SL NO.2/Sem4/4033

Scoring Indicators

~~FUNDAMENTALS OF ELECTRIC CIRCUITS~~

INDUCTION MACHINES

Q No	Scoring Indicators	Split score	Sub Total	Total Score
	PART A			9
I.1.	$\frac{E_2}{E_1} = \frac{N_2}{N_1}$ = K is called voltage transformation ratio	1		
I. 2.	Magnetizing component	1		
I. 3.	To reduce eddy current loss	1		
I. 4.	air cooling, oil cooling	1		
I. 5.	Short circuit test	1		
I. 6.	f_r=s*f	1		
I. 7.	Transformer	1		
I. 8.	Stator side control (by changing applied voltage, changing applied frequency, changing number of stator poles) Rotor side control (rotor rheostat control, injecting emf in the rotor)	1		
I. 9.	Lifts, Cranes, Hoists, Large capacity exhaust fans, Driving lathe machines, Crushers, Oil extracting mills, Textile and etc.	1		
	PART B			24
II. 1.	***Steps - 2 marks*** ***Final eqn – 1 mark***	2+1	3	
	Consider that an alternating voltage V_1 of frequency f is applied to the primary. The sinusoidal flux ϕ produced by the primary can be represented as: $\phi = \phi_m \sin \omega t$. The instantaneous e.m.f. E1 induced in the primary is $e_1 = - N_1 \frac{d\phi}{dt}$			

$$e_1 = -N_1 \frac{d(\phi_m \sin \omega t)}{dt} = -N_1\phi_m\omega \cos \omega t = -N_1\phi_m 2\pi f \cos \omega t$$

$$= N_1\phi_m 2\pi f \sin(\omega t - 90)$$

It is clear from the above equation that maximum value of induced e.m.f. in the primary is

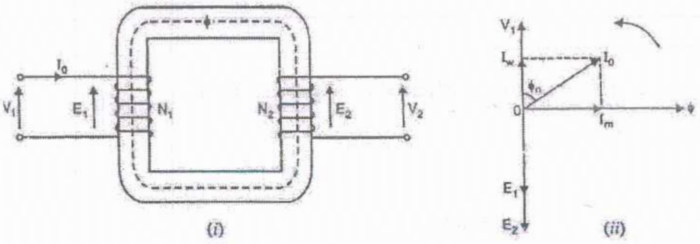
$E_{m1} = 2\pi f N_1\phi_m$

The rms value is $E_{rms1} = 2\pi f N_1\phi_m / \sqrt{2} = 4.44 f N_1\phi_m$

Similarly $E_{rms2} = 4.44 f N_2 \phi_m$

II. 2. ***Figure – 1 marks*** ***Explanation – 2 marks*** | 1+2 | 3

Consider a practical transformer on no load i.e., secondary on open-circuit as shown in Figure. The primary will draw a small current I_0 to supply (i) the iron losses and (ii) a very small amount of copper loss in the primary. Hence the primary no load current I_0 is not 90° behind the applied voltage V_1 but lags it by an angle $\phi_0 < 90°$ as shown in the phasor diagram

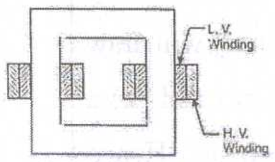
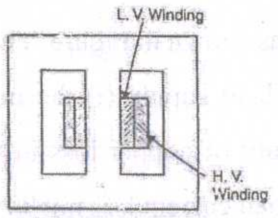


As seen from the phasor diagram , the no-load primary current I_0 can be resolved into two rectangular components viz. (i) The component I_W in phase with the applied voltage V_1. This is known as active or working or iron loss component and supplies the iron loss and a very small primary copper loss.

(b) The component I_m lagging behind V_1 by 90° and is known as magnetizing component. It is this component which produces the mutual flux f in the core.

II. 3. ***Any 3 differences – 3 marks*** | 3*1=3 | 3

	Core Type	Shell type

1	Winding encircles the core	Core encircles the major part of the windings
2	Has 2 limbs	Has 3 limbs
3	Requires more copper and less insulating material	Requires less copper and more insulation material
4	Leakage flux is more	Leakage flux is less
5	Economical for high voltage small kVA transformers	Economical for low voltage , large kVA rating transformers
6	Series magnetic circuit	Parallel magnetic circuit
7	 Core-type transformer	 Shell-type transformer

II.4 *Steps – 2 marks* / *Condition – 1 mark* — 2+1 — 3

Output power = $V_2 I_2 \cos \phi_2$

If R_{02} is the total resistance of the transformer referred to secondary, then,

Total Cu loss, $P_C = I_2^2 R_{02}$

Total losses = $P_i + P_C$

$$\therefore \quad \text{Transformer } \eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{02}}$$

$$= \frac{V_2 \cos\phi_2}{V_2 \cos\phi_2 + P_i/I_2 + I_2 R_{02}} \quad \text{(i)}$$

$$\frac{d}{dI_2}(\text{denominator}) = 0$$

or $$\frac{d}{dI_2}\left(V_2 \cos\phi_2 + P_i/I_2 + I_2 R_{02}\right) = 0$$

or $$0 - \frac{P_i}{I_2^2} + R_{02} = 0$$

or $$P_i = I_2^2 R_{02}$$

i.e., **Iron losses = Copper losses**

II.5.	***Any 3 conditions – 3*1 marks***	**3*1=3**	**3**
	1. The voltage and frequency ratings of the transformers should be for the incoming bus-bars voltage and frequency. 2. The terminals of the transformers should properly be marked and connected with regard to polarity otherwise the windings get short-circuited or lead to flow large circulating current. 3. The transformation or turn ratios of the transformers should be the same. Otherwise, the circulating current will produce in the secondaries of the transformers to equalize the voltage. This circulating current will reduce the capacity of the transformer. 4. The percentage (per-unit) impedance of the transformers operating parallelly should be the same in order to share the load on the transformers according to their kVA ratings. 5. The transformer's windings resistance to reactance ratio should same or else the power factors of the transformers supplying the load will be different with respect to their ratings.		
II.6.	***Synchronous speed – 1.5 marks*** ***Speed of rotor – 1.5 marks***	**1.5+** **1.5**	**3**
	Ns =120f/P = $\frac{120 \times 50}{4}$ = **1500 r.p.m** Frequency of rotor = sf = 0.04 * 1500 = **60 Hz**		
II.7.	***Any 3 points***	**1+1+1**	

Sl No	Wound rotor	Squirrel cage rotor
1	Rotor consists of a three phase winding similar to stator winding	Rotor consists of bars which are shorted at ends with end rings
2	Resistance can be added externally	As permanently shorted, external resistance cannot be added
3	Slip ring and brushes are present	Slip ring and brushes are absent

4	Speed control by rotor resistance is possible	Speed by rotor resistance is not possible
5	Construction is delicate and frequent maintenance required	Construction is robust and maintenance free
6	Used in lifts hoists cranes elevators etc	Used in lathes, drilling machines, fans blowers , grinders etc

II.8.	***Crawling definition – 1 mark*** ***Explanation – 2 marks***	1+2	3

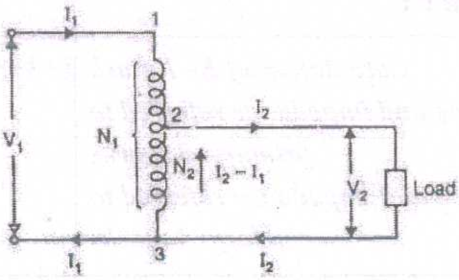
It has been observed that squirrel cage type induction motor has a tendency to run at very low speed compared to its synchronous speed, this phenomenon is known as crawling. The resultant speed is nearly $1/7^{th}$ of its synchronous speed slip ring and a squirrel cage induction motor

This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc. The fundamental wave revolves synchronously at synchronous speed Ns whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at Ns/3, Ns/5, Ns/7 speeds respectively. Hence, harmonic torques are also developed in addition with fundamental torque. 3rd harmonics are absent in a balanced 3-phase system. Hence 3rdd harmonics do not produce rotating field and torque. The total motor torque now consist three components as: (i) the fundamental torque with synchronous speed Ns, (ii) 5th harmonic torque with synchronous speed Ns/5, (iv) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).

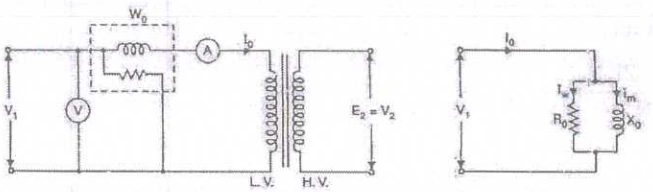
The small amount of 5th harmonic torque produces breaking action and can be neglected.

The 7th harmonic currents will have phase difference of 7 X 120 = 840° = 2 X 360 +120 = + 120°. Hence they will set up rotating field in forward direction with synchronous speed equal to Ns/7. If we neglect all the higher harmonics, the resultant torque will be equal to sum of fundamental torque and 7th harmonic torque. 7th harmonic torque reaches its maximum positive value just before1/7th of Ns. If the mechanical load on the shaft involves constant load torque, the torque developed by the

	motor may fall below this load torque. In this case, motor will not accelerate up to its normal speed, but it will run at a speed which is nearly 1/7th of of its normal speed. This phenomenon is called as crawling in induction motors			
II.9.	***Torque under running conditions- 1.5 marks*** ***Torque under standstill conditions- 1.5 marks***	**1.5 +1.5**	**3**	
	Torque under running conditions = $\frac{3}{2\pi N_s} \cdot \frac{sE_2^2 R_2}{R_2^2+(sX_2)^2}$ Torque under standstill conditions = $\frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2+(X_2)^2}$			
10	***Any 3 starter- 3 marks***	**1.5 + 1.5**	**3**	
	Direct Online starter, star delta starter, autotransformer starter, stator resistance starting			
	PART C			**42**
III	***Calculation of K- 1 mark*** ***Resistance, reactance and impedance referred to primary- 3 marks*** ***Resistance, reactance and impedance referred to secondary- 3 marks***	**1+3+3**	**7**	
	K =220/4400 =1/20 I1 = 50000/4400 = 11.36 A(assuming 100 % efficiency) I2 =50000/2220 =227 A R1= 3.45 Ω, X1 = 5.2 Ω, R2 =0.009 Ω and X2 =0.015 Ω (i) Referrred to HV side $R_{01} = R_1 + R_2'$ $= R_1 + R_2/K^2$ = 3.45 + (0.009 * 20* 20) = **7.05 Ω** $X_{01} = X_1 + X_2'$ $= X_1 + X_2/K^2$ = 5.2 + (0.015 * 20* 20) = **11.2 Ω** Z01 = $\sqrt{{R_{01}}^2 + {X_{01}}^2}$ = 15 Ω (ii) Referred to secondary $R_{02} = R_2 + R_1'$ $= R_2 + R_1 * K^2$			

	$= 0.009 + 3.45 * (1/20)^2$ $= 0.0176\ \Omega$ $X_{02} = X_2 + X_1'$ $= X_2 + X_1 * K^2$ $= 0.015 + 5.2 * (1/20)^2$ $= 0.028\ \Omega$ $Z_{01} = 13.23\ \Omega$ $Z_{02} = 0.03311\ \Omega$			
IV	***Maximum flux – 3 marks*** ***Core loss – 2 marks*** ***Magnetizing component- 2 marks***	**3+2+2**	**7**	
	$E_1 = 4.44\ f N_1 \phi_m$ $235 = 4.44 \times 50 \times 200 \times \phi_m$ ϕ_m = **5.29 mWb** Coreloss $= V_1 I_0 \cos\phi = 235 \times 5 \times 0.25 =$ **294 W** $I_\mu = I_0 \sin\phi = 5 \times 0.9682 =$ **4.84 A**			
V	***Derivation – 7 marks***	**7**	**7**	
	 The weight of the copper is proportional to the length and area of a cross-section of the conductor. Weight of Cu required in a winding α current x turns The length of the conductor is proportional to the number of turns, and the cross-section is proportional to the product of current and number of turns. Weight of autotransformer is proportional to: $W_a \propto I_1 (N_1 - N_2) + (I_2 - I_1) N_2$ $W_a \propto I_1 N_1 + I_2 N_2 - 2 I_1 N_2$ Weight of ordinary transformer is proportional to: $W_o \propto I_1 N_1 + I_2 N_2$ the ratio of the weight of the copper in an auto transformer to the weight of copper in an ordinary			

	transformer is given as $\frac{W_a}{W_o} = \frac{I_1N_1 + I_2N_2 - 2I_1N_2}{I_1N_1 + I_2N_2}$ OR $\frac{W_a}{W_o} = \frac{I_1N_1 + I_2N_2}{I_1N_1 + I_2N_2} - \frac{2I_1N_2}{I_1N_1 + I_2N_2}$ $\frac{W_a}{W_o} = 1 - \frac{2I_1N_2/I_1N_1}{I_1N_1/I_1N_1 + I_2N_2/I_1N_1} = 1 - K$ OR $W_a = (1 - K)W_o$			
VI	***SC test – 2.5 marks*** ***OC test – 2.5 marks*** ***Circuit- 2 marks***	**2.5+** **2.5 +** **2**	7	
	Open-Circuit or No-Load Test: This test is conducted to determine the iron losses (or core losses) and parameters R0 and X0 of the transformer. In this test, the rated voltage is applied to the primary (usually low-voltage winding) while the secondary is left open circuited. The applied primary voltage V1 is measured by the voltmeter, the no load current I0 by ammeter and no-load input power W0 by wattmeter as shown in Fig. As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current I0 is very small. Cu losses in the primary under no-load condition are negligible as compared with iron losses. Hence, wattmeter reading practically gives the iron losses in the transformer.			



Iron losses, Pi = Wattmeter reading = W_0

No load current = Ammeter reading = I_0

Applied voltage = Voltmeter reading = V_1

Input power, $W_0 = V_1 I_0 \cos \phi_0$

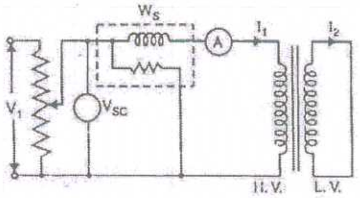
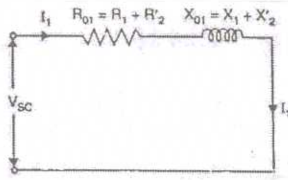
$$\text{No - load p.f.,} \quad \cos\phi_0 = \frac{W_0}{V_1} I_0$$

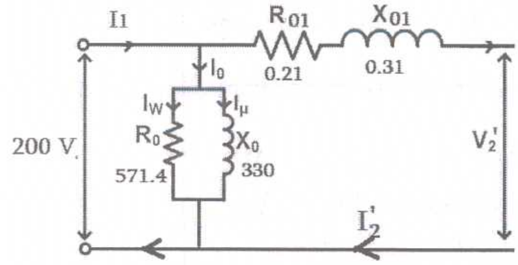
$$I_W = I_0 \cos\phi_0; \qquad I_m = I_0 \sin\phi_0$$

$$R_0 = \frac{V_1}{I_W} \quad \text{and} \quad X_0 = \frac{V_1}{I_m}$$

Short-Circuit or Impedance Test;

This test is conducted to determine R01 (or R02), X01 (or X02) and full-load copper losses of the transformer. In this test, the secondary (usually low-voltage winding) is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in Fig. The low input voltage is gradually raised till at voltage VSC, full-load current I1 flows in the primary. Then I2 in the secondary also has full-load value since I1/I2 = N2/N1. Under such conditions, the copper loss in the windings is the same as that on full load. There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage VSC is very small. Hence, the wattmeter will practically register the full-load copper losses in the transformer windings

	 Full load Cu loss, P_C = Wattmeter reading = W_S Applied voltage = Voltmeter reading = V_{SC} F.L. primary current = Ammeter reading = I_1 $P_C = I_1^2R_1 + I_1^2R'_2 = I_1^2R_{01}$ $R_{01} = \frac{P_C}{I_1^2}$ & $Z_{01} = \frac{V_{SC}}{I_1}$ $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$ Short-circuit p.f, $\cos\phi_2 = \frac{P_C}{V_{SC}I_1}$			
VII	***Calculation of various parameters – 5 marks*** ***Equivalent circuit – 2 marks***	**5+2**	**7**	
	$V_1I_0\cos\phi_0 = W_0$ 200 x 0.7 x $\cos\phi_0$ = 70 $\cos\phi_0$ = 0.5 and $\sin\phi_0$ = 0.866 $I_w = I_0\cos\phi_0$ = 0.7 x 0.5 = 0.35 A $I_\mu = I_0\sin\phi_0$ = 0.7 x 0.866 = 0.606 A $R_0 = V_1/I_w$ = 200/0.35 = **<u>571.4 Ω</u>** $X_0 = V1/I\mu$ = 200/0.606 = **<u>330 Ω</u>** $Z_{02} = V_{sc}/ I2$ = 15/10 = 1.5 Ω K = 400/200 = 2 $Z_{01} = Z_{02}/K^2$ = 1.5/4 = 0.375 Ω $I_2^2R_{02}$ = W **Thus R_{02} = 85/100 = 0.85 Ω** **$R_{01} = R_{02}/K^2$ = 0.85/4 = 0.21 Ω** **$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$ = 0.31 Ω** Output kVA = 5/0.8 Output current I_2 =5000/(0.8 x 400) = 15.6 A Z_{02} = 1.5 Ω R_{02} =0.85 Ω,			

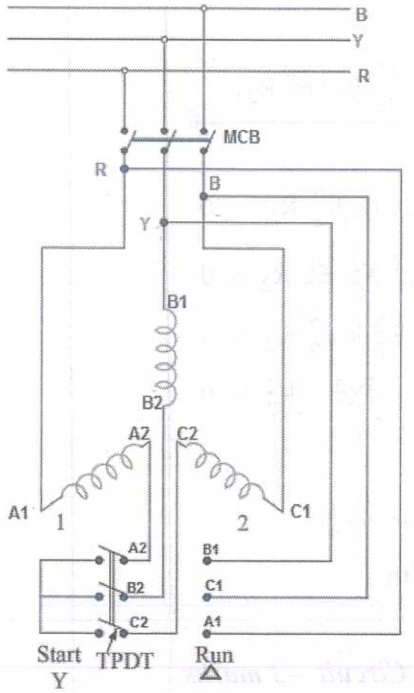
	$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = \mathbf{1.24\ \Omega}$ 			
VIII	***kVA load for maximum efficiency- 2 marks*** ***Maximum efficiency – 2 marks*** ***Efficiency at half full load and 0.8 pf – 3 marks***	2+2+3	7	
	(i) kVA load for maximum efficiency =FL kVA x $\sqrt{\frac{Iron\ loss}{FL\ Cu\ loss}}$ $= 250\text{x} \sqrt{\frac{1.6}{1.4}}$ = **<u>160 kVA</u>** For max efficiency Core loss = Copper loss Hence total loss =1.4 + 1.4 = 2.8 kW Max efficiency = 160/162.8 = **<u>98.2 %</u>** (ii) Cu loss at half full load= 1.6 x $(1/2)^2$ = 0.4 kW Total losses = 1.4 + 0.4 = 1.8 kW Half full load output at 0.8 p.f = (150/2) x 0.8 = 60 kW Efficiency = 60/(60 + 1.8) = **<u>97%</u>**			
IX	***Rotor input – 2 marks*** ***Rotor copper loss – 3 marks*** ***Mechanical power – 2 marks***	2+3+2	7	
	Rotor input , P2 = Tg ωs = Tg x 2π Ns ……………1 Rotor gross output, Pm = Tg ω= Tg x 2πN…………2 The difference of two equal rotor Cu loss Rotor copper loss = P2 – Pm Pcu = Tg x 2π (Ns – N) ………………………………3 By 1 and 3 we get **Rotor Cu loss/ Rotor input = (Ns – N)/Ns = s** Thus Rotor Cu loss = s * Rotor input			

	Pm = Input P2 – Rotor cu loss =input – s * rotor input = (1 – s) rotor input Thus $\frac{P_m}{Rotor\ input} = (1 - s)$			
X	***Torque equation – 1 mark*** ***Condition for max torque - 4 marks*** ***Maximum torque – 2 marks***	1+4+2	7	
	For maximum torque dT/ds = 0 $T = \frac{3}{2\pi N_S} \cdot \frac{sE_2^2 R_2}{R_2^2+(sX_2)^2}$ $\mathbf{T = k} \frac{sE_2^2 R_2}{R_2^2+(sX_2)^2}$ **dT/ds =** $\frac{(k\,s\,E_2^2\,R_2)\,\frac{d}{ds}\,(R_2^2+s^2\,X_2^2)-(R_2^2+s^2\,X_2^2)\,\frac{d}{ds}\,(k\,s\,E_2^2\,R_2)}{(R_2^2+s^2\,X_2^2)^2} = 0$ $\therefore \quad k\,s\,E_2^2\,R_2\,[2s\,X_2^2] - (R_2^2 + s^2\,X_2^2)\,(k\,E_2^2\,R_2) = 0$ $\therefore \; 2\,s^2\,k\,X_2^2\,E_2^2\,R_2 - R_2^2\,k\,E_2^2\,R_2 - k\,s^2\,X_2^2\,E_2^2\,R_2 = 0$ $\therefore \quad k\,s^2\,X_2^2\,E_2^2\,R_2 - R_2^2\,k\,E_2^2\,R_2 = 0$ $\therefore \quad s^2X_2^2 - R_2^2 = 0$ $s^2 = \frac{R2^2}{X2^2}$ or $s = \frac{R2}{X2}$ By substituting R2 = s X2 in Torque equation we get, $T = \boldsymbol{T} = \frac{3}{2\pi N_S} \cdot \frac{sE_2^2\,sX_2}{(sX_2)^2+(sX_2)^2} = \frac{3}{2\pi N_S} \cdot \frac{E_2^2}{2X_2}$ Nm			
XI	***Circuit – 3 marks*** ***Working – 4 marks***			
	Star-delta starting The stator winding of the motor is designed for delta operation and is connected in star during the starting period. When the machine is up to speed, the connections are changed to delta. The six leads of the stator windings are connected to the changeover switch as shown. At the instant of starting, the changeover switch is thrown to "Start" position which connects the stator windings in star. Therefore, each stator phase gets V/√3 volts where V is the line voltage. This reduces the starting current. When the motor picks up speed, the changeover switch is thrown			

to "Run" position which connects the stator windings in delta. Now each stator phase gets full line voltage V. The disadvantages of this method are: (a) With star-connection during starting, stator phase voltage is 1/ √3 times the line voltage. Consequently, starting torque is 1/3 times the value it would have with Delta-connection.
This is rather a large reduction in starting torque. (b) The reduction in voltage is fixed.

$$\frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f = \left(\frac{I_{sc}}{\sqrt{3} \times I_f}\right)^2 \times s_f$$

$$\frac{T_{st}}{T_f} = \frac{1}{3}\left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$



Ref: **https://electricalbaba.com/star-delta-starter/**

XII	***Construction – 3 marks*** ***Working – 2 marks*** ***Equivalent circuit- 2 marks***	**3+2+ 2**	**7**
	A rotor of double cage motor carries two squirrel cage windings embedded in two rows of slots. The outer slots contain high resistance and low reactance conductors and inner cage have low resistance and high reactance conductors.		

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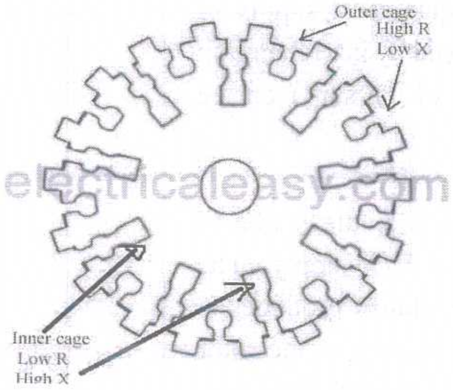
<tr><td></td><td>

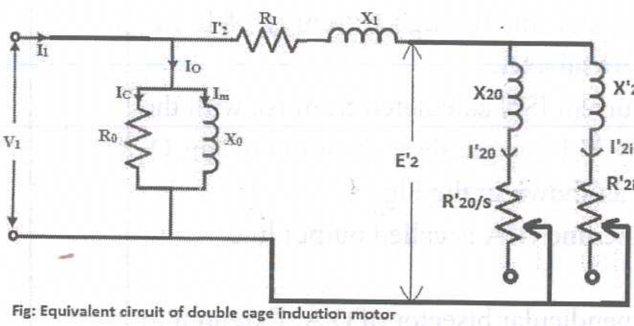
Reference:www.electricaleasy.com
At starting rotor has the same frequency as that of stator. Hence reactance of inner cage winding becomes higher than that of the outer cage.
Thus rotor current is forced to flow through the outer cage to produce sufficiently high starting torque.
At normal speed since frequency of rotor reduces to a low value the reactance of inner cage and hence impedance reduces to a very low value.
Then rotor current is forced to flow through the inner cage to produce sufficiently high running torque.


Fig: Equivalent circuit of double cage induction motor </td><td></td><td></td></tr>
<tr><td>XIII</td><td>Any two methods – 3.5 + 3.5</td><td>3.5+
3.5</td><td>7</td></tr>
<tr><td></td><td>(1) Regenerative braking: If the rotor speed becomes greater than synchronous speed, then the relative speed between the rotor conductor and air gap rotating field reverse and the power will be fed back to supply.</td><td></td><td></td></tr>
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	(2) Plugging: When the phase sequence of supply of the motor running at speed is reversed by interchanging the connection of any two phases of the stator on the supply terminal. The reversal of phase sequence reverses the direction of a rotating field. (3) Dynamic braking: In this method, the stator of induction is connected across the DC supply. The direct current flow through the stator produces a stationary magnetic field, and the motion of the rotor in this field induces voltage in the stationary windings. The machine therefore works as a generator and the generated energy is dissipated in the rotor circuit resistance, thus giving the dynamic braking.			
XIV	***Steps- 4 marks*** ***Figure showing all relevant points – 3 marks***	4+3	7	
	By using the data obtained from the no load test and the blocked rotor test, the circle diagram can be drawn using the following steps: Step 1: Take reference phasor V as vertical (Y-axis). Step 2: Select suitable current scale such that diameter of circle is about 20 to 30 cm. Step3: From no load test, Io and Φo are obtained. Draw vector Io, lagging V by angle Φo. This is the line OO' as shown in the Fig. Step 4: Draw horizontal line through extremity of Io i.e. O', parallel to horizontal axis. Step 5: Draw the current ISN calculated from Isc with the same scale, lagging V by angle Φsc, from the origin O. This is phasor OA as shown in the Fig. Step 6: Join O'A. the line O'A is called output line Step 7: Draw a perpendicular bisector of O'A. Extend it to meet line O'B at point C. This is the centre of the circle. Step 8: Draw the circle, with C as a center and radius equal to O'C. This meets the horizontal line drawn from O' at B as shown in the Fig. Step 9: Draw the perpendicular from point A on the horizontal axis, to meet O'B line at F and meet horizontal axis at D. Step 10: Torque line. The torque line separates stator and rotor copper losses. Thus, the vertical distance AD			

represents power input at short circuit i.e. W_{SN}, which consists of core loss and stator, rotor copper losses.

Now FD = O'G = Fixed loss Where O'G is drawn perpendicular from O' on horizontal axis. This represents power input on no load i.e. fixed loss.

Hence AF α Sum of stator and rotor copper losses ..

Then point E can be located as

AE/EF = Rotor copper loss/ Stator copper loss

The line O'E under this condition is called torque line