EE4530 POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 3

LOAD FREQUENCY CONTROL (I)

3.1 A 3-phase generator rated 100 MVA, 13.2 kV, X=20% is connected through a ∇/Y transfer to a transmission line whose series reactance is 40 Ω per phase. Assume that the base values in the line circuit are 200 MVA and 115 kV.
(a) Find the pu reactance of the transmission line;
(b) Find the generator and transformer reactance in pu for the following cases:
(i) the transformer is a 3-phase unit rated 100 MVA, 13.8∇/120Y kV, X=8%;
(ii) the transformer is composed of three single-phase units, each rated 35 MVA, 13.8/69 kV, X=8%.

[Ans: (a) 0.6049 pu; (b) (i) 0.3985 pu, 0.1742 pu; (ii) 0.3952 pu, 0.1646 pu.]

3.2 A 250 MW, 60-Hz power system has a speed regulation of 5% based on its own rating. The system frequency decreases from 60 Hz to a steady-state value of 59.7 Hz. Determine the increase in the turbine power output. Neglect losses and the dependence of load on frequency.

[Ans: 25 MW.]

3.3 Two generating units rated for 250 MW and 400 MW have their droop settings of 6.0% and 6.4%, respectively. The units operate in parallel at 50 Hz at no load. Determine the load taken by each unit for a total load of 500 MW. Neglect losses and the dependence of load on frequency.

[Ans: 200 MW, 300 MW.]

3.4 A 60-Hz power system consists of two interconnected areas. Area 1 has 1000 MW of generation and an area frequency response characteristic β_1 = 400 MW/Hz. Area 2 has 2000 MW of generation and β_2 = 800 MW/Hz. Each area operates initially at one-half its total generation, at $\Delta p_{tie1} = \Delta p_{tie2} = 0$ and at 60 Hz, when the load in area 1 suddenly increases by 300 MW. Neglect losses and the dependence of load on frequency. Determine the steady-state frequency error and the steady-state tie-line error Δp_{tie} for each area assuming that (a) the reference power settings of all turbine-governors are fixed, i.e. LFC is not employed in any area and (b) LFC is employed in both areas. The frequency bias coefficients are B_{f1} and B_{f2} MW/Hz, respectively.

[Ans: (a) -0.25 Hz, 200 MW, -200 MW; (b) 0 Hz, 0 MW, 0 MW.]

E430 POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 4

LOAD FREQUENCY CONTROL (II)

4.1 A single area consists of two generating units with the following characteristics.

Unit	Rating	Speed regulation R (pu on unit MVA base)
1	600 MVA	6%
2	500 MVA	4%

The units are operating in parallel, sharing 900 MW at the nominal frequency. Unit 1 supplies 500 MW and Unit 2 supplies 400 MW at 60 Hz. The load is increased by 90 MW. (a) Assume there is no frequency-dependent load, i.e., D=0. Find the steady-state frequency and the new generation change on each unit; (b) The load varies 1.5 percent for every 1 percent change in frequency on the base of 1000MVA, i.e., D=1.5. Find the steady-state frequency and the new generation change on each unit

[Ans: (a) 59.76 Hz, 40 MW, 50 MW; (b) 59.775 Hz, 537.5 MW, 446.875MW.]

4.2 Two identical 60 MW synchronous generators operate in parallel at 60 Hz. The governor settings on the machines are such that they have 4 per cent and 3 per cent droops (no-load to full-load percentage speed drop). Determine (a) the load taken by each machine for a total of 100 MW; (b) the percentage adjustment in no-load speed to be made by the speeder motor if the machines are to share the load equally.

[Ans: (a) 42.8 and 57.2 MW; (b) 0.83 per cent increase in no-load speed on the 4 per cent droop machine.]

4.3 A 60-Hz system consists of three units whose ratings are 300, 500 and 600 MW and whose speed-droop characteristics are 5%, 4% and 3% respectively. The system is connected to a neighboring system via a tie-line. Suppose that a generator in the neighboring system is forced out of service, and that the tie-line flow is observed to increase from the scheduled value of 400 to 631 MW. Determine the amount of the increase in generation of each of the three units.

[Ans: 36 MW, 75 MW, 120 MW.]

EE4530 POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 5

ECONOMIC DISPATCH (I)

5.1 A plant has two generators supplying the plant bus, and neither is operating below 100 MW or above 625 MW. Incremental costs with P_1 and P_2 in megawatts are:

$$\frac{dC_1}{dP_1} = 0.012P_1 + 8.0 \ \$/\mathrm{MWh}$$
$$\frac{dC_2}{dP_2} = 0.018P_2 + 7.0 \ \$/\mathrm{MWh}$$

For economic dispatch, find the plant λ when $P_1 + P_2$ equals (a) 200 MW, (b) 500 MW, and (c) 1150 MW.

[Ans: 9.2, 11.2, 16.45 $/MWh.]

5.2 A two-unit system has the following cost rate curves:

$$CR_1 = 900 + 45P_{G1} + 0.01P_{G1}^2 \qquad 50 \le P_{G1} \le 600MW$$
$$CR_2 = 2500 + 43P_{G2} + 0.02P_{G2}^2 \qquad 50 \le P_{G2} \le 800MW$$

(a) Determine the economic operating points for these two units when delivering a total load of 500 MW.

(b) Calculate the increase per hour in the production costs of the units due to the generation limits when the system load is increased to 1200 MW.

[Ans: (a) 300 MW; 200 MW. (b) $833.34 per hr.]

5.3 A four-generator system is supplying a peak load of 472.5 MW. The cost rate curve, in US$, of each generator, and maximum output, is given by:

$$CR_1 = 200 + 20.8P_1 + 0.20P_1^2 \qquad P_1 \le 100MW$$
$$CR_2 = 300 + 17P_2 + 0.10P_2^2 \qquad P_2 \le 120MW$$
$$CR_3 = 150 + 12P_3 + 0.20P_3^2 \qquad P_3 \le 160MW$$
$$CR_4 = 500 + 2P_4 + 0.07P_4^2 \qquad P_4 \le 200MW$$

Determine the optimal loading of each generator.

[Ans: 65.25 MW; 120MW; 87.25MW, 200MW.]

E430 POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 6

ECONOMIC DISPATCH (II)

6.1 A three-unit system has the following heat rate curves:

$$H_1(\text{MBTU/Hr}) = 510 + 7.20P_1 + 0.00142(P_1)^2 \qquad 150 \le P_1 \le 600 \text{ MW}$$
$$H_2(\text{MBTU/Hr}) = 310 + 7.85P_2 + 0.00194(P_2)^2 \qquad 100 \le P_2 \le 400 \text{ MW}$$
$$H_3(\text{MBTU/Hr}) = 78 + 7.97P_3 + 0.00482(P_3)^2 \qquad 50 \le P_3 \le 200 \text{ MW}$$

Determine the economic operating point for these three units when delivering a total of 850 MW. The fuel costs for unit 1, unit 2 and unit 3 are 1.1, 1.0 and 1.0 $/MBTU respectively.

[Ans: 393.2, 334.6, 122.2 MW.]

6.2 A two-unit power system has the following cost rate curves:

$$CR_1 = 900 + 4.1P_{G1} + 0.0035P_{G1}^2$$
$$CR_2 = 900 + 4.1P_{G2} + 0.0035P_{G2}^2$$

Assume that the transmission loss of the system is represented by

$$P_{loss} = 0.001\,(P_2 - 50)^2 \text{ MW}$$

Find the optimal generation for each unit, power loss in the transmission line and total load when $\lambda = 5$ $/MWh.

[Ans: 128.57 MW; 82.43 MW; 1.0 MW, 210 MW.]

6.3 Consider two generating units of a power plant that have cost rate functions of

$$CR_1 = 0.4P_1^2 + 10P_1 + 25 \quad \text{\$/hr}$$
$$CR_2 = 0.35P_2^2 + 6P_2 + 20 \quad \text{\$/hr}$$

(a) Determine the total load supplied if the incremental cost is λ = 150 $/MWh.
(b) Repeat the Part (a) with using the transmission losses

$$P_{LOSS} = 0.9\times10^{-4}P_1^2 + 1.4\times10^{-5}P_1P_2 + 0.8\times10^{-4}\times P_2^2 \text{ MW}$$

[**Ans: (a) 380.714MW, (b) 361 MW]**

EE4530 POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 7

REACTIVE POWER AND VOLTAGE CONTROL (I)

7.1 (a) Show how the scalar voltage difference between two nodes in a power network is given approximately by

$$\Delta V = \frac{RP + XQ}{V}$$

(b) Each phase of a 50 km, 132 kV overhead line has a series resistance of 0.156 Ω/km and an inductive reactance of 0.425 Ω/km. At the receiving end the voltage is 132 kV with a load of 100 MVA at a power factor of 0.9 lagging. Calculate the magnitude of the sending end voltage.

(c) Calculate also the approximate angular difference between the sending end and receiving end voltages.

[Ans: (b) 144.34 kV (line); (c) 4.73^0]

7.2 A three-phase induction motor delivers 500 hp (1 hp = 746 W) at an efficiency of 0.91 with the operating power factor being 0.76 lagging. A loaded synchronous motor with a power consumption of 100 kW is connected in parallel with the induction motor. Calculate the necessary kVA and the operating power factor of the synchronous motor if the overall power factor is to be unity.

[Ans: 364.51 kVA, 0.274 pf leading]

7.3 The load at the receiving end of a three-phase overhead line is 25 MW, at 0.8 power factor lagging, at a line voltage of 33 kV. A synchronous compensator is situated at the receiving end and the voltage at both ends of the line is maintained at 33 kV. Calculate the MVAr of the synchronous compensator. The line has a resistance of 5 Ω/phase and an inductive reactance of 20 Ω/phase.

[Ans: 25 MVAr]

7.4 A transformer connects two infinite busbars of equal voltage. The transformer is rated at 500 MVA and has a reactance of 0.15 p.u. Calculate the var flow for a tap setting of (a) 0.85:1; (b) 1.1:1.

[Ans: (a) 425 MVAr; (b) –367 MVAr]

EE4530 - POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 8

REACTIVE POWER AND VOLTAGE CONTROL (II)

8.1 A transmission link connects an infinite busbar supply of 400 kV to a load busbar supplying 1000 MW, 400 MVAr. The link consists of a line feeding the load busbar via a transformer with a maximum tap ratio of 0.9:1. The combined impedance of the line and transformer at 400 kV is (7 + j 70) Ω. Connected to the load busbar is a compensator. If the maximum overall voltage drop is to be 10% with the transformer taps fully utilized, calculate the reactive power requirement from the compensator. Use a base of 1000 MVA, 400 kV.

[Ans: 150 MVAr]

8.2 A 132 kV line is fed through an 11/132 kV transformer from a constant 11 kV supply. At the load end of the line the voltage is reduced by another transformer of nominal ratio 132/11 kV. The total impedance of the line and transformers at 132 kV is (25 + j 66) Ω. Both transformers are equipped with tap-changing facilities which are arranged so that the product of the two off-nominal settings is unity. If the load on the system is 100 MW at 0.9 p.f. lagging, determine the tap ratios of the transformers if the receiving-end voltage is to be maintained at 0.9 p.u. of the sending-end voltage. Use a base of 100 MVA, 11 kV.

[Ans: 1.18, 0.85]

8.3 In the system shown in Figure 8.1, determine the supply voltage necessary at Bus A to maintain a line voltage of 415 V at the load terminals at Bus C. The system data are given in Table 8.1.

Table 8.1

Line or Transformer	Rated Voltage (kV)	Transmission Rating	Impedance (Ω)
BC	0.415		0.0127 + j0.00909
T_A	11/0.415	2.5 MVA	1.5017 + j2.9667 at 11 kV

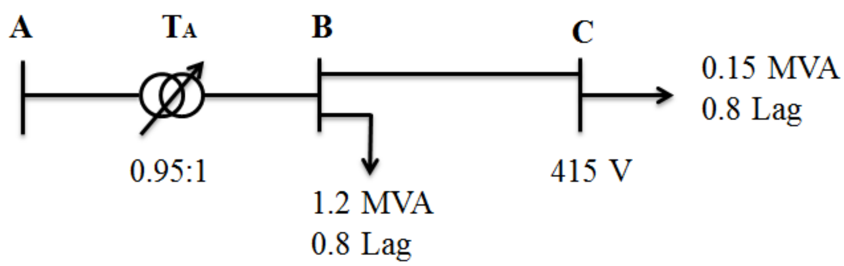

Figure 8.1

[Ans: 11 kV]

EE4530 - POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 9

REACTIVE POWER AND VOLTAGE CONTROL (III)

9.1 Two substations, A and B, are connected by two transmission lines in parallel, of negligible impedance, each containing a transformer of reactance 0.18 p.u. and rated at 120 MVA. Calculate the absorption of reactive power at substation B when the transformer taps are set to 1.15:1 and 0.85:1, respectively (i.e. stagger tap is used). The p.u. voltages are equal at the two ends and are constant in magnitude.

[Ans: -30 MVAr]

9.2 Figure 9.1 shows a transmission system which delivers 1000 MW, 500 MVAr to a load busbar B. The equivalent source at busbar A has a constant voltage of 400 kV and the equivalent reactance between the source and load busbar is 70 Ω. A tap-changing transformer is used to regulate the voltage at busbar B. The transformer leakage reactance is 10 Ω referred to 400 kV side. A compensator is connected to the load busbar. In order to maintain the maximum overall voltage drop to 5% with the transformer taps fully utilized, the compensated reactive power Q_C of 252 MVAr is required at busbar B. Calculate the minimum value of the transformer tap ratio "t". Use a base of 1000 MVA, 400 kV.

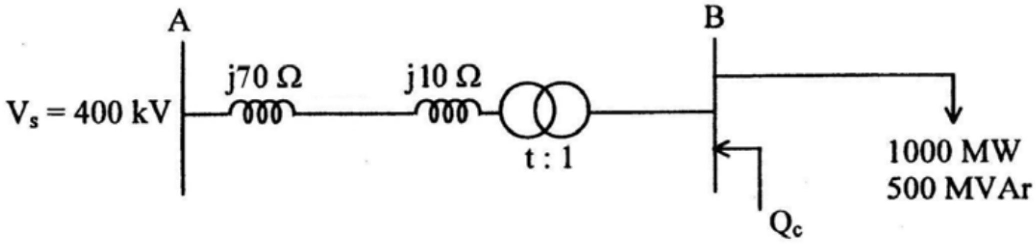

Figure 9.1

[Ans: t=0.9]

EE4530 - POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 10

ROTOR DYNAMICS AND SWING EQUATION

10.1 A 50-Hz, 4-pole generator rated 10 MVA, 13.2 kV has an inertia constant of H=6.5 MJ/MVA.

(a) Calculate the kinetic energy stored in the rotor at synchronous speed.
(b) Find the acceleration if the net mechanical power input is 13,400 hp and the electrical power developed is 8 MW.
(c) Assume that the acceleration computed in part (b) is constant for a period of 10 cycles. Find the change in δ in electrical degrees in that period.
(d) If the generator is delivering rated MVA at 0.8 power factor lagging when a fault reduces the electrical power output by 50%, determine the accelerating torque at the time the fault occurs.

[Ans: (a) 65 MJ; (b) 276.37 elect deg/sec^2; (c) 5.52 elect deg; (d) 25464.8 N-m]

10.2 A 250-MVA, 2-pole, 50 Hz, 3-phase generator has a synchronous reactance of 1.2 per unit and a moment of inertia of 40 x 10^3 kg.m^2. The generator is connected directly to an infinite bus operating at a voltage of $1.0\angle 0^0$ per unit. The generator no-load voltage is 1.25 per unit.

(a) The generator is running steadily at synchronous speed and delivering 200 MW to a load. If the load is suddenly removed, determine the rotor acceleration at this instant.
(b) If the acceleration of the rotor in part (a) is constant for a period of 13 cycles, find the change in the rotor angle in electrical radians over that period and the rotor speed in revolutions per minute at the end of this period.

[Ans.: (a) 15.907 rad/s^2; (b) 0.538 rad; 3039.5 rpm]

EE4530 POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 11

POWER-ANGLE EQUATION AND EQUAL-AREA CRITERION

11.1 A synchronous generator having reactance 1.25 per unit is connected to an infinite bus of voltage 1.0 per unit through a step-up transformer and a high-voltage transmission line of total reactance 0.55 per unit. The generator no-load voltage is 1.25 per unit and its inertia constant H = 4 MJ/MVA. Network resistances and machine damping are assumed negligible. The system frequency is 50 Hz. Calculate the frequency of natural oscillation under small disturbance conditions if the generator is loaded to (i) 50% and (ii) 80% of its maximum power limit.

[Ans.: 0.773 Hz, 0.645 Hz]

11.2 A 50-Hz generator is delivering 0.8 per unit real power to an infinite bus through a purely reactive network as shown in Figure 11.1. The magnitudes of both the generator terminal voltage and the infinite bus voltage are 1.0 per unit. All the per unit values are expressed using the same bases.

(a) Determine the critical clearing angle of the generator and the critical clearing time for a three-phase fault at the generator terminals.

(b) After the fault has been cleared and the system returns to steady-state condition, a reactive load of j0.1 per unit is suddenly connected to the generator terminals. Determine whether the system can maintain its stability.

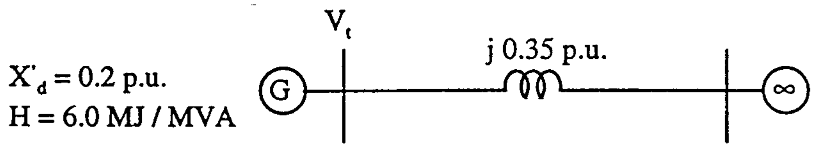

Figure 11.1

[Ans.: (a) 86.74^0, 0.32 sec; (b) Unstable]

EE4530 POWER SYSTEM ANALYSIS AND CONTROL

TUTORIAL 12

EQUAL-AREA CRITERION OF STABILITY

12.1 The generator shown in Figure 12.1 supplies an apparent power of 1.18 per unit at 0.85 power factor lagging to an infinite bus through a transformer and a double-circuit transmission line. The reactance shown are in per unit on a common system base.

(a) Determine the generator internal voltage and obtain the power-angle equation.

(b) A three-phase fault occurs at F which is located in the middle of one of the circuits and the fault is cleared by opening circuit breakers A and B. If the fault is cleared at a power angle of 52^0, determine whether the system is stable.

(c) If the same fault at F is sustained, show that the system is unstable. State the assumptions made in your calculation.

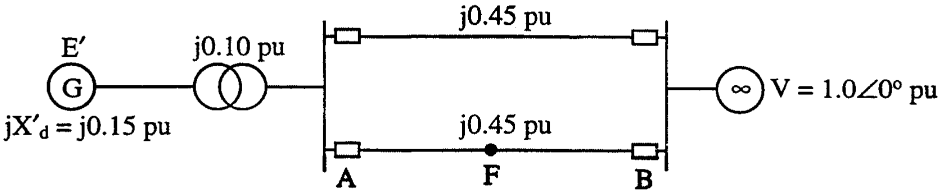

Figure 12.1 Tutorial Question 12.1

[Ans.: (a) 1.380∠20.193^0 pu; (b) Stable]

12.2 The power-angle equation for a generator supplying 1.0 per unit real power to an infinite bus is given by

$$P = 2.7 \sin \delta \text{ per unit}$$

where δ is the power angle. Under a three-phase fault condition, the power-angle equation is then described by

$$P = 1.1 \sin \delta \text{ per unit}$$

(a) If the fault is transient in nature and is cleared at a power angle of 70^0, the system returns to the prefault condition. Determine whether the system is stable.

(b) For the system and fault conditions described in part (a), determine the stability margin of the system.

(c) If the fault is not cleared, would the system be stable?

[Ans.: (a) stable; (b) 1.6972; (c) unstable]