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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

AUTUMN 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.

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

1. (a) Prove that the total instantaneous power delivered by a three-phase sinusoidal voltage source operating under balanced conditions is a constant. Explain the significance of this result in the context of the generation and distribution of large-scale electrical power.

[5]

(b) Sketch the layout of a combined-cycle gas turbine electrical power generating 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 50.5%. 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 a 2.2 kW electric cooker element for 1 hour.

[5]

(c) Derive an expression for the electrical output power P available from a hydroelectric power station in terms of the flow rate of water Q m^3/s, the head of water H m and the overall efficiency η.

A river-based hydroelectric power station has a mean head of 28.5 m. The minimum average flow rate of water in summer is 180 m^3/s and this increases to a maximum of 400 m^3/s in winter. Calculate the minimum and maximum generating capacities of the station assuming an overall efficiency of 91%. The density of water is 1000 kg/m^3

[5]

(Question 1 continued overleaf)

(d) A 3750 kW, three-phase, star-connected motor is connected to a 4000 V, three-phase, 50 Hz ac supply. If the motor produces an output power of 2700 kW at an efficiency of 90% and a power factor of 0.85 lagging, calculate the real, reactive and apparent powers drawn by the machine.

If a three-phase capacitor bank supplying 1800 kVAr is connected in parallel with the motor, calculate the operating power factor of the combined motor and capacitor bank.

[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. Prove 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 10.5 MJ/kWh which burns bituminous coal with a 72.5% carbon content and a calorific value of 27.5 MJ/kg. Approximately 16% of the thermal losses are lost via the stack and 84% 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 $9°\text{C}$.

(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 of output power.

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

[12]

3. (a) An unbalanced, three-phase, star-connected, sinusoidal voltage source with phase to star-point voltages defined by the phasors $\overline{V}_{ag}$, $\overline{V}_{bg}$ and $\overline{V}_{cg}$, is connected to a three-phase, four-wire, balanced impedance load of $\overline{Z}_Y$ Ω/phase. The star point of the load is connected to the star point of the supply by an impedance $\overline{Z}_n$ Ω. Derive from first principles expressions for (i) the current in the *a* phase and (ii) the load to source star-point voltage in terms of the sequence components, $\overline{V}_0$, $\overline{V}_1$ and $\overline{V}_2$, of the source voltage.

[10]

(Question 3 continued overleaf)

(b) A balanced three-phase, four-wire load consists of a star-connected impedance of $\bar{Z}_Y = (4 + j3)\ \Omega$ in each phase. Unbalanced phase-to-star-point source voltages defined by $\bar{V}_{ag} = 200\angle 0°\ \text{V}$, $\bar{V}_{bg} = 150\angle 270°\ \text{V}$ and $\bar{V}_{cg} = 230\angle 120°\ \text{V}$ are applied to the load. An impedance of $j1\ \Omega$ is connected between the star point of the load and the star point of the supply. Draw the positive, negative and zero sequence networks for this system. Calculate the corresponding sequence currents and the current in the *a* phase. Determine also the voltage of the load star point with respect to the voltage source star point.

[10]

4. (a) Prove that the per unit series impedance $\bar{Z}_{pu}$ 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 $\bar{Z}_{phase}\ \Omega$ 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 50 Hz, 30 MVA, 13.2 kV, three-phase, synchronous generator has a positive sequence reactance of 1.5 per unit based on its own rating. It is connected to a 35 MVA, 13.2Δ kV/115Y kV, delta/star connected, three-phase, step-up transformer bank. The transformer has a series impedance of (0.005 + j0.1) per unit, based on its own thermal ratings.

The electrical load on the busbars connected to the secondary terminals of the transformer bank is 15 MW at unity power factor and 115 kV. Calculate

(i) the transformer low-side voltage

(ii) the excitation voltage of the generator

(iii) the power factor at which the generator is operating.

[10]

5. (a) Draw the exact per-phase equivalent circuit of a three-phase, round-rotor, synchronous generator when connected to an infinite system and explain 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 power transfer limit of the generator.

[8]

(Question 5 continued overleaf)

(b) A three-phase, star-connected, 11 kV, four-pole, 50 Hz, round rotor, synchronous generator has a synchronous reactance of $j1.0\,\Omega/\text{phase}$ and an open-circuit line voltage of 12.5 kV. The machine is driven by a steam turbine and it is connected to 11 kV busbars. The steam supply to the turbine is adjusted until the generator supplies 80 MW of power to the busbars.

Calculate the load angle of the machine, the armature current and the power factor when operating under these conditions.

Evaluate the theoretical maximum power which the machine can supply to the busbars without losing synchronism and calculate the power factor of the machine at this point.

[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 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 positive, negative and zero sequence leakage reactances of the transformer are all equal to 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.

(i) Calculate the per-unit fault current and the actual fault current for a bolted, three-phase, symmetrical short circuit at the transformer high voltage terminals.

(ii) Calculate the per-unit fault current and the actual fault current for a bolted, single-line-to-ground short circuit at the transformer high voltage terminals

[12]

7. (a) Draw the schematic 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 waveforms for the input line voltage and the output capacitor voltage and comment on the waveshape of the input line current typically drawn by this converter.

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 an 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 that the input voltage is purely sinusoidal as defined by

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

A typical data-processing 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 2.25 kW when operating from a single-phase mains voltage of 230 V. It is found that the fundamental current is $I_{in1} = 10\text{ A}$ and the THD of the line current is 105%. Calculate the *DPF*, the power factor and the rms input current.

[6]