Electrical Engineering

Power Electronics

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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CHAPTER 10

Power Semiconductor Drives

10.1 DC Drives

- DC Drive consists of a DC Motor, Power Electronic Converter. i.e. Rectifier (or) chopper.
  Speed Sensing Mechanism – Tachometer,
  Feedback circuit and intelligent device (Micro controller)
- The following dc motors are suitable for speed control applications.
  1. Series motor
  2. Separately excited dc motor

In the speed control applications, load remains same i.e., output current is continuous and assumed to be constant.

$$E_a = \frac{Z\phi NP}{60A} = Z\phi n\left(\frac{P}{A}\right)$$

$$\omega_m = 2\pi n$$

$$E_a = Z\phi\left(\frac{\omega_m}{2\pi}\right)\left(\frac{P}{A}\right) = \left(\frac{Z}{2\pi}\cdot\frac{P}{A}\right)\phi\,\omega_m$$

$$\boxed{E_a = K_a\phi\omega_m}$$

where,
$$\boxed{K_a = \frac{Z}{2\pi}\left(\frac{P}{A}\right)}$$

$$E_a \cdot I_a \text{(Electrical power)} = \tau_e\omega_m \text{(Mechanical power)}$$

$$\tau_e = \frac{E_a I_a}{\omega_m}$$

$$\boxed{\tau_e = K_a\phi I_a}$$

Seperately Excited DC Motor

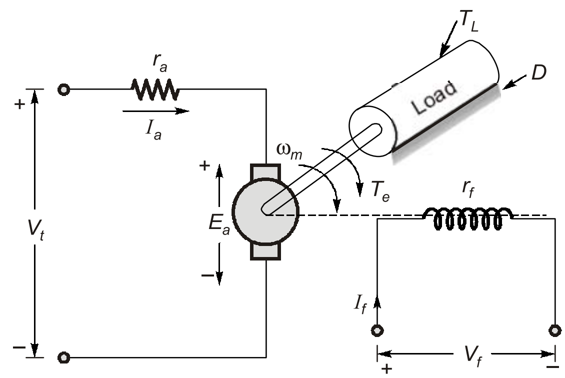


***Figure*-10.1**

$$E_a = K_a \phi \omega_m = (K_a \phi)\omega_m \Rightarrow \boxed{E_a = K_m \omega_m}$$

where, $K_m = K_a \phi$ (V-s/rad)

$$T_e = K_a \phi I_a \Rightarrow \boxed{T_e = K_m I_a}$$

where, units of K_m are N-m/A

***Example* - 10.1** A 250 V separately excited DC motor has armature resistance of 2.5 ohms. When driving a load at 600 r.p.m. with constant torque, the armature takes 20 A. The motor is controlled by a DC chopper operating with a frequency of 400 Hz and an input voltage of 250 V DC. What should be the value of duty ratio, if it is desired to reduce the speed from 600 r.pm. to 400 rpm? Also find the motor speed at rated current and a duty ratio of 0.5, if the motor is regenerating.

Solution:

For separately excited dc motor,

Armature Resistance = 2.5 Ω

∴ back emf $E_\phi = k_n \phi N$

where $E = V_t - I_a R_a = 250 - 20 \times 2.5 = 200$ V

∴ $$k_n \phi = \frac{200}{600} = \frac{1}{3}$$

Let (δ) be the duty ratio, then, $V_t = \delta V_i$ [where V_i = input voltage]

$$[\delta V_i - I_a R_a] = k_n \phi \times N'$$

Since torque remains constant,

∴ 'I' should be constant

$$[\delta \times 250 - 20 \times 2.5] = \frac{1}{3} \times 400$$

$$\delta = 0.733$$

At (δ = 0.5), and given, motor is regenerating working as a generator, then

$$N'' = \frac{[\delta V_i + I_a R_a]}{k_n \phi} = 3 \times [125 + 20 \times 2.5] = 525 \text{ rpm}$$

DC Series Motor

$$E_a = K_a \phi \omega_m$$
$$\phi \propto I_a$$
$$\phi = c I_a$$
$$E_a = K_a c I_a \omega_m \Rightarrow \boxed{E_a = K_1 I_a \omega_m}$$
$$T_e = K_a \phi I_a = K_a c I_a \cdot I_a \Rightarrow \boxed{T_e = K_1 I_a^2}$$

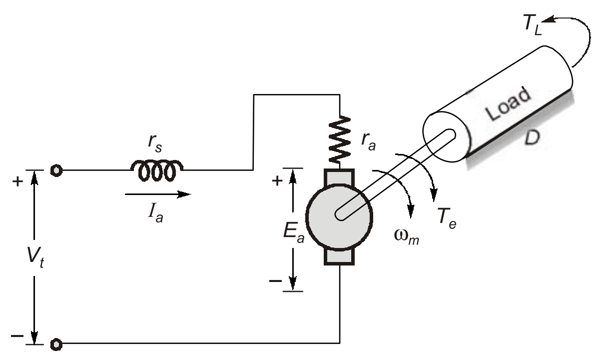


***Figure*-10.2**

K_1 units are [N-m/A²]

1-ϕ Half wave Rectifier Drive

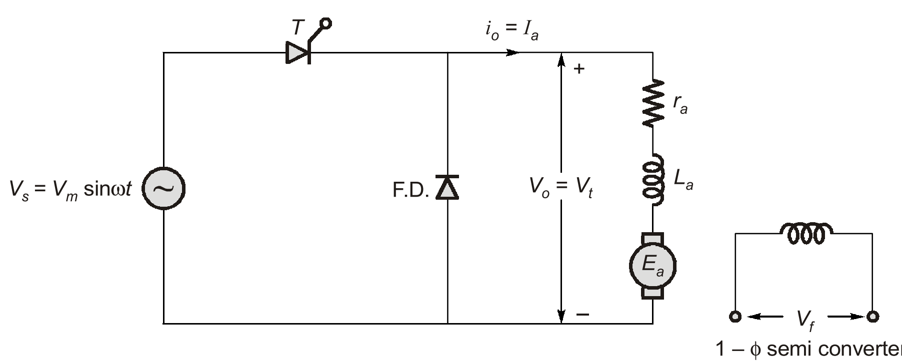


***Figure*-10.3**

$$V_0 = V_t = \frac{V_m}{2\pi}(1+\cos\alpha_1)$$

$$V_f = \frac{V_m}{\pi}(1+\cos\alpha_2)$$

Rms source current, $I_{sr} = I_{Tr} = I_a\sqrt{\left(\frac{\pi-\alpha_1}{2\pi}\right)}$

$$\text{Input power factor} = \frac{E_a I_a + I_a^2 r_a}{V_s I_{sr}} = \frac{I_a(E_a + I_a r_a)}{V_s \cdot I_{sr}}$$

$$\boxed{\text{Input power factor} = \frac{V_t \cdot I_a}{V_s \cdot I_{sr}}}$$

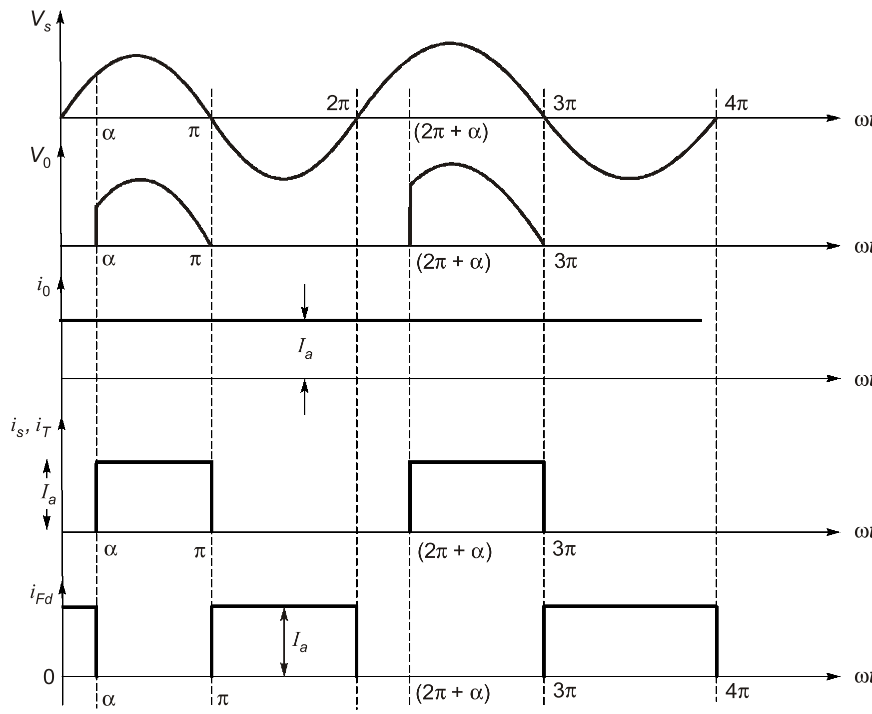


***Figure*-10.4**

1-ϕ Semi Converter Drive

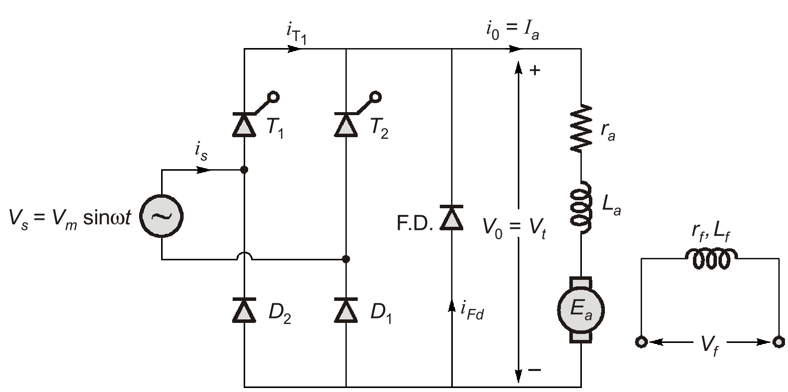


***Figure*-10.5**

For a 1-ϕ semiconverter, average output voltage

$$\boxed{V_0 = V_t = \frac{V_m}{\pi}(1+\cos\alpha)}$$

For field circuit, $$V_f = \frac{V_m}{\pi}(1+\cos\alpha_1)$$

Rms value of source current, $$I_{s\,\text{rms}} = I_a\sqrt{\left(\frac{\pi-\alpha}{\pi}\right)}$$

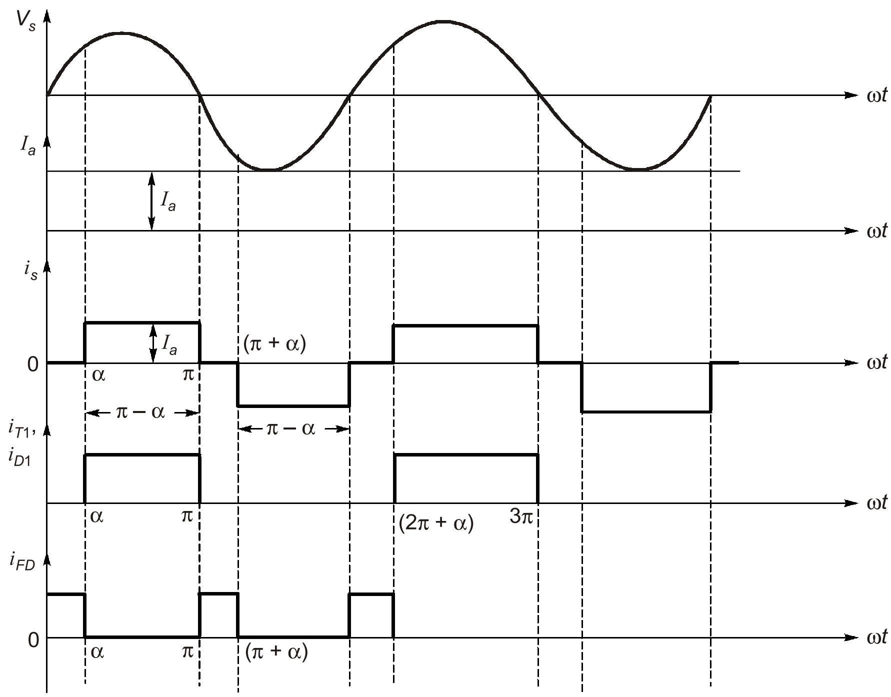


***Figure*-10.6**

Rms value of freewheeling diode current,

$$I_{FD\,rms} = I_a\sqrt{\left[\frac{\alpha}{\pi}\right]}$$

Rms value of thyristor current,

$$I_{T\,rms} = I_a\sqrt{\left(\frac{\pi-\alpha}{2\pi}\right)}$$

$$\text{Input power factor} = \frac{V_t \cdot I_a}{V_s \cdot I_{sr}} = \frac{\sqrt{2}V_s \cdot (1+\cos\alpha)\cdot I_a\sqrt{\pi}}{\pi \cdot V_s I_a\sqrt{\pi-\alpha}}$$

$$\boxed{\text{Input pf} = (1+\cos\alpha)\sqrt{\left[\frac{2}{\pi(\pi-\alpha)}\right]}}$$

A 1-ϕ semiconverter is also called 1-ϕ half controlled bridge converter.

***Example* - 10.2** A single-phase half-controlled rectifier is driving a separately excited dc motor. The dc motor has a back emf constant of 0.25 V/rpm. The armature current is 5 A without any ripple. The armature resistance is 2 Ω. The converter is working from a 230 V, single phase ac source with a firing angle of 30°. Under this operating condition, the speed of the motor will be

(a) 339 rpm
(b) 346 rpm
(c) 366 rpm
(d) 386 rpm

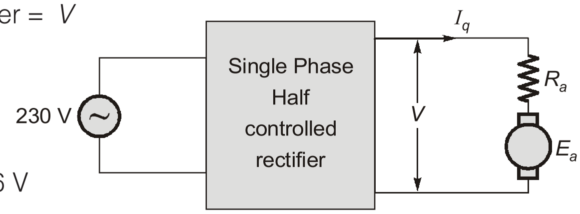
Solution : (b)

Back emf $= E_a = k\phi N$

or $E_a = k_b N$

where, k_b = Back-emf constant = 0.25 V/rpm

Average output voltage of 1-ϕ half controlled rectifier = V



$$V = \frac{V_m}{2\pi}(1+\cos\alpha) = \frac{230\sqrt{2}}{2\pi}(1+\cos 30°)$$

$\Rightarrow$ $V = 96.6$ V

$$E_a = V - I_a R_a = 96.6 - 5 \times 2 = 86.6 \text{ V}$$

$$\text{Speed} = N = \frac{E_a}{k_b} = \frac{86.6}{0.25} = 346.4 \text{ V}$$

So, option (a) is closer to 346.4 V.

Example - 10.3 A separately-excited dc motor is supplied from 230 V, 50 Hz source through a single-phase half-wave controlled converter. Its field is fed through 1-phase semiconverter with zero degree firing-angle delay. Motor resistance r_a = 0.7 Ω and motor constant = 0.5 V-sec/rad. For rated load torque of 15 Nm at 1000 rpm and for continuous ripple free currents, determine.

(a) Firing angle delay of the armature converter

(b) rms value of thyristor and freewheeling diode currents

(c) input power factor of the armature converter.

Solution:

(a) Motor constant = 0.5 V-sec/rad = 0.5 Nm/A = K_m

But motor torque, $T_e = K_m I_a$

$\therefore$ Armature current $= \dfrac{15}{0.5} = 30$ A

Motor emf, $E_a = K_m.\ \omega_m = 0.5 \times \dfrac{2\pi \times 1000}{60} = 52.36$ V

For 1-phase half-wave converter feeding a dc motor.

$$V_t = \frac{V_m}{2\pi}(1 + \cos\alpha) = E_a + I_a r_a$$

or

$$V_t = \frac{\sqrt{2}\times 230}{2\pi}(1 + \cos\alpha) = 52.36 + 30 \times 0.7 = 73.36 \text{ V}$$

$$\therefore \quad \alpha = \cos^{-1}\left[\frac{73.36 \times 2\pi}{\sqrt{2}\times 230} - 1\right] = 65.349°$$

Thus, firing angle delay of converter 1 is 65.336°

(b) Rms value of thyristor current, is

$$I_{Tr} = I_a\left(\frac{\pi - \alpha}{2\pi}\right)^{1/2} = 30\left(\frac{180 - 65.349°}{360}\right)^{1/2}$$

$$= 16.930 \text{ A} = I_{sr}$$

Rms value of freewheeling diode current,

$$I_{fd.r} = I_a\left(\frac{\pi+\alpha}{2\pi}\right)^{1/2} = 30\left(\frac{180+65.349°}{360}\right)^{1/2} = 24.766\text{ A}$$

(c) Input power factor of armature converter $= \frac{V_t.I_a}{V_s.I_{sr}} = \frac{73.36\times 30}{230\times 16.931} = 0.5651$ lag.

Also, input power factor of armature converter

$$= \frac{1+\cos\alpha}{\sqrt{\pi(\pi-\alpha)}} = \frac{1+\cos 65.349°}{\left[\pi(180-65.336°)\frac{\pi}{180}\right]^{1/2}} = 0.56518\text{ lag.}$$

1-ϕ Fullwave Rectifier Drive

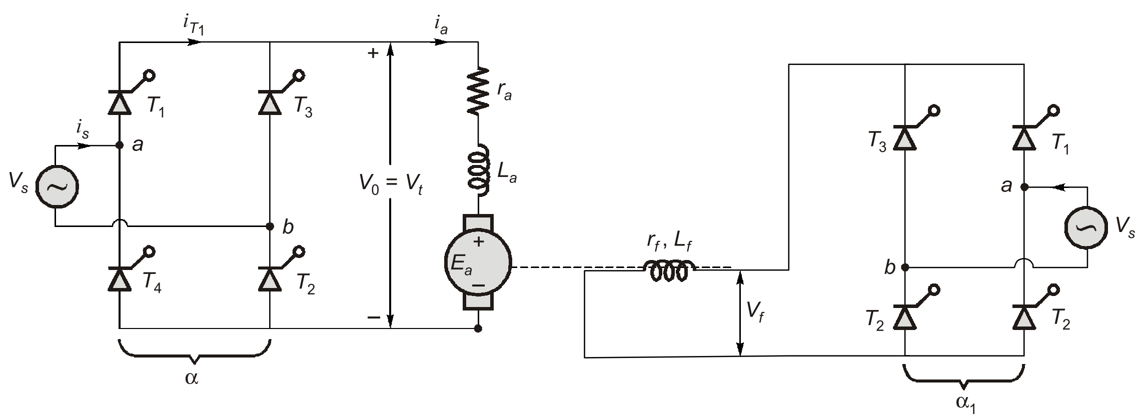


***Figure*-10.7**

- For the armature converter 1,

$$\boxed{V_0 = V_t = \frac{2V_m}{\pi}\cos\alpha} \quad \text{for } 0 < \alpha < \pi.$$

- For the field converter 2, $\quad V_f = \frac{2V_m}{\pi}\cos\alpha_1 \quad$ for $0 < \alpha_1 < \pi$

- Rms value of source current, $I_{s\,rms} = \sqrt{\left(I_a^2 \cdot \frac{\pi}{\pi}\right)} = I_a$

- Rms value of thyristor current, $I_{T\,rms} = \sqrt{\left(I_a^2 \cdot \frac{\pi}{2\pi}\right)} = \frac{I_a}{\sqrt{2}}$

- Input supply p.f. $= \frac{V_t \cdot I_a}{V_s \cdot I_{sr}} = \frac{2V_m}{\pi}\cos\alpha \frac{I_a\sqrt{2}}{V_m \cdot I_a}$

$$\boxed{\text{Input p.f.} = \frac{2\sqrt{2}}{\pi}\cos\alpha}$$

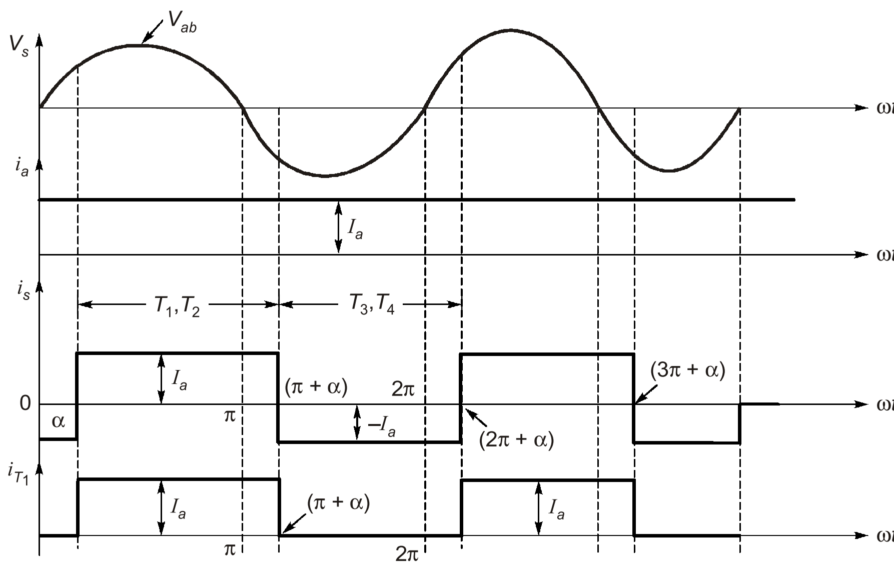
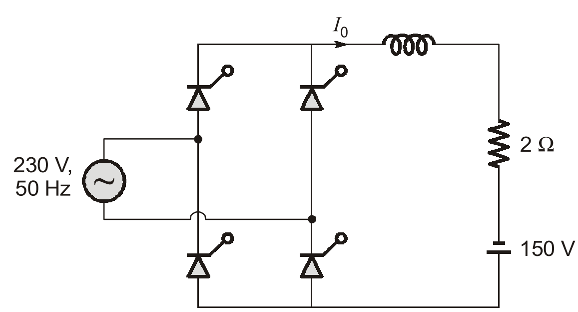


***Figure*-10.8**

Example - 10.4 A single phase fully controlled converter bridge is used for electrical braking of a seprately excited dc motor. The dc motor load is represented by an equivalent circuit as shown in the figure.



Assume that the load inductance is sufficient to ensure continous and ripple free load current. The firing angle of the bridge for a load current of I_0 = 10 A will be

(a) 44° (b) 51°
(c) 129° (d) 136°

Solution : (c)

Average output voltage of the converter,

$$V_0 = \frac{2V_m}{\pi}\cos\alpha$$

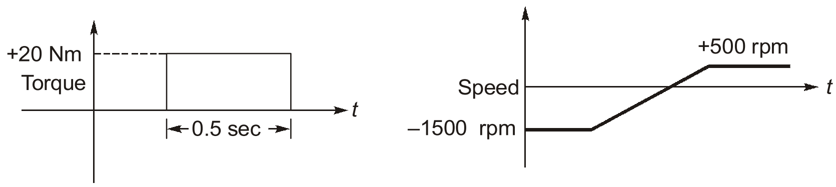
Load current = I_0 = 10 A
Back emf = E_b = 150 V
Armature resistance = R_a = 2 Ω

Applying KVL,

$$V_0 - 2I_0 + 150 = 0$$

$$\Rightarrow \quad V_0 = -150 + 2 \times 10 = -130 \text{ V}$$

Example - 10.11 A variable speed drive rated for 1500 rpm, 40 Nm is reversing under no load. Figure shows the reversing torque and the speed during the transient. The moment of inertia of the drive is



(a) 0.048 kg m^2
(b) 0.064 kg m^2
(c) 0.096 kg m^2
(d) 0.128 kg m^2

Solution : (a)

Speed changes from –1500 rpm to 500 rpm in 0.5 sec.

So angular acceleration,

$$\alpha = \frac{500-(-1500)}{0.5} \times \frac{2\pi}{60} \text{rad/sec}^2 = 418.88 \text{ rad/sec}^2$$

$$\text{Torque} = T = 20 \text{ N-m}$$

$$T = I\alpha$$

Moment of inertia,

$$I = \frac{T}{\alpha} = \frac{20}{418.88} = 0.048 \text{ kgm}^2$$

Example - 10.12 An electric motor, developing a starting torque of 15 Nm, starts with a load torque of 7 Nm on its shaft. If the acceleration at start is 2 rad/sec^2, the moment of inertia of the systems must be (neglecting viscous and Coulomb friction)

(a) 0.25 kg m^2
(b) 0.25 Nm^2
(c) 4 kg m^2
(d) 4 Nm^2

Solution : (c)

T_S = Starting torque developed by the motor = 15 N-m

T_L = Load torque = 7 N-m

T_a = Accelerating torque

= $T_S - T_L = 15 - 7 = 8$ N-m

α = Acceleration = 2 rad/sec^2

$T_a = I\alpha$

$$I = \text{Moment of inertia} = \frac{T_a}{\alpha} = \frac{8}{2} = 4 \text{ kg m}^2$$

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