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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2005

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) Define the terms *per-unit growth rate,* α, and *doubling time,* t_d of energy consumption in a national electrical power system which demonstrates exponential growth. Hence derive an expression for the doubling time in terms of the growth rate.

The electrical energy consumption curve over time in a given electrical power system is such that the per-unit growth rate increases from an average of 2.6% per annum to 9.5% per annum. Calculate the doubling times corresponding to these growth rates. Comment on the likely consequences of the higher level of growth if it is sustained over a number of years.

[5]

(b) 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.

The synchronous generator in a coal fired electrical power station is rated at 660 MW. The boiler used to raise steam for this turbo-alternator system burns black coal with a calorific value of 28 MJ/kg. If the overall station efficiency is 37.5%, calculate the mass flow rate of coal in tonnes/hour which is required to operate the synchronous generator at its rated output power.

[5]

(Question 1 continued overleaf)

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

Assume that the average head between two reservoirs, each of area 1.5 km^2, in a pumped-storage system is $H = 310$ m. The station is required to produce a power output of 250 MW over 6 hours. The efficiency of the complete system is 75%. Calculate the change in reservoir water level to produce this period of output power.

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

[5]

(d) A balanced, positive sequence, star-connected voltage source with a line voltage of 400 V is applied to a balanced, three-phase, delta-connected load with $\overline{Z}_{delta} = 60.0\angle 30° \,\Omega$. The impedance of the transmission line between the source and the load is $\overline{Z}_{line} = 2.0\angle 85° \,\Omega$. Calculate the transmission line current and the real power dissipated in the load.

[5]

2. (a) Derive from first principles an expression for the theoretical maximum power available from a wind turbine in terms of the swept area of the blades, $A \text{ m}^2$, the velocity of the wind, u m/s and the density of air at standard temperature and pressure, $\rho \text{ kg/m}^3$.

Sketch an approximate power versus wind speed curve for a typical wind turbine. Explain why the actual output power which is achievable in practice is considerably less that this value.

[8]

(b) A small wind generator is designed to generate 50 kW of electrical output power at a wind velocity of 11.2 m/s. Calculate the required blade diameter D assuming that the turbine can achieve a practical operating efficiency of 59% of the maximum theoretical value. The density of air at standard temperature and pressure is 1.201 kg/m^3.

If the wind speed were to vary between 20 km/hour and 50 km/hour, determine the range of available output power.

List two major advantages of this type of electrical power generation and comment on the possible disadvantages of the system compared to conventional fossil-fuel-based generating stations from the perspective of the power system operator.

[12]

3. (a) State the sequence component transformation for three-phase voltages and currents and hence develop the general expression for the sequence impedance matrix in terms of the phase impedance matrix for a general three-phase load.

(Question 3 continued overleaf)

A balanced, three-phase star-connected load consists of a self-impedance of $\bar{Z}_s$ Ω/phase and a mutual impedance between phases of $\bar{Z}_m$ Ω. The star point of the load is grounded via an impedance of $\bar{Z}_n$ Ω. Deduce the phase impedance matrix for this system and hence derive the sequence impedance matrix of the load.

[12]

(b) A three-phase, passive star-connected load has a balanced phase impedance of $\bar{Z}_s = (8 + j24)$ Ω/phase and the phases are mutually coupled via balanced impedances of $\bar{Z}_m = j4$ Ω. The load star point is grounded via an impedance of $\bar{Z}_n = j6$ Ω.

This load is supplied from the secondary of a delta/star connected transformer whose secondary winding star point is solidly grounded. The transformer secondary voltage is balanced and the line-to-line voltage supplied to the load is 400V.

Using the theory of symmetrical components, calculate the current in Phase *a* of the load.

A system fault occurs such that the transformer secondary phase-to-ground voltages become unbalanced. If the zero, positive and negative sequence components of these voltages are measured as $\bar{V}_0 = 32.7\angle 30.0°$ V, $\bar{V}_1 = 188.3\angle 7.6°$ V and $\bar{V}_{cg} = 44\angle -109.8°$ V, calculate the new current which flows in Phase *a*

[8]

4. (a) Prove that the per unit impedance 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 $\bar{Z}_{phase}$ Ω per phase referred to the star-side.

[8]

(b) A 50 Hz, 100 MVA, 13.2 kV, three-phase, synchronous generator has a positive sequence reactance of 1.5 per unit based on its ratings. This synchronous generator is connected to a 50 Hz, 110 MVA, 13.2Δ kV/115Y kV, delta/star connected, three-phase, step-up transformer unit. This transformer has a series impedance of (0.005 + *j*0.1) per unit, based on its own ratings. Calculate the per unit impedance of the generator based on the ratings of the transformer.

A load of 80 MW at unity power factor and at 115 kV is connected to the secondary terminals of the transformer. Choosing the transformer high-side voltage as reference, draw the phasor diagram corresponding to this condition and calculate (i) the transformer low-side voltage, (ii) the excitation voltage of the generator and (iii) the power factor at which the generator is operating.

Calculate also the real and reactive output power of the generator.

[12]

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

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 50 Hz, three-phase, star-connected, round rotor, synchronous generator has a synchronous reactance of $j8.5\,\Omega/\text{phase}$ 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.

[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 $\overline{Z}_n$ connected between the generator star-point and ground?

[8]

(b) A 500 MVA, 13.8 kV, three-phase, star-connected, synchronous generator with a solidly grounded star point has positive, negative and zero sequence sub-transient reactances of 0.2 per unit, 0.2 per unit and 0.05 per unit respectively.

The generator is connected to a three-phase, 500 MVA, 13.8 kV Δ/500 kV Y transformer with 0.1 per unit leakage reactance. The star-point on the high voltage side of the transformer is grounded via a reactance of 0.1 per unit.

Compare the sub-transient fault currents for the following bolted short circuits on the high-voltage terminals of the transformer unit:-

(i) a three-phase fault
(ii) a single-line to ground fault
(iii) a line-to-line 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 describe 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

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

Derive also an expression for the neutral current if one of these converters is connected between live and neutral in each phase of a balanced three-phase star-connected system.

[8]

A diode bridge rectifier and capacitor filter circuit supplies a switched mode power supply which requires a power of 2.2 kW when operating from a mains voltage of 230 V. It is found that the fundamental current is $I_{in1} = 11\,\mathrm{A}$ and the THD of the line current is 93%. Calculate the *DPF*, the power factor and the rms input current.

[6]