LEAD CITY UNIVERSITY, IBADAN FACULTY OF ENGINEERING AND TECHNOLOGY DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
SEMESTER/SESSION: 2ND SEMESTER, 2022/2023

Course Particulars
Course Code: EEE 315
Coarse Title: Electromechanical Devices and Machines II
Course Units: 3
Course Status: Core

Lecturer's Details

Name: AYANLADE, Samson Oladayo
Qualifications: B.Tech (Electronic and Electrical Engineering), M.Sc (Electronic and Electrical Engineering), PhD (In view), R.Engr. (COREN).
Phone: 08062786683
E-mail: ayanladeoladayo@gmail.com, samson.ayanlade@lcu.edu.ng

Areas of Specialization

Power system engineering, power system optimization, renewable energy and power system control

Course Description

This course introduces students to the basics of electromechanical energy conversion with emphasis on three-phase synchronous machines, transformers, and induction motors as well as their construction, operation and performance characteristics. The course also teaches performance and speed control of various types of a.c. machines, their industrial applications, special purpose motors and their applications.

Course Learning Outcomes (CLOs)
At the end of this course, students would be able to:

1. Analyze three phase circuit using phasor notation.
2. Understand and explain the purpose of electric machines in a power system.
3. Know different types of electric machines.
4. Understand the key differences between different types of electric machines.
5. Understand and explain how real electric machines approximate the operation of an idea electric machines.
6. Understand and know how to use the equivalent circuit of electric machines.
7. Be able to sketch phasor diagrams for machines.
8. Know how to derive the characteristics of electric machines from measurements.
9. Understand how electric motors can be started.
10. Understand electric machine ratings.
11. Understand the key differences between different types of electric machines.
12. Understand the principle of operation of electric machines.
13. Understand the operation of a stepper motor.

Lecture Delivery Method

- Lectures with interactive sessions.
- Solutions to example problems

LECTURE PLAN

Course Module
Module 1: Phasor Representation
Module 2: Principles and circuit models of different types of machines
Module 3: Principle of operation of Special Machines

Course Outline
Module 1: Phasor Representation
Number of Lecture Hours: 12

Lecture	Lecture Topic	Contents	Learning Objectives
1	Review of generation of alternating emf	Alternating emf, A.C. system	Understand and explain how alternating emf is generated
2	Symmetrical and asymmetrical waveforms,	Phasor representation of sinusoidal waveforms	Know how to represent sinusoidal waveforms using phasor
3-4	Three phase circuits	Balanced delta-delta and wye-wye connections, wye-delta and delta-wye connections	Analyze three phase circuit of different configurations.

Module 2: Principles and circuit models of different types of machines
Number of Lecture Hours: 27

Lecture	Lecture Topic	Contents	Learning Objectives
5-7	Three phase inductor motor	Principles and circuit models of three phase induction motor, steady state operation, speed control	Understand the working principles and circuit model of three phase inductor motor
8-10	Three phase Transformer	Principle and circuit models of three phase Transformers	Understand the working principles and circuit model of three transformers
11-13	Three phase synchronous machine	Generator and motor construction, synchronous reactance, equivalent circuits, regulation and steady state operation, power factor, control and starter, Parallel operation of Synchronous machines. Faults on machines, methods of starting and protection of machines.	Understand the working principles and circuit model of three synchronous generators and motors.

Module 3: Principle of operation of Special Machines
Number of Lecture Hours: 3

Lecture	Lecture Topic	Contents	Learning Objectives
14	Special Machines	Reluctance motors, Stepper motors	Understand principle of operation of reluctance and stepper motors.

Grading/Assessment

Attendance	-	10 marks
Assignment	-	10 marks
Mid-semester Test	-	20 marks
Examination	-	60 marks

References

1. Stephen J. Chapman- 'Electric Machinery and Fundamentals'- McGraw Hill International Edition, (Fifth Edition), 2012.
2. Alexander and Sadiku; Fundamentals of Electric Circuits, 5th Edition.

Tutorial Questions

1. A 450 V, 50 Hz, Δ connected, 4 pole, 3-phase synchronous generator has direct axis reactance of 0.15 Ω and quadrature axis reactance of 0.07 Ω. Its armature resistance may be neglected. At full load the generator supplies 150 A at a power factor of 0.8 lagging.
   (a) Find the internal generated voltage $\mathbf{E_A}$ of this generator at full load, assuming that it has cylindrical rotor reactance is X_d.
   (b) Find the generated internal voltage $\mathbf{E_A}$ of this generator at full load assuming that it has a salient pole rotor.
2. (a) Why are synchronous generators operated in parallel? (b) State the requirements for paralleling of alternators. (c) Explain the construction and principle of operation of 3-phase alternator. (d) Explain the various techniques of speed control of 3-phase induction motor. (e) Derive the emf equation of 3 phase alternator.
3. Convert the following instantaneous currents to phasors, using $\cos\omega t$ as the reference. Give your answers in both rectangular and polar form.
   (a) $i(t) = 400\sqrt{2}\cos(\omega t - 30^0)$
   (b) $i(t) = 5\sin(\omega t + 15^0)$
   (c) $i(t) = 4\cos(\omega t - 30^0) + 5\sqrt{2}\sin(\omega t + 15^0)$
4. (a) A three phase 600 kVA, 400 volts, delta connected alternator is reconnected in star. Calculate its new ratings in terms of voltage, current and volt-ampere.

(b) A 1200 kVA, 3300 volts, 50 Hz, three phase star connected alternator has an armature resistance of 0.25 Ω per phase. A field current of 40 Amps produces a short circuit current of 200 Amps and an open circuit emf of 1100 volts line to line. Find the percentage regulation at full load 0.8 pf lagging and leading by using emf method.

(c) Calculate the line currents in the three-wire Y-Y system in the Fig. Q4(c).

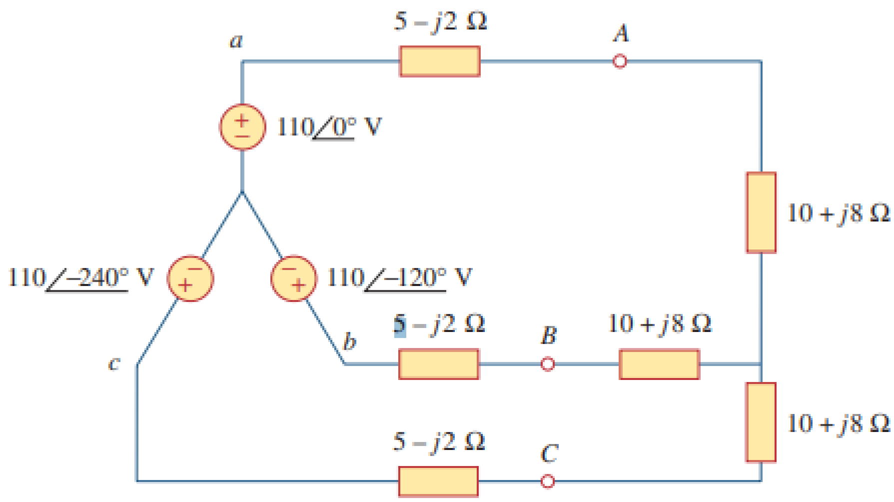

Fig. Q4(c)

5. (a) A 10 MVA 6.6 kV, 3phase star connected alternator gave open circuit and short circuit data as follows

Field current in amps:	25	50	75	100	125	150
OC voltage in kV (L-L):	2.4	4.8	6.1	7.1	7.6	7.9
SC Current in Amps:	288	528	875			

Find the voltage regulation at full load 0.8 pf lagging by EMF method. Armature resistance per phase.

(b) A balanced, positive-sequence, Y-connected voltage source with $E_{ab} = 480\angle 0^0$ V is applied to a balanced-Δ load with $Z_{\Delta} = 30\angle 40^0\ \Omega$. The line impedance between the source and load is $Z_L = 1\angle 85^0\ \Omega$ for each phase. Calculate the line currents, the Δ-load currents, and the voltages at the load terminals.

(c) If the rms phasor of a voltage is given by $V = 120\angle 60^0$ volts, then obtain the corresponding $v(t)$.

(d) A balanced *abc*-sequence Y-connected source with $\mathbf{V}_{an} = 100\angle 10^0$ is connected to a Δ-connected balanced load $(8 + j4)\ \Omega$ per phase. Calculate the phase and line currents.

6. (i) Two balanced three-phase motors in parallel, an induction motor drawing 400 kW at 0.8 power factor lagging and a synchronous motor drawing 150 kVA at 0.9 power factor leading, are supplied by a balanced, three-phase 4160-volt source. Cable impedances between the source and load are neglected, (a) Draw the power triangle for each motor and for the combined-motor load. (b) Determine the power factor of the combined-motor load. (c) Determine the magnitude of the line current delivered by the source.

(ii) The instantaneous voltage across a circuit element is $v(t) = 359.3\sin(\omega t + 15^0)$ volts, and the instantaneous current entering the positive terminal of the circuit element is $i(t) = 100\cos(\omega t + 5^0)$ A. For both the current and voltage, determine (a) the maximum value, (b) the rms value, (c) the phasor expression, using $\cos(\omega t)$ as the reference.

(iii) Determine the line currents for the three-phase circuit of Fig. Q6(iii). Let $\mathbf{V}_a = 110\angle 0^0$, $\mathbf{V}_b = 110\angle -120^0$, $V_c = 110\angle 120^0$ V.

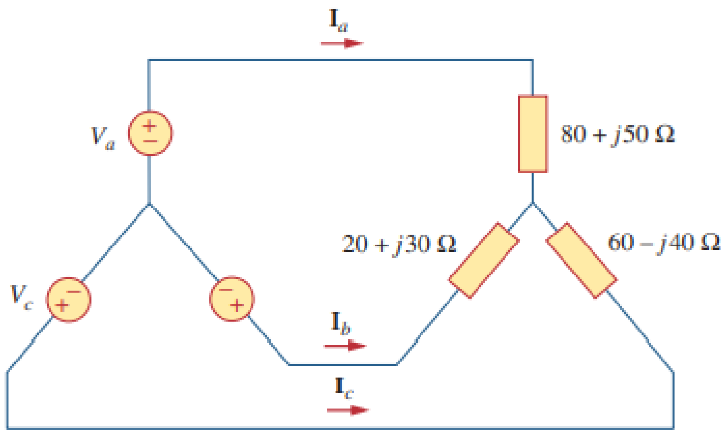

Fig. Q6(iii)

(iv) A 100-kVA 8000/277-V distribution transformer has the following resistances and reactances:

$R_P = 5\ \Omega$	$R_S = 0.005\ \Omega$
$X_P = 6\ \Omega$	$X_S = 0.006\ \Omega$
$R_C = 50\ \text{k}\Omega$	$X_M = 10\ \text{k}\Omega$

The excitation branch impedances are given referred to the high-voltage side of the transformer.

(a) Find the equivalent circuit of this transformer referred to the low-voltage side.

(b) Find the per-unit equivalent circuit of this transformer.

(c) Assume that this transformer is supplying rated load at 277 V and 0.85 PF lagging. What is this transformer's input voltage? What is its voltage regulation?

(d) What are the copper losses and core losses in this transformer under the conditions of part (c)?

(e) What is the transformer's efficiency under the conditions of part (c)?

(iv) Three 20-kVA 24,000/277-V distribution transformers are connected in Δ-Y. The open-circuit test was performed on the low-voltage side of this transformer bank, and the following data were recorded:

$V_{\text{line,OC}} = 480$ V, $I_{\text{line,OC}} = 4.10$ A, $P_{3\phi,\text{OC}} = 945$ W.

The short-circuit test was performed on the high-voltage side of this transformer bank, and the following data were recorded:

$V_{\text{line,SC}} = 1400$ V, $I_{\text{line,SC}} = 1.80$ A, $P_{3\phi,\text{SC}} = 912$ W.

(a) Find the per-unit equivalent circuit of this transformer bank.

(b) Find the voltage regulation of this transformer bank at the rated load and 0.90 PF lagging.

(c) What is the transformer bank's efficiency under these conditions?

7. (i) The internal generated voltage E_A of a 2-pole, Δ-connected, 60 Hz, three-phase synchronous generator is 14.4 kV, and the terminal voltage V_T is 12.8 kV. The synchronous reactance of this machine is 4 Ω, and the armature resistance can be ignored. (a) If the torque angle of the generator $\delta = 18°$, how much power is being supplied by this generator at the current time? (b) What is the power factor of the generator at this time? (c) Sketch the phasor diagram under these circumstances. (d) Ignoring losses in this generator, what torque must be applied to its shaft by the prime mover at these conditions?

(ii) A 13.8-kV, 50-MVA, 0.9-power-factor-lagging, 60-Hz, four-pole Y-connected synchronous generator has a synchronous reactance of 2.5 Ω and an armature resistance of 0.2 Ω. At 60 Hz, its friction and windage losses are 1 MW, and its core losses are 1.5 MW. The field circuit has a dc voltage of 120 V, and the maximum I_F is 10 A. The current of the field circuit is adjustable over the range from 0 to 10 A. The OCC of this generator is shown in Fig. Q7(ii).

(a) How much field current is required to make the terminal voltage V_T (or line voltage V_L) equal to 13.8 kV when the generator is running at no load?

(b) What is the internal generated voltage E_A of this machine at rated conditions?

(c) What is the phase voltage V_ϕ of this generator at rated conditions?

(d) How much field current is required to make the terminal voltage V_T equal to 13.8 kV when the generator is running at rated conditions?

(e) Suppose that this generator is running at rated conditions, and then the load is removed without changing the field current. What would the terminal voltage of the generator be?

(f) How much steady-state power and torque must the generator's prime mover be capable of supplying to handle the rated conditions?

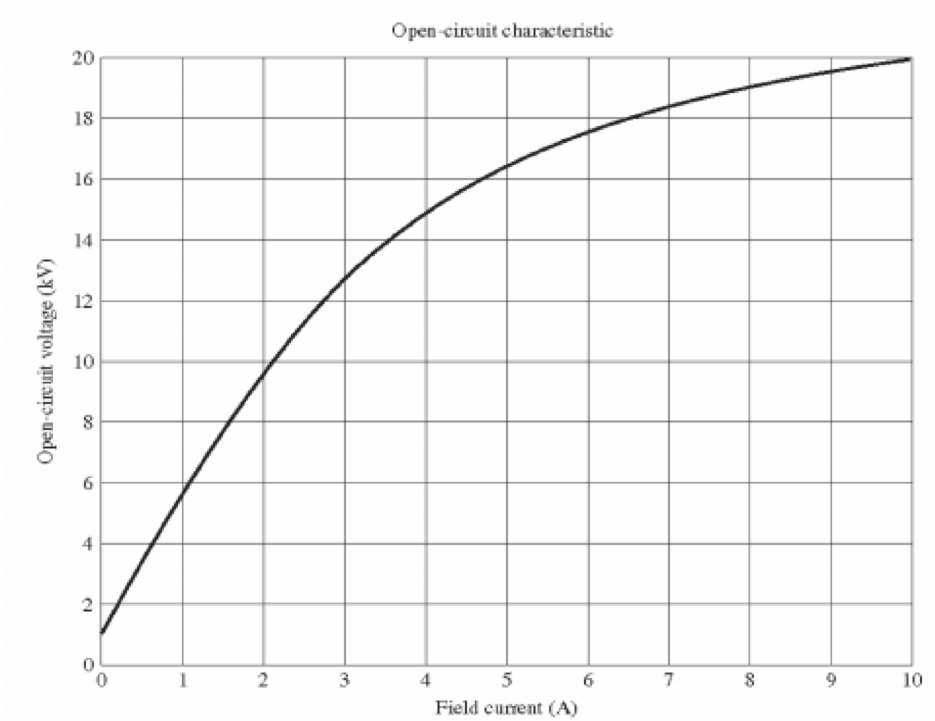

Fig. Q7(ii). Open-circuit characteristic curve

8. A 480-V, 60 Hz, 400-hp 0.8-PF-leading eight-pole Δ-connected synchronous motor has a synchronous reactance of 0.6 Ω and negligible armature resistance. Ignore its friction, windage, and core losses for the purposes of this problem. Assume that $|\mathbf{E}_A|$ is directly proportional to the field current I_F (in other words, assume that the motor operates in the linear part of the magnetization curve), and that $|\mathbf{E}_A| = 480$ V when $I_F = 4$ A. (a) What is the speed of this motor? (b) If this motor is initially supplying 400 hp at 0.8 PF lagging, what are the magnitudes and angles of $\mathbf{E}_A$ and $\mathbf{I}_A$? (c) How much torque is this motor producing? What is the torque angle δ ? How near is this value to the maximum possible induced torque of the motor for this field current setting? (d) If $|\mathbf{E}_A|$ is increased by 30 percent, what is the new magnitude of the armature current? What is the motor's new power factor? (e) Calculate and plot the motor's V-curve for this load condition.

9. The Y-connected synchronous motor whose nameplate is shown in Fig. Q8 has a per-unit synchronous reactance of 0.70 and a per-unit resistance of 0.02. (a) What is the rated input power of this motor? (b) What is the magnitude of $\mathbf{E}_A$ at rated conditions? (c) If the input power of this motor is 12 MW, what is the maximum reactive power the motor can simultaneously supply? Is it the armature current or the field current that limits the reactive power output? (d) How much power does the field circuit consume at the rated conditions? (e) What is the efficiency of this motor at full load? (f) What is the output torque of the motor at the rated conditions? Express the answer both in newton-meters and in pound-feet.

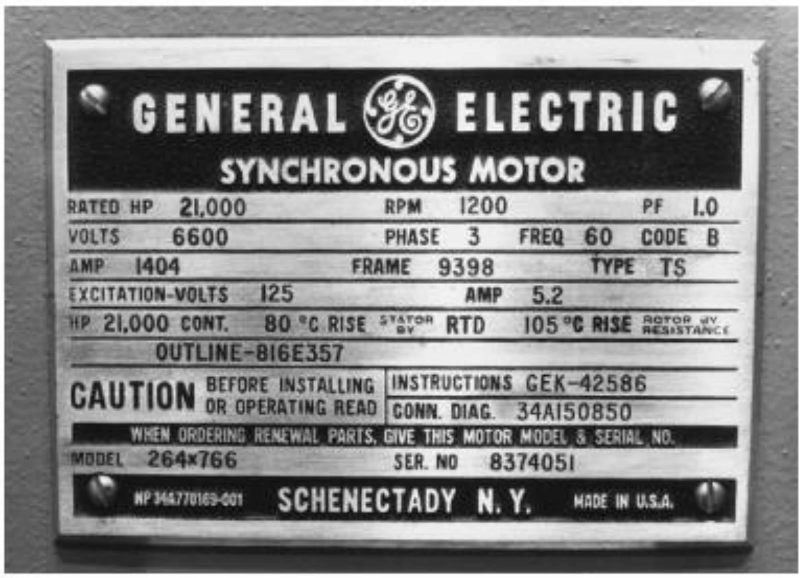

Fig. Q8

10. A 50-kW, 460-V, 50-Hz, two-pole induction motor has a slip of 5 percent when operating a full-load conditions. At full-load conditions, the friction and windage losses are 700 W, and the core losses are 600 W. Find the following values for full-load conditions: (a) The shaft speed n_m (b) The output power in watts (c) The load torque τ_{load} in newton-meters (d) The induced torque τ_{ind} in newton-meters (e) The rotor frequency in hertz

11. A 208-V four-pole 60-Hz Y-connected wound-rotor induction motor is rated at 30 hp. Its equivalent circuit components are

$R_1 = 0.100\ \Omega$	$R_2 = 0.070\ \Omega$	$X_M = 10.0\ \Omega$
$X_1 = 0.210\ \Omega$	$X_2 = 0.210\ \Omega$	
$P_{mech} = 500$ W	$P_{misc} \approx 0$	$P_{core} = 400$ W

For a slip of 0.05, find

The line current I_L (b) The stator copper losses P_{SCL} (c) The air-gap power P_{AG} (d) The power converted from electrical to mechanical form P_{conv} (e) The induced torque τ_{ind} (f) The load torque τ_{load} (g) The overall machine efficiency (h) The motor speed in revolutions per minute and radians per second

12. A three-phase 60-Hz two-pole induction motor runs at a no-load speed of 3580 r/min and a full-load speed of 3440 r/min. Calculate the slip and the electrical frequency of the rotor at no-load and full-load conditions. What is the speed regulation of this motor?
13. A 50-kVA, 13,800/208-V, Δ-Y distribution transformer has a resistance of 1 percent and reactance of 7 percent per unit.
    (a) What is the transformer's phase impedance referred to the high-voltage side?
    (b) Calculate this transformer's voltage regulation at full load and 0.8 PF lagging, using the calculated high-side impedance.
    (c) Calculate this transformer's voltage regulation under the same conditions, using the per-unit system.
14. A 100-MVA, 230/115-kV, Δ-Y three-phase power transformer has a er~ unit resistance of 0.0 15 pu and a per-unit reactance of 0.06 pu. The excitation branch elements are $R_C = 100$ pu and $X_M = 20$ pu.
    (a) If this transformer supplies a load of 80 MVA at 0.8 PF lagging, draw the phasor diagram of one phase of the transformer.
    (b) What is the voltage regulation of the transformer bank under these conditions?
    (c) Sketch the equivalent circuit referred to the low-voltage side of one phase of this transformer. Calculate all the transformer impedances referred to the low-voltage side.
    (d) Determine the losses in the transformer and the efficiency of the transformer under the conditions of part (b).
15. A 460-V, 25-hp, 6O-Hz, four-pole, Y-connected wound-rotor induction motor has the following impedances in ohms per phase referred to the stator circuit:

    $R_1 = 0.641\ \Omega$ $\quad$ $R_2 = 0.332\ \Omega$

    $X_1 = 1.\ 106\ \Omega$ $\quad$ $X_2 = 0.464\ \Omega$ $\quad$ $X_M = 26.3\ \Omega$

    (a) What is the maximum torque of this motor? At what speed and slip does it occur?
    (b) What is the starting torque of this motor?
    (c) When the rotor resistance is doubled, what is the speed at which the maximum torque now occurs? What is the new starting torque of the motor?

(d) Calculate and plot the torque- speed characteristics of this motor both with the original rotor resistance and with the rotor resistance doubled.