ELECTRICAL MACHINES II NOTES

ANNA UNIVERSITY TIRUCHIRAPPALLI

Regulations 2008

Curriculum

SEMESTER V

S. No.	Subject Code	Subject	L T P C
		Theory	
1	MG1301	Total Quality Management	3 0 0 3
2	EE1301	Electrical Machines II	3 1 0 4
3	EE1302	Transmission and Distribution Engineering	3 1 0 4
4	EC1307	Digital Signal Processing	3 1 0 4
5	EC1308	Principles of Communication Engineering	3 0 0 3
6	CS1312	Object Oriented Programming	3 0 0 3
		Practical	
7	EE1303	Electrical Machines II Laboratory	0 0 3 2
8	EC1309	Digital Signal Processing Laboratory	0 0 3 2
9	CS1313	Object Oriented Programming	

SYLLABUS

1. SYNCHRONOUS GENERATOR
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Constructional details – Types of rotors – emf equation – Synchronous reactance – Armature reaction – Voltage regulation – EMF, MMF, ZPF and A.S.A methods – Synchronizing and parallel operation – Synchronizing torque - Change of excitation and mechanical input – Two reaction theory – Determination of direct and quadrature axis synchronous reactance using slip test – Operating characteristics - Capability curves.

2. SYNCHRONOUS MOTOR
8

Principle of operation – Torque equation – Operation on infinite bus bars - V-curves – Power input and power developed equations – Starting methods – Current loci for constant power input, constant excitation and constant power developed.

3. THREE PHASE INDUCTION MOTOR
12

Constructional details – Types of rotors – Principle of operation – Slip – Equivalent circuit – Slip-torque characteristics - Condition for maximum torque – Losses and efficiency – Load test - No load and blocked rotor tests - Circle diagram – Separation of no load losses – Double cage rotors – Induction generator – Synchronous induction motor.

4. STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR 7

Need for starting – Types of starters – Rotor resistance, Autotransformer and Star-delta starters – Speed control – Change of voltage, torque, number of poles and slip – Cascaded connection – Slip power recovery scheme.

5. SINGLE PHASE INDUCTION MOTORS AND SPECIAL MACHINES
9

Constructional details of single phase induction motor – Double revolving field theory and operation – Equivalent circuit – No load and blocked rotor test – Performance analysis – Starting methods of single-phase induction motors - Shaded pole induction motor - Linear reluctance motor - Repulsion motor - Hysteresis motor - AC series motor.

Text Book(s):

1. D.P.Kothari and I.J. Nagrath, "Electrical machines", Tata McGraw Hill Publishing Company Ltd, 2003.
2. P.S.Bhimbhra "Electrical machinery" Khanna Publishers, 2003.

Reference Book(s):

1. A.E. Fitzgerald, Charles Kingsley, Stephen. D.Umans, "Electrical machinery", Tata McGraw Hill Publishing Company Ltd, 2003.
2. J.B.Gupta, „Theory and Performance of Electrical Machines", S.K.Kataria & sons, 2002.
3. K. Murugesh Kumar," Electrical Machines", Vikas publishing house Pvt Ltd, 2002.
4. B.L.Theraja & A.K.Theraja " A Text Book of Electrical Technology "vol II AC & DC Machines, S.Chand & Company Ltd.

EE2302 – ELECTRICAL MACHINES

UNIT I

1. SYNCHRONOUS GENERATOR 9

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SYNCHRONOUS GENERATOR

Constructional Details

Two types of Alternators

(a) Stationary armature - rotating field

(b) Stationary field – rotating armature

Constructional Details

Advantages of stationary armature - rotating field:

i) The HV ac winding and its insulation not subjected to centrifugal forces.

ii) Easier to collect large currents from a stationary member.

iii) The LV dc excitation easily supplied through slip rings and brushes to the rotor field winding.

Stationary Armature - Rotating Field

Stator:

Laminated core with slots to hold the armature conductors.

Rotor:

i) Salient pole type –

Projecting poles dove tailed on the shaft - Used in low speed alternators driven by water turbines or IC engines

Stationary Armature - Rotating Field

ii) Non Salient pole type

Smooth cylindrical rotor - slots cut to house the field winding - used in high speed alternators driven by steam turbines - smaller diameter and larger axial length compared to salient pole type machines, of the same rating.

EMF Equation

$$E_{ph} \quad 4.44K_cK_d f \quad T_{ph}$$

Where,

K_c = cos (α/2),

K_d = {sin (mβ/2)} / {m sin (β/2)}

f = PNs/120, Hz;

Φ = flux per pole, Wb

T_{ph} = Turns in series per phase

= (No. of slots * No. of cond. per slot) / (2 x 3)

EMF Equation

Short pitching and distribution of the winding:

- time harmonics of induced voltage reduced
- The waveform made more sinusoidal.
- Short pitching also reduces the length of the coil end connections

Armature Reaction

- **Effect of the armature flux on the main flux.**
- **Three phase current in a three - phase winding - a rotating magnetic field produced (MMF = 1.5 I_m T_{ph}).**
- **UPF - cross magnetizing.**
- **Lag PF - demagnetizing.**
- **Lead PF - magnetizing.**

Armature Leakage Reactance(X_L)

- **Three major components -Slot leakage reactance, end winding leakage reactance and tooth tip leakage reactance.**
- **Synchronous reactance/phase**

$X_s = X_L + X_{ar}$, where X_{ar} is the fictitious armature reaction reactance.

- **Synchronous impedance/phase**

$Z_s = (R_a + jX_s)$.

Voltage Regulation of Alternators

$$\overline{E_{ph}} \quad \overline{V_{ph}} \quad \overline{I_a Z_s}$$

$$E_{ph} \quad \sqrt{V_{ph}\cos \quad I_a R_a \;^2 \quad V_{ph}\sin \quad I_a X_s \;^2}$$

$$\frac{E_{ph} \quad V_{ph}}{V_{ph}} \quad 100$$

Methods Of Predetermination Of Regulation

- **Synchronous impedance method (EMF method)**
- **Magneto Motive Force method (MMF method)**
- **Zero Power Factor method (ZPF method)**
- **American Standards Association method (ASA method)**

Synchronous Impedance Method (EMF Method)

- OC and SC tests conducted.
- Z_s is calculated.
- R_a measured and X_s obtained.
- For a given armature current and power

factor, E_{ph} determined - regulation is calculated.

Magneto Motive Force Method (MMF Method)

- OC & SC tests conducted.
- field currents If1 (field current required to produce a voltage of(V_{ph} + $I_{aph}R_a\cos\Phi$) on OC) and If2 (field current required to produce the given armature current on SC) are added at an angle of (90± Φ).
- For this total field current, E_{ph} found from OCC and regulation calculated.

Zero Power Factor Method (ZPF Method)

OC test and ZPF test is conducted – characteristics are drawn. This is Potier triangle method

From this triangle the potier reactance (leakage reactance of the alternator), X_{Lph} is obtained.

The terminal voltage and the leakage reactance drop added *vectorially* - load induced EMF found

Zero Power Factor Method (ZPF Method)

- For this load induced emf, the corresponding field current If_1 obtained from OCC.
- The field current If_2 required to balance armature reaction obtained from potier triangle.

If_1 and If_2 are added at an angle of (90± Φ). For this total field current, Eph found from OCC – regulation calculated

American Standards Association Method (ASA Method

- The field currents If1 (field current required to produce the rated voltage of V_{ph} from theair gap line).
- If2 (field current required to produce the given armature current on short circuit) added at an angle of (90± Φ).
- Load induced EMF calculated as was done in the ZPF method - Corresponding to this EMF, the additional field current (If_3) due to saturation obtained from OCC and air gap

line - If_3 added to the resultant of If_1 and If_2 -For this total field current, Eph found from OCC and regulation calculated

Synchronizing And Parallel Operation Of Alternators

- Necessary conditions for synchronization :

The terminal voltage, frequency and phase sequence of the incoming machine should be same as those of the bus bars.

- Synchronization can be carried out using either i) Dark lamp method ii) Bright lamp method or iii) Synchroscope.

Synchronizing Power and Torque

- Power developed by an alternator

$$P_i \quad \frac{E}{Z_s} E\cos \qquad V\cos(\qquad)$$

Where

θ is the internal angle of the machine and

δ is the power angle.

Synchronizing power On no load .

Synchronizing torque = P_{SY} / ($2\pi N_s/60$).

Two Axis Theory

X_d , X_q : Direct & Quadrature axis

synchronous reactances in .

I_d, I_q : The current components of I_a in the

d & q axis

Part A

1. Calculate the distribution factor for a 36- slot, 4 -pole, single layer three phase winding.
2. Define voltage regulation of an alternator.
3. What are the two components of field current required for the predetermination of regulation by MMF method ?

4. What are the conditions to be fulfilled for connecting two alternators in parallel ?
5. Define short circuit ratio of an alternator.

PART B

1.The open circuit and short circuit test readings obtained on a 3 phase, star connected, 1000 kVA, 2000 V , 50 Hz alternator are :

Field Current, A	10	20	25	30	40	50
OC terminal voltage , V	800	1500	1760	2000	2350	2600
SC armature current, A	-	200	250	300	-	-

The effective armature resistance is 0.2 Ω per phase. Draw the characteristic curves and estimate the full-load regulation at a power factor of 0.8 lagging by synchronous impedance method.

2.Derive the EMF equation of an alternator.

3 What do you understand by direct and quadrature axis reactance in a salient pole alternator? Draw the phasor diagram of this alternator for a lagging power factor load

4. Derive the expression for power developed in a 3 phase synchronous motor in terms of E, V, Zs, θ and δ .

5. Sketch an excitation circle and a power circle of a synchronous motor and state what each one represents

UNIT – II

SYNCHRONOUS MOTOR

Principle of Operation

3Ø supply given to the 3Ø stator winding - Rotating magnetic field produced – rotating at synchronous speed(Ns) – Field winding on the rotor excited with dc – Field poles produced - if the rotor is brought to near synchronous speed, rotor pulled into synchronism - also rotates at Ns due to magnetic locking between the stator and rotor poles.

- Torque equation

Torque developed = Nm

Where,

P_m (mechanical developed) = P1 – $3I^2 r_a$,W

P1 (Power input to the stator) = 3VI cosΦ ,W

N_s (Synchronous speed) = (120f)/P, rpm

I = Stator current in A, P = No. of Poles,

f = frequency in Hz

V - Curves

The V – curves shows the variation of armature current with field current for different values of constant power input. Curves joining points of equal power factor are called compounding curves. Variation of power factor with field current gives the inverted V – curves.

- Effect of changing the Excitation (Load constant)
- Changing the excitation varies the power factor of the motor
- Normal excitation: E = V (PF Lag)
- Under excitation : E < V (PF lag)
- Over excitation : E > V (PF lead)
- Minimum armature current occurs at UPF

Effect of changing the Load (Excitation Constant)

Change in load changes the torque angle – armature current changes - induced emf does not change.

Pin = √3 VL IL cosΦ

- Power developed

Mechanical power developed, Pm =

If Ra is neglected, θ = 90˚, then Pm =

The maximum power developed =

- Circle Diagrams

- Excitation Circles :

The extremity of the armature current phasor varies over a circle when load varies (for a constant excitation)

Radius of the excitation circle =

V = applied phase voltage, volts

Zs = synchronous impedance per phase, Ω

- Circle Diagrams

Power Circles :

The extremity of the armature current phasor varies over a circle when excitation varies (load constant).

Radius of the power circle

= Amp

- Starting of synchronous Motors
- Using Pony motors
- Using damper winding
- As a slip ring induction motor

- Using small D.C. machine
- Circle Diagrams

Power Circles

- The extremity of the armature current phasor varies over a circle when excitation varies (load constant).
- Radius of the power circle = Amp
- Starting of synchronous Motors
- Using Pony motors
- Using damper winding
- As a slip ring induction motor
- Using small D.C. machine

PART A

- Why is the field system of an alternator made as a rotor?
- Sketch salient pole and non salient pole rotors.
- What is synchronous reactance?
- Define Pitch factor.
- Calculate the distribution factor for an 18 slots, 4-pole three-phase winding.

UNIT III

STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR 7

Need for starting – Types of starters – Rotor resistance, Autotransformer and Star-delta starters – Speed control – Change of voltage, torque, number of poles and slip – Cascaded connection – Slip power recovery scheme.

Three phase Induction Motor

Construction

The stator is similar to that of Synchronous machine and is wound for three phases.

Rotor is of two types (i) wound rotor

(ii) squirrel–cage rotor

The rotor core is laminated with slots punched for accommodating the rotor winding/ rotor bars.

Rotors

Slip ring: The winding is polyphase with coils placed in the slots of rotor core. The number of slots is smaller and fewer turns per phase of heavier conductor are used.

Squirrel-cage: These rotors has solid bars of conducting material placed in rotor slots and shorted through end-rings on each side.

Principle of operation

The stator is fed from a 3-phase supply. The resultant air gap flux/pole is established in the air-gap. The mmf vector Fr with associated flux density vector Br rotates at synchronous speed. The relative speed between Br and rotor causes induction of current in shorted rotor. Due to interaction of Br and rotor current torque is produced and the rotor tend to move in the direction of Br. Thus the motor is self starting.

Slip

The flux density vector Br moves at speed (ns-n) with respect to rotor conductors, this is known as slip speed.

Equivalent circuit

An induction motor can be assumed as a transformer having primary and secondary windings separated by an air gap. The mechanical load may be replaced by a variable resistance RL = r2(1-s)/s where r2 is the rotor resistance and s the slip.

Power input to rotor/phase = (I22 r2)/s

Rotor copper loss = I22 r2

Rotor current I2 = s2/(√(r22/s)2 + X22

PART A

6. Draw the phasor diagram of synchronous motor working with lagging power factor.

7. Sketch the V and inverted V- curve of a synchronous motor, clearly indicating the X and Y axes for each curve.

8. State the differences in construction between squirrel cage and slip ring rotors of an induction motor.

9. A 3 phase, 4 pole, 50 Hz induction motor runs at a speed of 1425 rpm. Calculate the slip and frequency of the rotor EMF.

10. Sketch the circle diagram of a 3 phase induction motor.

PART B

1. Using relevant phasor diagrams, describe the effect of changing the excitation,

on the armature current and power factor of a synchronous motor and thereby

obtain 'V' and inverted 'V' curves.

2. Deduce the Equivalent circuit of 3 phase induction motors

3. The power input to a 3 phase, 500 V, 50 Hz, 6 Pole, induction motor is 40 kW. The motor runs at a speed of 975 rpm. The stator losses amount to 1 kW and the friction and windage losses amount to 2 kW. Calculate the i) slip ii) rotor copper loss iii) hp output and iv) efficiency.

4. Draw the Circle diagram for a 5.6 kW, 400 V, 3 phase, star connected 4 pole 50 Hz slip ring induction motor which gave the following test data :

No-load: 400 V, 6 A, 360 W : Blocked rotor : 100 V, 12 A, 720 W

The ratio of stator to rotor turns is 2.6. The stator resistance per phase = 0.67 Ω . The rotor resistance per phase = 0.185 Ω. Calculate the full load current and maximum output.

5. With neat diagrams , explain the working of any two types of starters used for starting 3 phase squirrel cage induction motors.

UNIT IV
STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR
7

Need for starting – Types of starters – Rotor resistance, Autotransformer and Star-delta starters – Speed control – Change of voltage, torque, number of poles and slip – Cascaded connection – Slip power recovery scheme.

Need for Starting – Types of Starters

At starting when the rotor is at standstill, the squirrel cage rotor is just like a short circuited secondary. Therefore the current in the rotor circuit will be high and consequently the stator also will draw a high current from the supply lines if full line voltage were applied at start.

Auto –Transformer Starter

A three phase auto transformer can be used to reduce the voltage applied to the stator. The advantage of this method is that the voltage is reduced by transformation and not by dropping the excess in resistor and hence the input current and power from the supply are also reduced compared to stator resistor starting.

Auto –Transformer Starter

The ratio of starting torque (Tst) to full load

torque (Tf):

Ist = starting current and Ist = full load current

X = Transformer tapping as p.u. of rated voltage

Sf = Full load slip

Star-Delta Starter

This method applicable for motors designed to run normally with delta connected stator windings - At starting, the stator windings connected in star - After the motor has reached nearly the steady state speed, the windings are connected in delta – over load and single phasing protection are provided.

- Star-Delta Starter
- At starting the stator phase voltage reduced by $1/\sqrt{3}$ times the voltage.
- Phase current reduced by $1/\sqrt{3}$ times the current with the direct online starting.
- Line current reduce by 3 times.
- Rotor Resistance Starter

  Applicable to slip ring induction motors - Rated voltage applied to the stator - balanced three phase resistors connected in series with the rotor through slip rings – Resistance kept at maximum at starting – starting current reduced – starting torque increased – after starting resistance can be cut out .

Speed Control of Induction Motors

Synchronous speed of the rotating magnetic field produced by the stator, $N_s = 120\, f / P$

- By changing the frequency.

  The available AC voltage (50 Hz) is rectified and then inverted back to AC of variable frequency/ Variable voltage using inverters.

  Inverter can be Voltage source or current source inverter.

- Speed Control of Induction Motors
- By changing the number of poles.

  The stator winding is designed for operation for two different pole numbers: 4/6,4/8,6/8 etc. This can be applied only to squirrel cage induction motors.

- Stator voltage control.

  The stator voltage is varied – slip and operating speed varies.

- Speed Control of Induction Motors
- Rotor resistance control.

This method is applied to slip ring induction motor – rotor is connected to variable resistance through slip rings – resistance varied – slip and hence the operating speed varies – this method results in power loss in the resistor

Speed Control of Induction Motors

- Using cascade connection – Three phase voltage applied to the stator of a slip ring induction motor(P1 – poles) – slip ring voltage applied to the stator of squirrel cage induction motor (P2 – poles)– two rotors are coupled.

$$N_s = 120 f / (P_1 \pm P_2)$$

Slip Power Recovery Scheme

This scheme applied to slip ring induction motor:- Rated voltage applied to the stator - the rotor voltage is rectified using a diode bridge rectifier – the resulting DC voltage is inverted using line commutated inverter and the AC voltage is fed back to the supply through appropriate transformer – slip power is thus recovered from the motor and the speed reduced

PARTA

11. Calculate the pitch factor for a 36 slot, 4 pole winding having a coil pitch of 6 slots.

12. A 5 MVA, 10 kV, 1500 rpm, 3 phase, 50 Hz, 4 pole, star connected alternator is operating on infinite bus bars. Determine the synchronizing power per mechanical degree of displacement under no-load condition. Xs = 20 %.

13. When is a synchronous motor said to be under excited? What will be the nature of power factor under that condition?

14. What is hunting in a synchronous motor?

15. Under what condition, the slip in an induction machine is i) negative ii) greater than one?

PARTB

1. Describe the following methods of speed control of slip ring induction motors:

i) Using external rotor resistance
ii) Slip power recovery scheme

2. Based on double field revolving theory and using the torque – speed characteristics, explain the operation of single- phase induction motors.

ii) Draw the equivalent circuit of single-phase induction motor.

3. Describe the constructional features and the operation of the following:

i) Stepper motor
ii) Shaded pole motor
iii) Hysteresis motor

4. A 3 phase star connected synchronous motor is rated for 6600 V. For a particular load, the motor takes 50 A line current from the supply. The effective armature resistance is 1.0 Ω per phase and synchronous reactance is 20 Ω per phase. Calculate (a) the power supplied to the motor and (b) induced EMF for a power factor of 0.8 lag.

5. Explain why a synchronous motor is not self starting. Describe the method of starting the synchronous motor using damper winding.

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STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

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