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

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

SUMMER EXAMINATIONS, 2010

B.E. DEGREE (ELECTRICAL)

ELECTRICAL POWER SYSTEMS
EE4010

Professor Christophe Delabie
Dr. M. J. Creed
Dr. M.G. Egan

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) If the primary energy requirement of a country grows at a rate which is proportional to the present demand, the constant of proportionality being α, calculate the time taken for the energy requirement to triple.

The electrical energy consumption curve over time in a given electrical power system is such that the per-unit growth rate is 7.5 % per annum. In how many years will the energy consumption be tripled? Comment on the difficulties associated with high growth rates in energy demand from the perspective of power system planners and list some solutions for dealing with this issue.

[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 300 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 38%, calculate the mass flow rate of coal in tonnes/hour which is required to operate the synchronous generator at its rated output power. Give two advantages and two disadvantages of using of coal compared to natural gas for electrical power generation.

[5]

(c) Derive an expression for the generated power available from a pumped storage hydro-electric station in terms of the flow rate of water Q $\mathrm{m^3/s}$, the head of water H m and the generating efficiency, η_G.

[Q.1 Continued Overleaf]

This pumped storage system has an efficiency η_P while pumping. Derive an expression for the ratio of the energy supplied to the grid while generating to that consumed during the corresponding pumping period.

Assume that the average head between two reservoirs in a pumped-storage system, each of area $1.5\ \text{km}^2$, is $H = 310$ m. The station is required to produce an electrical 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 = $1000\ \text{kg/m}^3$]

[5]

(d) A small wind turbine is designed to generate 75 kW of electrical output power at a wind velocity of 12.5 m/s. Calculate the required turbine diameter D assuming that the turbine can achieve an operating efficiency of 51% of the maximum theoretical value. The density of air at standard temperature and pressure is $1.201\ \text{kg/m}^3$.

If the wind speed were to vary between 20 km/hour and 60 km/hour, determine the range of available output power. Comment on the significance of this result.

[5]

2. (a) Define the sequence component transformation $\overline{A}$ and hence derive an expression for the relationship between the sequence voltage vector $\overline{V}_s$ and the sequence current vector $\overline{I}_s$ of a general three-phase load, defined by its phase impedance matrix, $\overline{Z}_p$.

A balanced, three-phase, delta-connected load consists of an impedance $\overline{Z}_\Delta\ \Omega$ in each phase. Derive from first principles the zero, positive and negative sequence impedance networks corresponding to this load.

[10]

(b) A three-phase balanced star-connected generator produces a terminal voltage of sequence *abc* defined by the line voltage $\overline{V}_{ab} = 400\angle 30°$ V. This generator is connected to a balanced Δ-connected load whose impedance is $\overline{Z}_\Delta = 24\angle 40°\ \Omega$/phase. The line impedance between the generator and the load is $0.5\angle 80°\ \Omega$ for each phase. The generator neutral is grounded through an impedance $\overline{Z}_n = j5.0\ \Omega$. The sequence impedances of the generator are given by $\overline{Z}_{g0} = j7.0\ \Omega$, $\overline{Z}_{g1} = j15.0\ \Omega$ and $\overline{Z}_{g2} = j10.0\ \Omega$.

Draw the zero, positive and negative sequence networks corresponding to this system and calculate the sequence components of the line current which flows in Phase *a*.

Draw also the zero, positive and negative sequence networks of the system in the event of a direct, three-phase short circuit fault at the terminals of the generator and write down an expression for the resultant fault current in Phase *a*.

[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]

(b) A three-phase electrical power distribution transformer is connected in a star/star configuration with primary and secondary star points solidly earthed. The transformer supplies a balanced load of $(400 + j600)\ \Omega/\text{phase}$ through a transmission line of impedance $(4 + j6)\ \Omega/\text{phase}$.

The secondary winding of the transformer has 3 times as many turns as the primary, the primary series impedance is $(0.5 + j2.5)\ \Omega/\text{phase}$ and the corresponding secondary series impedance is $(5 + j25)\ \Omega/\text{phase}$. The transformer is fed from a three-phase star-connected synchronous generator rated at 1.5 MVA, 11 kV with an internal reactance of 0.20 per-unit based on its own ratings. The generator start point is solidly earthed.

Calculate the transformer secondary terminal voltage if the primary voltage is 11.0 kV. If a bolted short-circuit now occurs on all phases half way along the transmission line, estimate the generator current assuming that the excitation voltage behind its internal reactance can be assumed constant.

[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.

[10]

(b) A three-phase, round-rotor, star-connected, 5 MVA, 6.6 kV, synchronous generator has a synchronous reactance of X_s =3.6 Ω/phase. The machine is driven by a diesel engine and is connected to a set of infinite busbars at 6.6 kV.

(i) Calculate the open circuit voltage at the excitation which is necessary in order to deliver full rated load at 0.8 power factor lagging to the set of infinite busbars.

(ii) If the diesel engine input power is held constant, calculate the operating current and power factor when the excitation is increased by 10%.

(iii) If the mechanical input power is again held constant, calculate the operating current and power factor when the excitation is reduced to the minimum value required to maintain steady state stability.

[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. The parameters X_s and X are the machine transient and system reactances, 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) The parameters of the transmission lines in the power system illustrated in Figure 1 below are $X_1 = 0.4$ pu and $X_2 = X_3 = 0.2$ pu. The round-rotor synchronous generator has an excitation voltage of $E_f = 1.2$ pu and a transient reactance of $X_s = 0.2$ pu. The voltage of the system is $V = 1.0$ pu. The mechanical input power to the generator is held constant at $P_m = 1.5$ pu.

Use the Equal Area Criterion to assess the transient stability of this generator if a bolted three-phase short circuit fault occurs at the mid-point *F* of one of the two parallel transmission lines.

(i) If the fault is not removed will the generator be stable?
(ii) If the fault is removed by opening the breakers CB_1 and CB_2, calculate the critical clearing angle $\delta = \delta_{cc}$ of the breakers to maintain transient stability of the generator.

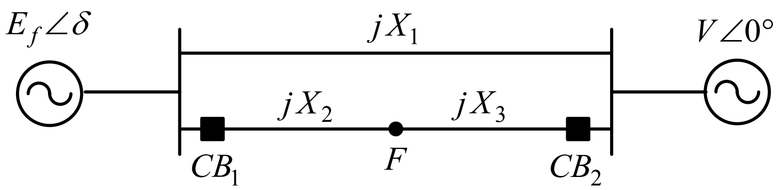

Figure 1: Power distribution system for Q.5.

[10]

6. (a) Derive an expression for the per unit fault volt-amperes arising from a symmetrical short-circuit fault in a three-phase system in which $X_{T\,pu}$ is the total per-unit reactance up to the fault point.

Explain the objective of sectionalising the busbars of a large generating station and connecting reactors between the sections. Sketch (i) the tie-bar configuration and (ii) the ring reactor configuration for interconnecting three sectionalised busbars in a power station.

[10]

[Q.6 Continued Overleaf]

(b) The busbars of a hydro-electric power generating station are to be divided into three sections, *A, B* and *C* by the use of three current limiting reactors. A 60 MVA synchronous generator having a reactance of 0.15 per unit is connected to each busbar section.

Determine the minimum reactance in ohms of the current limiting reactor *X* if the maximum MVA fed into a bolted symmetrical three-phase fault on any busbar section is to be limited to 500 MVA if the three reactors are connected to a common tie-bar.

The busbar voltage is 22 kV.

[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 33 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, 33 kV /132 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 132 kV transmission line which is 100 km in length. The positive and negative sequence reactances of the transmission line are $X_1 = X_2 = 0.7\ \Omega/\text{km}$ while the zero sequence reactance is $X_0 = 1.5\ \Omega/\text{km}$.

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 33 kV side is on open circuit.

(i) Deduce the per unit zero, positive and negative sequence networks for this system on a 45 MVA, 33 kV base in the 33 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]