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THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2011

B.E. DEGREE (ELECTRICAL)

ELECTRICAL POWER 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} $c = 3 \times 10^8$ ms^{-1}

1. (a) Define what is meant by the *per-unit growth rate* and *doubling time* of energy consumption in an electrical power system. Sketch a curve of doubling time (in years) as a function of growth rate (in per cent per year).

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 2.75% 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 an annotated 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.

Measurements show that 1 kg of a certain type of coal releases 30.5×10^6 J of thermal energy when incinerated in a power station. Assuming a thermal energy transformation efficiency of 36.5% and an electrical generation and transmission efficiency of 92%, calculate the length of time which the energy derived from the burning of 20 kg of this type of coal will run a domestic load of 7.5 kW.

[5]

(c) Derive an expression for the power 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 generating efficiency, η_G.

[Q.1 Continued Overleaf]

Describe briefly the characteristics of (i) a run-of-river hydroelectric power plant and (ii) a pumped-storage power plant and discuss how these stations are normally operated as part of a national electrical power grid.

On a particular day, the head of water in the dam at a large hydroelectric power generating station is 85.3 m and the generators deliver 6000 MVA at 0.9 power factor lagging. Assuming that the average turbine efficiency is 92% and that the average alternator efficiency is 98%, calculate the real and reactive powers supplied to the system and the flow rate of water.

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

[5]

(d) List two advantages and two disadvantages of a Pressurised Water Reactor (PWR) nuclear power station compared to a conventional coal-fired station.

A fuel rod of enriched uranium 235 has a mass of 22.2 kg when first inserted into the core of a PWR. If it releases an average power of 372.5 kW of thermal energy during its 19-month stay in the reactor core, calculate the total amount of heat generated by the fuel rod during this time and estimate the ideal reduction in the mass of uranium 235 required to produce this energy.

[5]

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

A three-phase, balanced star-connected load consists of a resistance R_Y in each phase and the load star-point n is isolated relative to ground g. This load is fed from a set of unbalanced three-phase voltages $\bar{V}_{ag}$, $\bar{V}_{bg}$ and $\bar{V}_{cg}$. Derive the sequence impedance matrix and the associated sequence networks for this load and hence deduce an expression for the current flowing in the resistance in Phase a.

[10]

(b) An unbalanced three-phase sinusoidal voltage source, of phase sequence *abc*, has phase-to-ground voltages given by $\bar{V}_{ag} = 100\angle 0°\ \text{V}$, $\bar{V}_{bg} = 200\angle 270°\ \text{V}$ and $\bar{V}_{cg} = 100\angle 120°\ \text{V}$. Three identical voltmeters, each of resistance 10 kΩ, are connected in star to this unbalanced supply via a three-wire connection in which the star point n is isolated relative to ground g. Calculate the voltage reading of the voltmeter connected to Phase a.

If a similar voltmeter is now connected between the star point and ground, what voltage will it indicate?

[10]

3. (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. Explain the reason why this result is so important in the analysis of large-scale power systems.

[8]

[Q.3 Continued Overleaf]

(b) Three single-phase, two-winding transformers, each rated at 25 MVA, 38 kV/10 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 10 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? Explain one advantage of this particular connection of a delta/delta transformer.

[12]

4. (a) Neglecting resistive losses, derive expressions for the real power P and the reactive power Q delivered by a three-phase, round-rotor, synchronous generator to a set of infinite busbars of phase voltage V_t V. The machine per-phase excitation voltage is E_f, the load angle is δ and the synchronous reactance of the machine is measured to be X_s Ω per phase. Assume a lagging power factor mode of operation.

Prove also 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 and locate on the diagram the operating power factor angle θ and the load angle, δ.

Comment also on the impact which a salient pole rotor construction has on the real electrical power transfer characteristic.

[10]

(b) A 100 MVA, 10 kV, 50 Hz, four-pole, three-phase, star-connected, round-rotor, synchronous generator has a synchronous reactance of $j1.0\,\Omega/\text{phase}$ and negligible armature resistance. The open circuit line voltage of the machine is held constant at 11.5 kV. When connected to a set of 10 kV busbars, the machine supplies a power of 72.5 MW.

Calculate the load angle, the armature current and the power factor for this operating condition.

What is the theoretical maximum power which the machine could supply before losing synchronism and evaluate the armature current and the operating power factor for this limit condition.

[10]

5. (a) A three-phase, round-rotor synchronous generator is connected to a set of infinite busbars such that the electrical power transfer from the machine to the infinite busbars is governed by the equations

$$P_e = \left(\frac{E_f V}{X_s + X}\right) Sin(\delta)$$

$$P_m - P_e = k\frac{d^2\delta}{dt^2}$$

where E_f and V are the machine excitation and system voltages respectively, δ is the power angle and k is a constant.

[Q.5 Continued Overleaf]

The parameters X_s and X are the machine transient reactance and system reactance, respectively. The mechanical power input P_m to the generator may be considered constant.

Define what is meant by the transient stability of this system and derive the Equal Area criterion which can be used to assess this phenomenon when the system reactance is suddenly altered.

[10]

(b) A particular three-phase, round-rotor synchronous generator is delivering 0.6 per unit real power to the national grid through an interconnector such that the per-unit power/load angle curve is given by

$$P_1(\delta) = 1.3\,Sin(\delta).$$

A symmetrical three-phase fault occurs on the interconnector which causes the synchronous generator to operate on a reduced per-unit power/load angle curve given by

$$P_2(\delta) = 0.1\,Sin(\delta).$$

This curve persists until the fault is cleared by the system circuit breakers. When the fault is cleared, the synchronous generator reverts to the original per-unit power/load angle curve, $P_1(\delta)$.

Calculate the critical clearing angle δ_{cc} of the fault in order for the synchronous generator to maintain transient stability.

[10]

6. (a) A large electrical power generating station consists of N busbar sections. A generator of rated volt-amperes S_B and per-unit reactance X_G is connected to every busbar section. The busbar sections are each connected to a common tie-bar by a reactor of per-unit reactance X_T on the same base parameters as the generators. Draw a single-line diagram illustrating this system. Show that, in the limit as $N \to \infty$, the bolted, three-phase symmetrical per-unit fault volt-amperes on any busbar section is given by

$$MVA_f = \left[\frac{1}{X_G} + \frac{1}{X_T}\right] S_B$$

[10]

(b) The busbars of a hydro-electric power generating station are to be divided into three sections, A, B and C, to each of which is connected a 16 MVA synchronous generator having 30% reactance based on the generator base.

The busbars are connected to a common tie-bar through 12 MVA current limiting reactors having a 15% reactance based on their ratings.

To each busbar section is connected a 10 MVA transformer having a 10% reactance based on the transformer ratings.

[Q.6 Continued Overleaf]

A 20 km, 10 MVA feeder transmission line having a per-phase reactance of 0.7 Ω/km and negligible resistance is connected to the 33 kV secondary side of the transformer connected to Busbar Section A.

Draw the single line diagram corresponding to this system and calculate the fault MVA and the fault current fed into a symmetrical three-phase short circuit current at the distant end of the feeder transmission line.

[10]

7. (a) Derive an expression for the fault current when a single line-to-ground short circuit fault occurs at the terminals of a three-phase, round-rotor, star-connected synchronous generator with a solidly grounded star point. It may be assumed that the generator is initially operating at rated voltage and frequency and that it is unloaded prior to the fault.

[8]

(b) A 38 kV voltage source has a three-phase fault level volt-amperes of 2000 MVA and it is assumed to have equal internal reactances to positive, negative and zero sequence currents.

The source supplies a 45 MVA, 38 kV /110 kV delta/star connected three-phase transformer bank with a solidly earthed star point. The transformer bank has a leakage reactance of 10% and it is connected to a 110 kV transmission line which is 100 km in length. The positive and negative sequence reactances of the transmission line are $X_1 = X_2 = 0.7$ Ω/km while the zero sequence reactance is $X_0 = 1.5$ Ω/km.

At the remote end of the line is connected a transformer bank identical to that at the sending end but at the remote end the 38 kV side is on open circuit.

(i) Deduce the per unit zero, positive and negative sequence networks for this system on a 45 MVA, 38 kV base in the 38 kV source zone.

(ii) Calculate the fault current for a zero-impedance, single line-to-ground short circuit at the mid-point of the transmission line. It can be assumed that the pre-fault current is negligible.

[12]