20EE603

Hall Ticket Number:

III/IV B.Tech (Regular) DEGREE EXAMINATION

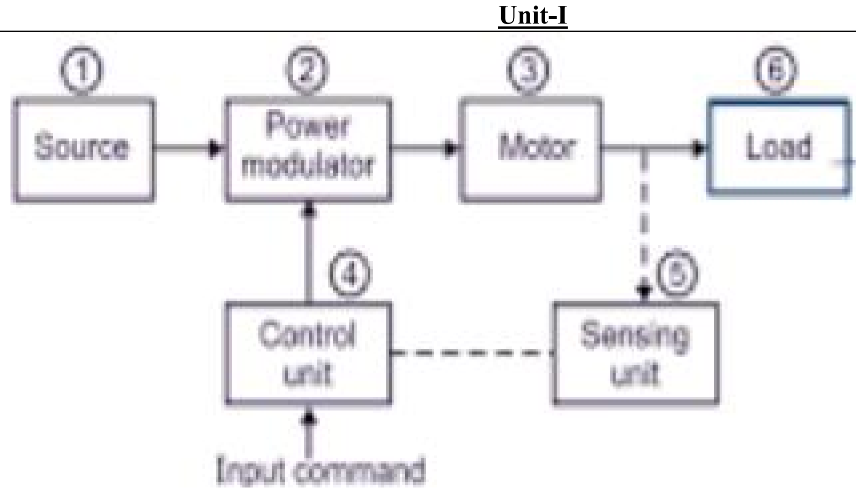
July/August, 2023 **Electrical and Electronics Engineering**

Sixth Semester **Electrical Drives**

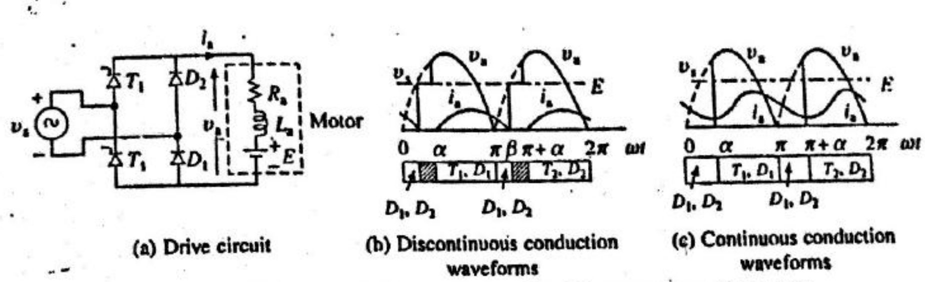
Time: Three Hours **Maximum:** 70 Marks

Answer question 1 compulsory. **(14X1 = 14Marks)**

Answer one question from each unit. **(4X14=56 Marks)**

			CO	BL	M
1	a)	Available in wide range of torque, speed and power. Compact in size; electric drives occupy less space. Do not require warm-up time; they can be started immediately.	CO1	L1	1
	b)	Group derive, individual drive.	CO1	L2	1
	c)	The control unit sends the signal to the power modulator. The control unit controls the power modulator which operates at the small voltage and power levels. It also generates commands for the protection of the power modulator and motor.	CO1	L1	1
	d)	**Load torque T_l and dynamic torque $J(d\omega_m/dt)$** will balance the motor torque.	CO2	L1	1
	e)	Regenerative braking is not possible in a series motor. Explanation: In regenerative braking, the motor acts as a generator. The back emf is more than the terminal voltage in case of regenerative braking.	CO2	L1	1
	f)	Number of **converters** ON simultaneously. Only one either P or N Both P and N · 2. Interconverter **circulating current**. Absent. **Present** ·	CO2	L2	1
	g)	Source current of a rectifier has harmonics. In a weak ac source, with high internal impedance, current harmonics distort source voltage. Furthermore, temporary short circuit of lines during commutation of thyristors, causes sharp current pulses, which further distort source voltage.	CO2	L1	1
	h)	There are two kinds of control strategies used in DC choppers namely time ratio control and current limit control.	CO1	L1	1
	i)	Voltage Control Method.Frequency Control Method.Pole Changing Speed Control. Stator Resistance Method.Rotor Resistance Control Method.Slip Power Recovery Method.	CO3	L1	1
	j)	he stator voltage control method is suitable for applications where the load torque decreases with the speed, as in the case of a fan load.	CO3	L1	1
	k)	This external resistance makes the rotor circuit current low. Hence by increasing the rotor resistance, we can improve the starting torque of the wound rotor induction motor	CO3	L1	1
	l)	In self controlled mode, the supply frequency is changed so that the synchronous speed is same as that of the rotor speed. Hence, rotor cannot pull-out of slip and hunting eliminations are eliminated.	CO4	L1	1
	m)	Computer hard drives and DVD/CD players. Electric vehicles, hybrid ehicles, and electric bicycles.Industrial robots, CNC machine tools, and imple belt driven systems.Washing machines, compressors and dryers.Fans, pumps and blowers.	CO4	L1	1
	n)	there are three types of braking i.e, regenerative, dynamic and plugging type braking. But for synchronous motor drives only dynamic braking can be applied though plugging can be applied theoretically	CO4	L1	1
		Unit-I			
2	a)	 (i) Modulates flow of power from the source to the motor in such a manner that motor is imparted speed torque characteristics required by the load. (ii) During transient operation, such as starting braking and speed reversal it restrict source and motor currents with in the permissable values; ecessive current drawn from source may overload it or may cause a voltage dip. (iii) Converts electrical energy of the source in the form suitable to the motor if	CO1	L2	7M

		source is dc and an induction motor is to be employed, then the power modulator is required to convert dc into a variable frequency ac. (iv) Selects the mode of operation of the motor, i.e. motoring or braking. When power modulator is employed mainly to perform function (iii), it is more appropriately called *converter.* While (iii) is the main function, depending on its circuit, a converter may also perform other functions of power modulator. Controls for power modulator are built in control unit which usually operates at much lower voltage and power levels. In addition to operating the power modulator as desired, it may also generate commands for the protection of power modulator and motor. Input command signal, which adjusts the operating point of the drive, forms an input to the control unit. Sensing of certain drive parameters, such as motor current and speed, may be required either for protection or for closed loop operation.			
	b)	(2)(b) $T = 150 - 0.1N$. $T_l = 100$ N-m. $T_l = -100$ N-m for steady state speed $T - T_l = 0$. $150 - 0.1N - 100 = 0$ $N = \frac{50}{0.1} = 500$ rpm —(1) $150 - 0.1N + 100 = 0$. $0.1N = 250$ $N = 2500$ rpm —(2)	CO1	L3	7M
		(OR)			
3	a)	Let us consider a motor driving two loads, one coupled directly to its shaft and other through a gear with n and n_1 teeth as shown in Fig. 2.4(a). Let the moment of inertia of motor and load directly coupled to its shaft be J_0, motor speed and torque of the directly coupled load be ω_m and T_{l0} respectively. Let the moment of inertia, speed and torque of the load coupled through a gear be J_1, ω_{m1} and T_{l1} respectively. Now, $$\frac{\omega_{m1}}{\omega_m} = \frac{n}{n_1} = a_1$$ where a_1 is the gear tooth ratio. If the losses in transmission are neglected, then the kinetic energy due to equivalent inertia must be the same as kinetic energy of various moving parts. Thus $$\frac{1}{2} J\omega_m^2 = \frac{1}{2} J_0\omega_m^2 + \frac{1}{2} J_1\omega_{m1}^2$$ $$J = J_0 + a_1^2 J_1$$ transmission system converting rotational motion to linear motion (Fig. 2.4(b)). Let moment of inertia of the motor and load directly coupled to it be J_0, load torque directly coupled to motor be T_{l0}, and the mass, velocity and force of load with translational motion be M_1 (kg), v_1 (m/sec) and F_1 (Newtons), respectively. If the transmission losses are neglected, then kinetic energy due to equivalent inertia J must be the same as kinetic energy of various moving parts. Thus $$\frac{1}{2} J\omega_m^2 = \frac{1}{2} J_0\omega_m^2 + \frac{1}{2} M_1 v_1^2$$ or $$J = J_0 + M_1\left(\frac{v_1}{\omega_m}\right)^2$$ Similarly, power at the motor and load should be the same, thus if efficiency of transmission be η_1 $$T_l\omega_m = T_{l0}\cdot\omega_m + \frac{F_1 v_1}{\eta_1}$$ or $$T_l = T_{l0} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right)$$ If, in addition to one load directly coupled to the motor shaft, there are m other loads with translational motion with velocities $v_1, v_2, \ldots v_m$ and masses $M_1, M_2, \ldots, M_m$, respectively, then $$J = J_0 + M_1\left(\frac{v_1}{\omega_m}\right)^2 + M_2\left(\frac{v_2}{\omega_m}\right)^2 + \ldots + M_m\left(\frac{v_m}{\omega_m}\right)^2$$	CO1	L3	7M

		$T_l = T_{l0} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right) + \frac{F_2}{\eta_2}\left(\frac{v_2}{\omega_m}\right) + \ldots + \frac{F_m}{\eta_m}\left(\frac{v_m}{\omega_m}\right)$			
	b)	(3)(b) $w = 500$ kg $v = 1.5$ m/s ↑ $N = 100$ rpm. $J = 0.5$ and 0.3 kg-m². $T = 100$ N-m $T_{running} = 1000$ rpm. T_m and J_{eq} $J = J_0 + M_1\left(\frac{V_1}{\omega_m}\right)^2 + M_2\left(\frac{V_2}{\omega_m}\right)^2$ $= 0.5 + 500\left(\frac{1.5}{1000\times\frac{2\pi}{60}}\right)^2 + 0.3$ ~~$= 9.76\times10^{-3}$~~ (or) $J = J_0 + J_0 + M\left(\frac{V}{\omega_m}\right)^2$ $= 0.5 + 0.3 + 500\left(\frac{1.5}{100\times\frac{2\pi}{60}}\right)^2 = 0.902$ kg-m² $T = T_{l0} + \frac{F}{\eta}\left(\frac{V}{\omega_m}\right)$ $= 100 + \frac{500\times9.8}{1}\left(\frac{1.5}{\frac{2\pi\times1000}{60}}\right) = 170.259$ N-m	CO1	L3	7M
Unit-II					
4	a)	The drive is shown in Fig. . In a cycle of source voltage defined by Eq. , T_1 receives gate pulse from α to π and T_2 from $(\pi+\alpha)$ to 2π. Motor terminal voltage and current waveforms for the dominant discontinuous and continuous conduction mode are shown in Figs. and (c) respectively. In discontinuous conduction mode, when T_1 is fired at α, motor gets connected to the source through T_1 and D_1 and $v_a = v_s$. The armature current flows and D_2 gets forward biased at π. Consequently, armature current freewheels through the path formed by D_1 and D_2, and the motor terminal voltage is zero. Conduction of D_2 reverse biases T_1 and turns it off. Armature current drops to 0 at β and stays zero until T_2 is fired at $(\pi+\alpha)$. Similarly, the continuous conduction mode can be explained. **Discontinuous Conduction** A cycle of motor terminal voltage consists of three intervals  (a) Drive circuit (b) Discontinuous conduction waveforms (c) Continuous conduction waveforms Fig. Single-phase half-controlled-rectifier fed separately excited motor (i) *Duty interval* ($\alpha \le \omega t \le \pi$): Armature current is given by Eq. Substitution of $\omega t = \pi$ in this equation gives $i_a(\pi)$. (ii) *Freewheeling interval* ($\pi \le \omega t \le \beta$): Operation is governed by the following equation: $i_a R_a + L_a \frac{di_a}{dt} + E = 0$ Solution of (5.87) subject to $i_a(\pi)$ as the initial current yields $i_a(\omega t) = \frac{V_m}{Z}[\sin\phi \cdot e^{-(\omega t-\pi)\cot\phi} - \sin(\alpha-\phi)\cdot e^{-(\omega t-\alpha)\cot\phi}] - \frac{E}{R_a}[1 - e^{-(\omega t-\alpha)\cot\phi}]$, for $\pi \le \omega t \le \beta$ (iii) *Zero current interval* ($\beta \le \omega t \le \pi+\alpha$): Equation is applicable. Since $i_a(\beta) = 0$, one	CO2	L2	7M

$$e^{\beta\cot\phi} = \frac{R_a V_m}{ZE}\left[\sin\phi\, e^{\pi\cot\phi} - \sin(\alpha-\phi)e^{\alpha\cot\phi}\right] + e^{\alpha\cot\phi}$$

β can be calculated by the solution of Eq. Now

$$V_a = \frac{1}{\pi}\left[\int_\alpha^\pi V_m \sin\omega t\, d(\omega t) + \int_\beta^{\pi+\alpha} E d(\omega t)\right]$$

$$= \frac{V_m(1+\cos\alpha) + (\pi+\alpha-\beta)E}{\pi}$$

From Eqs. (5.7), (5.8), (5.79) and (5.90)

$$\omega_m = \frac{V_m(1+\cos\alpha)}{K(\beta-\alpha)} - \frac{\pi R_a}{K^2(\beta-\alpha)}T$$

∵ Boundary between continuous and discontinuous conduction is reached when $\beta = \pi + \alpha$. Substituting $\beta = \pi + \alpha$ in gives the critical speed ω_{mc}, which separates continuous conduction from discontinuous conduction for a given α.

$$\omega_{mc} = \frac{R_a}{K}\frac{V_m}{Z}\left[\frac{\sin\phi \cdot e^{-\alpha\cot\phi} - \sin(\alpha-\phi)e^{-\pi\cot\phi}}{1-e^{-\pi\cot\phi}}\right]$$

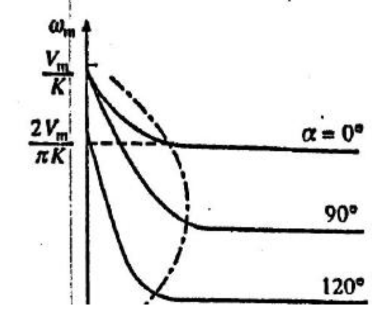
Continuous Conduction
From Fig. 5.29(c)

$$V_a = \frac{1}{\pi}\int_\alpha^\pi V_m \sin\omega t\, d(\omega t) = \frac{V_m}{\pi}(1+\cos\alpha)$$

From Eqs. (5.7), (5.8), (5.79) and (5.93)

$$\omega_m = \frac{V_m}{\pi K}(1+\cos\alpha) - \frac{R_a}{K^2}T$$

Speed-torque curves are shown in Fig. 5.30. No load speeds are given by Eqs. (5.85) and (5.86). Operation of drive, which operates in quadrant I only, is represented by equivalent circuit of Fig. 5.28(b). It is useful to note why the drive should not be operated in quadrant IV. Figure 5.31(a) shows plot of V_a with α (Eq. (5.93)) for half-controlled rectifier for continuous conduction operation. The output voltage cannot be reversed. When coupled to an active load, the motor speed can reverse, reversing E as shown in Fig. 5.31(b). As current direction does not change, machine now works as a generator producing braking torque. Since, rectifier voltage cannot reverse, generated energy cannot be transferred to ac source, and therefore, it is absorbed in the armature circuit resistance.



b) For a step-down chopper, — CO2 | L3 | 7M

$$\frac{V_o}{V_s} = \delta = \frac{T_{on}}{T} = fT_{on}$$

T_{on} is the ON time

T is time period

f is the chopping frequency

V_s is the input supply

V_0 is the average output voltage

Calculation:

Case 1:

Voltage (V_1) = 220 V

Line current (I) = 20 A

Speed (N_1) = 1000 rpm

		Speed (N_1) = 1000 rpm Armature resistance (R_a) = 1 Ω Back emf (E_{b1}) = $V_1 - IR_a$ = 220 – 20 (1) = 200 V **Case 2:** As the rated torque is the same, the current remains the same. Line current (I) = 20 A Speed (N_2) = 500 rpm $E_{b2} = E_{b1} \times \frac{N_2}{N_1}$ $= 200 \times \frac{500}{1000} = 100\ V$ Armature resistance (R_a) = 1 Ω Terminal voltage (V_2) = $E_{b2} + IR_a$ = 100 + 20(1) = 120 V The output of the chopper (V_0) = 120 V Terminal voltage (V_2) = $E_{b2} + IR_a$ = 100 + 20(1) = 120 V The output of the chopper (V_0) = 120 V Input of the chopper (V_i) = 250 V $V_0 = \delta V_i$ $\Rightarrow 120 = \delta \times 250$ $\Rightarrow \delta = 0.48$			
		(OR)			
5	a)	The variable voltage to the armature of a dc motor for speed control can be obtained from a dc chopper which is a single stage dc to dc conversion device. The voltage variation at the load terminals can be obtained by using either current limit control or time ratio control. In the former, as has already been discussed, the chopper is controlled such that the load current has a variation between two limits. When the current reaches the upper limit the chopper is turned off to disconnect the motor from the supply. The load current freewheels through freewheeling diode and decays. When it falls to the lower limit the chopper is turned on, connecting the motor to the supply. An average current is always maintained. When the chopper is controlled by TRC the ratio of T_{ON}/T_{OFF} of the chopper is changed. In this case the operation is at fixed frequency if ($T_{ON}+T_{OFF}$) is kept constant. T_{ON} only is varied to obtain voltage control. The operation will be at variable frequency with T_{ON} kept constant and ($T_{ON}+T_{OFF}$) varied. But owing to several advantages of simplicity, a fixed frequency TRC is normally used. Chopper circuits are used to control both separately excited and series motors. Chopper circuits have several advantages over phase controlled converters: **1.Ripple content in the output is small. Peak/average and rms/average current ratios are small. This improves the commutation and decreases the harmonic heating of the motor. The pulsating torques are also less.** **2.The chopper is supplied from a constant de voltage using batteries. The problem of power factor does not occur at all. The conventional phase control method suffers from a poorer power factor as the angle is delayed. This means that the current drawn by the chopper is smaller than in a ac/dc phase controlled converter.** **3.The circuit is simpe and can be modified to provide regeneration.** **4.The control circuit is simple.** However, because of the forced commutation employed, the chopper may be costlier than a phase controlled converter. • DC chopper device has the advantages of high efficiency, flexibility in	CO2	L2	7M

control, light weight, small size, quick response and regeneration down to very low speed.

- CHOPPER FED DC DRIVES • A dc chopper is connected between a fixed-voltage dc source and dc motor to vary the armature voltage. • A chopper is a high speed on/off semiconductor switch which connects source to load and disconnects the load from source at a fast speed.
- The superior torque performance of the DC Chopper method is due to the fact that there is higher impedance in the motor windings when the motor is operated in the Phase Angle method, and also because the applied power is varying sinusoidally.At higher speeds, the torque performance of each control method begins to

Chopper circuits are used in multiple applications, including:

- Switched mode power supplies, including DC to DC converters.
- Speed controllers for DC motors.
- Driving brushless DC torque motors or stepper motors in actuators.
- Class D electronic amplifiers.
- Switched capacitor filters.
- Variable-frequency drives.

	b)		CO2	L3	7M

At rated operation, $E = 230 - 200 \times 0.02 = 226$ V
(i) E at 350 rpm

(i)

At rated operation, $E = 230 - 200 \times 0.02 = 226$ V
(i) E at 350 rpm $= \frac{350}{960} \times 226 = 82.4$ V
Motor terminal voltage $V_a = E + I_a R_a$

Motor terminal voltage Va = E +IaRa = 86.4 V

At rated operation, $E = 230 - 200 \times 0.02 = 226$ V
(i) E at 350 rpm $= \frac{350}{960} \times 226 = 82.4$ V
Motor terminal voltage $V_a = E + I_a R_a = 86.4$ V
Duty ratio

$$\delta = \frac{86.4}{230} = 0.376$$

Unit-III

6	a)		CO3	L2	7M

Pole changing method discussed in Sec. allows a change of speed by a factor 2. In some applications, speed change is required only by a small amount, e.g. some fan and pump drives require speed reduction to reduce power output at the most to half of rated. Since, torque is proportional to speed squared in a fan drive, power is proportional to (speed)^3. Half of rated power is obtained when speed is reduced approximately by 20%. Such a small change in speed is possible by pole amplitude modulation.

The mmf distribution in air-gap owing to stator winding of a three-phase induction motor may be written generally as

$$F_A = F_{mA} \sin p\theta$$
$$F_B = F_{mB} \sin (p\theta - 2\pi/3)$$
$$F_C = F_{mC} \sin (p\theta - 4\pi/3)$$

where θ is the mechanical angle.

In an ordinary induction motor, the amplitudes of mmfs F_{mA}, F_{mB} and F_{mC}, are constant and equal. In method under discussion, amplitudes are varied (or modulated) according to the rule:

$$F_{mA} = F \sin k\theta$$
$$F_{mB} = F \sin (k\theta - \alpha)$$
$$F_{mC} = F \sin (k\theta - 2\alpha)$$

theoretically k and α may have any values.

Substitution from Eq. (6.65) into (6.64) yields

$$F_A = F \sin p\theta \sin k\theta$$
$$F_B = F \sin (p\theta - 2\pi/3) \sin (k\theta - \alpha)$$
$$F_C = F \sin (p\theta - 4\pi/3) \sin (k\theta - 2\alpha)$$

which may be written as

$$F_A = \frac{F}{2} \{\cos (p-k)\theta - \cos (p+k)\theta\}$$

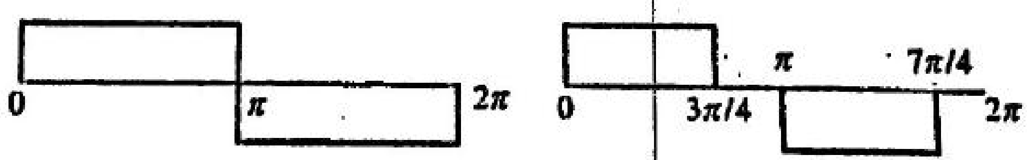
$$F_B = \frac{F}{2}\left\{\cos\left[(p-k)\theta - \frac{2\pi}{3} + \alpha\right] - \cos\left[(p+k)\theta - \frac{2\pi}{3} - \alpha\right]\right\}$$

$$F_C = \frac{F}{2}\left\{\cos\left[(p-k)\theta - \frac{4\pi}{3} + 2\alpha\right] - \cos\left[(p+k)\theta - \frac{4\pi}{3} - 2\alpha\right]\right\}$$

Thus, modulation of amplitude of mmfs in a three-phase machine haing p poles, produces two sets of three-phase mmfs with $(p - k)$ and $(p + k)$ poles. Since, two sets of poles will produce torques in opposite directions, one of them must be suppressed. This can be achieved by choosing the value of α either $2\pi/3$ or $-2\pi/3$. From Eq. (6.67) it is evident that modified pole numbers will be $(p + k)$ in former and $(p - k)$ in the latter, as other pole system produces co-phasal mmfs which do not produce any average torque.

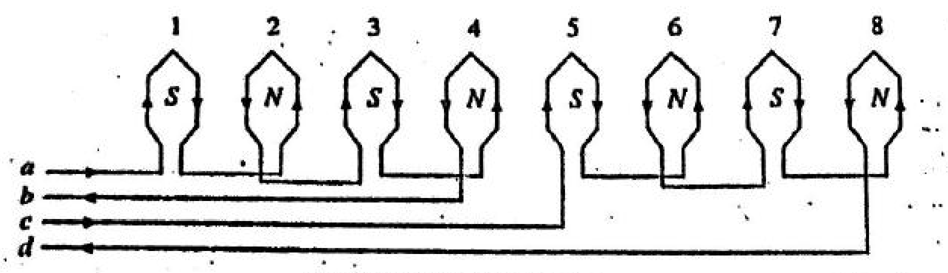
Usually value of k, which is known as modulation cycle, is made unity. Even then it is very difficult to implement the modulation law of Eqs. (6.66) because of its sinusoidal nature. It can, however, be simplified as

$$F_{mA} = F \quad \text{for} \quad 0 < \theta < \pi$$
$$= -F \quad \text{for} \quad \pi < \theta < 2\pi$$
$$F_{mB} = F \quad \text{for} \quad 2\pi/3 < \theta < 5\pi/3$$
$$= -F \quad \text{for} \quad 5\pi/3 < \theta < 8\pi/3$$
$$F_{mC} = F \quad \text{for} \quad 4\pi/3 < \theta < 7\pi/3$$
$$= -F \quad \text{for} \quad 7\pi/3 < \theta < 10\pi/3$$

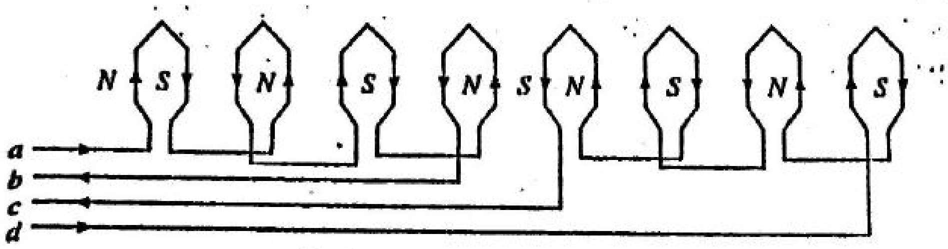


(a) Coil inversion (b) Coil inversion and omission

Modulation law for phase A



(a) Connection for 8 poles



(b) Connection for 10 poles

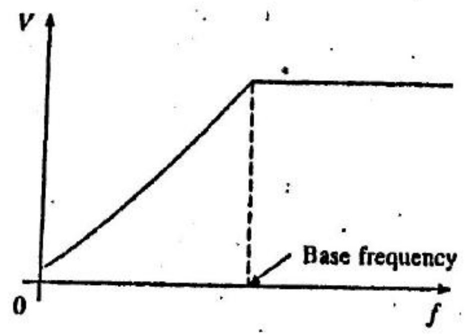
Pole amplitude modulation by coil inversion

<table>
<tr><td></td><td>b)</td><td>6(b) V=440 P=6, N=965 Δ
f=50
Rs=2 | Xs=3
Rr=2 | Xr=4
V at 800 rpm. G at 280V
$T = \frac{3}{\omega_{ms}} \times \frac{V^2 R_r'/s}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2}$
$N_s = \frac{120 \times 50}{6} = 1000$ | $\omega_{ms} = 1000 \times \frac{2\pi}{60} = 104.7$
$s = \frac{1000-965}{1000} = 0.035$
$\therefore T = \frac{\frac{3}{104.7} \times 440^2 \times \frac{2}{0.035}}{\left(2+\frac{2}{0.035}\right)^2 + (3+4)} = 136.4$ N-m.
$T_L = K(1-s)^2$ for fan load.
for full load $T = T_L$
$K(1-0.035)^2 = 136.4$
$K = 152.73$
$T_L = 152.73(1-0.035)^2$
at 800 rpm $s = \frac{1000-800}{1000} = 0.2$
$T_L = 152.73(1-0.2)^2 = 97.74$
$T = T_L$, $T = 97.74$.
$\therefore \frac{\frac{3}{104.7} \times V^2 \frac{2}{0.2}}{\left(2+\frac{2}{0.2}\right)^2 + (3+4)} = 97.74$
$V^2 = 341.11 \times 169 = 510.11$
$V = 22.58$</td><td>CO3</td><td>L3</td><td>7M</td></tr>
<tr><td colspan="6">(OR)</td></tr>
<tr><td>7</td><td>a)</td><td>Variable Frequency Control of an Induction Motor
Synchronous speed, therefore, the motor speed can be controlled by varying supply frequency. Voltage induced in stator is proportional to the product of supply frequency and air-gap flux. If stator drop is neglected, terminal voltage can be considered proportional to the product of frequency and flux.
Any reduction in the supply frequency, without a change in the terminal voltage, causes an increase in the air-gap flux. Induction motors are designed to operate at the knee point of the magnetization characteristic to make full use of the magnetic material. Therefore, the increase in flux will saturate the motor. This will increase the magnetizing current, distort the line current and voltage, increase the core loss and the stator copper loss, and produce a high-pitch acoustic noise. While an increase in flux beyond the rated value is undesirable from the consideration of saturation effects, a decrease in flux is also avoided to retain the torque capability of the motor. Therefore, the variable frequency control below the rated frequency is generally carried out at rated air-gap flux by varying terminal voltage with frequency so as to maintain (V/f) ratio constant at the rated value. From Eq. (6.13)
$$T_{max} = \frac{K(V/f)^2}{\frac{R_s}{f} \pm \left[\left(\frac{R_s}{f}\right)^2 + 4\pi^2 (L_s + L_r')^2\right]^{1/2}}$$
where K is a constant, and L_s and L_r' are, respectively, the stator and stator referred rotor inductances. Positive sign is for motoring operation and negative sign is for braking operation.
When frequency is not low, $(R_s/f) \ll 2\pi(L_s + L_r')$ and therefore, from
$$T_{max} = \pm \frac{K(V/f)^2}{2\pi(L_s + L_r')}$$</td><td>CO3</td><td>L2</td><td>7M</td></tr>
</table>

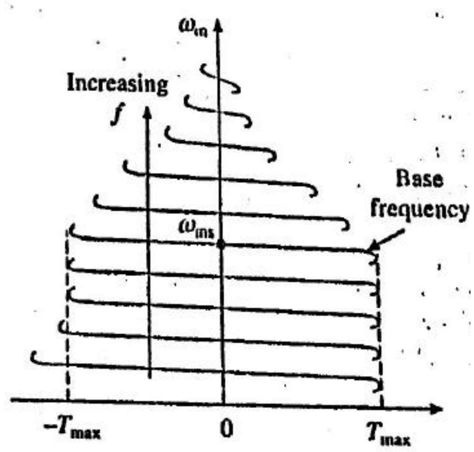
Equation suggests that with a constant (V/f) ratio, motor develops a constant maximum torque, except at low speeds (or frequencies). Motor therefore operates in constant torque mode. According to Eq. (6.69), for low frequencies (or low speeds) due to stator resistance drop [i.e. when (R_s/f) is not negligible compared to $2\pi(L_s + L_r')$] the maximum torque will have lower value in motoring operation (+ve sign) and larger value in braking operation (–ve sign). This behavior is due to reduction in flux during motoring operation and increase in flux during braking operation. When it is required that the same maximum torque is retained at low speeds also in motoring operation, (V/f) ratio is increased at low frequencies. This causes further increase in maximum braking torque and considerable saturation of the machine in braking operation.

When either V saturates or reaches rated value at base speed, it cannot be increased with frequency. Therefore, above base speed, frequency is changed with V maintained constant. According to Eq. (6.70), with V maintained constant, maximum torque decreases with increase in frequency (or speed).

Variation in terminal voltage with frequency is therefore as shown in Fig. 6.33(a). V is kept constant above the base speed. Below the base speed (V/f) ratio is maintained constant, except at low frequencies where (V/f) ratio is increased to keep maximum torque constant. Corresponding speed torque curves are shown in Fig. 6.33(b) both for motoring and braking operations. The curves suggest that speed control and braking operation are available from nearly zero speed to above synchronous speed.

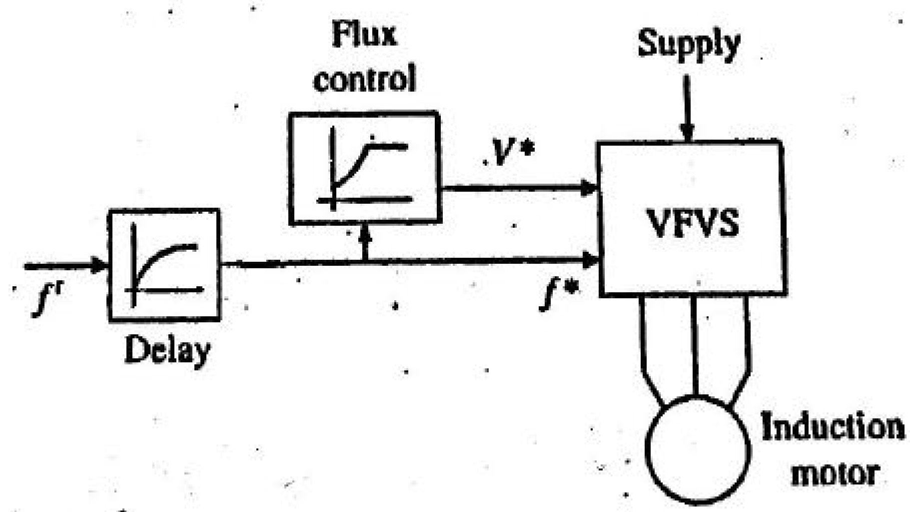


(a) V-f relation



(b) Speed-torque characteristics

Variable frequency control



Variable frequency control

The most important advantage of variable frequency control is that it allows a variable speed drive with above-mentioned good running and transient performance to be obtained from a squirrel cage induction motor. The squirrel cage motor has a number of advantages over a dc motor. It is cheap, rugged, reliable and longer lasting. Because of the absence of commutator and brushes, it requires practically no maintenance, it can be operated in an explosive and contaminated environment, and can be designed for higher speeds, voltage and power ratings. It also has lower inertia, volume and weight. Though the cost of a squirrel cage motor is much lower compared to that of a dc motor of the same rating, the overall cost of variable frequency induction motor drives, in general are higher. But because of the advantages listed above, variable frequency induction motor drives are preferred over dc motor drives for most applications. In special applications requiring maintenance free operation, such as underground and underwater installations, and also in applications involving explosive and contaminated environments, such as in mines and chemical industry, variable frequency induction motor drives are a natural choice. They have several other applications such as traction, mill run out tables, steel mills, pumps, fans, blowers, compressors, spindle drives, conveyers, machine tools, and so on.

b)	A Y-connected squirrel-cage induction motor has following ratings and parameters:	CO3	L3	7M

400 V, 50 Hz, 4-pole, 1370 rpm, $R_s = 2\ \Omega$, $R'_r = 3\ \Omega$, $X_s = X'_r = 3.5\ \Omega$

Motor is controlled by a voltage source inverter at constant V/f ratio. Inverter allows frequency variation from 10 to 50 Hz.

(i) Obtain a plot between the breakdown torque and frequency.
(ii) Calculate starting torque and current of this drive as a ratio of their values when motor is started at rated voltage and frequency.

Solution

$$\omega_{ms} = 50\pi$$

From Eq. (6.13), for a frequency K times the rated frequency and with V/f ratio constant

$$T_{max} = \frac{3}{2K\omega_{ms}} \times \left[\frac{K^2V^2}{R_s + \sqrt{R_s^2 + K^2(X_s + X'_r)^2}}\right]$$

$$= \frac{3}{2\omega_{ms}} \times \frac{V^2}{(R_s/K) + \sqrt{(R_s/K)^2 + (X_s + X'_r)^2}}$$

Substitution of values of parameters gives

$$T_{max} = \frac{509.296}{(2/K) + \sqrt{(2/K)^2 + 49}}$$

From Eq. (1), values of T_{max} can be calculated for various values of frequency. These results are tabulated below:

K	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
f, Hz	50	45	40	35	30	25	20	15	10
T_{max}, N-m	54.88	53.24	51.24	48.89	45.94	42.22	37.44	31.18	22.93

A plot between T_{max} and f is given in Fig. E.6.9 which shows that for a constant (V/f) ratio, breakdown torque decreases with frequency.

(ii) Since the minimum frequency available is 10 Hz, motor will have to be started at 10 Hz. From Eq. (6.10) starting torque is given by

$$T_{st} = \frac{3}{\omega_{ms}}\left[\frac{V^2R'_r}{(R_s + R'_r)^2 + (X_s + X'_r)^2}\right] \quad (2)$$

At 50 Hz $$T_{st} = \frac{3}{50\pi}\left[\frac{(400/\sqrt{3})^2 \times 3}{(2+3)^2 + (3.5+3.5)^2}\right] = 41.29 \text{ N-m}$$

Starting current $$I_{st} = \frac{V}{\sqrt{(R_s + R'_r)^2 + (X_s + X'_r)^2}}$$

$$= \frac{400/\sqrt{3}}{\sqrt{(5)^2 + (7)^2}} = 26.85 \text{ A}$$

With variable frequency control and constant V/f ratio; for frequency K times rated, from I

$$T'_{st} = \frac{3}{\omega_{ms}} \times \frac{V^2R'_r/K}{\left[\left(\frac{R_s + R'_r}{K}\right)^2 + (X_s + X'_r)^2\right]}$$

Similarly from $$I'_{st} = \frac{V}{\sqrt{\left(\frac{R_s + R'_r}{K}\right)^2 + (X_s + X'_r)^2}}$$

for 10 Hz, $K = 10/50 = 0.2$.
Substitution in Eqs

$$T'_{st} = \frac{3}{50\pi} \times \frac{(400/\sqrt{3})^2 \times 3/0.2}{\left[\left(\frac{5}{0.2}\right)^2 + 7^2\right]} = 22.67 \text{ N-m}$$

$$I'_{st} = \frac{400/\sqrt{3}}{\sqrt{\left(\frac{5}{0.2}\right)^2 + 7^2}} = 8.895 \text{ A}$$

Now $$\frac{T'_{st}}{T_{st}} = \frac{22.67}{41.29} = 0.549$$

$$\frac{I'_{st}}{I_{st}} = \frac{8.895}{26.85} = 0.33$$

<table>
<tr><td colspan="6"><u>Unit-IV</u></td></tr>
<tr><td>8</td><td>a)</td><td>

Single-Stack Variable Reluctance Motor

A variable reluctance stepper motor has salient pole (or tooth) stator and rotor. While rotor has no windings, stator has concentrated coils placed over the stator poles (teeth). Stator winding phase number depends on the connection of stator coils. When the stator phases are excited in a definite sequence from a dc source with the help of semiconductor switches, resultant air-gap field steps around and rotor follows the axis of air-gap field due to reluctance torque developed by the tendency of magnetic circuit to occupy the position of minimum reluctance.

A four-phase, 4/2-pole (4-poles in the stator and 2 in rotor), single-stack, variable reluctance stepper motor is shown in Fig. 8.1. Four-phases A, B, C and D are connected to dc source with the help of semiconductor switches S_A, S_B, S_C and S_D respectively. Phases are excited in the sequence of A, B, C, D, A. When A is excited, the reluctance torque causes rotor to turn, until it aligns with the axis of phase A. The rotor is stable in this position and cannot move until phase A is de-energised. Next, phase B is excited and A is disconnected. Rotor turns through 90° in clockwise direction to align with the resultant air-gap field which now lies along the phase B axis. Thus, as the phases are excited in the sequence A, B, C, D, A, rotor turns with a step of 90° in clockwise direction. Direction of rotation can be reversed by reversing the sequence of switching the phases, that is A, D, C, B, A. Direction of rotation depends only on the sequence in which phases are switched and is independent of the direction of currents through the phases.

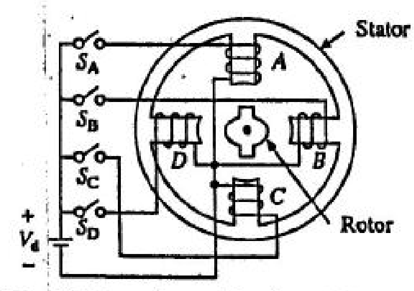


Fig. 8.1 Four-phase, 4/2-pole variable reluctance stepper motor

The step-angle can be reduced from 90 to 45° by exciting phases in sequence A, A + B, B, B + C, C, C + D, D, D + A, A. When phase A is excited, the rotor aligns with the axis of A. When, both phases A and B are excited, the resultant air-gap field axis, and therefore, rotor turns by 45° in the clockwise direction. Rotor can be turned in anticlockwise direction with a step of 45° by switching phases in sequence of A, A + D, D, D + C, C, C + B, B, B + A, A. This technique of gradually shifting excitation from one phase to another (e.g. from A to B with an intermediate step of A + B) is known as microstepping and is used to realise smaller steps.

</td><td>CO4</td><td>L2</td><td>7M</td></tr>
<tr><td></td><td>b)</td><td>

Vector control is an elegant method of controlling the permanent magnet synchronous motor (PMSM), where field-oriented theory is used to control space vectors of magnetic flux, current, and voltage.

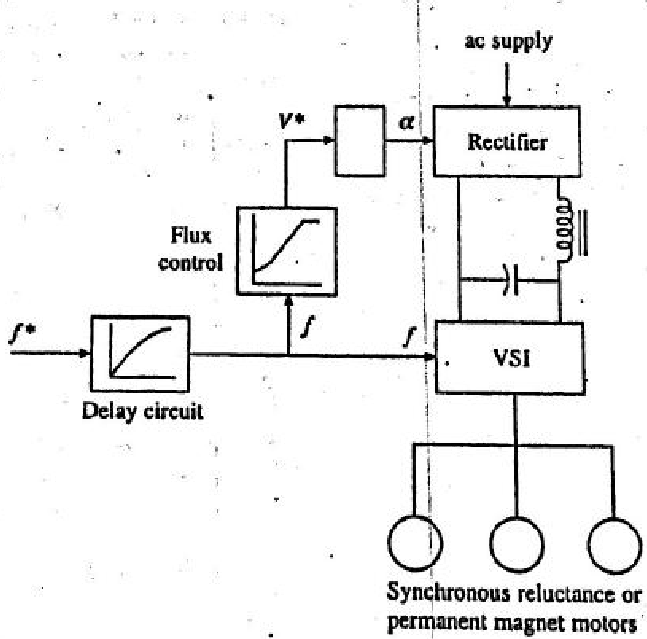
Advantages

1. They are compatible with digital systems and do not require digital to analog conversion at the input, as do conventional servos, when used with digital systems or a computer.
2. While simple open-loop control is good enough for the control of position and speed, it can also be used in closed loop position and speed control systems with either analog or digital feedback.
3. A wide range of step angles is available off-the-shelf from most manufacturers, in the range of 1.8 to 90°. The range of torque is from 1 μNm (tiny wristwatch motor) to 50 Nm (machine tool applications).
4. Bidirectional control is available.
5. Maximum torque occurs at low pulse rates. The stepper motor can, therefore, accelerate its load easily.
6. Low speeds are possible without a reduction gear.
7. Moment of inertia is usually low.
8. The starting current is low.
9. Multiple stepper motors driven from the same source can maintain perfect synchronisation.

Disadvantages

1. Efficiency is low.
2. Proper matching between load, motor and its drive is required.
3. Resonance can be a problem with variable reluctance motores.

</td><td>CO4</td><td>L4</td><td>7M</td></tr>
<tr><td colspan="6">(OR)</td></tr>
</table>

9	a)	A drive operating in true synchronous mode is shown in Fig. 7.9. Frequency command f^* is applied to a voltage source inverter through a delay circuit so that rotor speed is able to track the changes in frequency. A flux control block changes stator voltage with frequency to maintain a constant flux below rated speed and a constant terminal voltage above rated speed. This scheme is commonly used for the control of multiple synchronous reluctance or permanent magnet motors in fiber spinning, textile and paper mills where accurate speed tracking between the motors is required.  Fig. Variable frequency control of multiple synchronous motors	CO4	L2	7M
	b)	• SRMs have better efficiency, better reliability, high fault tolerance, high constant power speed ratio (CPSR), and resistance to high temperatures compared with other types of motors such as induction motors, permanent magnet synchronous motors, and brushless. • Both types of motors offer specific advantages and characteristics that make them suitable for different applications. Switched reluctance motors provide easy control and high torque at low speeds. On the other hand, synchronous reluctance motors offer high efficiency and a wider speed range. The inductance of a stator phase winding is a function of rotor position due to the salien stator and rotor. In the fully-aligned position, the phase winding inductance is maximum ar reluctance of the magnetic circuit is minimum. Similarly in the non-aligned position, the induc is minimum and reluctance is maximum. Variation of phase 1 winding inductance for va values of θ is shown in Fig. 8.14, where θ is the angle between the reference axis and th of rotor pole 1 (Fig. 8.13). Reference axis has been chosen in non-aligned position. Rotor h poles, therefore, when rotor completes one revolution (i.e. for $\theta = 0°$ to 360°), inductanc pass through 6 maximum and 6 minimum values. The angle between the axis of two conse rotor poles is 60° and that of stator poles is 45°, hence, if variation of inductance for phas plotted, it will have similar variation as of phase 1, but displaced by 15° (Fig. 8.13). Ther waveforms of phase 3 and 4 will similarly be shifted with respect to phase 1 waveforms b • and 45° respectively.	CO4	L2	7M

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