2520 Electrical Machines I
Tutorial 1 – Transformer

1. A single-phase, 300 kVA, 11 kV/2.2 kV, 60 Hz transformer has the following equivalent circuit parameters referred to the high-voltage side:
   $R_{c(HV)}$=57.6kΩ, $X_{m(HV)}$=16.34kΩ $R_{eq(HV)}$=2.784Ω, $X_{eq(LV)}$=8.45Ω
   Determine
   (a) (i) No-load current as a percentage of full-load current.
   (ii) No-load power loss (i.e., core loss), no-load power factor and the Full-load copper loss.
   (b) If the load impedance on the low-voltage side is $Z_{load} = 16\angle 60^{o}$ Ω determine the voltage regulation using the approximate equivalent circuit.
   (Ans. Q1(a)(i) 2.57%, 2100W, 0.27 lag, 2070W (b) 2.17%)

2. A single phase, 250 kVA, 11 kV/2.2 kV, 60Hz transformer has the following parameters.
   R_{HV}=1.3Ω X_{HV}=4.5Ω R_{LV}=0.05Ω X_{LV}=0.16Ω $R_{C(LV)}$=2.4kΩ $X_{m(LV)}$=0.8kΩ
   (a) Draw the approximate equivalent circuit (i.e., magnetizing branch, with R_c and X_m connected to the supply terminals) referred to the HV side and show the parameter values.
   (b) Determine the no-load current in amperes (HV side) as well as in per unit.
   (c) If the low-voltage winding terminals are shorted, determine
   (i) The supply voltage required to pass rated current through the shorted winding.
   (ii) The losses in the transformer.
   (d) The HV winding of the transformer is connected to the 11 kV supply and a load, $Z_{load} = 15\angle -90^{o}$ Ω is connected to the low-voltage winding. Determine:
   (i) Load voltage. (ii) Voltage regulation = $(|V_2|_{load} - |V_2|_{No\text{-}load}) / |V_2|_{load} \times 100\%$
   (Ans. Q2 Req=2.55Ω, Xeq=8.5Ω, Rc=60kΩ, Xm=20kΩ (b) 0.5797A, 2.55% (c) 201.7V, 1314W (d) 11255V, -2.27%)

3. (a) A single phase 100 kVA, 2300/460V transformer has the following circuit parameters.
   $R_{EQ(HV)}$=1.25Ω $X_{EQ(HV)}$=3.75Ω
   The transformer is connected to a supply on the LV (low-voltage) side, and the HV (high-voltage) side is shorted. For rated current in the HV winding, determine
   (i) The current in the LV winding and the voltage applied to the transformer.
   (ii) The power loss in the transformer.
   (b) The HV side of the transformer is now connected to a 2300 V supply and a load is connected to the LV side. The load is such that rated current flows through the transformer, and the supply power factor is unity. Determine the load impedance, the load voltage and the voltage regulation.
   (Ans. Q3 (a) (i) 43.478A, 34.38V(ii) 2362.94W (b)Z_L=51.65-j3.75, 2229.99V, 3.14%)

4. A single phase, 25 kVA, 2300/230 V transformer has the following parameters:
   $Z_{eq,H}$= 4.0 +j5.0Ω $R_{c,L}$= 450 Ω $X_{m,L}$=300Ω
   (a) Determine efficiency when the transformer delivers full load at rated voltage and 0.85 power factor lagging.
   (b) Determine the percentage loading of the transformer at which the efficiency is a maximum and calculate this efficiency if the power factor is 0.85 and load voltage is 230 V.
   (Ans. Q4. (a) 97.3% (b) 49.9% full load, 98.15%)

5. A single phase, 10 kVA, 2400/240 V, 60 Hz distribution transformer has the following characteristics:
   Core loss at full voltage = 100W Copper loss at half load = 60W
   (a) Determine the efficiency of the transformer when it delivers full load at 0.8 power factor lagging.
   (b) Determine the per-unit rating at which the transformer efficiency is a maximum. Determine this efficiency if the load power factor is 0.9. (Ans. Q5 (a) 95.92% (b) 96.67%)

6. The transformer of Q5. is to be used as an autotransformer
   (a) Show the connection that will result in maximum kVA rating.
   (b) Determine the voltage ratings of the high-voltage and low-voltage sides.
   (c) Determine the kVA rating of the autotransformer. Calculate for both HV and LV sides.

   (Ans. Q6 (a) HV 2530V, LV 2300V, 275.01 kVA)

7. A single phase, 10 kVA, 460/120 V, 60 Hz transformer has an efficiency of 96% when it delivers 9 kW at 0.9 power factor. This transformer is connected as an auto-transformer to supply load to a 460 V circuit from a 580 V source.
   (a) Show the autotransformer connection.
   (b) Determine the maximum kVA the autotransformer can supply to the 460 V circuit.
   (c) Determine the efficiency of the autotransformer for full load at 0.9 power factor.

   (Ans. Q7 (a) 48.33 kVA, 99.2%)

8. A single phase, 200 kVA, 2100/210 V, 60 Hz transformer has the following characteristics. The impedance of the high-voltage winding is $0.25 + j1.5\Omega$ with the low-voltage winding short-circuited. The admittance (i.e., inverse of impedance) of the low-voltage winding is $0.025 - j0.075\ \Omega$ with the high-voltage winding open-circuited.
   (a) Taking the transformer rating as base, determine the base values of power, voltage, current, and impedance for both the high-voltage and low-voltage sides of the transformer.
   (b) Determine the per-unit value of the equivalent resistance and leakage reactance of the transformer.
   (c) Determine the per-unit value of the excitation current at rated voltage.
   (d) Determine the per-unit value of the total power loss in the transformer at full-load output condition.

   (Ans. Q8 (a) 200 kW, 2100V, 210V, 95.24 A, 952.4 A, 22.05Ω, 0.2205Ω (b) R_{EQ}=0.01134 p.u. X_{EQ}=0.068 p.u. (c) 0.01743 p.u. (d) 0.01685 p.u.)

9. Three single phase, 10 kVA, 460/120 V, 60 Hz transformers are connected to form a three phase, 460/208 V transformer bank. The equivalent impedance of each transformer referred to the high-voltage side is $1.0+j2.0\ \Omega$. The transformer delivers 20 kW at 0.8 power factor (leading).
   (a) Draw a schematic diagram showing the transformer connection and determine the transformer winding current.
   (b) Determine the primary voltage and the voltage regulation.

   (Ans. Q9 (a) 454.5V, -1.2%)

10 A single phase, 25 kVA, 220/440 V, 60 Hz transformer gave the following test results. Open circuit test (440 V side open): 220 V, 9.5 A, 650 W Short-circuit test (220 V side shorted): 37.5 V, 55 A, 950 W
   (a) Derive the approximate equivalent circuit in per-unit values.
   (b) Determine the voltage regulation at full load, 0.8 PF lagging and draw the phasor diagram.

   (Ans. Q10 (a) R_{EQ}=0.0405 p.u., X_{EQ}=0.0779 p.u., R_C=38.46 p.u. X_M=12.58 p.u. (b) 8%)

2520 Electrical Machines I
Tutorial 2 – DC Machines

1. Two dc machines of the following rating are required:
   DC machine 1:120 V. 1500 rpm, four poles   DC machine 2: 240 V, 1500 rpm, four poles
   Coils are available which are rated at 4 volts and 5 amperes. For the same number of coils to be used for both machines, determine the
   (a) Type of armature winding for each machine.
   (b) Number of coils required for each machine.
   (c) kW rating of each machine.
   (Ans. Q1 (a)120V lap winding, 240 wave winding (b) 120V DC machine, parallel path=4, coils/path=30,total coils=120, 240V DC machine, parallel path =2, coil/ path=60, total coils=120 (c) 120V, 20A, 2.4kW, 240V, 10A, 2.4kW)

2 A four-pole dc machine has a wave winding of 300 turns. The flux per pole is 0.025 Wb. The dc machine rotates at 1000 rpm. Determine the generated voltage and the kW rating if the rated current through the turn is 25 A. (Ans. Q2. 500V, 25kW)

3 A dc machine (6 kW, 120 V, 1200 rpm) has the following magnetization characteristics at 1200 rpm.

I_f (A)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.2
E_a (V)	5	20	40	60	79	93	102	114	120	125

The machine parameters are R_a =0.2Ω, R_{fw}= 100Ω. The machine is driven at 1200 rpm and is separately excited. The field current is adjusted at I_f=0.8A. A load resistance R_L = 2Ω is connected to the armature terminals. Neglect armature reaction effect.
(a) Determine the quantity $K_a\Phi$ for the machine.
(b) Determine E_a, I_a, torque T and load power P_L.
(Ans. Q3 (a) $K_a\Phi$=0.907V/rads^{-1} (b) 114V, 51.82A, 47Nm, 5370W)

4 The dc machine in Problem Q3 has a field control resistance whose value can be changed from 0 to 150*Ω*. The machine is driven at 1200 rpm. The machine is separately excited and the field winding is supplied from a 120V supply.
(a) Determine the maximum and minimum values of the no-load terminal voltage.
(b) The field control resistance (R_{fc}) is adjusted to provide a no-load terminal voltage of 120 V. Determine the value of R_f. Determine the terminal voltage at full load for no armature reaction and also if $I_{f(AR)}$=0.1 A.
(Ans. Q4. (a) Min=92V, Max=125V (b) Rc=20ohm, 110V, 107.5V)

5 The dc machine in Problem Q3 is self-excited.
(a) Determine the maximum and minimum values of the no-load terminal voltage.
(b) R_{fc} is adjusted to provide a no-load terminal voltage of 120 V. Determine the value of R_{fc}.
(c) Assume no armature reaction. Determine the terminal voltage at rated armature current. Determine the maximum current the armature can deliver. What is the terminal voltage for this situation?
(Ans. Q5 (a) 100V, 8V (b) 20ohm, (c) 107V, 170A, 60V)

6 A dc machine (10 kW, 250V, 1000 rpm) has R_a = 0.2 Ω and R_{fw}= 133Ω. The machine is self-excited and is driven at 1000 rpm. The data for the magnetization curve are

I_f (A)	0	0.1	0.2	0.3	0.4	0.5	0.75	1.0	1.5	2.0
E_a (V)	10	40	80	120	150	170	200	220	245	263

Determine:

(a) The generated voltage with no field current and the critical field circuit resistance.

(c) The value of the field control resistance (R_{fc}) if the no-load terminal voltage is 250 V.

(d) The value of the no-load generated voltage if the generator is driven at 800 rpm and $R_{fc} = 0$.

(e) The speed at which the generator is to be driven such that no-load voltage is 200 V with $R_{fc} = 0$.

(Ans. Q6 (a) 10V, (b) = 400 ohm (c) 23.25ogm (d) 195 (e) 816.3 rpm)

7 The self-excited dc machine in Problem Q6 delivers rated load when driven at 1000 rpm. The rotational loss is 500 watts.

(a) Determine the generated voltage and the developed torque.

(b) Determine current in the field circuit and the efficiency of the machine. (Neglect the armature reaction effect)

(Ans. Q7 (a) 258V, 98.55Nm (b) I_f=1.86A, 88.12%)

8 A dc machine is connected across a 240-volt line. It rotates at 1200 rpm and is generating 230 volts. The armature current is 40 amps.

(a) Is the machine functioning as a generator or as a motor?

(b) Determine the resistance of the armature circuit.

(c) Determine power loss in the armature circuit resistance and the electromagnetic power.

(d) Determine the electromagnetic torque in newton-meters.

(e) If the load is thrown off, what will the generated voltage and the rpm of the machine be, assuming (i) No armature reaction. (ii) 10% reduction of flux due to armature reaction at 40 amps armature current.

(Ans. Q8 (a) motor, (b) 0.25ohm (c) 400W, 9200W (d) 73.19Nm (e) 1252 rpm, 1127 rpm)

9 A dc shunt motor (50 hp, 250V) is connected to a 230 V supply and delivers power to a load drawing an armature current of 200 amperes and running at a speed of 1200 rpm. $R_a = 0.2\Omega$.

(a) Determine the value of the generated voltage at this load condition.

(b) Determine the value of the load torque. The rotational losses are 500 watts.

(c) Determine the efficiency of the motor if the field circuit resistance is 115Ω.

(Ans. Q9 (a) 190V (b) 298.4Nm (c) 80.71%)

10. A dc shunt machine (23 kW, 230V, 1500 rpm) has $R_a = 0.1\ \Omega$.

(i). The dc machine is connected to a 230 V supply. It runs at 1500 rpm at no-load and 1480 rpm at full-load armature current.

  (a) Determine the generated voltage at full load.

  (b) Determine the percentage reduction of flux in the machine due to armature reaction at full-load condition.

(ii). The dc machine now operates as a separately excited generator and the field current is kept the same as in part 1. It delivers full load at rated voltage.

  (a) Determine the generated voltage at full load.

  (b) Determine the speed at which the machine is driven.

  (c) Determine the terminal voltage if the load is thrown off.

(Ans. Q10. (i) 220, 3% (ii) 240V, 1614.6 rpm (c) 247.6V)

11 The dc machine of Problem 4.13 is operated at I_f= 1.0 A. The terminal voltage of the dc machine is 220 V and the developed torque is 100 Nm. Determine the speed of the dc machine when it operates

(a) As a motor. (b) As a generator.

(c) The dc machine in Problem 4.13 is operated as a dc shunt motor. Determine the minimum and maximum no-load speeds if R_{fc} is varied from 0 to 200Ω.

(Ans. Q11. (a) 1895.2rpm (b) 2064.9 rpm (c) 1651.4 rpm, 2400 rpm)

2520 Electrical Machines I
Tutorial 3 – Induction Machines

1. A three phase, 460 V, 100 hp, 60 Hz, six-pole induction machine operates at 3% slip (positive) at full load.
   (a) Determine the speeds of the motor and its direction relative to the rotating field.
   (b) Determine the rotor frequency.
   (c) Determine the speed of the stator field.
   (d) Determine the speed of the air gap field.
   (e) Determine the speed of the rotor field relative to (i) the rotor structure. (ii) the stator structure. (iii) the stator rotating field.
   (Ans. Q1(a) 1164 rpm same as rotating field (b) 1.8Hz (c) 1200 rpm (d) 1200 rpm (e)(i) = 36 rpm same as motor motion (ii) 1200 rpm (iii) 0 rpm)

2. A three phase, 10 hp, 208 V, six-pole, 60 Hz, wound-rotor induction machine has a stator-to-rotor turns ratio of 1: 0.5 and both stator and rotor windings are connected in star.
   (a) The stator of the induction machine is connected to a three phase, 208 V, 60 Hz supply, and the motor runs at 1140 rpm.
      (i) Determine the operating slip
      (ii) Determine the voltage induced in the rotor per phase and frequency of the induced voltage.
      (iii) Determine the rpm of the rotor field with respect to the rotor and with respect to the stator.
   (b) if the stator terminals are shorted and the rotor terminals are connected to a three phase, 208 V, 60 Hz supply and the motor runs at 1164 rpm,
      (i) Determine the direction of rotation of the motor with respect to that of the rotating field.
      (ii) Determine the voltage induced in the stator per phase and its frequency.
   (Ans. Q2 a(i) 0.05, (ii) 3V, 3 Hz (iii) 60 rpm, 1200 rpm b(i) opposite (ii) 7.2 V 1.8 Hz)

3. A 4-pole, 3-phase induction motor operates from a supply whose frequency is 50 Hz. Calculate:
   (i) the speed at which the magnetic field of the stator is rotating.
   (ii) the speed of the rotor when the slip is 0.04.
   (iii) the frequency of the rotor currents when the slip is 0.03.
   (iv) the frequency of the rotor currents at standstill.
   (Q3 Ans. 1500 rpm, 1440 rpm, 90 rpm, 50 Hz)

4. A 373 kW, 3-phase, 440-V, *50-Hz* induction motor has a speed of *950* rpm on full-load. The machine has 6 poles. Calculate the slip. How many complete cycles will the rotor voltage make per minute? (Ans. Q4. 0.05*,* 2.5 Hz, 150 rpm)

5. A 3-phase induction motor having a star-connected rotor has an induced emf of 80 volts between slip-rings at standstill on open-circuit. The rotor has a resistance and reactance per phase of 1 ohm and 4 ohm respectively. Calculate starting rotor current and power factor when (a) slip-rings are short-circuited, (b) slip-rings are connected to a star-connected rheostat of 3 ohm per phase. (Ans. Q5. 11.2 A, 0.243, 8.16 A, 0.707)

6. A 3-phase, 400V, star-connected induction motor has a star-connected rotor with a stator to rotor turn ratio of 6.5. The rotor resistance and standstill reactance per phase are 0.05 ohm and 0.25 ohm respectively. What should be the value of external resistance per phase to be inserted in the rotor circuit to obtain maximum torque at starting and what will be the rotor starting current with this resistance? (Ans. Q6. 0.2 ohm, 100 A)

7. The synchronous speed of an induction motor is 100 rpm. The rotor resistance and standstill reactance of this motor are respectively 0.015 ohm and 0.09 ohm per phase. At normal voltage, the full-load slip is 3%. Estimate the percentage reduction in stator voltage to develop full-load torque at half full-load speed. Also calculate the power factor.(Ans. Q7. 22.8%, 0.31)

8. The power supplied to a three-phase induction motor is 40 kW and the corresponding stator losses are *1.5* kW. Calculate (i) the total mechanical power developed and rotor I^2 R loss when the slip is 0.04 per unit (ii) the output kW of the motor and (iii) the efficiency of the motor, if the friction and windage losses are 0.8 kW. Neglect rotor iron and copper losses. (Ans. Q8. 38.5 kW, 1.54 kW, 36.96 kW, 36.26 kW, 90.4%)

9. A 400-V, 4-pole, 3-phase, 50 Hz, Y-connected induction motor has a rotor resistance and reactance per phase of 0.01 ohm and 0.1 ohm respectively. Determine (a) the maximum torque and the corresponding slip, (b) the full-load slip and power output, if maximum torque is twice the full-load torque. The ration of stator to rotor turns is 4. (Ans. Q9. 10%, 318 N-rn, 0.027, 25,135 W)

10. A 220-V, three-phase, 60-Hz, four-pole, Y-connected induction motor has a per-phase stator resistance of 0.25 ohm. The no-load and locked-rotor test data on this motor are:

NO LOAD TEST	
Stator voltage	220V
Input Current	3A
Input Power	600W
Firction & windage losses	300W

LOCKED-ROTOR TEST	
Stator voltage	34.6V
Input current	15A
Input Power	720W

(a) Obtain the approximate equivalent circuit for the machine.
(b) If the machine runs as a motor with *5%* slip, calculate the developed power (Air gap power), developed torque (Gross mechanical torque), and efficiency.
(c) Determine the slip at which maximum torque occurs and calculate the maximum torque.
(Ans. Q10. Rm=163 ohm, Xm = 43.8 ohm, R_2'= 0.82 ohm, Xe =0.8 ohm, 2857W, 15.16 N-m, 75%, 0.98, 118N-m)

Tutorial 4 –Synchronous Machines

1. When a 50 kVA, 3-phase,440-V, 60 Hz, star connected synchronous generator is driven at its rated speed, it is found that the open-circuit terminal voltage is 440 V line-to-line with a field current of 7 A. When the stator terminals are short circuited, rated current is produced by a field current of 5.5 A. Determine the synchronous reactance per phase. (Q1 Ans. 3.04 ohm)

2. If the same machine as in Q1, is used to supply an independent load of 40 kW with 0.85 lagging power factor at a potential of 440 V,
   (a) determine the field current required; and
   (b) if the load is reduced to 20 kW at 0.75 lagging power factor, to what value will the field current have to be reduced to maintain rated load potential? (Q2 Ans. l0.7A, 9.2A)

3. The following data are taken from the open-circuit and short-circuit characteristics of a 45 kVA, 3-phase, Y-connected 220 V, 6-pole 60 Hz synchronous machine:

Open-circuit Characteristic	Line-to-line voltage (V)	220	
	Field Current (A)	2.84	
Short-circuit characteristic	Armature Current (A)	118	152
	Field Current (A)	2.20	2.84
Air-gap Line	Line-to-line voltage (V)	202	
	Field Current (A)	2.2	

Compute the unsaturated value of the synchronous reactance, its saturated value at rated voltage and the short-circuit ratio. (Q3 Ans. 0.987ohm, 0.836 ohm, 1.29)

4. Calculate the percent voltage regulation for a three-phase Y-connected 2500 kVA, 6600 V turbo-alternator operating at full load and 0.8 p.f. lagging. The per-phase synchronous reactance and the armature resistance are 10.4 and 0.071 ohm, respectively. What is the percent voltage regulation for 0.8 p.f. leading? (Q4. Ans. 44%, -20%)

5. (Textbook Q6.3) The following test data are obtained for a 3 phase, 195 MVA, 15 kV, 60 Hz star-connected synchronous machine:

Open Circuit Test	I_f (A)	150	300	450	600	750	900	1200
	V_{LL} (kV)	3.75	7.5	11.2	13.6	15	15.8	16.5
Short Circuit Test	I_f= 750A, I_a= 7000A The armature resistance is very small.							

   (a) Draw the open-circuit characteristic, the short-circuit characteristic, the air gap line, and the modified air gap line.
   (b) Determine the unsaturated and saturated values of the synchronous reactance in ohms and also in pu.
   (c) Find the field current required if the synchronous machine is to deliver 100 MVA at rated voltage, at 0.8 leading power factor.
   (d) Find the voltage regulation of the synchronous generator for the load of part (c). Voltage regulation (VR) is defined as: VR=($V_t|_{\text{load removed}}$) – $V_t|_{\text{with load}}$)/ $V_t|_{\text{with load}}$x100%
   (Ans. Q5(b) $Z_{unsaturated}$=1.547Ω, $Z_{saturated}$=1.237Ω (c) 601.2A (d) –9.33%)

6. (Textbook Q6.5) The synchronous motor of Example 6.2 (3 phase, 10 MVA, 14kV, star-connected, R_s=0.07ohm/phase, X_s=16.5 ohm.phase) is connected to a 3 phase, 14 kV, 60 Hz infinite bus and draws 5 MW at 0.85 leading power factor. Determine the values of the stator current (I_a), the excitation voltage (E_f), and the field current (I_f). Draw the phasor diagram. (Ans. Q6 I_a=242.6A, E_f=10.73kV, I_f=265A)

7. (Textbook Q6.9) A 34, 2000 kVA, 11 kV, 1800 rpm synchronous generator has a resistance of 1.5 ohms and synchronous reactance of 15 ohms per phase.

(a) The field current is adjusted to obtain the rated terminal voltage at open circuit.

(i) Determine the excitation voltage E_f.

(ii) If a short circuit is applied across the machine terminals, find the stator current.

(b) The synchronous machine is next connected to an infinite bus. The generator is made to deliver the rated current at 0.8 power factor lagging.

(i) Determine the excitation voltage E_f.

(ii) Determine the percentage increase in the field current relative to the field current of part (a).

(Ans. Q7 (a)(i) 3.65kV (ii) 421.65A (b)(i) 7510V (ii) 18%)

8. (Textbook Q6.15) The nameplate of a Y-connected synchronous motor has the following information.

17 MVA, Hp 20,000, RPM 1800, PF 1.0 (1Hp=746W) Volts 6600, Ampere 1350, Phase 3, Frequency 60 Excitation voltage 120, Amp 5.5

The per-unit synchronous reactance is X_s= 0.95, and the per-unit resistance is R_a= 0.012.

(a) Determine the number of poles of the synchronous motor.

(b) Determine X_s and R_a in ohms.

(c) For rated (full-load) condition

(i) Determine the output torque in newton-meter and the efficiency.

(ii) Determine the rotational loss, the power loss in the field circuit and the excitation voltage E_f.

(Ans. Q8 (a) p=4 (b) R=0.031Ω/phase, X=2.432Ω/phase (c)(i) 79512 Nm, 96.68% (ii) Rotational Loss=345.24W, Exciter Loss=660W, E_f=5223V/phase)