The University Of Sheffield.

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DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2013-14 (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. State the definition of ‘infinite bus-bar’ in relation to an electrical power system and list the main conditions to be satisfied to synchronise a wound field synchronous machine to an infinite bus-bar system. **(2)**

b. A 3-phase synchronous motor which has negligible winding resistance is connected to an infinite busbar system. The motor is initially on no-load and is idling on the system with negligible current flow through its terminals. Using a suitable equivalent circuit model and phasor diagrams of the steady-state conditions explain the following:

(i) the initial operating conditions of the machine **(2)**

(ii) what happens when the machine excitation is increased whilst it remains on no-load? **(2)**

(iii) what happens when the excitation remains unchanged from the idling conditions in part **(i)** but a mechanical load is applied to the shaft? **(2)**

c. A 15kV star-connected 3-phase synchronous motor has a synchronous reactance of 10Ω per phase and negligible resistance. The motor is to be used in a factory with a general load requirement of 20MVA at 0.75 power factor lagging. When the motor is installed it will be used to provide an **additional** 3MW of mechanical power and also to correct the total power factor of the factory to a value of 0.95 lagging.

(i) Calculate the MVA rating and the power factor at which the synchronous motor must operate. **(5)**

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

(iii) If the mechanical load on the synchronous machine reduces to 2.4MW calculate the new load angle at which the motor will operate assuming the excitation emf is unchanged. **(3)**

A2.

a. Describe what in general is meant by the per-unit value of any quantity. **(1)**

b. Briefly describe, with suitable diagrams where appropriate, methods for limiting fault levels in interconnected power systems. **(5)**

c. Figure A2.1 shows a line diagram of a 3-phase power system consisting of two 11kV busbars linked by a fault limiting busbar reactor of 0.12Ω. The two 132kV feeders supply passive loads, and the Grid Infeed can supply 500MVA into a symmetrical 3-phase fault.

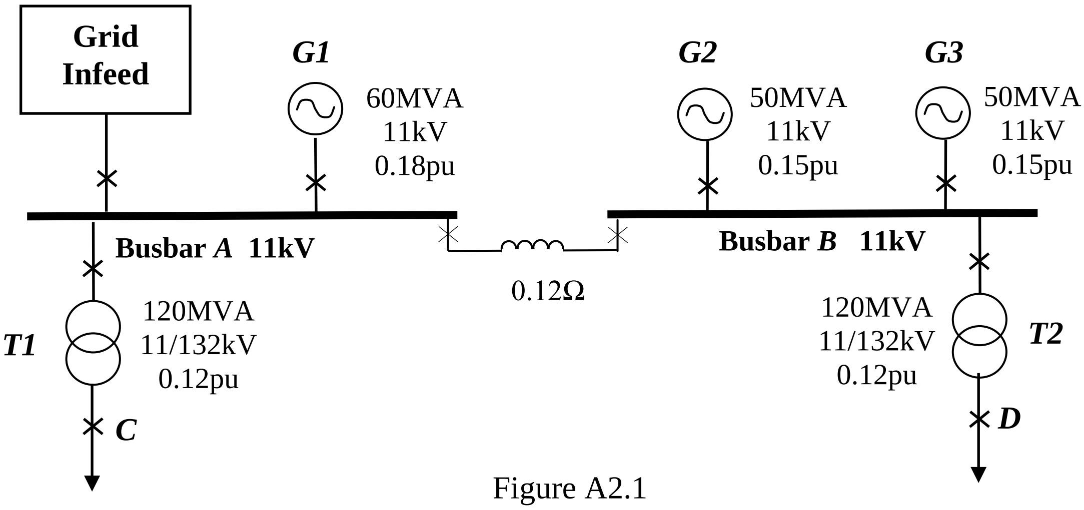


Figure A2.1

(i) Using a reference base of 50MVA calculate the required MVA rating of the circuit breakers at points ***C*** and ***D*** on each of the feeders. **(7)**

(ii) For a 3-phase symmetrical fault at point *D*, calculate the rms phase current which flows in Generator *G2* (Assume *G2* is star-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 3-phase, star-connected load is supplied via a balanced 415V, 3-phase, 3-wire supply, of phase sequence ABC. The 3-phase load consists of three single-phase loads of (10 − j4) Ω, (4 + j6) Ω and (5 + j16) Ω, connected between phases *A, B, C* and the load star point respectively, as illustrated in Figure A3.1.

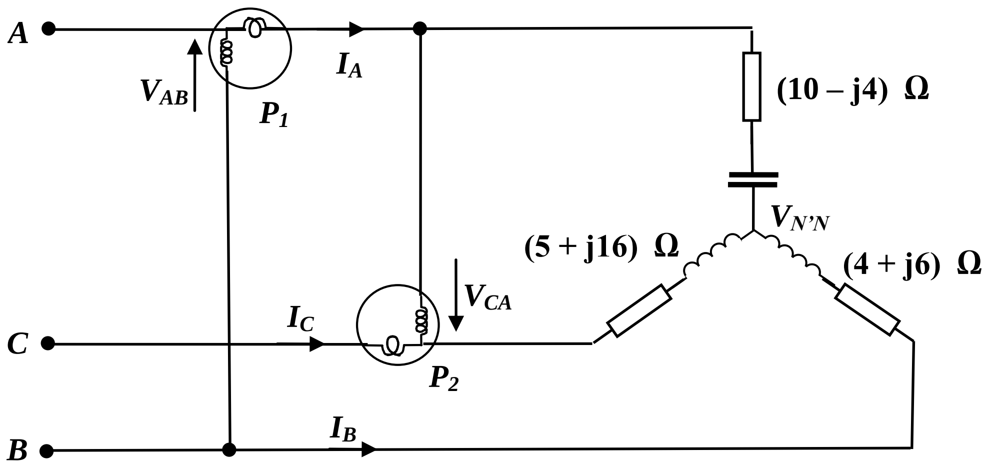


Figure A3.1

a. Using Millman's theorem, or otherwise:

(i) calculate the voltage across each phase of the load **(8)**

(ii) hence calculate the three line currents **(2)**

b. During installation, the wattmeters, P_1 and P_2, were not correctly connected as shown in Figure A3.1:

(i) sketch the phasor diagram for the system showing the three phase and line voltages, the three line currents and their relevant angles. **(3)**

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

c. **(i)** Describe how P_2 may be reconnected to correctly measure the power in the unbalanced load and calculate the new reading for P_2. **(2)**

(ii) Verify that the sum of the power readings on the two wattmeters measures the true power dissipated in the unbalanced 3-phase load. **(1)**

(iii) If the star point of the load was connected to the neutral point of the supply would the sum of the power readings on the two wattmeters still measure the true power? Explain your answer. (Assume the neutral conductor has zero impedance and that the Wattmeters are correctly connected). **(2)**

A4.

a. State two major benefits and two drawbacks of induction machines over synchronous machines, connected to an infinite bus-bar system, for wind generation applications. **(2)**

b. Figure A4.1 shows a per-phase equivalent circuit of a 3-phase induction machine. Explain what each of the components represents. **(2)**

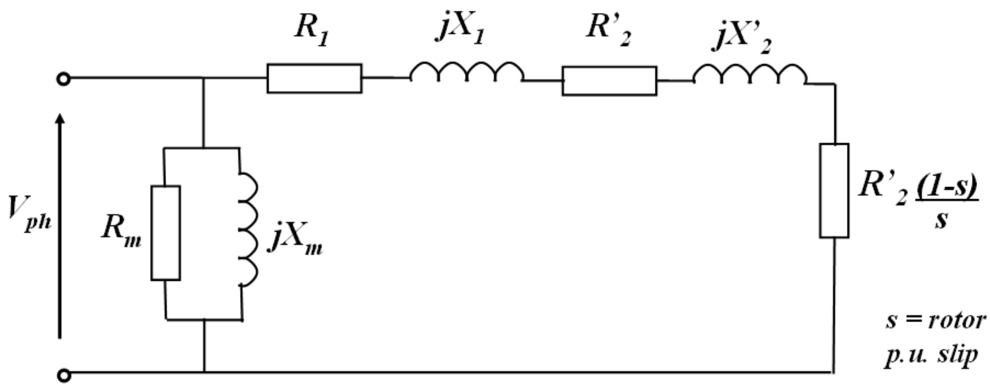


Figure A4.1

c. A small factory has a typical base load demand of 50MVA at 0.72pf lagging. To reduce their annual energy requirements, the company installed a wind turbine. The turbine drives a 3-phase, star-connected, 8-pole induction machine generating into an 11kV, 50Hz, infinite bus-bar system. The machine can be modelled via a simplified, per phase equivalent circuit, as illustrated in Figure A4.1 which has the equivalent circuit parameters as detailed in Table A4.1

R_1 **= 0.25Ω**	R'_2 **= 1.2Ω**	R_m **= 280Ω**
$jX_1 = j$ **2.6Ω**	$jX'_2 = j$ **2.5Ω**	$jX_m = j$ **65Ω**

Table A4.1. Equivalent circuit parameters

(i) Calculate the apparent power at the machine terminals and hence the net electrical real and reactive power generation if the rotor speed is 870rpm. **(7)**

(ii) For this operating condition, calculate the turbine mechanical power input and hence the efficiency of the induction generator. **(2)**

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

(iv) Calculate the value of capacitance per phase of a star-connected capacitor bank, connected in parallel with the factory base load and the induction generator to improve the overall power-factor to 0.95 lagging. Assume the induction generator is at the operating condition of part **(c)(i).** **(3)**

(v) If the capacitor bank is permanently connected, calculate the power-factor of the factory when the wind turbine is not in operation. **(1)**

Part B

B1.

A 3-phase 50Hz, fully transposed, transmission line, shown in Figure B1.1 has the horizontal formation shown in Figure B1.2.

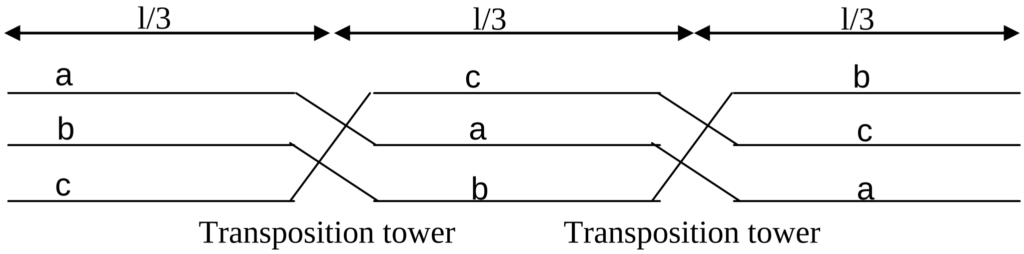
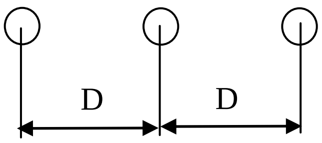


Figure B1.1 Transposed Transmission Line



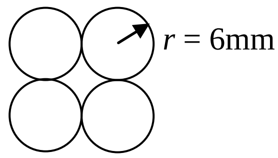


Figure B1.2 Horizontal Conductor Layout **Figure B1.3 Layout of Strands**

a. If the line carries symmetrical currents and has one conductor per phase, show that the inductance per phase is given by:

$$\boldsymbol{L} = \frac{\mu_0}{2\pi}\ln\left(\frac{\sqrt[3]{2}\boldsymbol{D}}{\boldsymbol{r}'}\right)$$

where $\boldsymbol{r}' = \boldsymbol{e}^{-0.25}\boldsymbol{r} = 0.7788\boldsymbol{r}$ and r is the conductor radius.
You may assume that:

- the flux linking a conductor, λ_p, to an external point P, at a distance D_P from the conductor, due to a current I flowing in the conductor itself is:

$$\lambda_P = \frac{\mu_0}{2\pi} I \ln\left(\frac{D_P}{r'}\right)$$

- the total flux linkage between two external points at distances D_1 and D_2 from a conductor carrying a current I is:

$$\lambda_P = \frac{\mu_0}{2\pi} I \ln\left(\frac{D_2}{D_1}\right)$$ **(6)**

b. The distance between the conductor centres is 1.5m (distance D in Figure B1.2). Calculate the inductance per phase for a 20km long line, if:

(i) the line has one solid conductor per phase having a radius of 12mm **(4)**

(ii) the line uses stranded conductors with each conductor comprising 4 strands of radius 6mm, arranged as shown in Figure B1.3. **(4)**

c. If the transmission line using the stranded conductors (see part **b(ii)**) supplies a 33kV, 900kW load at 0.9 power factor lagging, calculate the voltage at the sending end of the line. The resistance of the conductor is 0.04Ω/km. **(4)**

d. Explain briefly why it is necessary to use bundled conductors on high voltage lines. **(2)**

B2.

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. Describe a type of protection relay which may be used to detect faults in an oil-filled transformer 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 on-load tap changing transformer with relevance to a power distribution transformer. **(2)**

d. Figures B2.1 and B2.2 show a per-phase circuit of a tap-changer 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:

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

(4)

e. A 100MVA 132kV/66kV, star/delta transformer, with the star point solidly earthed, has a nominal tap impedance (Z_{HL_NOM}) of j0.08 pu. The tap changer is assumed to be on the 132kV winding. Draw the equivalent circuits for the nominal tap and the +10% 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 +10% tap setting. Calculate the fault current on the high voltage side of the transformer if the fault level on the high voltage side is 1000MVA. **(3)**

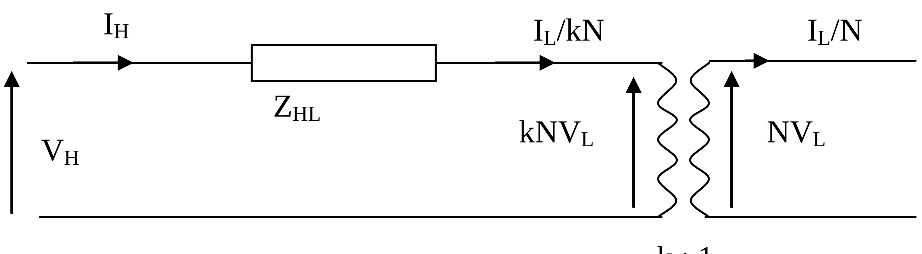


Figure B2.1

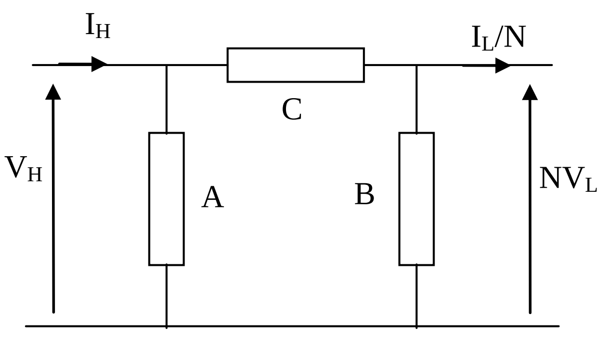


Figure B2.2

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 50MVA gas turbine driven synchronous machine, having a synchronous reactance of j0.3 pu, delivers 40MW over a double-circuit transmission line to a large power system which may be regarded as an infinite busbar. The transmission system has negligible resistance, and each line has a reactance of j0.25 pu as shown in Figure B3.1. The generator voltage is 1.1 pu and the voltage of the infinite busbar is 1.0 pu.

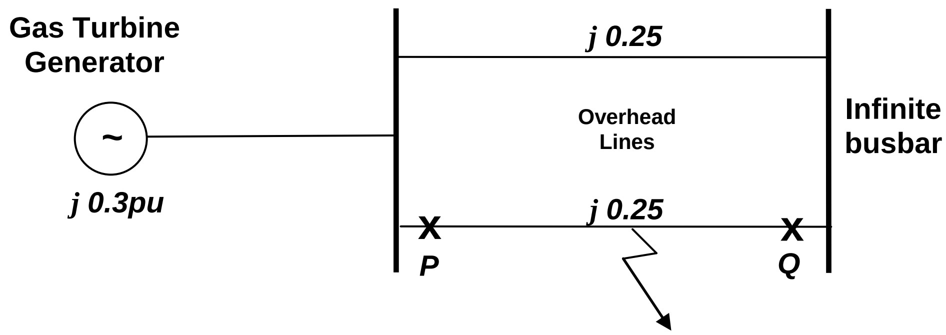


Figure B3.1 Gas Turbine driven generator and transmission system.

(i) Determine the power-load angle equation for the system and the load angle of the generator. **(3)**

(ii) When a 3-phase short-circuit occurs at the middle of one of the overhead transmission lines, between *P* and *Q*, the effective system reactance becomes j1.2pu. Determine the power-load angle equation for the system under fault conditions. **(1)**

(iii) The short-circuit 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. **(4)**

(v) By deriving an analytical expression or otherwise, determine the critical load angle at which the fault must be cleared in order to ensure system stability. **(5)**

c. Explain briefly how the transient stability of the power system could be improved. **(2)**

B4. Figure B4.1 shows a single line diagram of a power system in which both the generators operate at rated voltage. Generator *A* is directly connected to a 15kV busbar, *Bus 1*, which supplies a pair of overhead transmission lines, *D* and *E*, through step-up transformers *B* and *C* respectively. The other ends of the overhead lines are connected to a 132kV busbar, *Bus 2*, which is also supplied by Generator *G* through a step-up transformer, *F*. All star points in the system are solidly earthed.

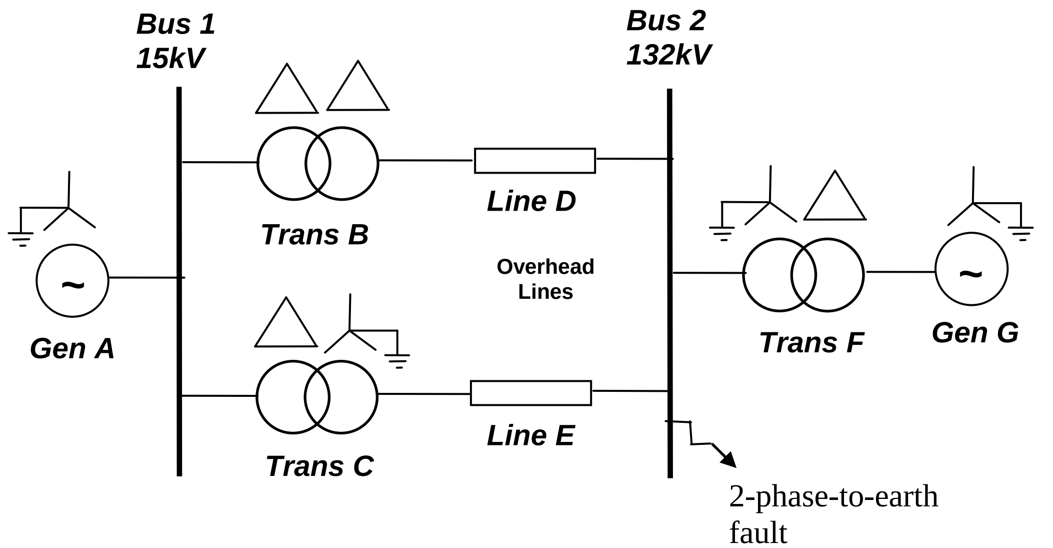


Figure B4.1 Line diagram of power system

	Rating	Voltage	X_+	X_-	X_0
Gen A	30 MVA	15 kV	j0.1pu	j0.1 pu	j0.08 pu
Gen G	50 MVA	22 kV	j0.1 pu	j0.08 pu	j0.05 pu
Trans B	30 MVA	15/132 kV	j0.3 pu	j0.3 pu	j0.4 pu
Trans C	40 MVA	15/132 kV	j0.3 pu	j0.3 pu	j0.3 pu
Trans F	30 MVA	25/132 kV	j0.08 pu	j0.08 pu	j0.04 pu
Line D	-	132 kV	j20Ω	j20Ω	j30Ω
Line E	-	132 kV	j20Ω	j20Ω	j30Ω

a. Calculate all the per-unit reactances of the system using a reference base of 30MVA. **(4)**

b. Draw the positive, negative and zero sequence diagrams for the system and calculate the equivalent positive, negative and zero sequence reactances. **(7)**

c. Determine the total fault current, and the line to line voltages at the fault, when a double phase-to-earth fault occurs on phases *B* and *C* at the 132kV busbar, *Bus 2*, as shown in Figure B4.1. **(8)**

d. If the star point of Generator A was connected to ground through an earthing reactor (instead of being solidly earthed), 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. **(1)**

KM/AG