OLLSCOIL NA hÉIREANN, CORCAIGH
THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2006

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 a Casio *fx570w* or *fx570ms* calculator is permitted.

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

1. (a) Define what is meant by the *daily load curve* of a national electrical power system. Sketch a typical curve and explain how a hydro-electric pumped-storage generating station can be used to influence the shape of this curve.

The daily load curve of a small electrical power system regularly varies between 60 MW and 110 MW over the course of 24 hours and the curve has an average demand of 80 MW. The following two options are being considered to produce the required power:

(i) Install a base-power generating unit and a diesel-engine peaking unit
(ii) Install a base-power generating unit and a pumped-storage unit.

What are the respective capacities required of the base-power and the peaking power units in each case? **[5]**

(b) Briefly describe the basic concept a combined-cycle gas turbine electrical power generation station and explain why its efficiency is considerably higher that the normal open-cycle power station efficiency.

A combined-cycle, natural gas electrical power plant has an overall efficiency of 52%. Natural gas has an energy density of approximately 55 MJ/kg. Estimate the mass of gas required by this station to generate the electrical energy necessary to operate an 8 kW domestic electric shower for 7.5 minutes.

[5]

(Question 1 continued overleaf)

(c) Draw a block diagram of a hydro-electric generating station and derive an expression for the power available from such a station in terms of the flow rate of water Q m^3/s and the head of water H m.

On a particular day, the head of water in a large hydro-electric power station is 85 m and the generators deliver 6000 MVA at a power factor of 0.9 lagging to the electrical grid. Assuming that the average turbine efficiency is 92% and that the generator efficiency is 98%, calculate

(i) the real power delivered to the grid in MW
(ii) the reactive power supplied to the grid in MVAr
(iii) the volume flow rate of water through the turbines in m^3/s.

[Density of water = 1000 kg/m^3]

[5]

(d) The electrical power system of an industrial plant consists primarily of induction motor loads which absorb 1000 kW at 0.7 power factor lagging.

If a three-phase synchronous motor with a rated output of 750 kW at 90% efficiency is added to the plant and it is operated at rated load and unity power factor, calculate the resulting power factor of the electrical system.

[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

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

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 27.3 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. 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* as applied to an item of equipment in a three-phase electrical power system.

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

$$\overline{Z}_{phase} = \begin{bmatrix} \overline{Z}_s & \overline{Z}_m & \overline{Z}_m \\ \overline{Z}_m & \overline{Z}_s & \overline{Z}_m \\ \overline{Z}_m & \overline{Z}_m & \overline{Z}_s \end{bmatrix}.$$

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

Unbalanced phase-to-ground source voltages defined by $\overline{V}_{ag} = 277\angle 0°$ V, $\overline{V}_{bg} = 260\angle -120°$ V and $\overline{V}_{cg} = 295\angle 115°$ 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 per unit series impedance $\overline{Z}_{pu}$ of a three-phase star/delta connected transformer is the same whether computed from the star-side parameters or from the delta-side. Assume a three-phase volt-ampere rating of S VA, a line-to-line input voltage to the star side of V_L V, a turns ratio of $1{:}N$ (star/delta) and an impedance of $\overline{Z}_{phase}\ \Omega$ per phase referred to the star-side.

Explain the advantages of using a star connection on the high voltage side and a delta connection on the low voltage side of a three-phase star/delta-connected three-phase transformer bank.

[10]

(b) A 200 MVA, 50 Hz, $220\text{ kV Y}/20\text{ kV }\Delta$, star-delta connected substation transformer has an 8% leakage reactance. Winding resistance and excitation current may be neglected. The busbars connected to the high voltage windings can be assumed to be an ideal 220 kV, positive sequence, three-phase voltage source with negligible source impedance. Calculate the magnitude of the voltage drop across the transformer in per unit and the per unit voltage and the actual voltage on the low voltage busbars when rated current at 0.8 power factor lagging enters the high voltage windings.

Estimate also the per unit fault current which flows when a bolted three-phase-to-ground short circuit occurs at the low voltage terminals.

Repeat the calculations for a similar transformer designed with a 16% leakage reactance and comment on the significance of the result.

[10]

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.

Deduce the steady-state stability limit governing this power transfer.

[8]

(b) A 5000 kVA, 6.6 kV, 50 Hz, three-phase, star-connected, round rotor, synchronous generator has a synchronous reactance of $j3.6\,\Omega/\text{phase}$ and negligible armature resistance. The machine is synchronised onto 6.6 kV infinite busbars. Calculate the open-circuit voltage at the excitation which is necessary in order to deliver full rated power to the infinite busbars at 0.8 power factor lagging.

If the prime mover input power is held constant, calculate the armature current and power factor at which the alternator will operate when the excitation is increased to a value which would give a 10% greater open-circuit voltage.

If the excitation is now gradually reduced, again with the prime mover input power held constant, calculate the armature current and power factor when the alternator is operating at its steady state stability limit.

[12]

6. (a) Derive expressions for the fault current when (i) a three-phase fault and (ii) a single-phase-to-ground fault occur at the terminals of a three-phase, star-connected synchronous generator with a solidly grounded star point.

In both cases, what is the effect on the fault current magnitude of an impedance $\bar{Z}_n$ connected between the generator star-point and ground?

[8]

(b) A three-phase, 75 MVA, 11.8 kV, 50 Hz, round-rotor, star-connected alternator with a solidly-earthed star-point has per-unit positive, negative and zero sequence impedances of $j\,2.0$, $j\,0.16$ and $j\,0.08$ respectively. The machine is initially operating on no-load at its rated voltage and frequency. Determine the steady-state fault current for (a) a three-phase symmetrical short circuit and (b) a single-line-to-ground fault.

Find also the value of the reactance in ohms which must be connected between the generator star point and earth such that the fault current for a single-line-to-ground fault does not exceed that for a symmetrical three-phase fault.

[12]

7. (a) Draw the circuit diagram of a single-phase, full-wave, diode-bridge rectifier and output capacitor filter circuit which is used to provide an approximately dc input voltage to switched-mode dc/dc power converters for electronic products.

Sketch typical waveforms for (i) the input line voltage (ii) the output capacitor voltage and (iii) the input line current in this power converter.

Briefly list the principal disadvantages associated with this simple rectifier circuit from the perspective of both the utility company and the product manufacturer.

[6]

(b) Derive a general expression for the power factor of a single-phase diode-bridge rectifier with a capacitor filter circuit in terms of the fundamental displacement power factor, *DPF*, and the total harmonic distortion, *THD*, of the input current waveform. It may be assumed, using the usual notation, that the input voltage is purely sinusoidal,

$$v_{in}(t) = \sqrt{2}\,V_{in}\,Sin(\omega_1 t)$$

while the input line current is given by

$$i_{in}(t) = \sqrt{2}\,I_{in\,1}\,Sin(\omega_1 t - \phi_1) + \sum_{k \neq 1}^{\infty} \sqrt{2}\,I_{in\,k}\,Sin(k\omega_1 t - \phi_k)\,.$$

A typical internet-based telecommunications centre will have a very large number of personal computers each of which will draw a line current similar to that described above. In general, these loads are distributed approximately evenly across the three phases of the power distribution system. Explain the consequences for the neutral current of (a) an equal number of computer loads in each phase and (b) an uneven distribution of computer loads across the three phases.

[8]

A diode bridge rectifier and capacitor filter circuit supplies a switched mode power supply which requires a power of 2.5 kW when operating from a single-phase mains voltage of 230 V. It is found that the fundamental current is $I_{in1} = 12$ A and the THD of the line current is 98%. Calculate the *DPF*, the power factor and the rms input current.

[6]