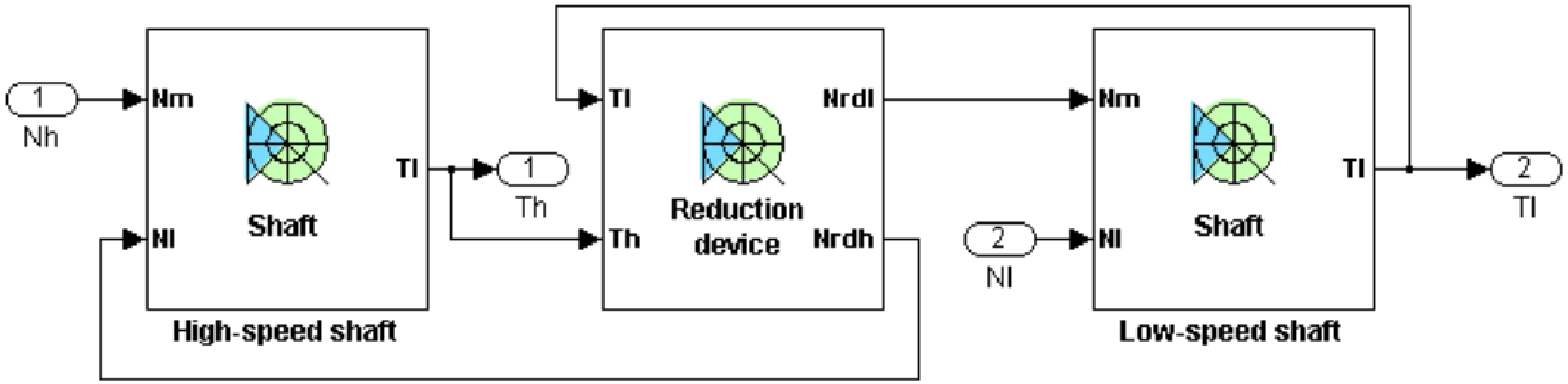
$$J_{\text{rdh}}\ddot{\theta}_{\text{rdh}} = T_h - \frac{T_l}{\eta i}$$

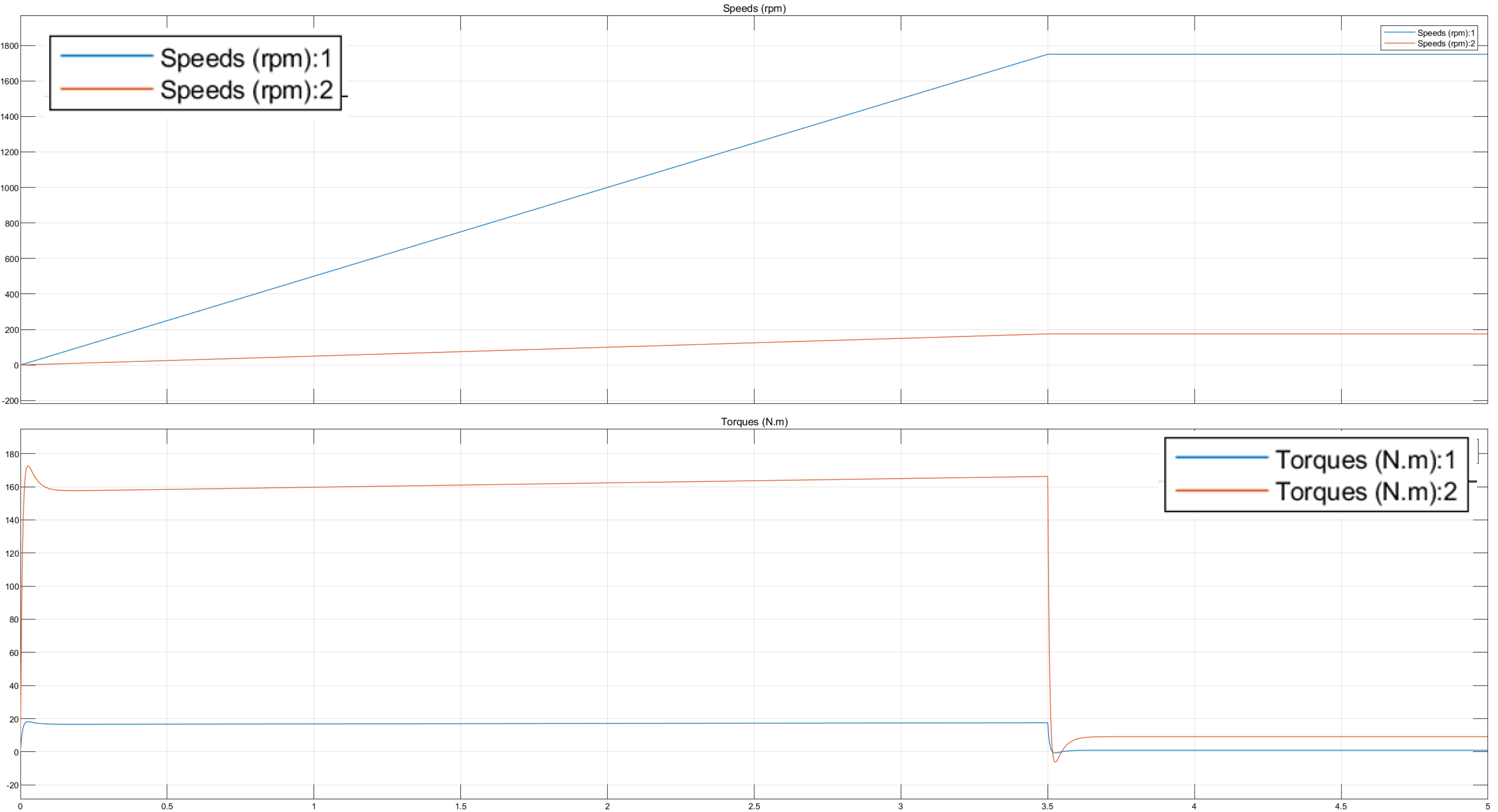
$N_{\text{rdl}} = N_{\text{rdh}} / i$, reduction ratio ($i \geq 1$).

η is the efficiency of the reduction device,

Simulink Schematic

The next figure shows the Simulink® schematic of the speed reducer model.





Speeds (rpm)
Speeds (rpm):1
Speeds (rpm):2
1800
1600
1400
1200
1000
800
600
400
200
0
-200
Torques (N.m)
Torques (N.m):1
Torques (N.m):2
180
160
140
120
100
80
60
40
20
0
-20
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

12-2-1 MATCH BETWEEN THE MOTOR AND THE LOAD

- Assuming the energy efficiency of the gear in Fig. 12-5a to be 100%, the torques on the two sides of the gear are related as

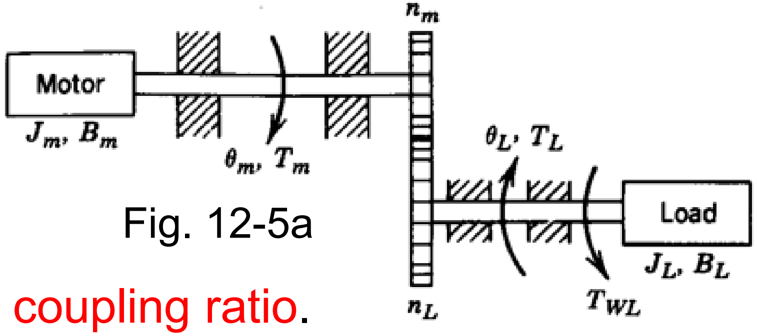


Fig. 12-5a

$$\frac{T_m}{T_L} = \frac{\omega_L}{\omega_m} = \frac{\theta_L}{\theta_m} = \frac{n_m}{n_L} = a \qquad (12\text{-}1)$$

- where the angular speed, the number of teeth, $\omega = \dot{\theta}$, n_m and n_L and a is the coupling ratio.
- In the feed-screw drive of Fig. 12-5b, the torque and the force are related as

$$\frac{T_m}{F_L} = \frac{v_L}{\omega_m} = \frac{x_L}{\theta_m} = \frac{s}{2\pi} = a \qquad (12\text{-}2)$$

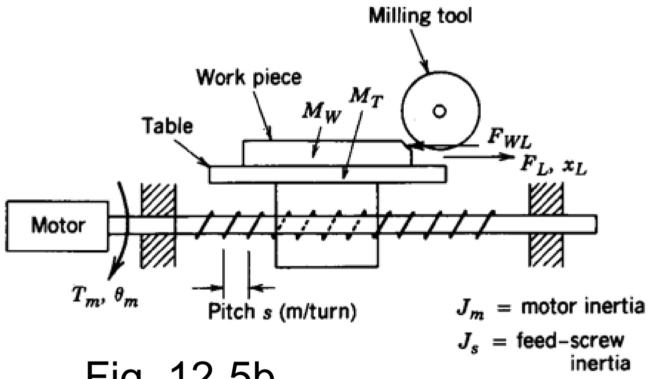


Fig. 12-5b

- where the linear velocity $v_L = \dot{x}_L$, s - is the pitch of the feed screw in m/tum, and a is the coupling ratio.
- The electromagnetic torque T_{em} required from the motor can be calculated on the basis of energy considerations in terms of the inertias, required load acceleration, coupling ratio a, and the working torque or force.

12-2-1 MATCH BETWEEN THE MOTOR AND THE LOAD

- In Fig. 12-5a, T_{wL} is the working torque of the load and $\dot{\omega}_L$ is the load acceleration. Therefore,

(12-3a)
$$T_{em} = \frac{\dot{\omega}_L}{a}[J_m + a^2 J_L] + aT_{WL} + \frac{\omega_L}{a}(B_m + a^2 B_L)$$

- This equation can be written in terms of the motor speed (recognizing that $\omega_m = \omega_L/a$), the equivalent total inertia $J_{eq} = J_m + a^2 J_L$, the equivalent total damping $B_{eq} = B_m + a^2 B_L$ and the equivalent working torque of the load $T_{Weq} = a\, T_{WL}$

(12-3b)
$$T_{em} = J_{eq}\dot{\omega}_m + B_{eq}\omega_m + T_{Weq}$$

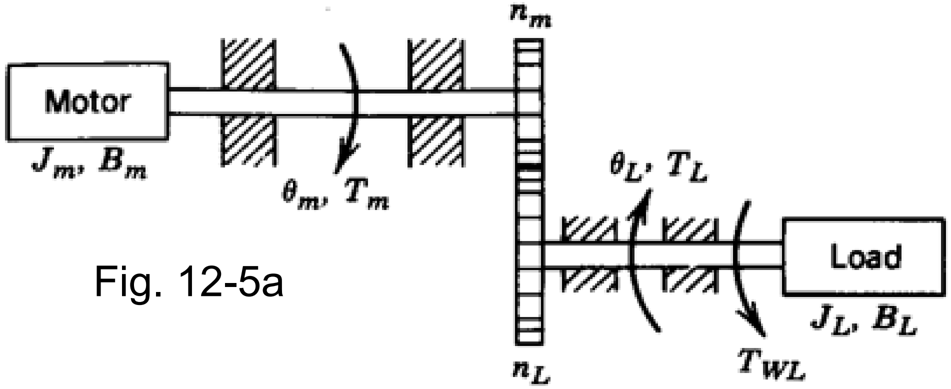
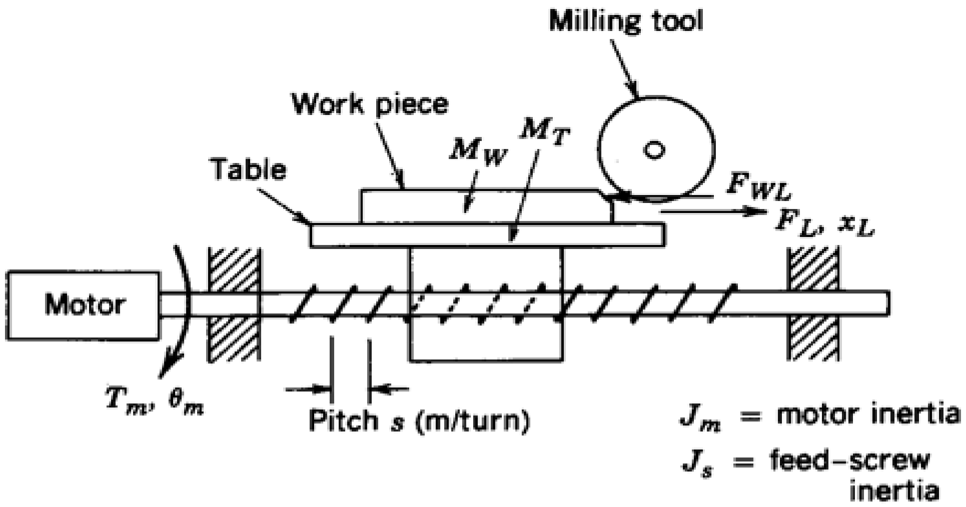


Fig. 12-5a

Fig. 12-5b



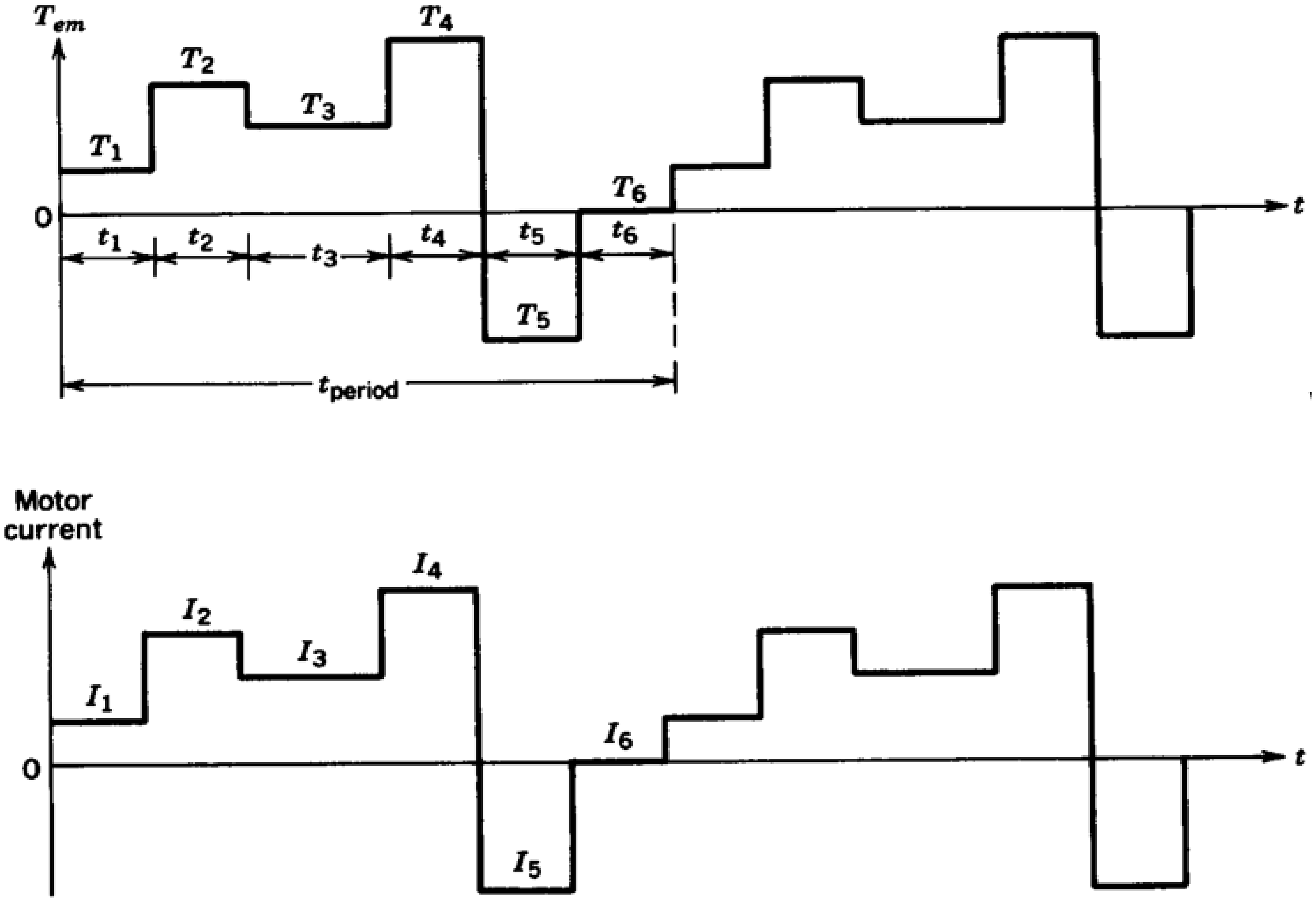
- Similarly, for the feed-screw system in Fig. 12-5b with F_{WL} as the working or the machining force and a as the coupling ratio calculated in Eq. 12-2 in terms of pitch *s*, T_{em} can be calculated as (see Problem 12-3)

(12-4)
$$T_{\mathrm{em}} = \frac{\dot{v}_L}{a}\left[J_m + J_s + a^2(M_T + M_W)\right] + aF_{WL}$$

- where $\dot{v}_L$ is the linear acceleration of the load.
- As indicated by Eqs. 12-1 and 12-2, the choice of the coupling ratio a affects the motor speed. At the same time, the value of a affects the peak electromagnetic torque T_{em} required from the motor, as is indicated by Eqs. 12-3a and 12-4.
- In selecting the optimum value of the coupling ratio a, the cost and losses associated with the coupling mechanism must also be included.

12-2-2 THERMAL CONSIDERATIONS IN SELECTING THE MOTOR

- As another example, the electromagnetic torque required from the motor as a function of time is obtained as shown in Fig. 12-6a. In electric machines, the electromagnetic torque produced by the motor is proportional to the motor current i, provided the flux in the air gap of the motor is kept constant.
- Therefore, the motor-current profile is identical to the motor-torque profile, as shown in Fig. 12-6b. The motor current in Fig. 12-6b during various time intervals is a dc current for a dc motor.



12-2-2 THERMAL CONSIDERATIONS IN SELECTING THE MOTOR

- For an ac motor, the motor current shown is approximately the rms value of the ac current drawn during various time intervals. The power loss P_R in the winding resistance R_M due to the motor current is a large part of the total motor losses, which get converted into heat.
- This resistive loss is proportional to the square of the motor current and, hence, proportional to T_m during various time intervals in Figs. 12-6a and 12-6b.
- If the time period t_{period} in Fig. 12-6, with which the waveforms repeat, is short compared with the motor thermal time constant, then the motor heating and the maximum temperature rise can be calculated based on the resistive power loss P_R averaged over the time period t_{period}.

The rms value of the current over the period

$$P_R = R_M I^2_{\text{rms}} \tag{12-5}$$

$$I^2_{\text{rms}} = \frac{\sum_{k=1}^{m} I_k^2 t_k}{t_{\text{period}}} \tag{12-6}$$

m = 6 in this example

The rms value of the motor torque over t_{period}

$$T^2_{\text{em, rms}} = k_1 \frac{\sum_{k=1}^{m} I_k^2 t_k}{t_{\text{period}}} \tag{12-7}$$

12-2-2 THERMAL CONSIDERATIONS IN SELECTING THE MOTOR

- and therefore,

$$T^2_{em,\ rms} = k_1 I^2_{rms} \qquad (12\text{-}8)$$

where k_1 is a constant of proportionality.

- From Eqs. 12-5 and 12-8, the average resistive power loss P_R is given as

$$P_R = k_2 T^2_{em,\ rms} \qquad (12\text{-}9)$$

where k_2 is a constant of proportionality.

- In addition to P_R, there are other losses within the motor that contribute to its heating. These are P_{FW} due to friction and windage, P_{EH} due to eddy currents and hysteresis within the motor laminations, and P_S due to switching frequency ripple in the motor current, since it is supplied by a switching power electronic converter rather than an ideal source. There are always some power losses called stray power losses P_{stray} that are not included with the foregoing losses. Therefore, the total power loss within the motor is

$$P_{loss} = P_R + P_{FW} + P_{EH} + P_s + P_{stray} \qquad (12\text{-}10)$$

12-2-2 THERMAL CONSIDERATIONS IN SELECTING THE MOTOR

- Under a steady-state condition, the motor temperature rise $\Delta\theta$ in degrees centigrade is given as

$$\Delta\Theta = P_{\text{loss}} R_{\text{TH}} \qquad (12\text{-}11)$$

where P_{loss} is in watts and the thermal resistance R_{TH} of the motor is in degrees centigrade per watt.

- For a maximum allowable temperature rise $\Delta\Theta$ the maximum permissible value of P_{loss} in steady state depends on the thermal resistance R_{TH} in Eq. 12-11.

12-2-2 THERMAL CONSIDERATIONS IN SELECTING THE MOTOR

- In general, the loss components other than P_R in the right side of Eq. 12-10 increase with the motor speed. $$P_{\text{loss}} = P_R + \boxed{P_{\text{FW}} + P_{\text{EH}} + P_s + P_{\text{stray}}}$$
- Therefore, the maximum allowable P_R and, hence, the maximum continuous motor torque output from Eq. 12-9 would decrease at higher speed, if R_{TH} remains constant. $$P_R = k_2 T^2_{\text{em, rms}}$$
- However, in self-cooled motors with the fan connected to the motor shaft, for example, R_{TH} decreases at higher speeds due to increased air circulation at higher motor speeds.

12-2-2 THERMAL CONSIDERATIONS IN SELECTING THE MOTOR

- Therefore, the maximum safe operating area in terms of the maximum rms torque available from a motor at various speeds depends on the motor design and is specified in the motor data sheets (specially in case of servo motors).
- For a motor torque profile like that shown in Fig. 12-6a, the motor should be chosen such that the rms value of the torque required from the motor remains within the motor's safe operating area in the speed range of operation.

Motor Torque

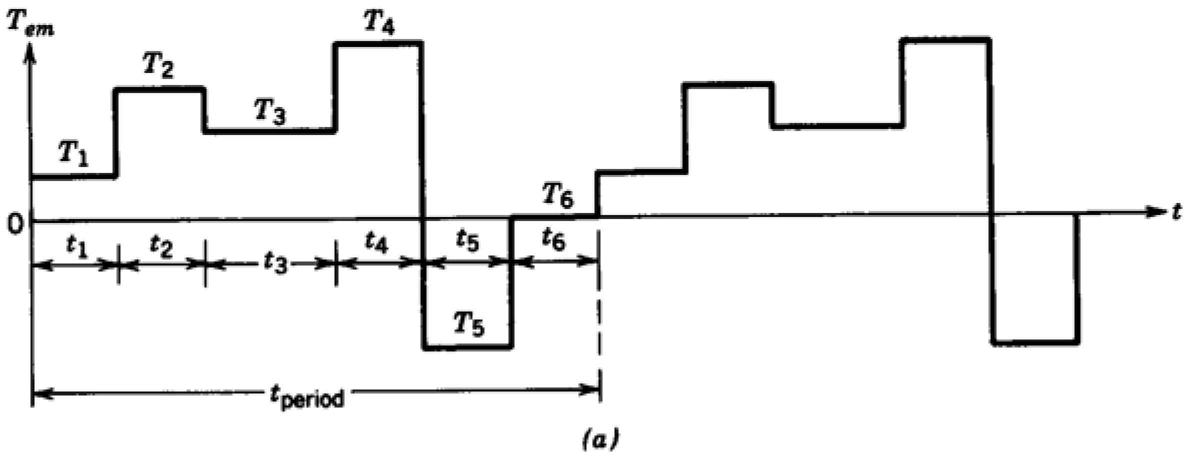


Figure 12-6 Motor torque and current.

- Their RMS values may determine the limit

12-2-3-1 Current Rating

- As we discussed previously, the rms value of the torque that a motor can supply depends on its thermal characteristics. However, a motor can supply substantially larger peak torques (as much as four times the continuous maximum torque) provided that the duration of the peak torque is small compared with the *thermal time constant of the motor*.
- Since T_{em} is proportional to the current i, a peak torque requires a corresponding peak current from the power electronic converter.
- The current capability of the power semiconductor devices used in the converter is limited by the maximum junction temperature within the devices and other considerations. A higher current results in a higher junction temperature due to power losses within the power semiconductor device.
- The thermal time constants associated with the power semiconductor devices are in general much smaller than the thermal time constants of various motors.
- Therefore, the current rating of the power electronic converter must be selected based on both the rms and the peak values of the torque that the motor is required to supply.

12-2-3 MATCH BETWEEN THE MOTOR AND THE POWER ELECTRONIC CONVERTER

12-2-3-2 Voltage Rating

- In both dc and ac motors, the motor produces a counter-emf e that opposes the voltage v applied to it, as shown by a simplified generic circuit of Fig. 12-7. The rate at which the motor current and, hence, the torque can be controlled is given by

$$\frac{di}{dt} = \frac{v-e}{L} \qquad (12\text{-}12)$$

where L is the inductance presented by the motor to the converter.

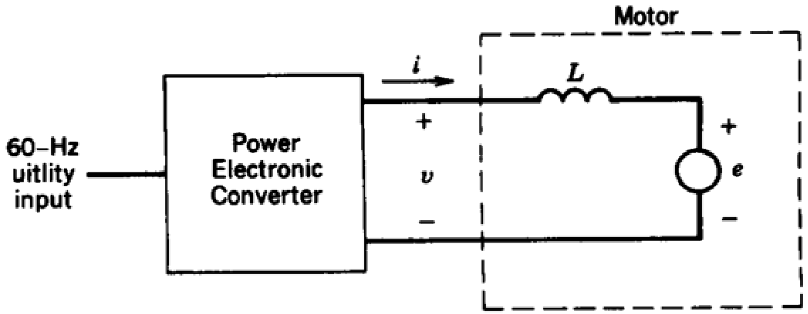


Figure 12-7 Simplified circuit of a motor drive.

- To be able to quickly control the motor current and, hence, its torque, the output voltage v of the power electronic converter must be reasonably greater than the counter emf e.

- The magnitude of e in a motor increases linearly with the motor speed, with a constant flux in the air gap of the motor.
- Therefore, the voltage rating of the power electronic converter depends on the maximum motor speed with a constant air-gap flux.