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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

AUTUMN EXAMINATIONS, 2008

B.E. DEGREE (ELECTRICAL)

ELECTRICAL AND ELECTRONIC POWER SUPPLY SYSTEMS
EE4010

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Time allowed: *3 hours*

Answer *five* questions.

All questions carry equal marks.
The use of approved calculators is permitted.

$\mu_0 = 4\pi \times 10^{-7}$ H m^{-1} $\varepsilon_0 = 8.854 \times 10^{-12}$ F m^{-1}

1. (a) Draw a schematic diagram illustrating the structure of a national electrical power system, indicating in particular, the typical voltage levels encountered for generation, transmission and distribution of the electrical power. List three reasons why three-phase ac is employed as the primary mode of operation of this system. Briefly describe three situations within this power system structure in which it may be necessary to employ a high voltage direct current (HVDC) power transmission link.

[5]

(b) Derive an expression for the power available from a hydroelectric power station in terms of the flow rate of water Q $\mathrm{m^3/s}$ and the head of water H m. A large hydroelectric power station has a head of 300 m and an average flow rate of 1250 $\mathrm{m^3/s}$. The reservoir is composed of a number of lakes covering an area of 6400 $\mathrm{km^2}$. Calculate (i) the available hydraulic output power and (ii) the number of days this output power could be sustained if the level of impounded water were allowed to drop by 1 m.

[Density of water = 1000 kgm^{-3}]

[5]

(c) Draw a schematic diagram of a Pressurised-Water nuclear fission Reactor, (PWR) and hence describe the process by which the nuclear fuel in this reactor generates thermal energy for steam production via a controlled nuclear reaction. Estimate the annual fuel requirements of a typical 1 GW PWR nuclear power station and compare with that of a similar-sized coal-fired electrical power station.

[5]

[Q.1 continued overleaf]

(d) Describe the use of solar energy for direct generation of electricity using a bank of photovoltaic cells and describe a typical power electronic system which is necessary to interface the solar cells with the ac grid. Comment on the advantages and disadvantages associated with this form of renewable energy from the perspective of the utility company.

[5]

2. (a) Draw a schematic diagram illustrating the operation of a typical coal-fired electrical power generating station. Give approximate values for boiler inlet and outlet temperatures and estimate the ideal efficiency of such a process.

[8]

(b) The thermal efficiency of electrical power stations is often expressed in terms of *heat rate*, which is defined as the thermal input power required to deliver 1 kWh of electrical output power. Show that the heat rate is given by

$$Heat\ rate = \frac{3.6}{\eta}\ \text{MJ/kWh}$$

for a power station with an overall efficiency of η.

Consider a power plant with a heat rate of 10.8 MJ/kWh which burns bituminous coal with a 75% carbon content and a calorific value of 27 MJ/kg. Approximately 15% of the thermal losses are lost via the stack and 85% of the remaining losses are dissipated to the cooling water which is provided by a river. Local environmental regulations require that the maximum temperature rise of the river water is to be limited to 10°C.

(i) Estimate the efficiency of the power plant.
(ii) Find the mass of coal required per kWh of electrical power delivered.
(iii) Estimate the mass of carbon dioxide (CO_2) emissions from the plant per kWh of output power.
(iv) Find the minimum flow rate of cooling water per kWh

[Specific heat of water = 4.18 kJ/kg°C]
[Atomic mass of carbon = 12]
[Atomic mass of oxygen = 16]

[12]

3. (a) Define the terms (i) *sequence voltage vector* (ii) *sequence current vector* and (iii) *sequence impedance matrix* for a three-phase electrical load.

Define also what is meant by a *symmetrical load* in a three-phase system.

[8]

(b) A three-phase, four-wire load with a solidly grounded star point is defined by the following phase impedance matrix

$$Z_{phase} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix}.$$

Derive the positive, negative and zero sequence impedance networks corresponding to this load.

[Q.3 continued overleaf]

Unbalanced phase-to-ground source voltages defined by $\overline{V}_{ag} = 270\angle 0°$ V, $\overline{V}_{bg} = 260\angle -120°$ V and $\overline{V}_{cg} = 290\angle 115°$ V are applied to the three-phase load described above in which $\overline{Z}_s = (10 + j30)\ \Omega$ and $\overline{Z}_m = (5 + j20)\ \Omega$. The load star point is solidly grounded. Calculate the line current in Phase a of the load.

[12]

4. (a) Prove that the use of the per-unit method of analysis can eliminate the ideal transformer element from the single-phase transformer equivalent circuit model and define the conditions on the selection of base parameters under which this simplification can be achieved.

[8]

(b) Three single-phase, two-winding transformers, each rated at 25 MVA, 34.5 kV/13.8 kV, are connected to form a three-phase delta-delta bank. Balanced, positive sequence voltages are applied to the high voltage terminals and a balanced three-phase resistive load which is connected to the low voltage terminals absorbs 75 MW at 13.8 kV. Calculate the currents in the transformer windings. If one of the transformers is now removed and the load is reduced to 43.3 MW, calculate the MVA supplied by the two remaining transformers and determine if these devices are overloaded?

[12]

5. (a) Draw the exact per-phase equivalent circuit of a three-phase, round-rotor, synchronous generator when connected to an infinite system, noting the significance of each component of the model.

Neglecting resistive losses, derive expressions for the real power P and the reactive power Q delivered by the machine to the system in terms of the terminal voltage V_t, the generated back-emf, E_f, the synchronous reactance X_s and the load angle δ.

Prove that the locus of the complex power transfer derived above is a circle in the complex P/Q plane. Deduce the radius and the centre of this circle in terms of the specified parameters.

[10]

(b) A 50 Hz, three-phase, star-connected, round rotor, synchronous generator has a synchronous reactance of $j8.5\ \Omega$/phase and negligible resistance. The machine is synchronised onto 11 kV infinite busbars and it is initially delivering a per-phase armature current of 180 A at 0.9 power factor lagging. Calculate the internal emf of the machine.

If the steam turbine mechanical output power is held constant while the generator field excitation is increased by 25%, calculate the new armature current and power factor for this operating condition.

The field excitation current is now maintained constant at the new value and the turbine mechanical power is slowly increased. Compute the value of electrical output power at which the synchronous generator loses synchronism.

Briefly describe one other mechanism by which the generator may lose synchronism with the system.

[10]

6. (a) Prove that the per-unit fault volt-amperes for a three-phase symmetrical short-circuit fault in an electrical power system is given approximately by

$$VA_{f\,pu} = \frac{1}{X_{T\,pu}}$$

where $X_{T\,pu}$ is the total per-unit phase reactance up to the fault point.

Explain the use of current limiting reactors and describe, in particular, the ring reactor method of connecting such reactors in a large multi-generator power station.

[8]

(b) A small rural electrical power generating station has two generators, a 5 MVA machine with 8% reactance and a 4 MVA machine with 6% reactance, connected in parallel to 11 kV, 50 Hz busbars. These busbars feed an industrial load via switchgear which has a rated short circuit breaking capacity of 180 MVA.

It is desired to extend the station by connecting a new grid supply to the station busbars via a 10 MVA transformer having a leakage reactance of 10%. A current limiting reactor is to be used in series with this transformer in order to safeguard the existing switchgear. Calculate the value, in ohms, required for this reactor and also determine the per-unit current which it carries under three-phase symmetrical short circuit conditions on the station busbars.

[12]

7. (a) Derive an expression for the fault current when a single-phase-to-earth fault occurs at the terminals of a three-phase, star-connected synchronous generator with a solidly earthed star point. What is the effect on the fault current magnitude of a grounding impedance connected between the generator star-point and earth? **[8]**

(b) A 500 MVA, 13.8 kV synchronous generator with $X_1 = X_2 = 0.20$ per unit and $X_0 = 0.05$ per unit is connected to a three-phase, 500 MVA, 13.8 kV/400 kV power transformer in which the low voltage side is connected in delta and the high voltage side is connected in star. The generator and transformer neutrals are solidly earthed. The leakage reactance of the transformer is 0.10 per unit.

The generator is operated at no-load and rated voltage and the high voltage side of the transformer is disconnected from the power system. Compare the per-unit fault current levels for the following bolted short-circuit faults at the transformer high voltage terminals:

(i) a single line to earth fault

and

(ii) a line to line fault.

[12]