Power Electronics

Introduction to Motor Drives

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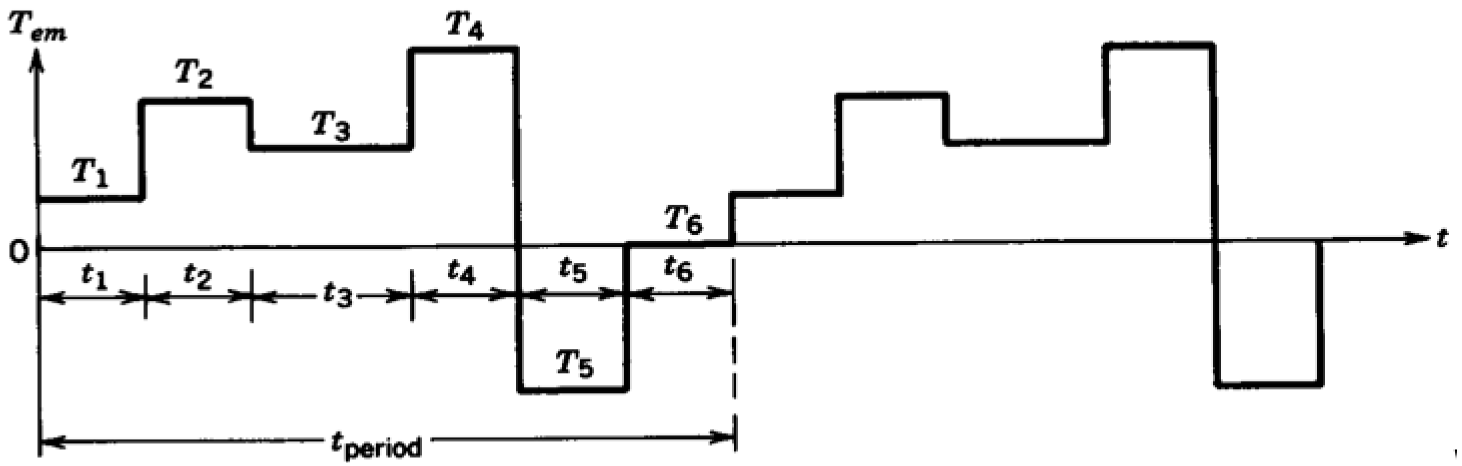
Chapter 12

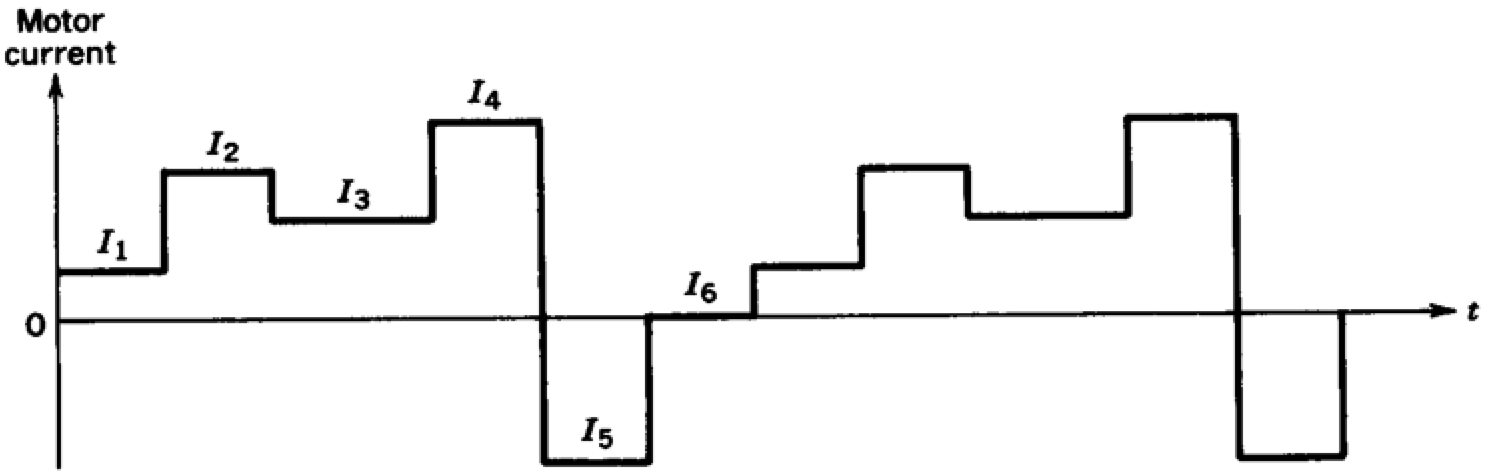
Introduction to Motor Drives

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

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

$$P_R = R_M I_{\text{rms}}^2 \qquad (12\text{-}5)$$

$$I_{\text{rms}}^2 = \frac{\sum_{k=1}^{m} I_k^2 t_k}{t_{\text{period}}} \qquad (12\text{-}6)$$

m = 6 in this example

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

$$T_{\text{em, rms}}^2 = k_1 \frac{\sum_{k=1}^{m} I_k^2 t_k}{t_{\text{period}}} \qquad (12\text{-}7)$$

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. $P_{loss} = P_R + \boxed{P_{FW} + P_{EH} + P_s + P_{stray}}$
- 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. $P_R = k_2 T^2_{em,\,rms}$
- 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

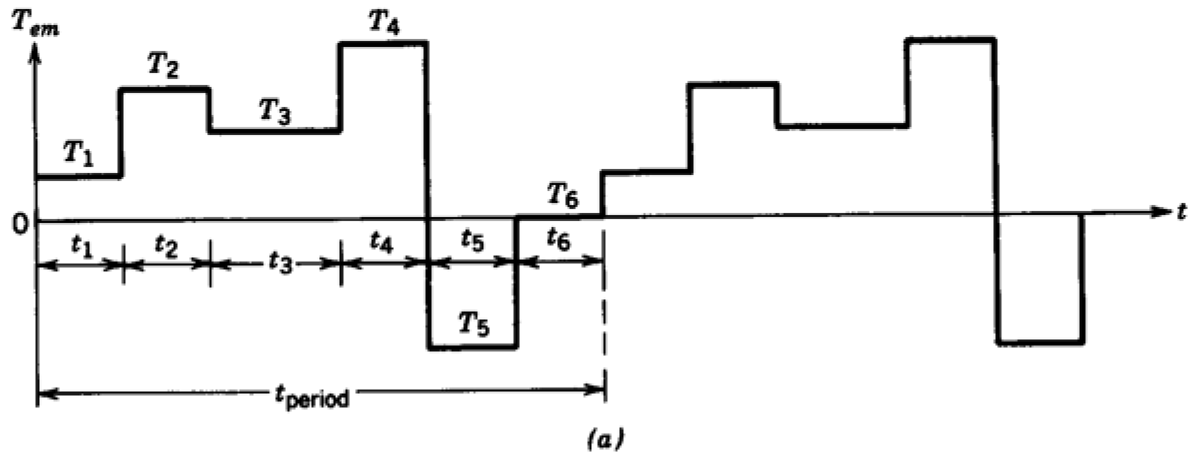


Figure 12-6 Motor torque and current.

- 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.

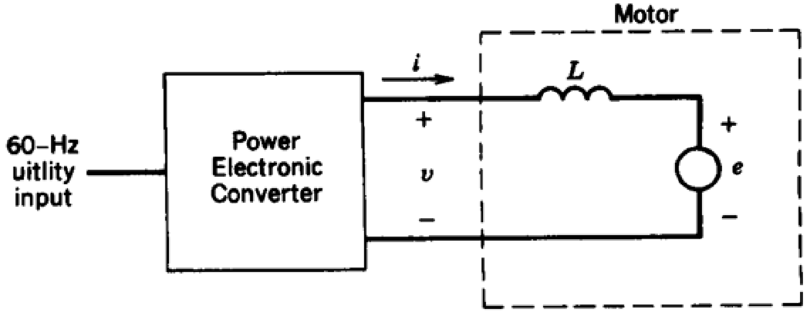


Figure 12-7 Simplified circuit of a motor drive.

- 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.

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

12-2-3-3 Switching Frequency and the Motor Inductance

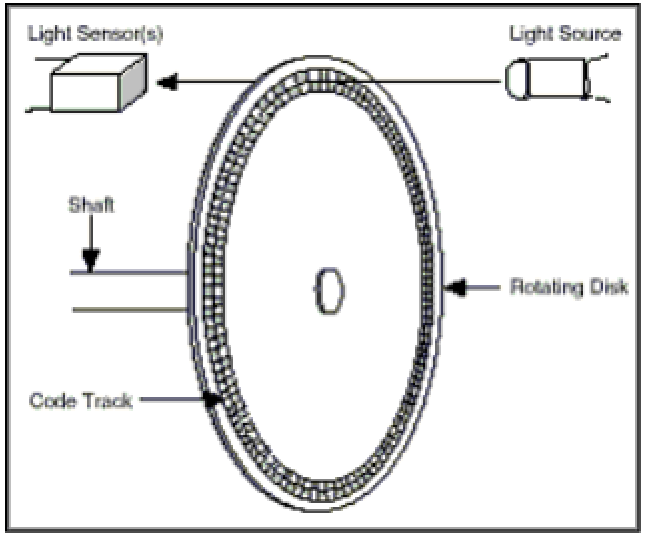
$$\frac{di}{dt} = \frac{v-e}{L} \qquad (12\text{-}12)$$

- In a servo drive, the motor current should be able to respond quickly to the load demand, thus requiring L to be small as shown in Eq. 12-12.
- Also, the steady-state ripple in the motor current should be as small as possible to minimize the motor loss P_s in Eq. 12-10 and the ripple in the motor torque. $P_{\text{loss}} = P_R + P_{\text{FW}} + P_{\text{EH}} + \boxed{P_s} + P_{\text{stray}}$
- A small current ripple requires the motor inductance L_m Eq. 12-12 to be large.
- Because of the conflicting requirements on the value of L, the ripple in the motor current can be reduced by increasing the converter switching frequency.
- However, the switching losses in the power electronic converter increase linearly with the switching frequency. $\boxed{P_s = \frac{1}{2} V_d I_o f_s (t_{c(on)} + t_{c(off)})}$
- Therefore, a reasonable compromise must be made in selecting the motor inductance L and the switching frequency.

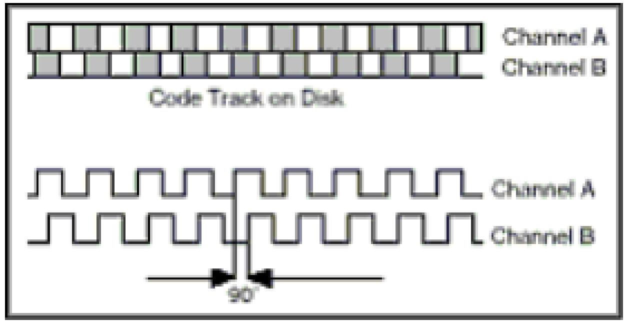
12-2-4 SELECTION OF SPEED AND POSITION SENSORS

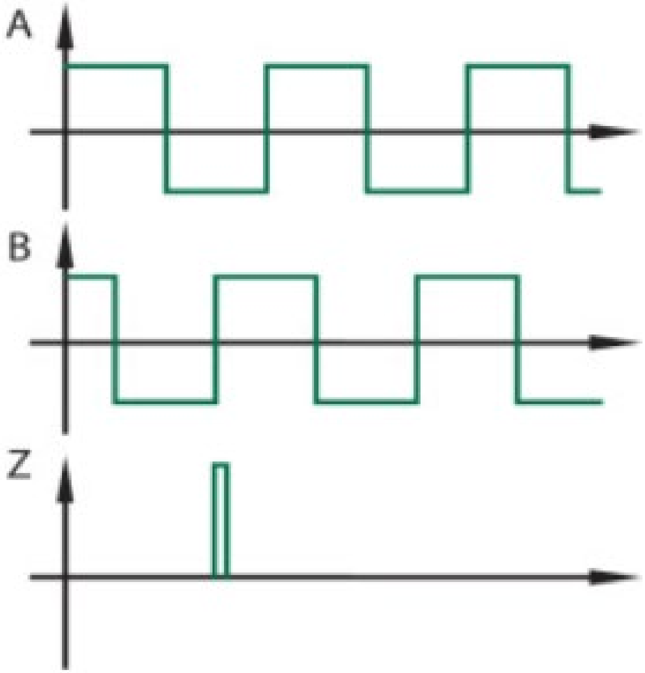
- In selecting the speed and position sensors, the following items must be considered: *direct or indirect coupling, sensor inertia, possibility and avoidance of torsional resonance, and the maximum sensor speed*.
- To control the instantaneous speed within a specified range, the ripple in the speed sensor should be small.
- This can be understood in terms of incremental position encoders, which are often used for measuring speed as well as position. If such a sensor is used at very low speeds, the number of pulse outputs per revolution must be large to provide instantaneous speed measurement with sufficient accuracy.
- Similarly, an accurate position information will require an incremental position encoder with a large number of pulse outputs per revolution.

12-2-4 SELECTION OF SPEED AND POSITION SENSORS



https://www.pc-control.co.uk/incremental_encoders.htm





ns

12-2-5 SERVO DRIVE CONTROL AND CURRENT LIMITING

- In most practical applications, a very fast response to a sudden change in position or speed command would require a large peak torque, which would result in a large peak current.
- This may be prohibitive in terms of the cost of the converter.
- Therefore, the converter current (same as the motor current) is limited by the controller.
- Figures 12-8a and 12-8b show two ways of implementing the current limit.

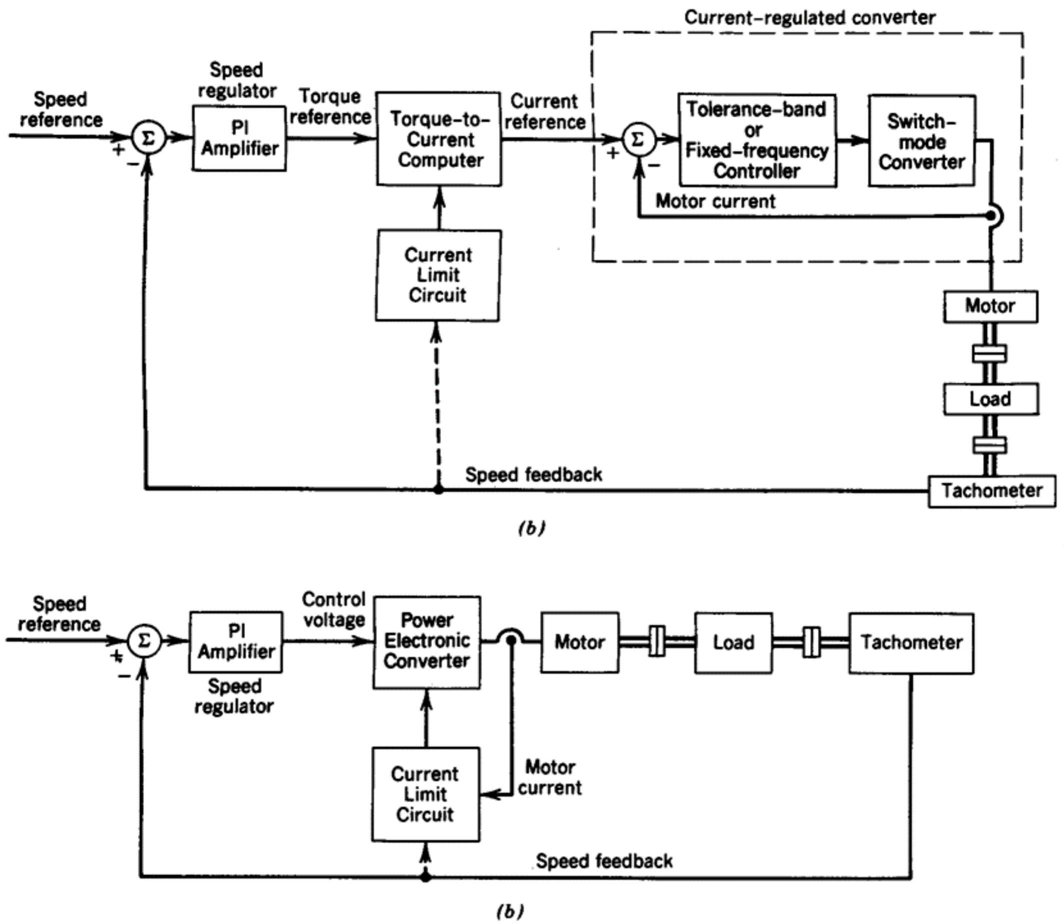
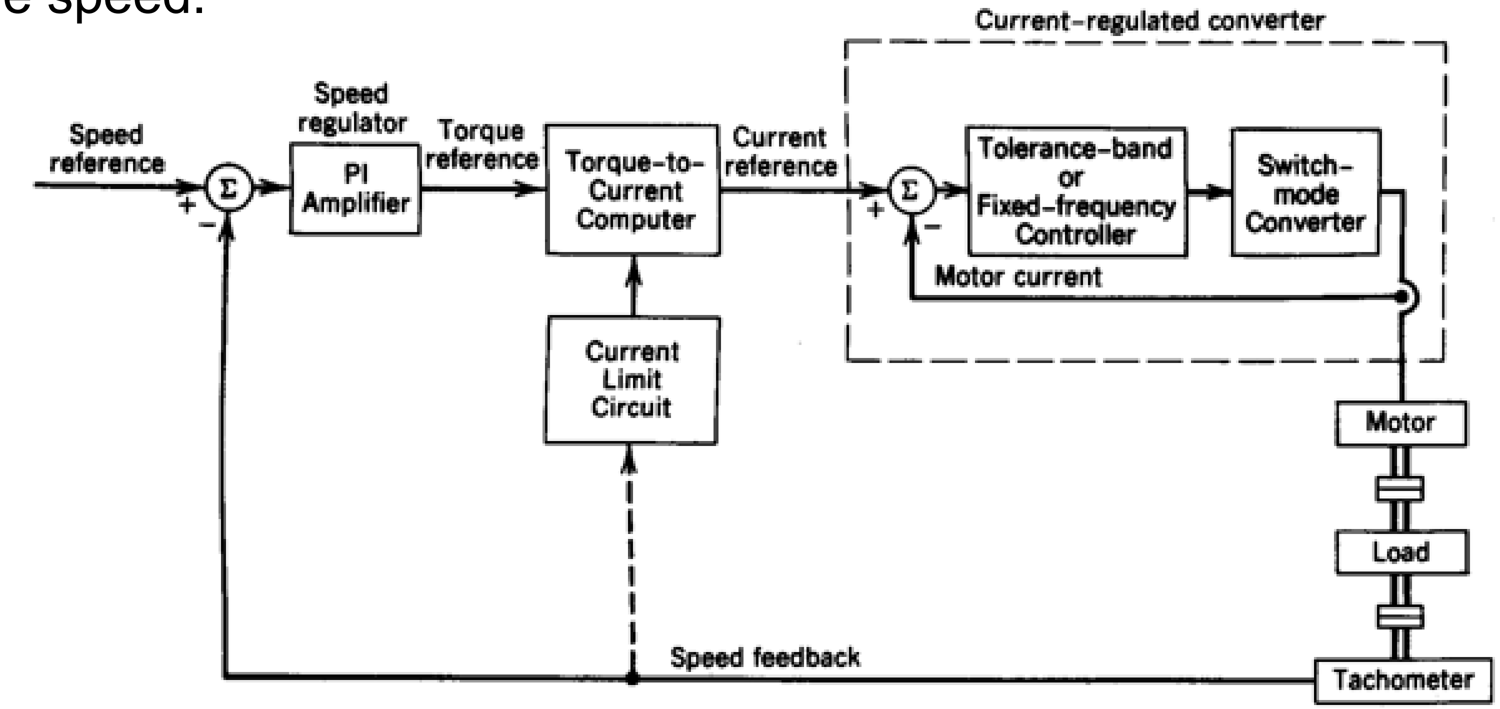


Figure 12-8 Control of servo drives: (*a*) inner current loop; (*b*) no inner current loop.

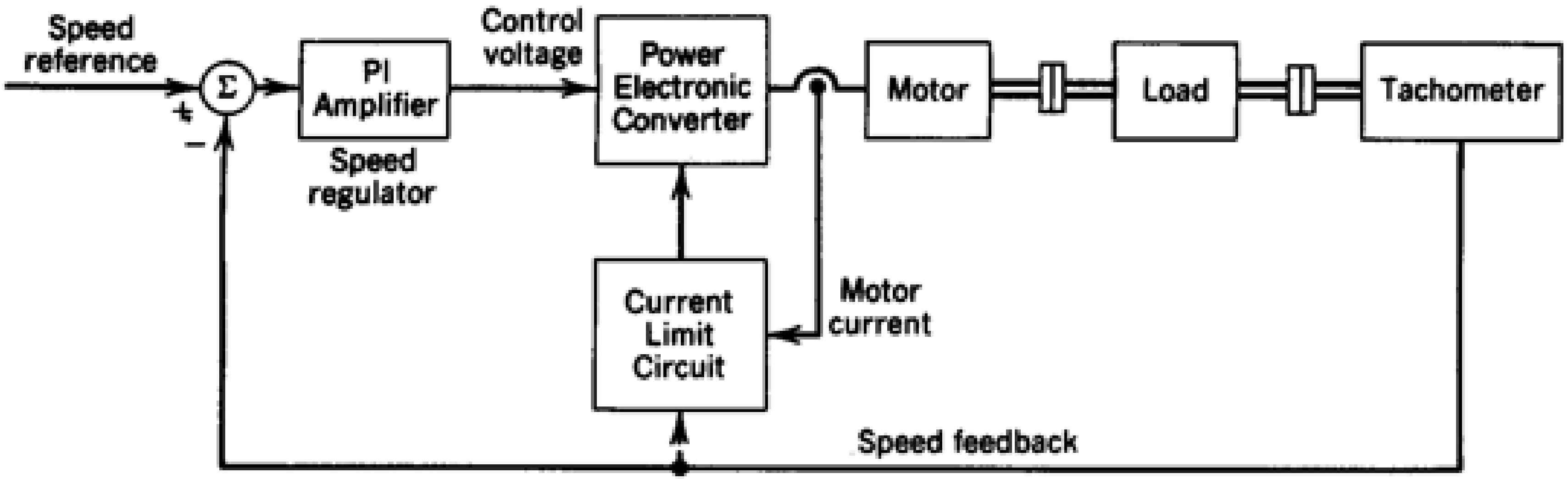
12-2-5 SERVO DRIVE CONTROL AND CURRENT LIMITING

- In Fig. 12-8a, an inner current loop is used where the actual current is measured, and the error between the reference and the actual current controls the converter output current by means of a current-regulated modulation.
- Here, the power electronic converter operates as a current-regulated voltage source converter. An inner control loop improves the response time of the drive. As shown, the limit on the reference current may be dependent on the speed.



12-2-5 SERVO DRIVE CONTROL AND CURRENT LIMITING

- In the other control scheme shown in Fig. 12-8b, the error between the speed reference and the actual speed controls the converter through a proportional-integral (PI) amplifier.
- The output of the PI amplifier, which controls the converter, is suppressed only if the converter current exceeds the current limit. The current limit can be made to be speed dependent.
- In a position control system, the speed reference signal in Figs. 12-8a and 12-8b is obtained from the position regulator. The input to such a position regulator will be the error between the reference position and the actual position.



(b)

12-2-6 CURRENT LIMITING IN ADJUSTABLE-SPEED DRIVES

In adjustable-speed drives such as that shown in Fig. 12-3, the current is kept from exceeding its limit by means of limiting the rate of change of control voltage with time in the block diagram of Fig. 12-9.

Limiters in the Control Structure

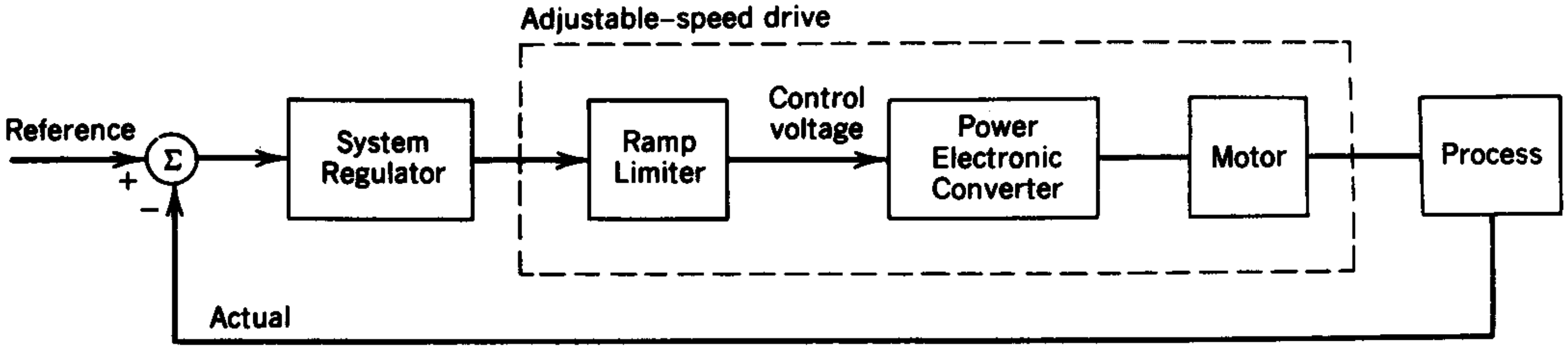


Figure 12-9 Ramp limiter to limit motor current.

- By providing ramp limiters, for example, drive can be prevented from "triping" under sudden changes

SUMMARY

1. Primary types of motor drives are dc motor drives, induction motor drives and synchronous motor drives.

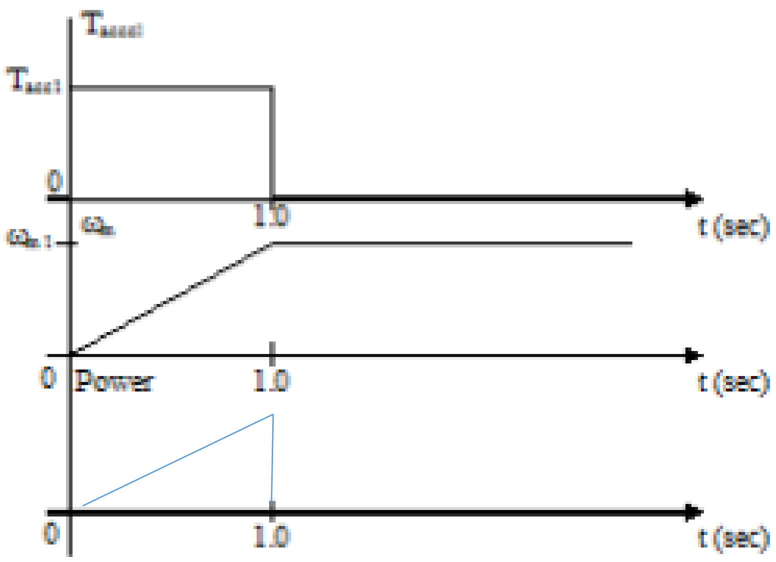
2. Most of the applications of motor drives belong to one of the two categories: ***servo drives*** or ***adjustable-speed drives***.

- In servo drive applications, the *response time and the accuracy* with which the motor follows the speed and/or position commands are extremely important.
- In adjustable-speed drive applications, *response time to changes in speed command is not as critical*;

3. A modeling of the mechanical system is necessary to determine the dynamics of the overall system and to select the motor and the power electronic converter of the appropriate ratings.

4. Servo drives require speed and/or position sensors to close the feedback loop. It is possible to operate with or without an inner current feedback loop. In an adjustable speed drive, the current is kept within its limit by limiting the rate of change of control voltage to the power electronic converter with time.

Problem Example 1



Given accelleration torque and the speed profile. The accelleration torque $T_{acc1} := 1000 \cdot N \cdot m$, the rotational speed $w_{m1} := 5 \cdot \frac{rad}{sec}$. Calculate the following at t = 1 sec

a) 10 pts Draw the mechanical power.

b) 10 pts Calculate the mech. power at t=1 sec

$$w_m(t) := \frac{w_{m1}}{sec} \cdot t$$

c) 10 pts Calculate the energy W at t = 1sec

$$P_m(t) := T_{acc1} \cdot w_m(t)$$

$$P_m(1 \cdot sec) = (5 \cdot 10^3)\ W$$

$$W := \int_{0 \cdot sec}^{1 \cdot sec} P_m(t)\, dt$$

$$W = (2.5 \cdot 10^3)\ J$$

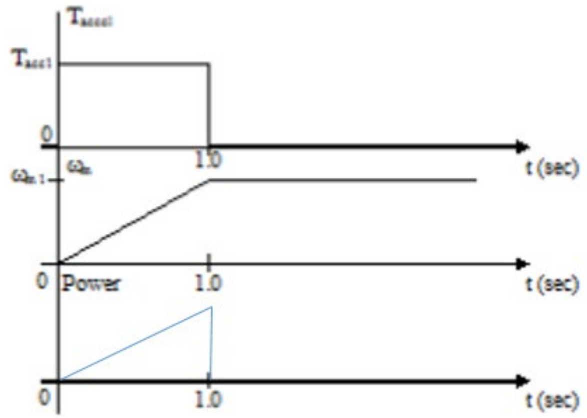
Example Problem 2:

Same plot as in problem 1

a) 10 pts Given the inertia Jm = 0.2 kJ/(rad/sec)2, calculate the rotational speed ωm1 if the energy at t=1sec, W = 2.5 kJ.sec

$$J_m := 0.2 \cdot \frac{1000 \cdot J}{\left(\frac{rad}{sec}\right)^2} \qquad w_{m1} := \sqrt{\frac{W}{0.5 \cdot J_m}} \qquad w_{m1} = 5\ \frac{rad}{sec}$$

b) 10 pts From the plot it is shown that the rotational speed is constant when the accelerating torque is removed at t>1sec. It means that there is no friction (for t>1sec). True or False *True*



Problem 12.1

In the system shown in Figure 12.5a, the gear ratio $n_L/n_m = 2$, $J_L = 10$ kg.m^2, and $J_m = 2.5$ kg.m^2. Damping can be neglected. For the load-speed profile in Figure below, draw the torque profile and the rms value of the electromagnetic torque required from the motor.

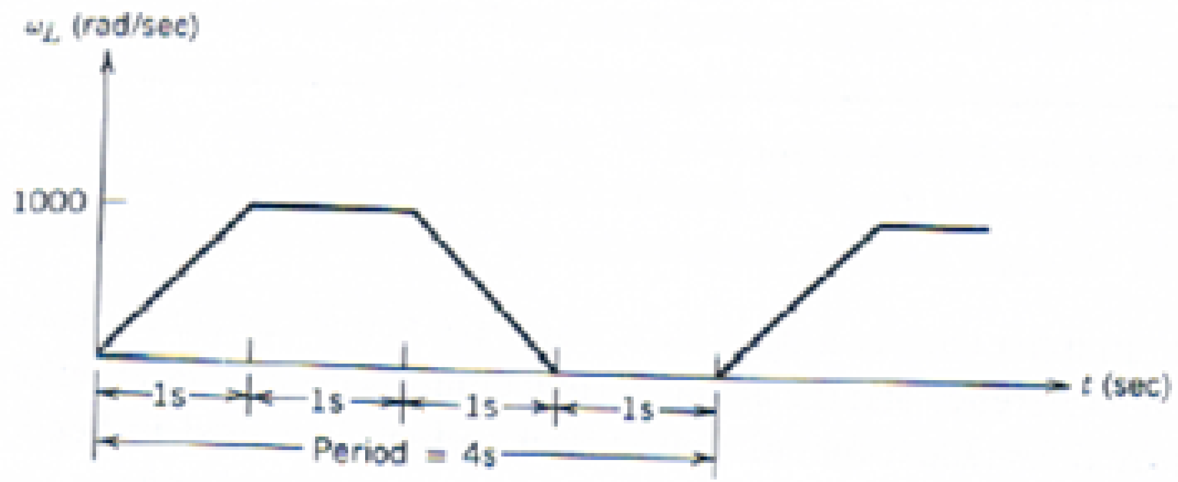
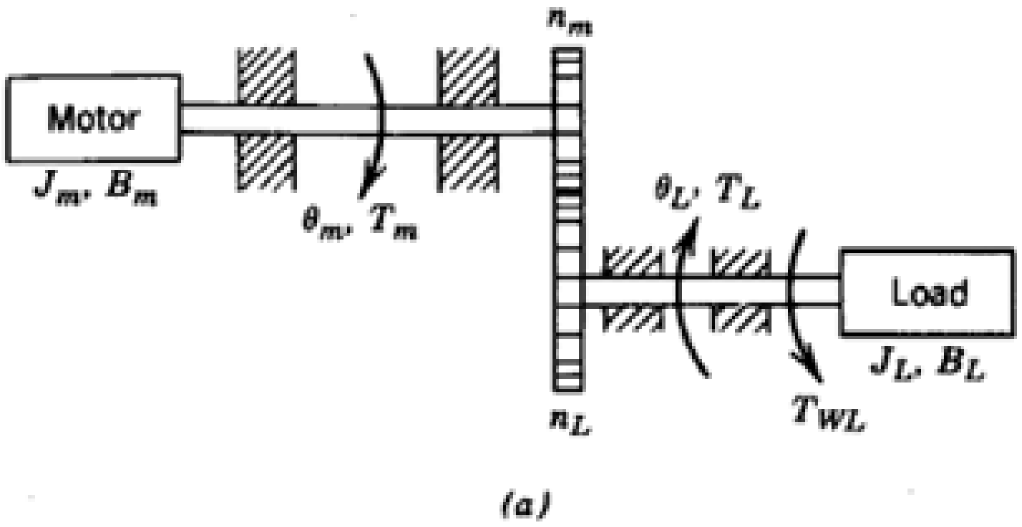
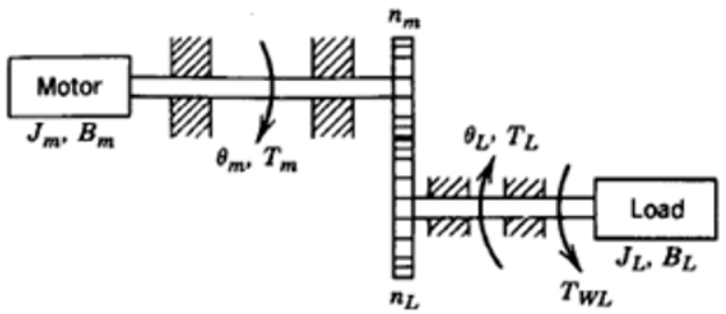


Figure P12-1



$$\frac{n_L}{n_m} = \frac{1}{a} = 2 \ , \ \therefore \quad a = 0.5$$



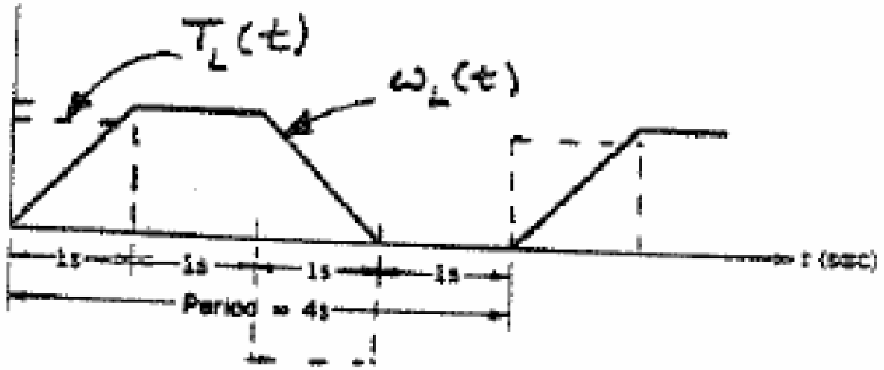
$$J_L = 10 \text{ kg-m}^2 \ , \quad J_m = 2.5 \text{ kg-m}^2$$

$$J_{eq} = J_m + a^2 J_L = 2.5 + (0.5)^2 \times 10 = 5 \text{ kg-m}^2$$

$$B_{eq} = 0 \quad \text{(damping neglected)}$$

$$T_{WL} = 0$$

$$T_L = J_L \frac{d\omega_L}{dt}$$



where, $\frac{d\omega_L}{dt} = 1000 \frac{\text{rad}}{s^2}$

From Eq. -3a,

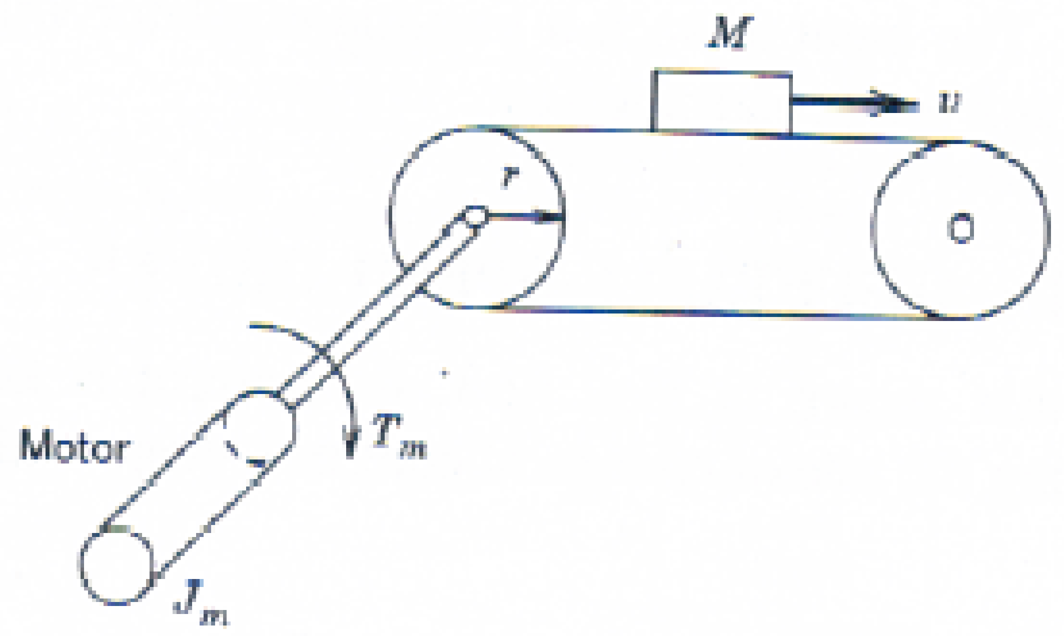
$$T_{em} - aT_{WL} = \frac{J_{eq}}{a}(s^2 \theta_L) = 10\, s^2 \theta_L$$

$$T^2_{em}(RMS) = \frac{1}{t_{period}} \int_0^{t_{period}} T^2_{em}(t)\cdot dt = \frac{1}{4}\left[\int_0^1 (10^4)^2\, dt + \int_2^3 (10^4)^2\, dt\right]$$

$$= \frac{1}{4}(10^8 + 10^8) = 0.5 \times 10^8$$

$$\therefore \quad T_{em}(RMS) = \sqrt{0.5} \times 10^4 = 7071.1 \quad \text{N-m}$$

Problem 12.2



Consider the belt and pulley system shown with J_m = motor inertia = 0.006 kg.m^2, M = mass of load = 0.5 kg, and r = pulley radius = 0.1 m.

Calculate the torque Tem from the motor to accellerate a load from rest to a velocity v = 1 m/s in a time of 3 seconds. Assume the motor torque to be constant during this interval.

The stored kinetic energy of the system is given by

$$W = \frac{1}{2} J_m \omega_m^2 + \frac{1}{2} M v^2$$

r^2 = radius^2

$$= \frac{1}{2} \omega_m^2 \boxed{\left(J_m + \boxed{\frac{v^2}{\omega_m^2}} M\right)} = \frac{1}{2} J_{eq} \omega_m^2$$

J_{eq}

$$r\theta_m = x, \quad \therefore \quad v = r \frac{d\theta_m}{dt} = r\omega_m$$

$$\therefore \quad \boxed{J_{eq} = J_m + r^2 M,}$$

$$T_{em} = J_{eq} \frac{d\omega_m}{dt}$$

$$\omega_m = \frac{v}{r}, \quad v_0 = 0, \quad v_f = 1 \text{ m/s}$$

$\Delta t = t_f - t_0 = 3$ s where $t_0 = 0$, $t_f = 3$ s

$M = 0.5$ kg

T_{em} is constant during Δt

$$\int_0^{t_f} T_{em}\, dt = \int_0^{t_f} J_{eq} \frac{d\omega_m}{dt} dt = J_{eq}[\omega(t_f) - \omega(o)] = J_{eq}\, \omega_f$$

where $(r^2 M)$ is the equivalent moment of inertia of the load reflected to the rotating part. (motor side)
where $\omega(o) = 0$ and $\omega(t_f) = \omega_f$.

$$\therefore \quad T_{em} \cdot t_f = J_{eq} \cdot \omega_f$$

$$T_{em} \approx \frac{J_{eq} \cdot \omega_f}{\underbrace{t_f}_{\Delta t}} = \boxed{\overbrace{\frac{v_f}{r t_f}}^{\omega_f / t_f}} \boxed{\overbrace{(J_m + r^2 M)}^{J_{eq}}}$$

$$\boxed{\text{Note: } \omega_f = \frac{v_f}{r}}$$

$$\boxed{T_{em} = \frac{1}{3r}(J_m + 0.5\, r^2)}$$

$r = 0.1$ m

$J_m = 0.006$ kg-m^2

$$\therefore \quad T_{em} = \frac{1}{3 \times 0.1} (0.006 + 0.5 \times 0.01) = 0.0367 \text{ N-m}$$