جامعة بنها - كلية الهندسة ببنها - قسم الهندسة الكهربية

الإجابة النموذجية لمادة نظم التحريك الكهربية ك1439 الفرقة الرابعة كهرباء قوى وتحكم

يوم الاربعاء الموافق11/1/2017 د شوقي حامد عرفه ابراهيم

Benha University	**Time: 3 hours**
Benha Faculty of Engineering	**Forth Year : 11/1/2017**
Subject: Electrical drive systems (E1439)	**Elect.Eng.Dept.**

Solve & draw as much as you can (questions in two pages)

Question (1) **[10] Points**

a- Explain in details: Electrical drives- Speed control of a DC motor?

b- A three phase- Y- induction motor [380V, 60Hz, 1700rpm, pf=0.8, η_m=0.85, 4 poles]. Find ω_{syn}, S, I_s, P_m, T_{dev} when used to:

i-Drive a load of 80Nm, 1440 rpm across gear box of η_{gear}= 0.9.

ii-Drive an elevator of η_{elev}=0.75 and loaded by 8000Kg to 100m in one minute (design to half load).

iii-Drive a water pump of 20m^3/hour, height =25m across gear box of η_{gear}=0.8.

Question (2) **[15] Points**

a- The closed loop control system is used for speed control of a separately excited DC motor. Draw the steady state block diagram and prove that

$$\frac{\omega_r}{V_r} = \frac{K_1 K\phi}{BR_a + K\phi(K_1K_2 + K\phi)} \qquad \frac{\omega_r}{-T_w} = \frac{R_a}{BR_a + K\phi(K_1K_2 + K\phi)}$$

b- A [80Hp, 200V, 1200 rpm] separately excited DC motor is used in a speed control system. The field current is held constant at a value for which $R_a = 0.1\Omega$, $B = 0.03\ N.m.s/rad$, $K\Phi = 1.3\ V.S/rad$, $K_1 = 200$, $K_2 = 0.1V\ s/rad$.

i- Find V_r required to drive the motor at rated speed with no load?

ii- Find the motor speed if V_r is not changed and the motor supplied rated torque?

iii- Find the motor speed if V_r is decreased by 15%?

Question (3) **[30] Points**

A separately excited DC motor has

$11hp, 240V,\ 1500rpm,\ R_a = 0.125\Omega,\ R_f = 120\Omega,\ K\Phi = 1.5Nm/A,\quad T_{losses} = constant = 2.24Nm, load\ torque\ is\ 50Nm.$

a- Find the motor speed if the armature voltage is 190 V?

b- Find the motor speed and (pf) if its armature is supplied by fully controlled single phase rectifier [firing angle = 25 degrees, 240 V, 60Hz AC supply] and assume constant armature current and field current?

c- Find the motor speed and (pf) if its armature is supplied by a semi-controlled single phase rectifier [firing angle = 20 degrees, 240 V, 60Hz AC supply] and assume constant armature current and field current?

d- Find the motor speed if its armature is supplied by fully controlled single phase rectifier [firing angle = 25 degrees, 240 V, 60Hz AC supply]. Assume constant field current but the armature current discontinuous for 10 degrees every half cycle?

e- Draw the wave forms of voltages and currents and the power circuit for b, c, and d?

Question (4) **[10] Points**

A separately excited DC motor has[$\boldsymbol{K\Phi = 0.5\frac{Nm}{A}, R_a = 0.3\Omega,\ L_a = 0.06H}$]

a- If the load is [5Nm at 859 rpm] and the motor armature supplied from class A chopper and 72V dc source. The chopping frequency is 1 KHz. The field current is held constant.

i-Find the minimum duty cycle?

ii-Find the armature current equations during the on and off periods?

iii- Draw the power circuit and current and voltage waveforms?

Question (5) **[25] Points**

a- Explain how to control the speed of the 3-phase induction motor?

b- A three phase 460V, 60Hz, 4 poles, 1750 rpm, wye-connected induction motor has the following equivalent circuit parameters referred to the stator side:

$\boldsymbol{R_s = 1.01\Omega,\ R_r = 0.69\Omega,\ \ X_m = 43.5\Omega,\ X_1 = 1.3\Omega,\ X_2 = 1.94\Omega,\ T_L = K\omega_r{}^2 = 41Nm\ at 1740rpm}$

i-Draw the equivalent circuit and find ω_{syn}, ω_{r}, S, I_s, I_r , P_{gap}, P_{copper} , T_{dev}?

ii- If the motor is connected to a 3-phase full wave AC/AC converter. Find the firing angle required to run the motor with speed range of 1000 rpm to 1750 rpm.

iii- If the motor is connected to a 3-phase six step inverter. Find the required DC supply to run the motor with speed of 1000 rpm?

iv- Draw the power circuit and current and voltage waveforms for case ii and case iii?

Answer

Question (1) **[20] Points**

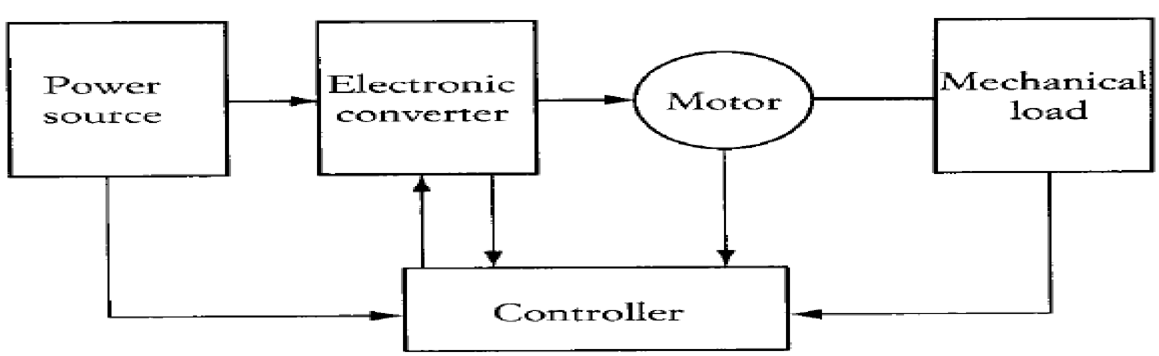
a- Explain in details: Electrical drives- Speed control of a DC motor?

The study of electric drive systems involves controlling electric motors in the steady state and in dynamic operations, taking into account the characteristics of mechanical loads and the behaviors of power electronic converters.

The electrical Drive is a system converts the electrical Energy to the mechanical energy with electrical control.

Drive types are: 1-line shaft drive 2-single motor single load drive 3-multimotor drives.

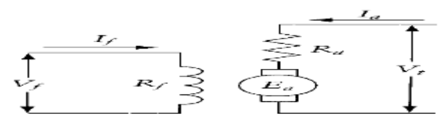
Functional blocks of an electric drive system



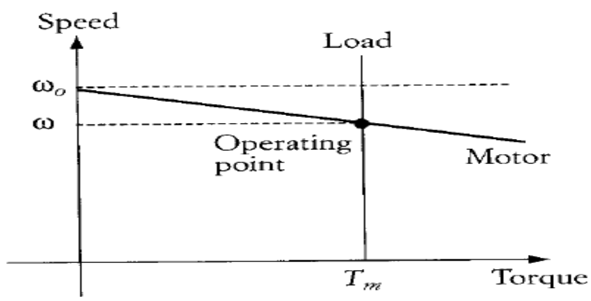
1. *Separately excited machines.* The field winding is composed of a large number of turns with small cross-section wire. This type of field winding is designed to withstand the rated voltage of the motor. The field and armature circuits are excited by separate sources.

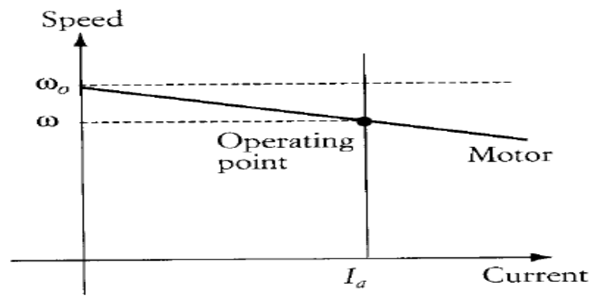
Speed control of DC drive: Common dc drives are 1-rectifier drives 2-dc chopper drives 3-dual converter drives

Equivalent circuit of a dc motor in steady-state operation

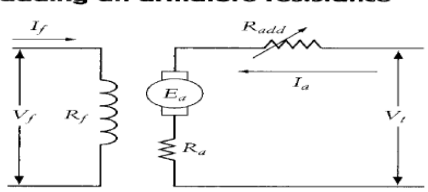


$$\omega = \frac{V_t}{K\phi} - \frac{R_a}{(K\phi)^2} T_d \qquad \omega = \frac{V_t}{K\phi} - \frac{R_a I_a}{K\phi}$$

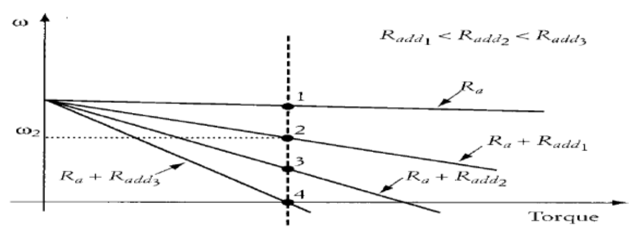




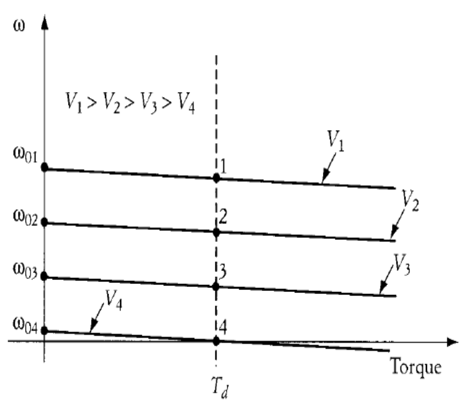
A setup for speed change by adding an armature resistance



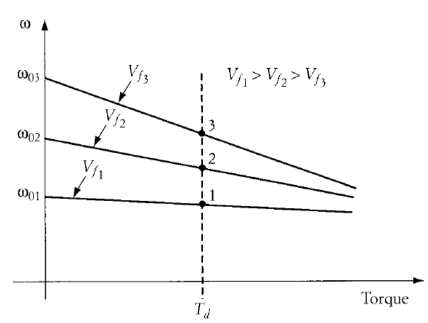
Effect of adding an armature resistance on speed



Motor characteristics when armature voltage changes



Effect of field voltage on motor speed



$$T_{mech} = K_a \Phi_d i_a, \qquad e_a = K_a \Phi_d \omega_m$$

In a motor the relation between the emf E_a generated in the armature and and the armature terminal voltage V_a is

$$V_a = E_a + I_a R_a \quad (7.11)$$

$$I_a = \frac{V_a - E_a}{R_a} \quad (7.12)$$

Torque and power:

The electromagnetic torque T_{mech}

$$T_{mech} = K_a \Phi_d I_a$$

The generated voltage E_a

$$E_a = K_a \Phi_d \omega_m$$

$$K_a = \frac{\text{poles} C_a}{2\pi m}$$

$E_a I_a$: electromagnetic power

$$T_{mech} = \frac{E_a I_a}{\omega_m} = K_a \Phi_d I_a$$

b-Athree phase- Y- induction motor [380V, 60Hz, 1700rpm, pf=0.8, η_m=0.85, 4 poles]. Find ω_{syn}, S, I_s, P_m, T_{dev} when used to:

i-Drive a load of 80Nm, 1440 rpm across gear box of η_{gear}= 0.9.

ii-Drive an elevator of η_{elev}=0.75 and loaded by 8000Kg to 100m in one minute (design to half load).

iii-Drive a water pump of 20m^3/hour, height =25m across gear box of η_{gear}=0.8.

i----n_s=120*60/4=1800rpm, ω_s=1800*pi/30=188.5rad/s, S=(n_s-n_r)/ n_s =(1800-1700)/1800=0.056

P_L=T_L* ω_L=80*1440*pi/30=12.06KW, $P_{inp\ gear}$= P_L/ η_{gear}=12.06/0.9=13.4KW

$P_{inp\ m}$= P_{outm}/ η_m=13.4/0.85=15.8KW=√3 $V_L I_L$cosΦ, I_L=15800/(√3*380*0.8)=29.95A

ii-----P_L=F*V=m*g*V=8000*9.81*100/60=130.8KW, $P_{inp\ ele}$= P_L/ η_{ele}=130.8/0.75=174.4KW

$P_{inp\ m}$= P_{outm}/ η_m=174.4*0.5/0.85=102.6KW=√3 $V_L I_L$cosΦ, I_L=102600/(√3*380*0.8)=124.7A

iii----P_L=F*V=Q*g*h*ρ/t=20*9.81*25*1000/3600=1.3625KW, $P_{inp\ pump}$= P_L/ η_{gear}=1.3625/0.8=1.703KW, $P_{inp\ m}$= P_{outm}/ η_m=1.703/0.85=2.004KW=√3 $V_L I_L$cosΦ, I_L=2004/(√3*380*0.8)=3.81A

Question (2) **[15] Points**

a- The closed loop control system is used for speed control of a separately excited DC motor. Draw the steady state block diagram and prove that

$$\frac{\omega_r}{V_r} = \frac{K_1 K\phi}{BR_a + K\phi(K_1 K_2 + K\phi)} \qquad \frac{\omega_r}{-T_w} = \frac{R_a}{BR_a + K\phi(K_1 K_2 + K\phi)}$$

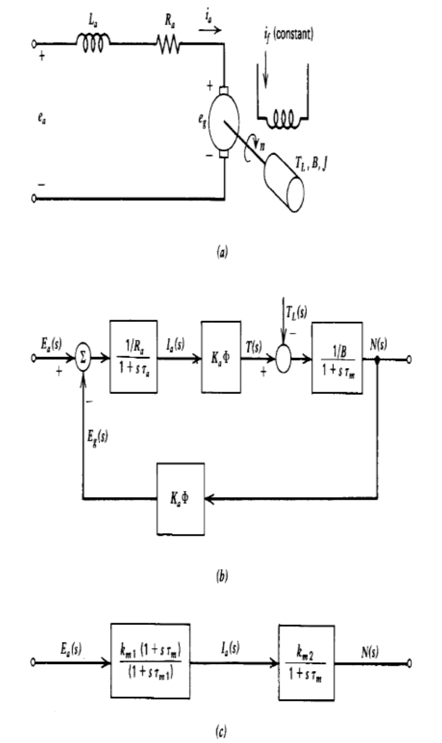


Fig. 6.2 Development of motor transfer function. (a) Separately excited dc motor model. (b) Functional block diagram. (c) Simplified functional block diagram.

In the Laplace domain, equations 6.1 through 6.4 can be written as

$$E_a(s) = E_g(s) + R_a I_a(s) + L_a s I_a(s) \qquad (6.5)$$

$$E_g(s) = K_a \Phi N(s) \qquad (6.6)$$

$$T(s) = T_L(s) + BN(s) + JsN(s) \qquad (6.7)$$

$$T(s) = K_a \Phi I_a(s) \qquad (6.8)$$

$$I_a(s) = \frac{E_a(s) - E_g(s)}{R_a + sL_a} = \frac{[E_a(s) - E_g(s)]1/R_a}{1 + \tau_a s}$$

where $\tau_a = L_a/R_a$ = electrical time constant of the motor armature

$$N(s) = \frac{T(s) - T_L(s)}{B + Js} = \frac{[T(s) - T_L(s)]1/B}{1 + \tau_m s}$$

where $\tau_m = J/B$ = mechanical time constant of the motor.

$$\frac{N(s)}{E_r(s)} = \frac{k_s k_{IC} k_{m2}}{1 + k_s k_{IC} k_{m2} k_t} \frac{(1 + s\tau_t)}{1 + s\frac{(\tau_m + \tau_t)}{k^1} + \frac{s^2 \tau_m \tau_t}{k^1}}$$

$$\frac{N(s)}{E_a(s)}=\frac{K_a\Phi}{(K_a\Phi)^2+R_aB+sR_aB\tau_m}=\frac{k_m}{1+s\tau_{m1}}$$

$$\frac{N(s)}{E_a(s)}=\frac{K_a\Phi}{(K_a\Phi)^2+R_aB(1+s\tau_a)(1+s\tau_m)}$$

$$\tau_{m1}=\frac{R_aB}{(K_a\Phi)^2+R_aB}\tau_m$$

$$k_m=\frac{K_a\Phi}{(K_a\Phi)^2+R_aB}$$

$$\tau_{m1}<\tau_m$$

2b

$$\frac{N(s)}{I_a(s)}=\frac{K_a\Phi/B}{1+s\tau_m}=\frac{k_{m2}}{1+s\tau_m}$$

om equations 6.12a and 6.13

$$\frac{I_a(s)}{E_a(s)}=\frac{N(s)}{E_a(s)}\times\frac{I_a(s)}{N(s)}$$

$$=\frac{k_mB(1+s\tau_m)}{K_a\Phi(1+s\tau_{m1})}=\frac{k_{m1}(1+s\tau_m)}{1+s\tau_{m1}}$$

$$k_{m1}=\frac{B}{(K_a\Phi)^2+R_aB}=\frac{k_m}{K_a\Phi/B}$$

$$k_{m2}=\frac{K_a\Phi}{B}$$

$$k_m=k_{m1}k_{m2}$$

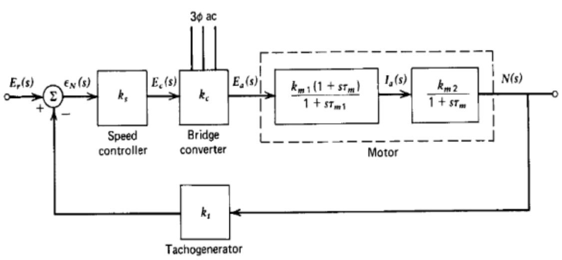


Fig. 6.3 Speed-control loop.

E_c and the armature voltage E_a can be obtained. If the small time delay associated with the converter is neglected then

$$\frac{E_a(s)}{E_c(s)}=k_c=\frac{3\sqrt{2}\,V_{LL}}{\pi\hat{E}_c}$$

where $\hat{E}_c$ corresponds to 0° firing angle and V_{LL} is the ac line to line rms voltage.

Proportional (P) Controller

Several types of speed controllers[2] are possible. Two of the more co ones are proportional (P) and proportional-integral (PI). First, a P cor is considered.

From Fig. 6.3

$$\frac{N(s)}{E_r(s)}=\frac{G(s)}{1+G(s)H(s)}$$

where

$$G(s)=\frac{k_sk_ck_{m1}k_{m2}}{1+s\tau_{m1}}$$

$$H(s)=k_t$$

From equations 6.15, 6.15a, and 6.15b

$$\frac{N(s)}{E_r(s)}=\frac{k_1}{1+s\tau_1}$$

where

$$k_1 = \frac{k_s k_c k_{m1} k_{m2}}{k_s k_c k_{m1} k_{m2} k_t + 1}$$

$$\tau_1 = \frac{\tau_{m1}}{k_s k_c k_{m1} k_{m2} k_t + 1}$$

If $k_s k_c k_{m1} k_{m2} k_t \gg 1$, then

$$k_1 \simeq \frac{1}{k_t}$$

$$\tau_1 \simeq \frac{\tau_{m1}}{k_s k_c k_{m1} k_{m2} k_t}$$

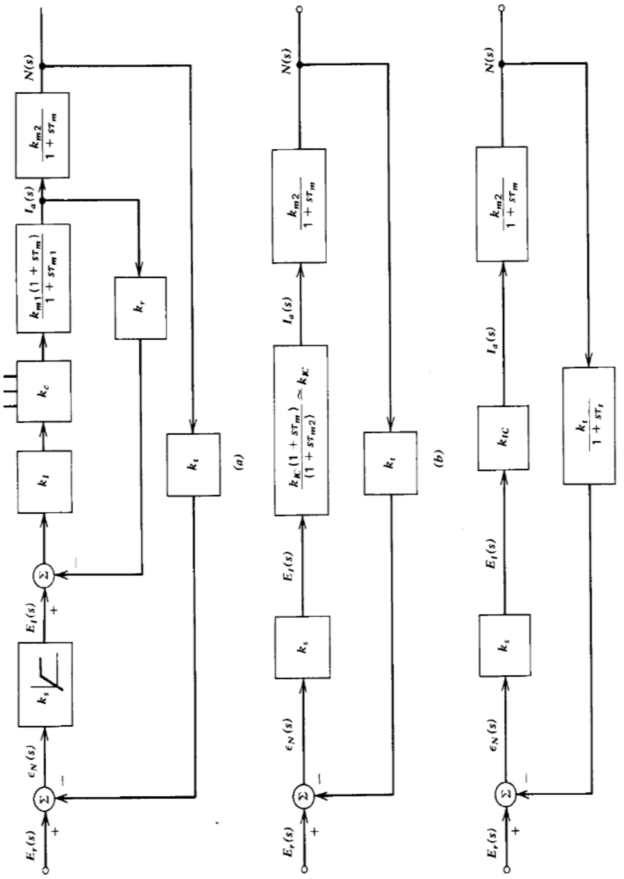


Fig. 6.5 Proportional speed control with inner current-control loop. (a) Functional block diagram. (b) Simplified functional block diagram. (c) Functional block diagrams with added tachogenerator filter.

b- A [80Hp, 200V, 1200 rpm] separately excited DC motor is used in a speed control system. The field current is held constant at a value for which $R_a = 0.1\Omega$, $\mathrm{B} = 0.03\,N.m.s/rad$, $\mathrm{K\Phi} = 1.3\,V.S/rad$, $K_1 = 200$, $K_2 = 0.1\mathrm{V}\,s/rad$.

i- Find V_r required to drive the motor at rated speed with no load?

ii- Find the motor speed if V_r is not changed and the motor supplied rated torque?

iii- Find the motor speed if V_r is decreased by 15%?

i- P=Tω=(2pi/60)(1200*T)=80*746, T=474.8Nm, or T=(200-40pi*1.3)*1.3/0.1=476.2Nm

rated speed=1200rpm=125.7rad/s.

$$\frac{\omega_r}{V_r} = \frac{K_1 K\phi}{\mathrm{B}R_a + K\phi(K_1 K_2 + K\phi)} = \frac{200 * 1.3}{27.7} = 9.39$$

Vr=125.7/9.39=13.39V

$$\frac{\Delta\omega_r}{-\Delta T_w} = \frac{R_a}{BR_a + K\phi(K_1K_2 + K\phi)} = \frac{0.1}{27.7} = \frac{0.089}{41.9} = 0.00361,$$

$$\Delta\omega_r \quad = -0.00361 * 474.8 = -\frac{1.714\text{rad}}{\text{s}}, \Delta\omega_r \quad = -0.00361 * 476.2 = -\frac{1.72\text{rad}}{\text{s}}$$

$$\omega_r = 125.7 - 1.72 = \frac{124.rad}{s} = 1184rpm$$

iii-As Vr decreased to =0.85*13.39=11.38V, wr=11.38*9.39=106.87rad/s

As motor loaded then wr=106.87-1.74=105.rad/s=1004rpm

Question (3) **[30] Points**

A separately excited DC motor has

$11hp, 240V,\ 1500rpm,\ R_a = 0.125\Omega,\ R_f = 120\Omega,\ K\Phi = 1.5Nm/A,\quad T_{losses} = constant = 2.24Nm, load\ torque\ is\ 50Nm.$

a- Find the motor speed if the armature voltage is 190 V?

b- Find the motor speed and (pf) if its armature is supplied by fully controlled single phase rectifier [firing angle = 25 degrees, 240 V, 60Hz AC supply] and assume constant armature current and field current?

c- Find the motor speed and (pf) if its armature is supplied by a semi-controlled single phase rectifier [firing angle = 20 degrees, 240 V, 60Hz AC supply] and assume constant armature current and field current?

d- Find the motor speed if its armature is supplied by fully controlled single phase rectifier [firing angle = 25 degrees, 240 V, 60Hz AC supply]. Assume constant field current but the armature current discontinuous for 10 degrees every half cycle?

e- Draw the wave forms of voltages and currents and the power circuit for b, c, and d?

a-I_a=[50+2.24]/1.5=34.83A, E_a==190-34.83*0.125=185.65V, w=185.65/1.5=123.76rad/s, n=1182rpm ,Va=E_a+IaRa

b-For a single phase rectifier with continuous armature current Va>Ea

α=25 degrees , $V_a=[2V_{max}\cos\alpha]/pi=(2*240*1.414\cos25)/pi=195.83$V, w=[195.83-34.83*0.125]/1.5=127.65rad/s, n=1219rpm ,$V_a=E_a+I_aR_a$,

pf= $\cos\alpha=0.9\cos25=0.82$, pf_1(fundamental)= $\cos\alpha=\cos25=0.91$

c-For a single phase semi-cont. rectifier with continuous armature current

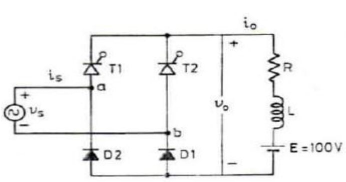
α=20 degrees , $V_a=[V_{max}(1+\cos\alpha)]/pi=[240*1.414(1+\cos20)/pi]=209.56$V, w=[209.56-34.83*0.125]/1.5=136.8rad/s, n=1306.4rpm

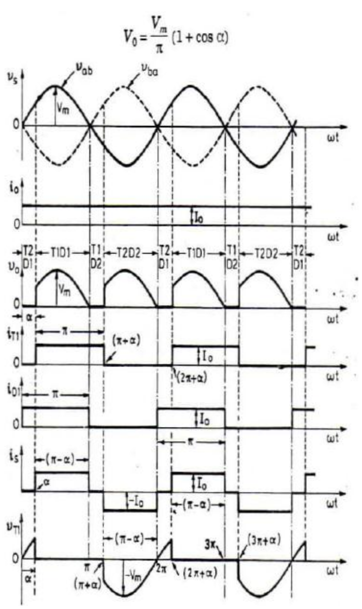
pf_1(fundamental)= $\cos\alpha/2=\cos10=0.985$, pf=$(\sqrt{2}/(pi(pi-\alpha)))(1+\cos\alpha)=0.99$

d-For a single phase fully-cont. rectifier with discontinuous (10deg.) armature current

α=25 degrees , $V_a=[V_{max}(\cos\alpha -\cos195)]/pi=[240*1.414(0.966+\cos25)/pi]=202.3$V,

w=[202.3-34.83*0.125]/1.5=131.95rad/s, n=1260rpm





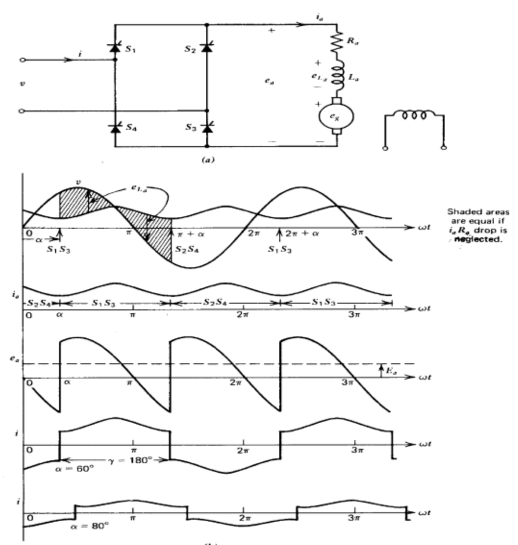


Fig. 2.3 Speed control of a separately excited dc motor by a single-phase full-converter. (*a*) Power circuit. (*b*) Voltage and current waveforms for continuous motor current (motor operation). (*c*) Waveforms for inversion operation.

Question (4) **[10] Points**

A separately excited DC motor has[$\boldsymbol{K\Phi = 0.5\frac{Nm}{A}, R_a = 0.3\Omega, L_a = 0.06H}$]

a- If the load is [5Nm at 859 rpm] and the motor armature is supplied from class A chopper and 72V dc source. The chopping frequency is 1 KHz. The field current is held constant.

i-Find the minimum duty cycle?

ii-Find the armature current equations during the on and off periods?

iii- Draw the power circuit and current and voltage waveforms?

Ia=5/0.5=10A, E=(2pi/60)*859*0.5=45V,E/Vdc=45/72=0.625,

Ta=La/Ra=0.06/0.3=0.2S,Tp=1/1000=1mS, Tp/Ta=0.005,

$$t_{on\ critical} = \tau \ln\left[1 + \frac{E}{V_{dc}}\left(e^{T_p/\tau} - 1\right)\right] = \ 0.626\text{msec.}$$

$K_{critical} = \frac{\tau}{T_p}\ln[1 + \frac{E}{V_{dc}}\left(e^{T_p/\tau} - 1\right)]$=0.626, $V_a=E_a+I_aR_a$ = 45+10*0.3= 48V,

$K=t_{on}/T_p=V_{av}/V_{dc}$=48/72=0.67> Kc then continuous current mode

$I_{max} = \frac{V_{dc}(1-e^{-t_{on}/\tau})}{R_a(1-e^{-T_p/\tau})} - \frac{E}{R_a}$ =10.2A, $I_{min} = \frac{V_{dc}(e^{t_{on}/\tau}-1)}{R_a(e^{T_p/\tau}-1)} - \frac{E}{R_a} = 9.9A$

$$i_{on\ period} = \frac{V_{dc}-E}{R_a} - \left(\frac{V_{dc}-E}{R_a} - I_{min}\right)e^{-t/\tau} \quad =90\text{-}80\exp(-5t)$$

$$i_{off\ period} = \frac{-E}{R_a} + \left(\frac{E}{R_a} + I_{max}\right)e^{-t/\tau} \quad =-150+160\exp(-5t)$$

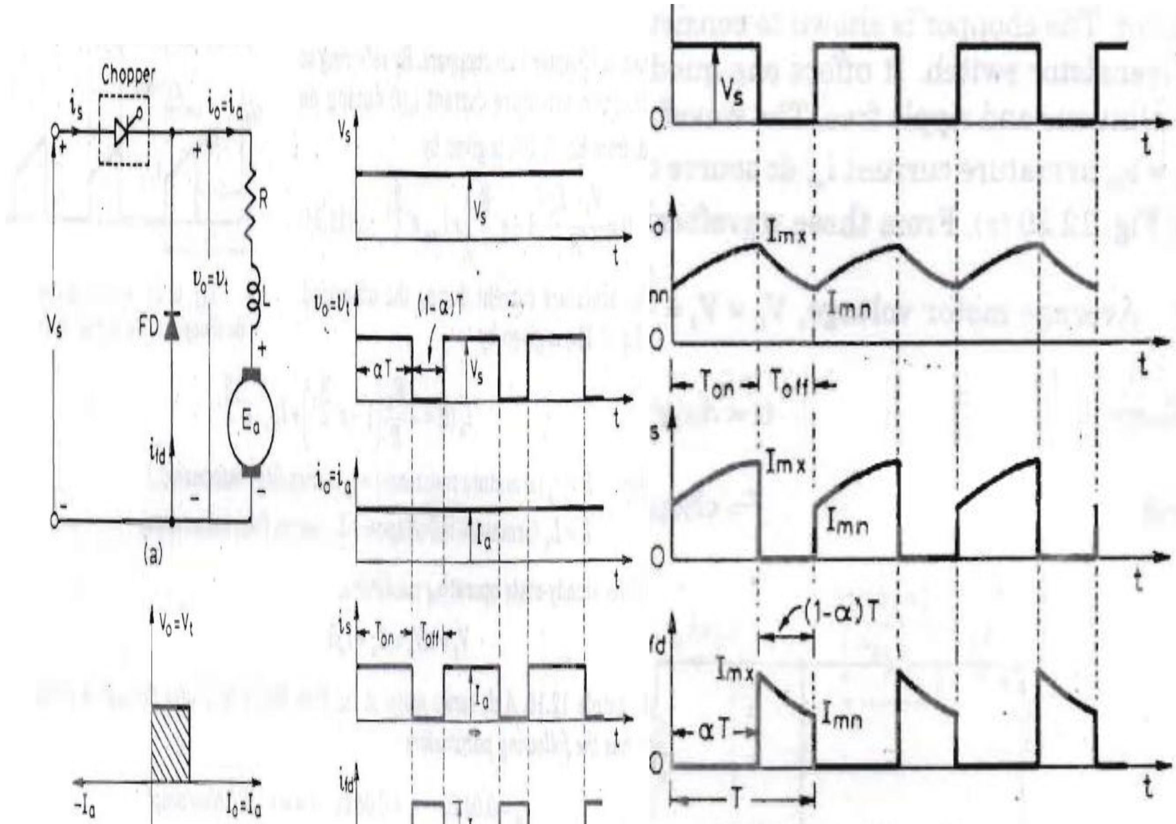


Fig. 12.21. Waveforms for dc chopper drive of Fig. 12.20 (*a*).

<u>Question (5)</u> **<u>[25] Points</u>**

a- Explain how to control the speed of the 3-phase induction motor?

The speed control of an induction motor requires more elaborate techniques than the speed control of dc machines. First, however, let us analyze the basic relationship for the speed–torque characteristics of an induction motor given in Equation (5.57).

$$T_d = \frac{P_d}{\omega} = \frac{V^2 R'_2}{s\omega_s\left[\left(R_1 + \frac{R'_2}{s}\right)^2 + X_{eq}^2\right]} \quad (7.1)$$

By examining this equation, one can conclude that the speed ω (or slip s) can be controlled if at least one of the following variables or parameters is altered:

1. armature or rotor resistance
2. armature or rotor inductance
3. magnitude of terminal voltage
4. frequency of terminal voltage

Using three tools are 1-inverter 2-AC/AC converter 3-cycloconverter

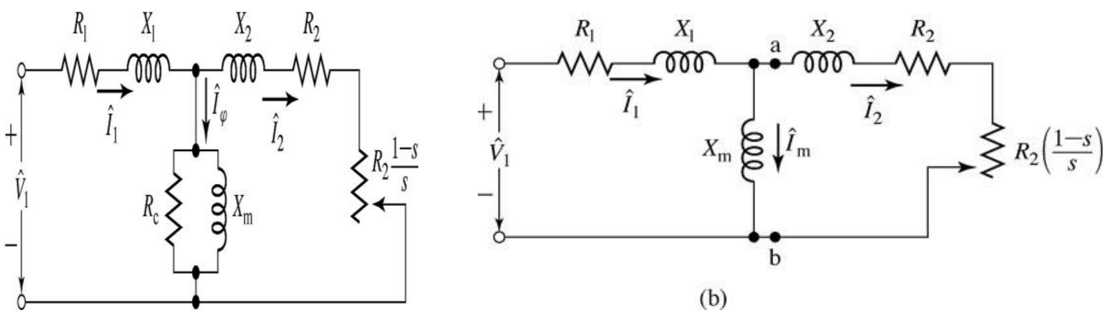


Figure 6.9 Single-phase equivalent circuit for a three-phase induction motor.

Equivalent circuits with the core-loss and iron losses are neglected

b-A three phase 460V, 60Hz, 4 poles, 1750 rpm, wye-connected induction motor has the following equivalent circuit parameters referred to the stator side:

$\boldsymbol{R_s = 1.01}\Omega$, $\boldsymbol{R_r = 0.69}\Omega$, $\boldsymbol{X_m = 43.5}\Omega$, $\boldsymbol{X_1 = 1.3}\Omega$, $\boldsymbol{X_2 = 1.94}\Omega$, $\boldsymbol{T_L = K\omega_r{}^2 = 41Nm\ at 1740rpm}$

i-Draw the equivalent circuit and find $\boldsymbol{\omega}_{syn}$, $\boldsymbol{\omega}_r$, S, I_s, I_r , P_{gap}, P_{copper} , T_{dev}?

ii- If the motor is connected to a 3-phase full wave AC/AC converter. Find the firing angle required to run the motor with speed range of 1000 rpm to 1750 rpm.

iii- If the motor is connected to a 3-phase six step inverter. Find the required DC supply to run the motor with speed of 1000 rpm?

iv- Draw the power circuit and current and voltage waveforms for case ii and case iii?

n_s=120*60/4=1800rpm, ω_s=1800*pi/30=188.5rad/sec., ω_r=1740*pi/30=182.2rad/sec.

$S1=(n_s-n_r)/n_s = (1800-1750)/1800 = 0.028$, $\omega_{r1}=1750*pi/30=183.3$ rad/sec.

$S2=(n_s-n_r)/n_s = (1800-1000)/1800 = 0.444$, $\omega_{r2}=1000*pi/30=104.72$ rad/sec.

$$\textbf{motor torque} = \frac{3I_2'^2R_2}{S\omega_S} = \textbf{load torque} = K\omega_r^2 = k(182.2)^2 = 41Nm, K = 0.001235$$

$$\textbf{load torque1} = K\omega_{r1}^2\ Nm = 0.001235(183.3)^2 = 41.5Nm = \frac{3*0.69*I_2'^2}{0.028*188.5} = I_2' = 10.3A,$$

$$V_{ph} = I_2' * Z = I_2' * \sqrt{\left[\left(R_1 + \frac{R_2'}{S}\right)^2 + \left(X_1 + X_2'\right)^2\right]}$$

$$V_{ph} = 10.3 * \sqrt{\left[\left(1.01 + \frac{0.69}{0.028}\right)^2 + \left(1.3 + 1.94\ \right)^2\right]} = 266.32V$$

$$\textbf{load torque2} = K\omega_{r2}^2\ Nm = 0.001235(104.72)^2 = 13.54Nm = \frac{3I_2'^2R_2}{S\omega_S}$$

$$I_2' = (0.444 * 188.5 * 13.54)/(3 * 0.69) = 23.4A,$$

$$V_{ph} = 23.4 * \sqrt{\left[\left(1.01 + \frac{0.69}{0.444}\right)^2 + \left(1.3 + 1.94\ \right)^2\right]} = 96.7V$$

As 1750rpm,

$$\frac{R_2'}{S} = \frac{0.69}{0.028} = 24.64, \quad Z'_2 = 1.01 + 24.64 + j(1.3 + 1.94) = 25.86\angle 7.2\ \Omega$$

$$V_{ph} = \frac{460\angle 0}{\sqrt{3}} = 265.6\angle 0\text{V}, I_2' = \frac{265.6\angle 0}{25.86\angle 7.2} = 10.3\angle -7.2\text{A then } \alpha = 7deg.$$

As 1000rpm

$$\frac{R_2'}{S} = \frac{0.69}{0.444} = 1.55, \quad Z'_2 = 1.01 + 1.55 + j(1.3 + 1.94) = 4.13\angle 51.7\ \Omega$$

$$V_{ph} = \frac{460\angle 0}{\sqrt{3}} = 265.6\angle 0\text{V}, I_2' = \frac{265.6\angle 0}{4.13\angle 51.7} = 64.3\angle -51.7\text{A}$$

$$\frac{T_{cont.}}{T_{rate}} = \left[\frac{(1 - S_{cont.})}{1 - S_{rate})}\right]^2 = \frac{S_{rate}}{S_{cont.}}\left(\frac{I_{cont.}}{I_{rate}}\right)^2$$

$$I_{cont.} = 10.3\frac{0.444}{0.028} * [\frac{1 - 0.444}{1 - 0.028}]^2 = 53.44A$$

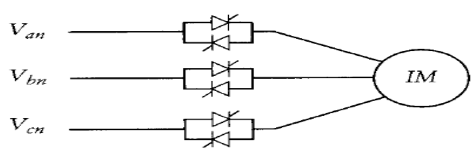
then α, β from table or curves as $I_{aN} = \frac{53.44}{64.3} = 0.83A, angle = 51.7deg.$

The AC/AC converter used to control the speed of the 3-phase induction motor for six-step inverter $V_{ph} = \sum_{n=6k\pm1}^{\infty} \frac{2*V_{dc}}{n*pi} sinn\omega t$,

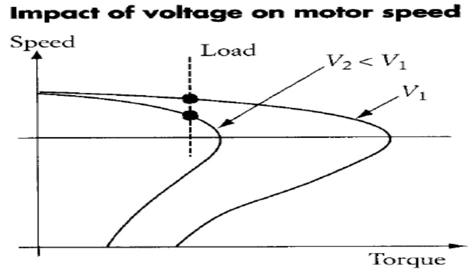
$$V_{1-ph-rms} = \frac{\sqrt{2}*V_{dc}}{pi} = 96.7, V_{dc} = 215V = 600K, K = 0.36$$

$$V_{1-ph-rms} = \frac{\sqrt{2}*V_{dc}}{pi} = 266.3, V_{dc} = 266.3V = 600K, K = 0.99$$

Phase control of induction motor



Impact of voltage on motor speed



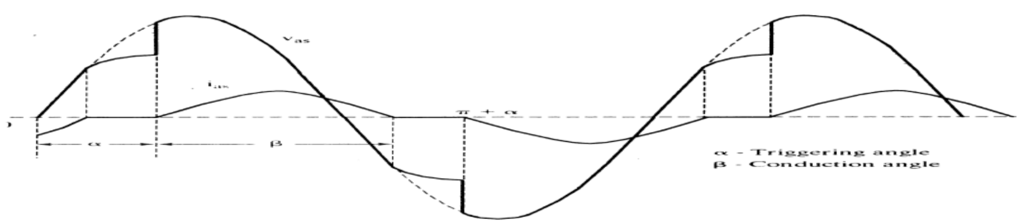
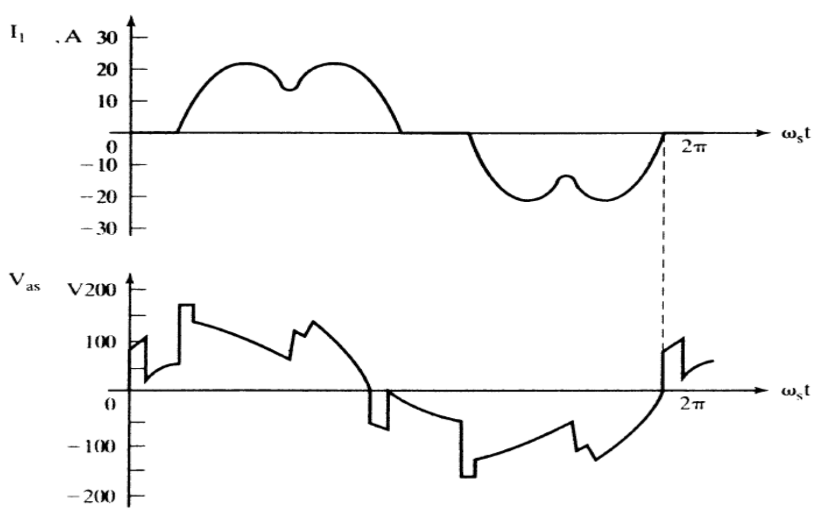
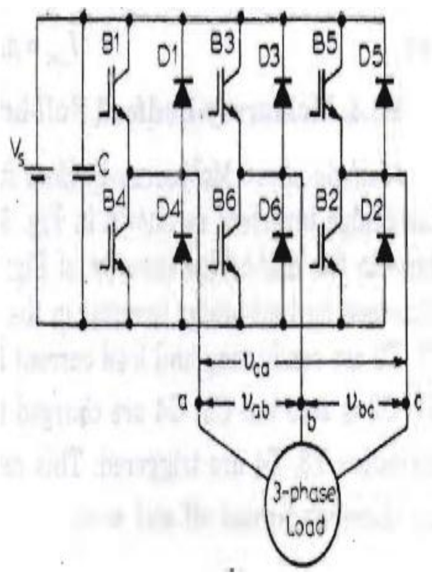


Figure 6.4 Phase voltage and current waveforms



e 6.10 Typical line-current and phase-voltage waveforms of a phase-controlled induction motor drive



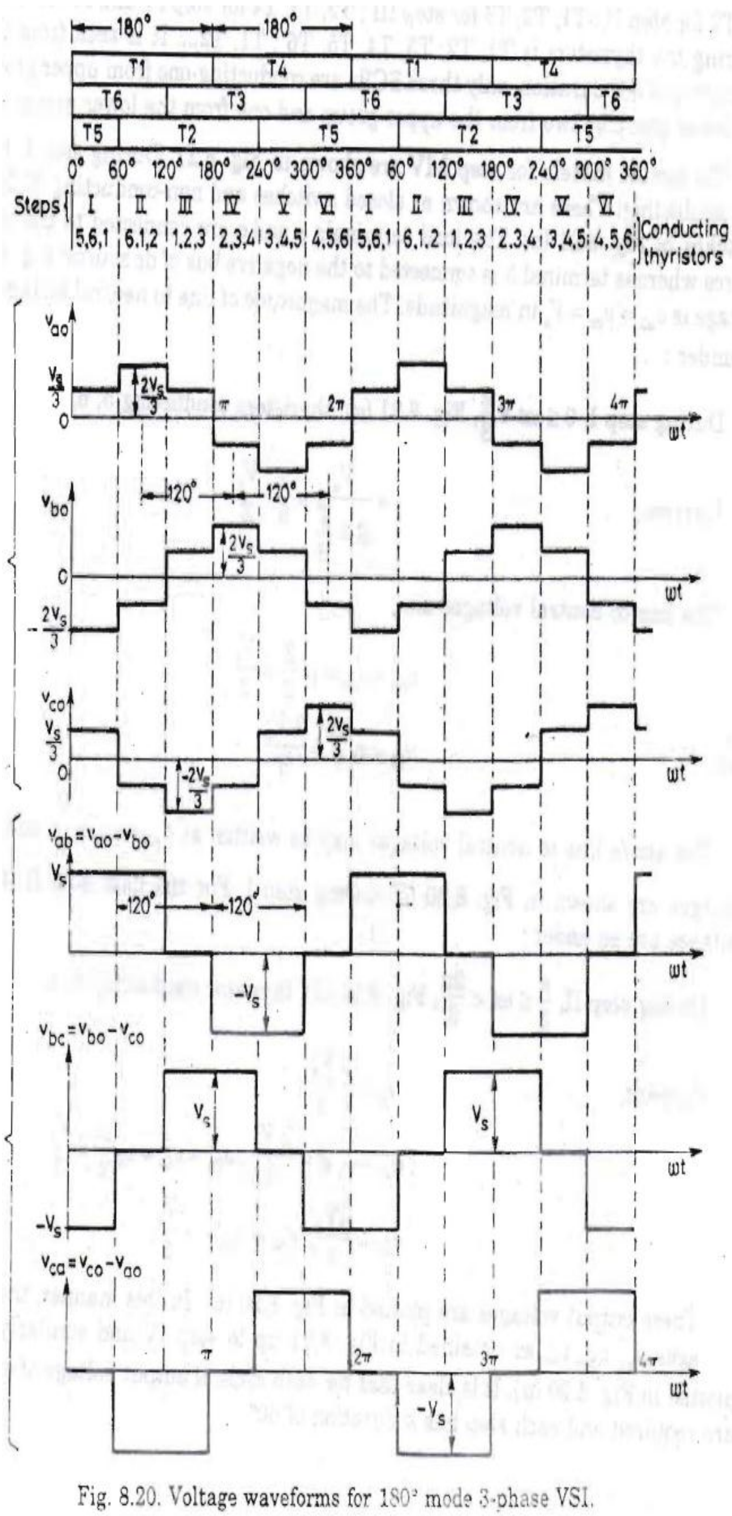


Fig. 8.20. Voltage waveforms for 180° mode 3-phase VSI.

Fourier series expansion of line to neutral voltage v_{ao} in Fig. 8.20 is given by

$$v_{ao} = \sum_{n=6k\pm1}^{\infty} \frac{2\,V_s}{n\pi} \sin n\omega t$$

ıere $\quad k = 0, 1, 2, \ldots$

and line currents can be obtained from Eqs. (8.44) to (8.46). From Eq. (8.44), rms value of nth component of line voltage is

$$V_{Ln} = \frac{4\,V_s}{\sqrt{2}\,n\pi} \cos \frac{n\pi}{6} \qquad \ldots(8.48)$$

Rms value of fundamental line voltage,

$$V_{L1} = \frac{4\,V_s}{\sqrt{2} \cdot \pi} \cos \frac{\pi}{6} = 0.7797\,V_s \qquad \ldots(8.49)$$

$$V_L = \left[\frac{1}{\pi}\int_0^{2\pi/3} V_s^2\, d(\omega t)\right]^{1/2} = \sqrt{\frac{2}{3}}\; V_s = 0.8165\, V_s$$

Rms value of phase voltage V_p is

$$V_p = \frac{V_L}{\sqrt{3}} = \frac{\sqrt{2}}{3}\, V_s = 0.4714\, V_s$$

Rms value of fundamental phase voltage, from Eq. (8.47), is

$$V_{p1} = \frac{2V_s}{\sqrt{2}\,\pi} = 0.4502\, V_s = \frac{V_{L1}}{\sqrt{3}}$$

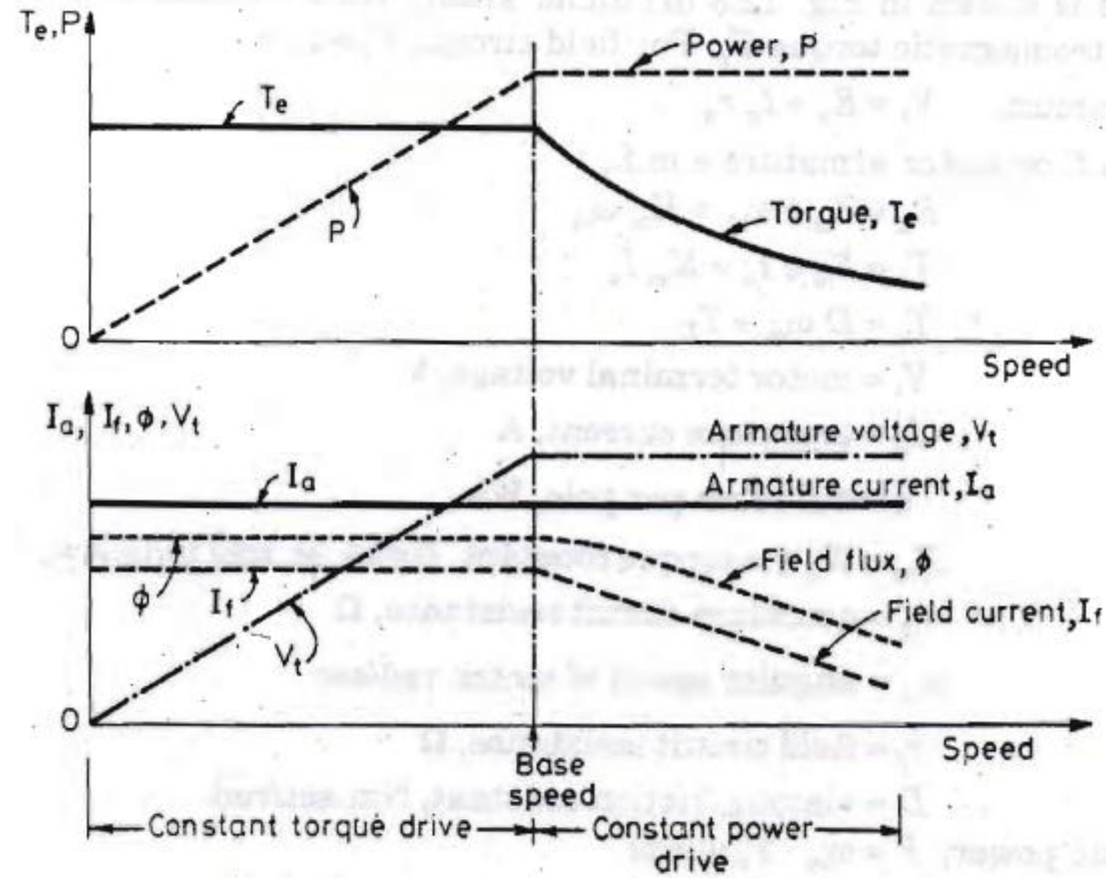


Fig. 12.4. Characteristics of a separately-excited dc motor.

12.19. *A separately-excited dc motor is fed from 220 V dc source through a* *ting at 400 Hz. The load torque is 30 Nm at a speed of 1000 rpm. The motor has* *nH and K_m = 1.5 V-sec/rad. Neglecting all motor and chopper losses, calculate*

nimum and maximum values of armature current and the armature current

nature current expressions during on and off periods.

As the armature resistance is neglected, armature current varies linearly inimum and maximum values.

ge armature current, $I_a = \frac{T_e}{K_m} = \frac{30}{1.5} = 20$ A

f, $E_a = K_m \cdot \omega_m = 1.5 \times \frac{2\pi \times 1000}{60} = 157.08$ V

ut voltage, $\alpha V_s = V_t = E_a + I_a r_s = 157.08 + 0$

$$\alpha = \frac{157.08}{220} = 0.714$$

ime, $T = \frac{1}{f} = \frac{1}{400} = 2.5$ ms

, $T_{on} = \alpha T = 0.714 \times 2.5 = 1.785$ ms

, $T_{off} = (1 - \alpha) T = 0.715$ ms

-period $T_{on,}$ armature current will rise which is governed by the equation,

$$0 + L \frac{di_a}{dt} + E_a = V_s$$

$$\frac{di_a}{dt} = \frac{V_s - E_a}{L} = \frac{220 - 157.08}{0.02} = 3146 \text{ A/s}$$

f period, $\frac{di_a}{dt} = -\frac{E_a}{L} = \frac{-157.08}{0.02} = -7854$ A/s

ent rising linearly, it is seen from Fig. 12.21 that

$$I_{mx} = I_{mn} + \left(\frac{di_a}{dt} \text{ during } T_{on}\right) \times T_{on}$$

$$= I_{mn} + 3146 \times 1.785 \times 10^{-3}$$

$$I_{mx} = I_{mn} + 5.616 \quad ...(i)$$

variation between I_{mn} and I_{mx}, average value of armature current

$$I_a = \frac{I_{mx} + I_{mn}}{2} = 20 \text{ A}$$

$$I_{mx} = 40 - I_{mn} \quad ...(ii)$$

qs. (*i*) and (*ii*), we get I_{mx} = 22.808 A

re current expression during turn-off,

$$i_a(t) = I_{mx} + \left(\frac{di_a}{dt} \text{ during } T_{off}\right) \times t$$

$$= 22.808 - 7854\,t \quad \text{for } 0 \le t \le T_{off}$$

le 12.20. *Repeat Example 12.19, in case motor has a resistance of 0.2 Ω for its rcuit.*

n. (*a*) From Example 12.19, armature current, $I_a = 20$ A and motor emf, $E_a = 157.08$ V; e, $V_s = 220$ V.

ature circuit, $\alpha V_s = V_0 = V_t = E_a + I_a r_a = 157.08 + 20 \times 0.2 = 161.08$ V

$$\alpha = \frac{161.08}{220} = 0.7322$$

$$T_{on} = \alpha T = 0.7322 \times 2.5 = 1.831 \text{ ms}$$

$$T_{off} = T - T_{on} = 0.669 \text{ ms}, \frac{R}{L} = \frac{0.2}{0.02} = 10$$

T_{on}, from Eq. (12.34), armature current is

$$i_a(t) = \frac{220 - 157.08}{0.2}(1 - e^{-10t}) + I_{mn} \cdot e^{-10t}$$

$$= 314.6\,(1 - e^{-10t}) + I_{mn} \cdot e^{-10t}$$

$_{on}$ = 1.831 ms, current become I_{mx}. This gives

$$i_a(t) = I_{mx} = 5.7079 + 0.98187\,I_{mn} \quad \text{...}(i)$$

T_{off}, from Eq. (12.35), armature current is

$$i_a(t) = \frac{-157.08}{0.2}(1 - e^{-10t}) + I_{mx} \cdot e^{-10t}$$

$$= -785.4\,(1 - e^{-10t}) + I_{mx} \cdot e^{-10t}$$

669 ms, $i_a(t) = I_{mn}$. This gives

$$i_a(t) = I_{mn} = -5.237 + 0.9933\,I_{mx} \quad \text{...}(ii)$$

Eqs. (*i*) and (*ii*), we get

$$I_{mx} = 5.7079 + 0.98187\,(-5.237 + 0.9933\,I_{mx})$$

$$= 0.5658 + 0.9753\,I_{mx}$$

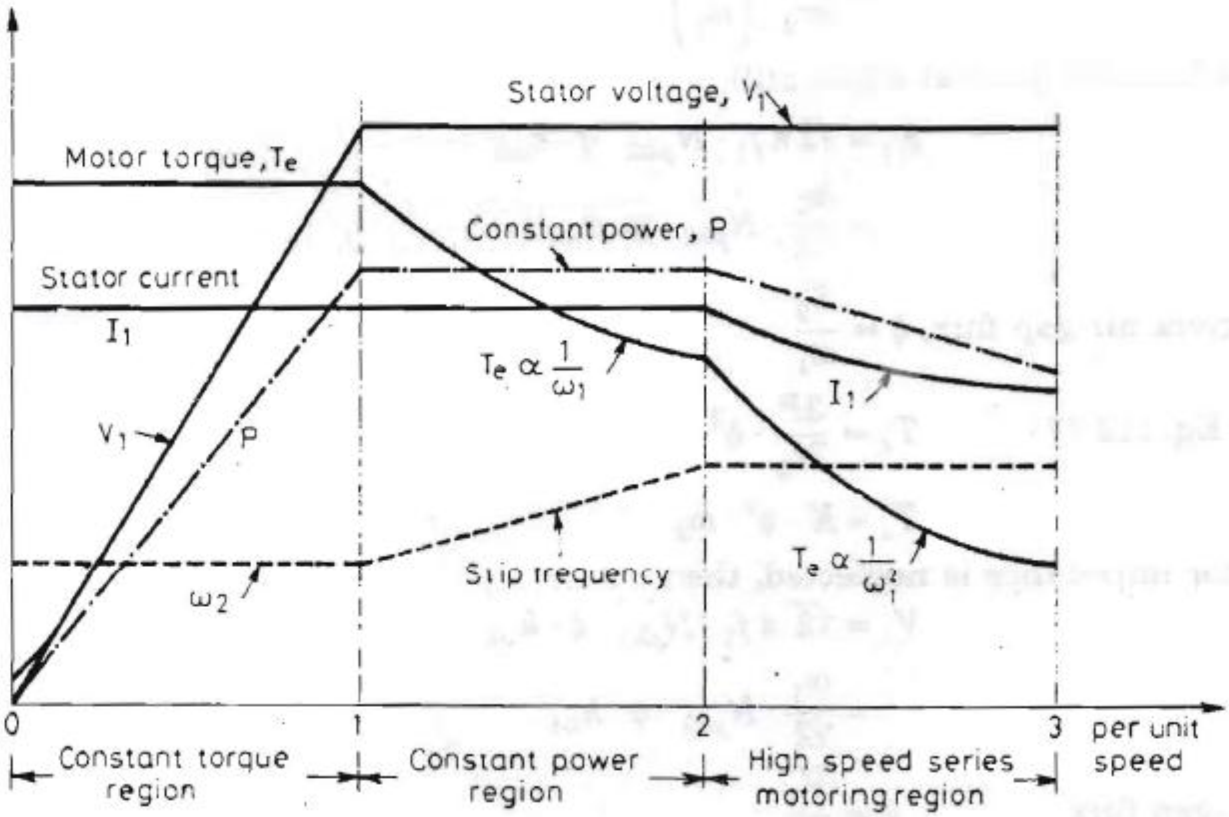
$$I_{mx} = \frac{0.5658}{0.0247} = 22.907 \text{ A}$$

$$I_{mn} = -5.237 + 0.9933 \times 22.907 = 17.516 \text{ A}$$

ature current excursion

$$= I_{mx} - I_{mn} = 22.907 - 17.516 = 5.39 \text{ A}$$

t-torque region. As explained before, this region of constant torque can be volts/hertz control as shown in Fig. 12.29. In the low-frequency range of speed, stator resistance is compensated by a boost in the stator voltage as shown in Fig. s region, stator current is kept constant at its rated value. Power, equal to the onstant torque and speed, varies linearly with speed as shown. Slip frequency stant during this region.



ig. 12.35. Stator voltage, current, slip-frequency, torque and power variation with speed for speed-torque characteristics of Fig. 12.34.

power region. When maximum speed, called base speed, is attained in the e region, stator voltage reaches its rated value. Motor speeds beyond base (or e obtained by keeping stator voltage constant and lowering the stator frequency.

3-phase induction motor is given by

$$T_e = \frac{3}{\omega_s} \text{ (Power input to rotor)}$$

$$= \frac{3}{\omega_s} \cdot E_2 I_2 \cos \theta_2$$

or frequency, $\cos \theta_2 \left(= \frac{r_2}{\sqrt{r_2^2 + (2\pi f_2 l_2 s)^2}} \right)$ is almost nearer to unity.

$$T_e = \frac{3}{\omega_s} \cdot E_2 I_2 \quad \text{...(12.76)}$$

current, $I_2 = \dfrac{E_2}{\dfrac{r_2}{s} + j\, x_2}$

ips, $\dfrac{r_2}{s} \gg x_2$. This gives $I_2 = \dfrac{sE_2}{r_2}$

The three line output voltages can be described by the Fourier series as follows :

$$v_{ab} = \sum_{n=1,3,5,}^{\infty} \frac{4V_s}{n\pi} \cos \frac{n\pi}{6} \sin n(\omega t + \pi/6) \quad \text{...(8.44)}$$

$$v_{bc} = \sum_{n=1,3,5,}^{\infty} \frac{4V_s}{n\pi} \cos \frac{n\pi}{6} \sin n(\omega t - \pi/2) \quad \text{...(8.45)}$$

$$v_{ca} = \sum_{n=1,3,5,-}^{\infty} \frac{4V_s}{n\pi} \cos \frac{n\pi}{6} \sin n\left(\omega t + \frac{5\pi}{6}\right) \quad \text{...(8.46)}$$

For $n = 3$, $\cos \frac{3\pi}{6} = 0$. Thus, all triplen harmonics are absent from the line voltages as given by Eqs. (8.44) to (8.46).