The University Of Sheffield.

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DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2015-16 (3.0 hours)

EEE338 Power Engineering

Answer **FIVE QUESTIONS** comprising **AT LEAST TWO** each from **part A** and **part B. No marks will be awarded for solutions to a sixth question, or if you answer more than three questions from parts A or B.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

Part A

A1.

a. Sketch a typical torque-speed characteristic for an induction machine identifying both motoring and generating regions, the synchronous speed and any critical operating points from a generator perspective. **(3)**

b. A chemical processing company has a base load demand of 15MVA at 0.7 power-factor lagging which it draws from an 11kV, 50Hz, infinite busbar supply. To reduce its carbon footprint, the company decides to use waste steam from one of the production processes to operate a steam turbine which drives a 6-pole, 3-phase, star-connected induction generator. The induction generator can be modelled using a simplified, per phase equivalent circuit, as shown in Figure A1.1. The equivalent circuit parameters of the machine are given in Table A1.1

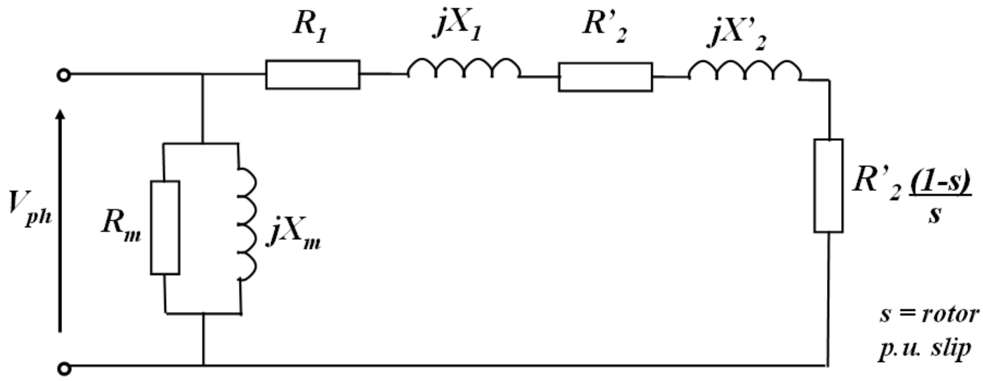

Figure A1.1

$R_1 = 0.9\ \Omega$	$R'_2 = 1.7\ \Omega$	$R_m = 850\ \Omega$
$jX_1 = j\ 8\ \Omega$	$jX'_2 = j\ 6.5\ \Omega$	$jX_m = j\ 200\ \Omega$

Table A1.1. Equivalent circuit parameters

(i) Calculate the apparent power at the terminals of the induction machine and hence the net electrical real and reactive power generation if the speed of the steam turbine is 1080rpm. **(6)**

(ii) For this operating condition, calculate the turbine mechanical power input and hence the efficiency of the induction generator. Check your answer by performing an audit of the machine losses. **(3)**

(iii) By combining the output of the induction generator with the base load demand of the chemical company, comment on the resultant real and reactive power drawn from the supply. **(3)**

c. The company decide to install a permanent, delta-connected, capacitor bank in parallel with the incoming supply. The capacitor bank has a capacitance of 50μF per phase. Calculate the apparent power and operating power factor of the company when at base load and:

(i) the steam turbine is not in operation **(2)**

(ii) when the steam turbine is operating at 1080 rpm, as in part **b (i)** **(1)**

d. Comment on the factory's real and apparent power consumption for the two scenarios **c (i)** and **(ii)** above. **(2)**

A2.

a. Given that the real power transfer through a transmission line can be approximated by:

$$P = \frac{V_S V_R}{X} \sin(\delta)$$

Briefly discuss methods for increasing the power flow through the line and any problems associated with these methods. **(3)**

b. Briefly outline three methods which can be used to limit fault levels in power systems. **(3)**

c. Figure A2.1 shows a line diagram of a 3-phase power system consisting of two 20kV busbars linked by a fault limiting reactor of 1.5Ω. The Grid Infeed can supply 250MVA into a symmetrical 3-phase fault.

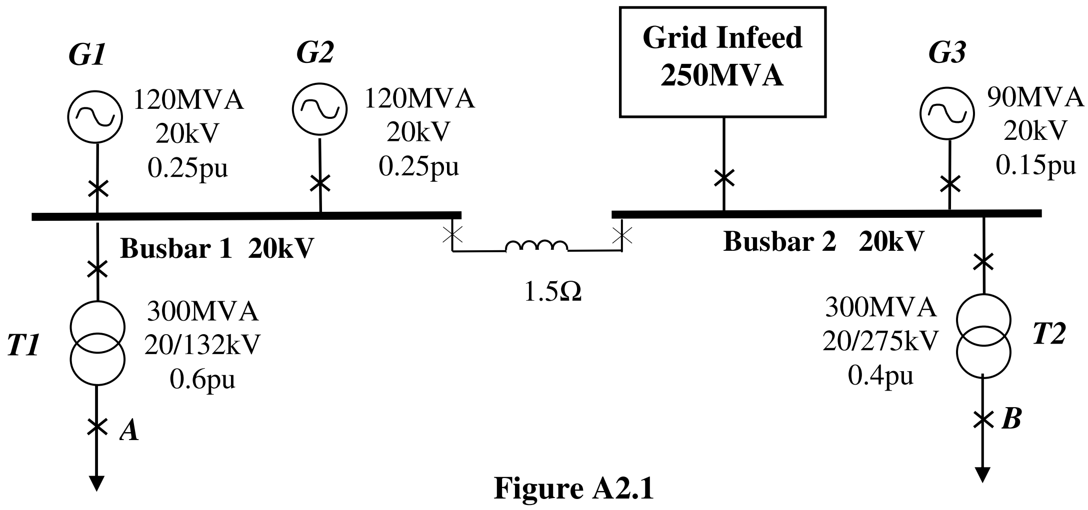

Figure A2.1

(i) Using a reference base of 120MVA calculate the required MVA rating of the circuit breakers at points *A* and *B*. **(7)**

(ii) For a 3-phase symmetrical fault at point *B*, calculate the rms phase current which flows in Generator *G1* (Assume *G1* is delta-connected). **(3)**

(iii) Assuming faults may occur at any point in the system, calculate the maximum fault current rating of the busbar reactor. **(4)**

A3.

A star-connected load is supplied via a balanced 400V, 3-phase, 4-wire supply of phase sequence *ABC*. The 3-phase load consists of three single phase loads of $(10 - j3)\Omega$, $(7 + j12)\Omega$ and $(9 + j5)\Omega$, connected between lines *A,B,C*, and the neutral respectively as shown in Figure A3.1. All the supply lines and the neutral wire have negligible impedance.

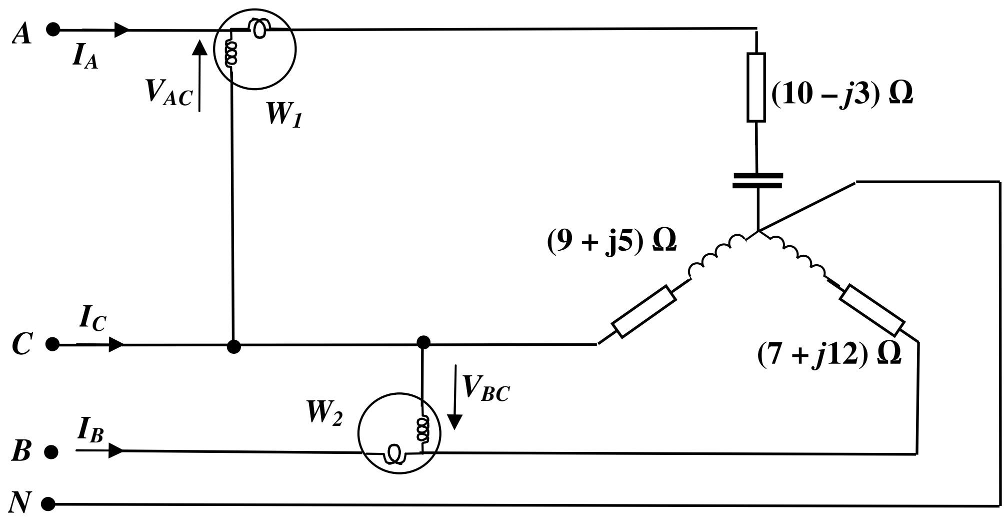

Figure A3.1

a. Calculate the magnitude and phase of the three line currents and the neutral current. State which voltage you have taken as reference. **(2)**

b. Two wattmeters are installed to measure the total input power to the load. One is connected with its current coil in line *A* and its voltage coil between lines *A* and *C*, the other with its current coil in line *B* and voltage coil between lines *B* and *C*, as illustrated in Figure A3.1.

(i) Sketch a phasor diagram showing the voltages and currents which are measured by the two wattmeters and their respective phase angles. **(3)**

(ii) Hence, calculate the readings on the two wattmeters and the sum of the two wattmeter readings. **(2)**

(iii) What percentage error, if any, would be incurred if it was assumed that the sum of the two wattmeter readings gave the total input power to the system? **(2)**

(iv) Briefly describe a more appropriate method of measuring the total 3-phase power. **(1)**

c. Due to poor installation the neutral wire has become disconnected at the supply and is open circuit.

(i) Using a star-delta transformation or otherwise calculate the three line currents and the voltage across each phase for this condition. State which voltage you have taken as reference. **(7)**

(ii) Hence, calculate the readings on the two wattmeters. **(2)**

(iii) Verify that the sum of the power readings on the two wattmeters measures the true power dissipated in the unbalanced three-phase load. **(1)**

A4.

a. Write down the circuit equations of a synchronous machine (for operation as both a motor and a generator) and use them to derive phasor diagrams for the machine operating as a generator on leading power-factor and as a motor on lagging power-factor. **(3)**

b. A synchronous machine is operated as a motor and is connected to an infinite bus-bar. The machine has a fixed mechanical output power and the resistance of the armature winding can be neglected.

Initially, the excitation, E, is set so that it is much greater than the system voltage, V (i.e. $E_1 > V$). The mechanical output power is then kept constant and the field current is gradually reduced until the excitation, E, is less than the voltage, V (i.e. $E_2 < V$). Graphs are then plotted of the line current magnitude and power-factor against field current.

By the use of the relevant phasor diagrams, and by carefully explaining the changing operating conditions, explain what happens to the line current magnitude and power-factor as the excitation is decreased from E_1 to E_2. Hence, plot the expected form of the two graphs. **(5)**

c. A small manufacturing company has an existing general load requirement of 6MVA at 0.8 power-factor lagging. The company plans to expand and obtains an 11kV, three-phase star-connected synchronous motor, having a synchronous reactance of 12Ω per phase and negligible resistance, to provide the **additional** 1MW of mechanical power required. The motor will also be used to improve the overall power-factor of the company from 0.8 lagging to a value of 0.98 lagging.

(i) Calculate the MVA rating and the power factor at which the synchronous motor must operate. **(4)**

(ii) Calculate the motor line current, excitation emf and the load angle at which the motor will be operating. **(4)**

(iii) Overnight the load on the motor falls to 800kW and the excitation emf is adjusted to 7kV. Calculate the new phase current and power factor of the motor. **(3)**

d. Briefly comment on the reasons for employing the synchronous machine to improve the total company power-factor. **(1)**

Part B

B1.

a. **(i)** Describe why electrical power systems require protection. **(1)**

(ii) Draw a diagram showing the key components of a simple protection system and briefly describe their function. **(3)**

b. Sketch a diagram showing the main components of an induction relay and explain its operation. **(3)**

c. Explain why tap changing transformers are used in a power system and describe the difference between an off-load and an on-load tap changing transformer. What is meant by an "off-nominal transformer"? **(3)**

d. Figures B1.1 and B1.2 show a per-phase circuit of a tap-changing transformer and an equivalent 'π' network respectively. By consideration of the no-load voltage transformation ratios and short circuit impedances, show that the parameters A, B and C may be represented as:

$$A = \frac{Z_{HL}}{(1-k)} \qquad B = \frac{Z_{HL}}{k(k-1)} \qquad C = \frac{Z_{HL}}{k}$$

(3)

e. A 200MVA 275kV/132kV, star/delta transformer, with the star winding solidly earthed, has a nominal tap impedance (Z_{HL_NOM}) of j0.09 pu. The tap changer is assumed to be on the 275kV winding. Draw the equivalent circuits for the nominal tap and the +12% tap setting. (Assume the impedances Z_H and Z_L are proportional to the square of the number of turns on the winding concerned). **(4)**

f. A 3-phase symmetrical fault occurs on the low voltage side of the transformer when it is operating on the +12% tap setting. Calculate the fault current on the high voltage side of the transformer if the fault level on the high voltage side is 900MVA. **(3)**

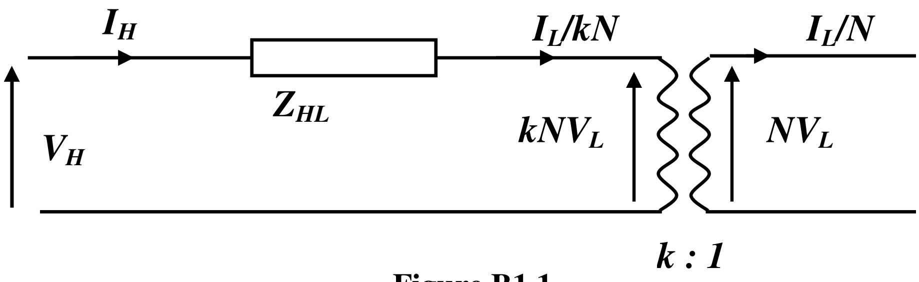

Figure B1.1

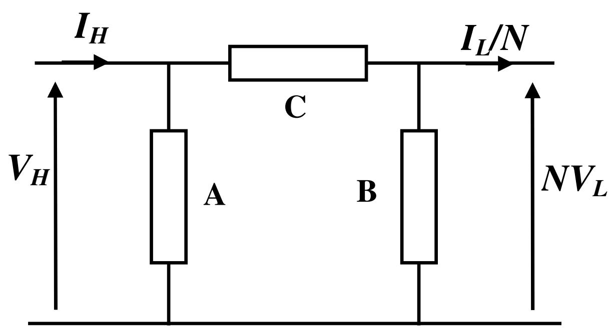

Figure B1.2

B2.

a. **(i)** Explain the advantage of using bundled conductors on high voltage overhead transmission lines. **(2)**

(ii) Explain why the conductors of long overhead transmission lines are transposed. **(2)**

(iii) Show that, if skin effect is neglected, the component of self-inductance due to the magnetic field within a solid circular conductor is independent of the radius of the conductor. **(4)**

b. A 11kV 50Hz, fully transposed 3-phase transmission line is proposed to connect a new wind turbine to a local sub-station. The line will use the 6-strand bundled conductor shown in Figure B2.1 and will have a phase layout as shown in Figure B2.2. The length of the line is 15km.

(i) Show that the geometric mean radius of the 6-strand conductor shown in Figure B2.1, in which the radius of each strand is 4 mm, is 8.4 mm. **(6)**

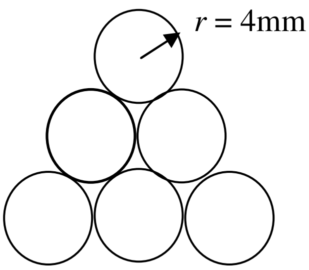

Figure B2.1 Layout of Strands

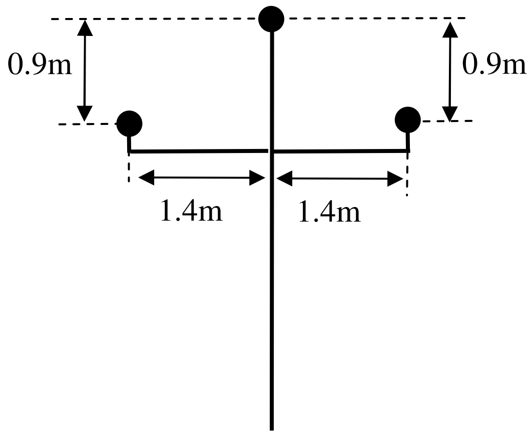

Figure B2.2 Layout of Phases

(ii) Calculate the geometric mean distance between phases for the layout shown in Figure B2.2, and hence calculate the reactance of the 15km line.
(You may assume the inductance per metre for the fully transposed line is given by:

$$L = 2 \times 10^{-7} \ln\left(\frac{D_g}{R_g}\right) \text{ H/m}$$

where D_g is the geometric mean distance between conductors, and R_g is the geometric mean radius of the conductors). **(2)**

(iii) If the line has a phase resistance of 0.1 Ω/km and the wind turbine is supplying 4MW at 0.8 power-factor lagging, determine the voltage at which the wind turbine must operate if the voltage at the sub-station is 11kV. **(3)**

(iv) If the real power supplied remains constant at 4MW, but the power-factor increases to 0.9, explain briefly whether the voltage of the wind turbine would need to be increased or decreased to maintain the 11kV at the sub-station. **(1)**

B3.

a. A synchronous motor is connected to an infinite busbar system by a short transmission line. Initially the system is stable and the motor is providing constant power to a mechanical load. With the aid of a suitable diagram explain what would happen to the rotor load angle when there is a sudden increase in the mechanical load, and the conditions required to ensure the motor would not lose synchronism. **(4)**

b. A synchronous motor connected to an infinite grid system is operating at 25% of its maximum rated power. If the load on the motor is doubled calculate the maximum load angle during swinging around the new equilibrium condition. **(4)**

c. Figure B3.1 shows a 150MVA Combined Heat and Power (CHP) generator connected to a grid system by a pair of overhead lines. The per-unit reactances of the various components are given for a common base of 150MVA.

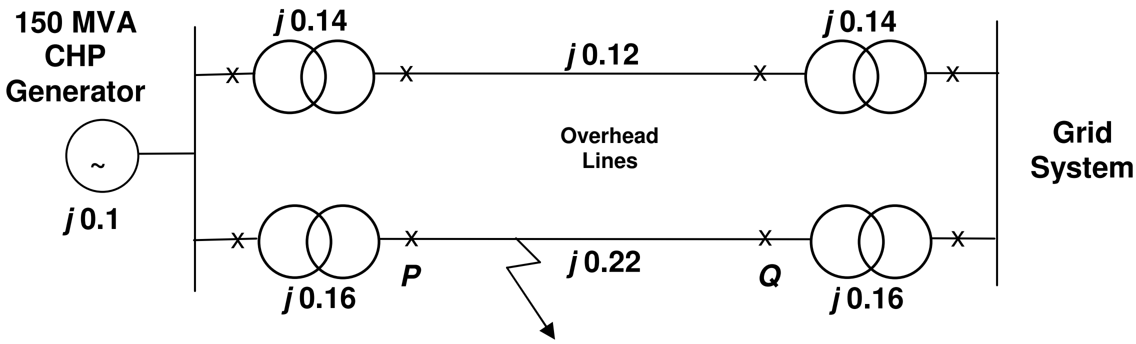

Figure B3.1 CHP Generator System

(i) If the terminal voltage is 1.0pu throughout the system determine the power-load angle equation for the system. If the generator is delivering 120MW calculate its load angle. **(2)**

(ii) When a 3-phase fault occurs on one of the overhead lines the effective system reactance becomes j1.10pu. Determine the power-load angle equation for the system under fault conditions. **(1)**

(iii) The fault is then cleared by the simultaneous opening of the circuit breakers, *P* and *Q* at each end of the faulted line. Determine the new power-load angle equation for the system. **(1)**

(iv) Sketch the power transfer curves for before, during, and after the fault. Mark on the sketch the accelerating area, decelerating area, and the critical clearance angle. **(3)**

(v) If the circuit breakers clear the fault in 0.2s determine if this is sufficient to maintain system stability if the inertia constant of the generator, $M = 0.00025$ pu. Use a time interval, $\Delta t = 0.05$s in conjunction with the swing equation.

(Use may be made of the equation: $\Delta\delta_n = \Delta\delta_{n-1} + \frac{(\Delta t)^2}{M} P_{a(n-1)}$) **(5)**

B4.

Figure B4.1 shows the single-line diagram of a power system comprising two 132kV busbars, *A* and *B*, connected together by an overhead transmission line. Each busbar is supplied from a generator via a step-up transformer. The star points of generators *G1* and *G2* and transformers *T1* and *T2* are all solidly earthed. A single phase to earth fault occurs on busbar *B*.

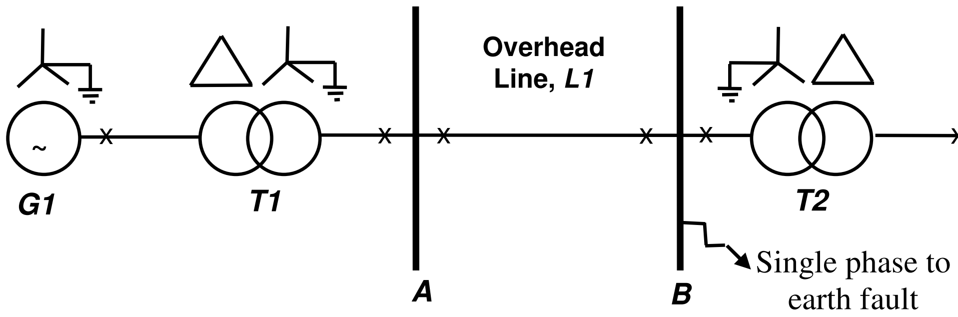

Figure B4.1 Line diagram of Power System

	Rating MVA	Voltage kV	X_+	X_-	X_0
G1	90	22	0.21 pu	0.21 pu	0.075 pu
G2	80	12	0.2 pu	0.2 pu	0.06 pu
T1	90	22/132	0.12 pu	0.12 pu	0.075 pu
T2	110	13/132	0.11 pu	0.11 pu	0.11 pu
L1		132	8 Ω	8 Ω	25 Ω

a. Calculate all the per-unit reactances of the system using a reference base of 90MVA. **(4)**

b. Draw the positive, negative and zero sequence diagrams for the system. **(6)**

c. Determine the total fault current when a single phase to earth fault occurs at busbar B. **(4)**

d. Hence calculate the current which flows in each phase of the 132kV overhead transmission line during fault conditions. **(5)**

e. The power system is upgraded and the star point of generator *G1* is now connected to ground through an earthing reactor (instead of being solidly earthed) and generator *G2* is replaced by a machine having delta connected windings (the MVA rating, voltage rating and per-unit reactances remain the same). Comment on the effect this would have on the level of fault current for the system and type of fault shown in figure B4.1. Briefly justify your answer. **(1)**

KM/AG