EE4-48
EE9CS6-2

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2012

MSc and EEE PART IV: MEng and ACGI

POWER SYSTEM CONTROL, MEASUREMENT AND PROTECTION

Monday, 14 May 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible	First Marker(s) :	B.C. Pal
	Second Marker(s) :	B. Chaudhuri

The Questions

1.

a) Answer the following:

i) How is saliency power produced in a synchronous machine connected to network?

[4]

ii) Why frequency control cannot be influenced by the network?

[3]

iii) Why are characteristics of lightning phenomena important in protection design?

[3]

iv) How can both transient and small signal stability be maintained by a large synchronous generator control?

[3]

b) A 3-phase, star connected, 15.75 kV (V_t) (line-line), 300 MVA alternator is connected to the grid operating at 50 Hz. The resistance is negligible and the synchronous reactance (X_s) is 1.5 Ohm.

i) Find the excitation voltage (line-line) and the power angle when the generator is delivering a full load at 0.90 power factor lagging.

[4]

ii) Keeping the prime mover power at the value obtained in (i), if the excitation is gradually decreased by 10% the generator will continue to deliver the same MW but at a different power angle. Find the new power angle and comment on the impact of the decreased excitation voltage on the machine stability.

[3]

2.

a) Describe briefly two major functions of excitation system from power network operation perspective.

[8]

b) A solid state static excitation system has gain K_A and T_A. The system voltage (V_t) fed (negative feedback) to the automatic voltage regulator (AVR) is by a sensing circuit with a first order response time constant T_r. The other input to the AVR is reference voltage V_{ref}. The output of the excitation system is generator rotor field voltage E_{fd}. Draw appropriate block diagram and then derive the relevant differential equations.

[7]

c) Briefly describe how the high voltage lines and cables can contribute to the reactive power control of power systems.

[5]

3.

a) Answer the following

i) The terminal voltage of a synchronous generator drops with increasing loading. Generally higher is the synchronous reactance larger is the drop. Too much voltage drop at the terminal is not desirable from network voltage support perspective. Nevertheless, machine with large synchronous reactance is a standard design practice. Justify with reasons.

[3]

ii) A synchronous generator has lower VAR absorption capacity than VAR generation capacity. Justify the statement with reason.

[3]

iii) Define H constant in the context of synchronous machine electromechanical dynamics.

[2]

iv) A steam turbine driving a generator of capacity 500 MW has H constant of similar range to that of a wind turbine driving 5 MW generator. Justify the statement with reason.

[3]

iv) What is "field flashing" in the context of synchronous generator and how is it realised in practice?

[3]

b) A synchronous generator supports a terminal voltage of 23.5 kV line to line at the generator terminal bus. This bus is part of a large network which has a reference bus at a different location. The power flow solution produces an angle of 10 degrees for this bus voltage. The generator load angle (δ) is 30 degrees. Compute the direct and quadrature axis component of this voltage in machine reference frame

[6]

4.

a)

i) What is *droop* in speed governing?

[2]

ii) Describe in reasonable details how primary frequency control is implemented in a system with different droop settings in many generators.

[6]

b) An interconnected power system has two commercial areas. The composite droop and load frequency sensitivity of Area 1 are R_1 and D_1 respectively and the same for Area 2 are R_2 and D_2. For a change in Area 1 load by ΔP_{L1} the change in the generation in Area 1 and 2 are ΔP_{m1} , ΔP_{m2} respectively. The associated change in the tie line flow is ΔP_{12}. Derive that the associated frequency deviation Δf is related as:

$$\Delta f = -\frac{\Delta P_{L1}}{D_1 + \frac{1}{R_1} + D_2 + \frac{1}{R_2}}$$

[6]

c) Area 1 has Gen 9,000 MW, Load 10,000 MW; Area 2 has Gen 31,000 MW and Load 30,000 MW. The load in each area varies 1% with 1% change in the frequency. The composite droop is 4% for both areas. Area 1 is importing 1000 MW from Area 2. For the loss of 1000 MW load in Area 1, find the change in the system frequency when there is no tie-line supplementary control. Assume the nominal system frequency to be 50 Hz.

[6]

5.

a)

i) Why do numerical relays require a lower burden compared to other types?

[3]

ii) How can adaptability be implemented in numerical relays?

[3]

b)

i) Define any two desirable attributes of a relay.

[5]

ii) You are asked to design protection system for a network which is likely to operate under stressed operating condition frequently. Which attribute of the relay should you be giving higher consideration and why?

[3]

c) The performance of an over current relay was monitored for a period of three years. It was found that the relay operated 38 times, out of which 34 were correct trips. If the relay failed to issue trip decisions on 5 occasions, compute dependability, security and reliability of the relay as percentages.

[6]

6

a) A 1000/5 C400 current transformer (CT) is connected to a relay with a burden of 1.0 Ω. The secondary resistance of the CT is 0.51 Ω. The total lead (connecting the CT to the relay room) resistance is 1.0 Ω. For a secondary current of 110 A flowing through the relay coil;

i) Is the CT still expected to behave in a linear manner? Justify your answer.

[5]

ii) The magnetising impedance (as referred to the secondary of the CT) is 3 kΩ. Calculate the % ratio error.

[3]

b) The secondary of a CT accidentally gets disconnected from the relay and other connected burden. Describe in details possible consequences.

[5]

c)

i) Why are capacitive coupled voltage transformer (CCVT) used for metering and protection?

[3]

ii) What are the possible limitations of using CCVT in system protections and how are they overcome?

[4]

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The Answers 2012

1.

a) *Answer the following:*

i) *How is saliency power produced in a synchronous machine connected to network?*

[4]

Usually salient pole generator has variable air gap leading to different synchronous reactance along direct and quadrature axes. This variable reactance produces reluctance torque that is independent of excitation system voltage. This is clear from the second term in the power angle relation of synchronous machine.

$$P = \frac{E_{fd}V_t}{X_d}\sin\delta + \frac{V_t^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

ii) *Why frequency control cannot be influenced by the network?*

[3]

The network comprises of transmission lines, transformers, reactors and capacitors. Generally they influence system voltage as they can produce/absorb reactive power. Frequency is very much related to balance of real power which is mainly sourced by generators or energy storage devices. Because of this fundamental arrangement in power system, frequency control cannot be influenced by the network.

iii) *Why are the characteristics of lightning phenomena important in protection design?*

[3]

The current associated with lightning is very high and of short duration. Such high current produces very high transient voltage across electrical devices which can be damaging for the operating life of those devices. It is important to provide safe and solid path of the passage of the current to the ground. In some soil condition soil resistivity is very high and dependant on climatic condition requiring grounding through finite tower footing resistance. It becomes very important to have a clear idea about the ampere seconds relation of the lightning phenomena to design ground resistance and hence the protection.

iv) *How can both transient and small signal stability be maintained by a large synchronous generator control?*

[3]

High gain fast acting excitation control provides good transient stability limit. This is done through large excitation voltage produced over very short period of time. The small signal stability is maintained or even improved by power system stabiliser that introduces high and positive damping torque.

b) *A 3-phase, star connected, 15.75 kV (V_t) (line-line), 300 MVA alternator is connected to the grid operating at 50 Hz. The resistance is negligible and the synchronous reactance (X_s) is 1.5 Ohm.*

i) *Find the excitation voltage (line-line) and the power angle when the generator is delivering a full load at 0.90 power factor lagging.*

[4]

The rated capacity is $\sqrt{3V_L I_L} = 300\ MVA$, The full load current is 10990 A. Power factor -25.84 degree.

$$E_{fd} = 15.75 + \sqrt{3} * j * I_L * X_s = 38.14 < 42.34^0$$

ii) *Keeping the prime mover power at the value obtained in (i), if the excitation is gradually decreased by 10% the generator will continue to deliver the same MW but at a different power angle. Find the new power angle and comment on the impact of the decreased excitation voltage on the machine stability.*

[3]

Full load real power is 300*0.9 = 270 MW.

At 10% reduced excitation:

$$P = \frac{V_t E_{fd}}{X_s} sin\delta$$

270 = 0.9*38.14*15.75*sin(delta_new)/1.5

delta_new = 48.51 degree

The stability margin is reduced as the load angle has increased.

2.

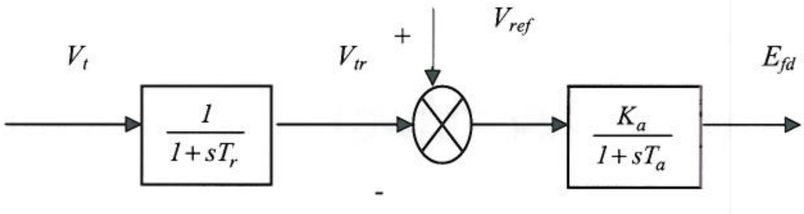
a) *Describe briefly two major functions of excitation system from power network operation perspective.*

[8]

Two important functions of excitation system is voltage/VAR control and stability control. The students are expected to write how voltage/VAR support is provided by excitation system. They should demonstrate their understanding of magnetic excitation flux and its relationship to reactive power (both in leading and lagging direction). In terms of stability they should elaborate on the response time and capability to produce high synchronising torque when machine is subjected short circuit. They can also mention about oscillatory stability and how additional control through excitation system the margin of that stability is increased.

b) *A solid state static excitation system has gain K_A and T_A. The system voltage (V_t) fed (negative feedback) to the automatic voltage regulator (AVR) is by a sensing circuit with a first order response time constant T_r. The other input to the AVR is reference voltage V_{ref}. The output of the excitation system is generator rotor field voltage E_{fd}. Draw appropriate block diagram and then derive the relevant differential equations.*

[7]



Block Diagram of a Fast Excitation System

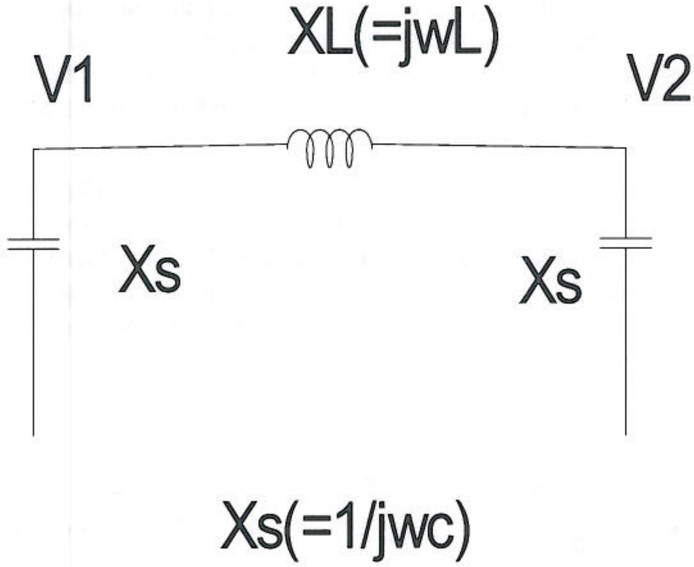
A set of differential equation can be written as follows:
dVtr / dt = 1/Tr [-Vtr + Vt]
dEfd / dt = 1/TA [(Vref-Vtr)-Efd]

c) *Briefly describe how the high voltage lines and cables can contribute to the reactive power control of power systems.*

[5]

Lines and cables are passive sink and source of reactive power. They accordingly influence the network voltage control.

- Typically a 400-KV single circuit line produces 60-70 MVAR per 100 km
- 400-KV cable produces 20 MVAR per km.



- At light load (during night) generation is more than the absorption: hence the system voltage is higher than nominal.
- At higher load (during peak hours) absorption in the series branch is considerably higher than the generation in the shunt branch: the net effect brings the system voltage lesser than normal.

3.

a) *Answer the following*

i) *The terminal voltage of a synchronous generator drops with increasing loading. Generally higher is the synchronous reactance larger is the drop. Too much voltage drop at the terminal is not desirable from network voltage support perspective. Nevertheless, machine with large synchronous reactance is a standard design practice. Justify with reasons.*

[3]

Larger synchronous reactance is because of low air gap construction. The advantage is economics of constructions, overall smaller size generator. The disadvantage is poor voltage regulation. But with static brushless or potentially controlled AC excitation system, the poor voltage regulation is eliminated through high gain fast acting Automatic voltage regulator (AVR).

ii) *A synchronous generator has lower VAR absorption capacity than VAR generation capacity. Justify the statement with reason.*

[3]

The leading power factor operation is always a problem from the temperature rise perspective in the end part of the stator winding. The flux distribution during leading power operation in the collar of end winding produces larger circulating current. This is the reason during leading current operation (absorption) the limit of reactive current that can be accommodated is low. While for lagging power factor operation, it is always other way round. The stator and rotor flux are demagnetising in nature resulting in partial cancellation. This is good from the localised heating in the end ring as well as other parts of the stator.

iii) Define H constant in the context of synchronous machine electromechanical dynamics.

[2]

H constant is defined as stored energy (in Mega joules) per rated capacity (in MVA). It is expressed in seconds

iv) A steam turbine driving a generator of capacity 500 MW has H constant of similar range to that of a wind turbine driving 5 MW generator. Justify the statement with reason.

[3]

Stored energy in wind generator is quite considerable as the angular moment of inertia is very high because large diameter of the blades. The speed of rotation is much less compared to synchronous machine. When normalised to capacity, the H constants turn out to be similar.

iv) What is "field flashing" in the context of synchronous generator and how is it realised in practice?

[3]

During starting up of synchronous generator, the rotor current is not readily available as the excitation system depends on either the terminal voltage (static excitation system) or generator speed (brushless excitation system). To produce initial voltage flux from the rotor circuit is needed. This comes from residual magnetism of the rotor circuit but that is not always adequate or guaranteed. It becomes necessary to excite the rotor winding through current from some other sources. Generally power station battery are used to do this. This process is known as filed flashing.

b) A synchronous generator supports a terminal voltage of 23.5 kV line to line at the generator terminal bus. This bus is part of a large network which has a reference bus at a different location. The power flow solution produces an angle of 10 degrees for this bus voltage. The generator load angle (δ) is 30 degrees. Compute the direct and quadrature axis component of this voltage in machine reference frame

[6]

Vmachine = Vnetwork e $^{-j(\text{angle between two references})}$
In this case

Vmachine = $23.5\ e^{-j(30-10)}$
Vmachine = $23.5\ e^{-j20}$
= 22.08 – j 8.03 kV.
V_q = 22.08 kV
V_d = -8.03 kV

This reference frame transformation is an orthogonal (rotation can be easily visualized in two dimension) – does preserve line length.

4.

a)

i) What is *droop* in speed governing?

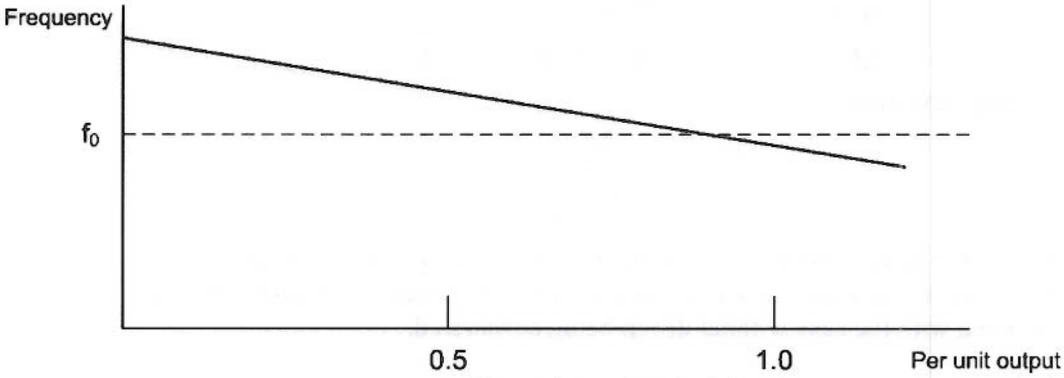
[2]

The droop is a power output versus frequency characteristics of synchronous machine in the steady state. This is used to control the output power of a generator as the system frequency slightly changes. This is very necessary in stable and synchronous operation of many generators.

ii) Describe in reasonable details how primary frequency control is implemented in a system with different droop settings in many generators.

[6]

The droop can be set at different values for different generators in order to define their relative shares on the total change in demand. This will also allow insertion of new input load reference point.



Speed-droop characteristic

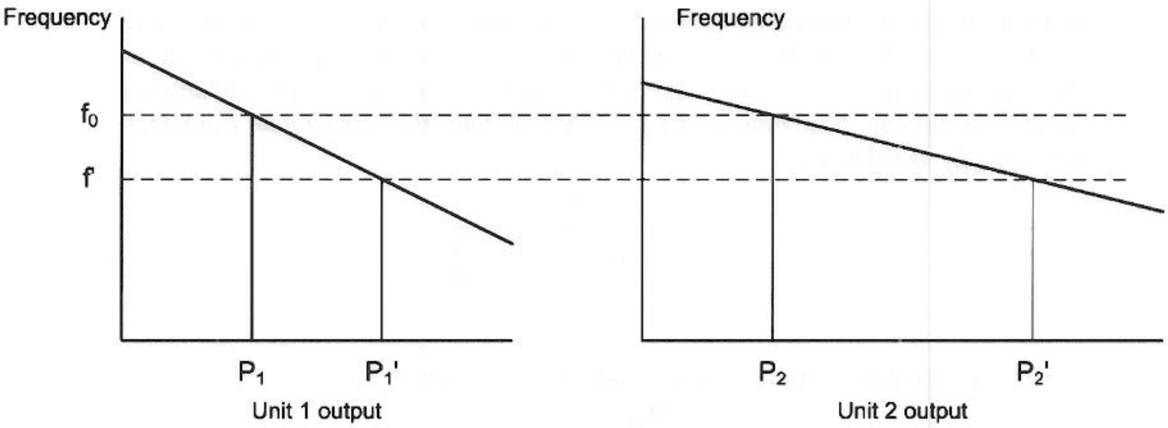


Fig: load sharing through proper droop arrangement

Let's now turn our attention to the influence of speed governing control on the frequency deviation due to change in load. We assume a generic turbine model $G_t(s)$.

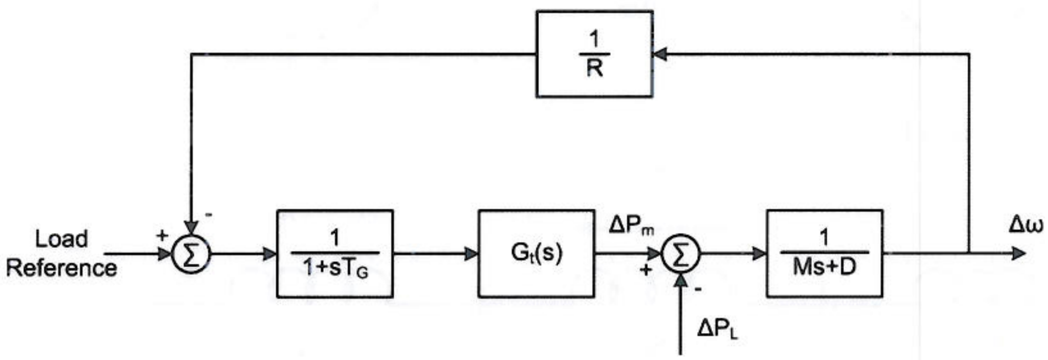


Fig: Block diagram of governor with droop for generator speed control

Let us assume that generic transfer function of turbine (steam as well as hydro) is expressed as $G_t(s)$. Assuming 100% efficiency the gain between the power input to the turbine to the power output will be unity. The transfer characteristic between ΔP_L and $\Delta\omega$ can be expressed as

$$\frac{\Delta\omega}{\Delta P_L} = -\frac{R(1+sT_G)}{G_t(s)+(Ms+D)R(1+sT_G)}$$

The steady state frequency deviation

$$\Delta\omega_{ss} = -\frac{\Delta P_L}{D+\frac{1}{R}}$$

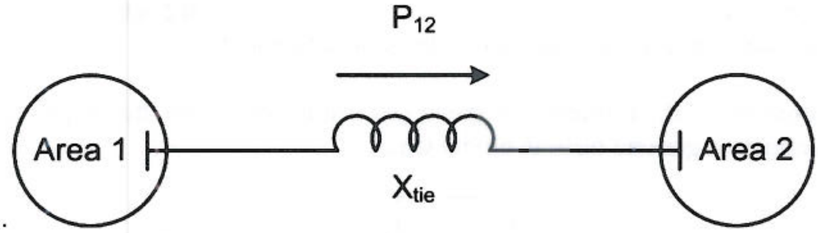
It is interesting to note that the denominator is now dominated by the reciprocal of the droop (R). This will reduce the steady state speed deviation because of change in demand. This can easily be compared with the case without droop being considered.

b) *An interconnected power system has two commercial areas. The composite droop and load frequency sensitivity of Area 1 are R_1 and D_1 respectively and the same for Area 2 are R_2 and D_2. For a change in Area 1 load by ΔP_{L1} the change in the generation in Area 1 and 2 are ΔP_{m1} , ΔP_{m2} respectively. The associated change in the tie line flow is ΔP_{12}. Derive that the associated frequency deviation Δf is related as:*

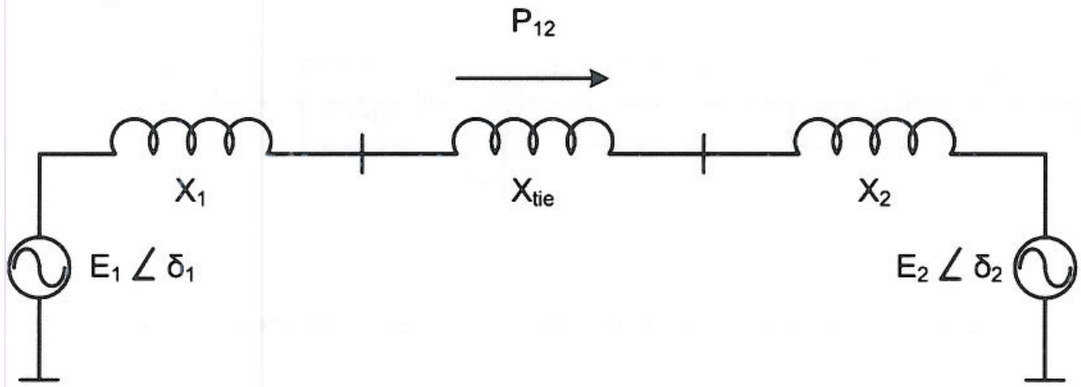
$$\Delta f = -\frac{\Delta P_{L1}}{D_1+\frac{1}{R_1}+D_2+\frac{1}{R_2}}$$

[6]

For interconnected system schedule tie line power is an additional variable.



The electrical equivalent is as follows:

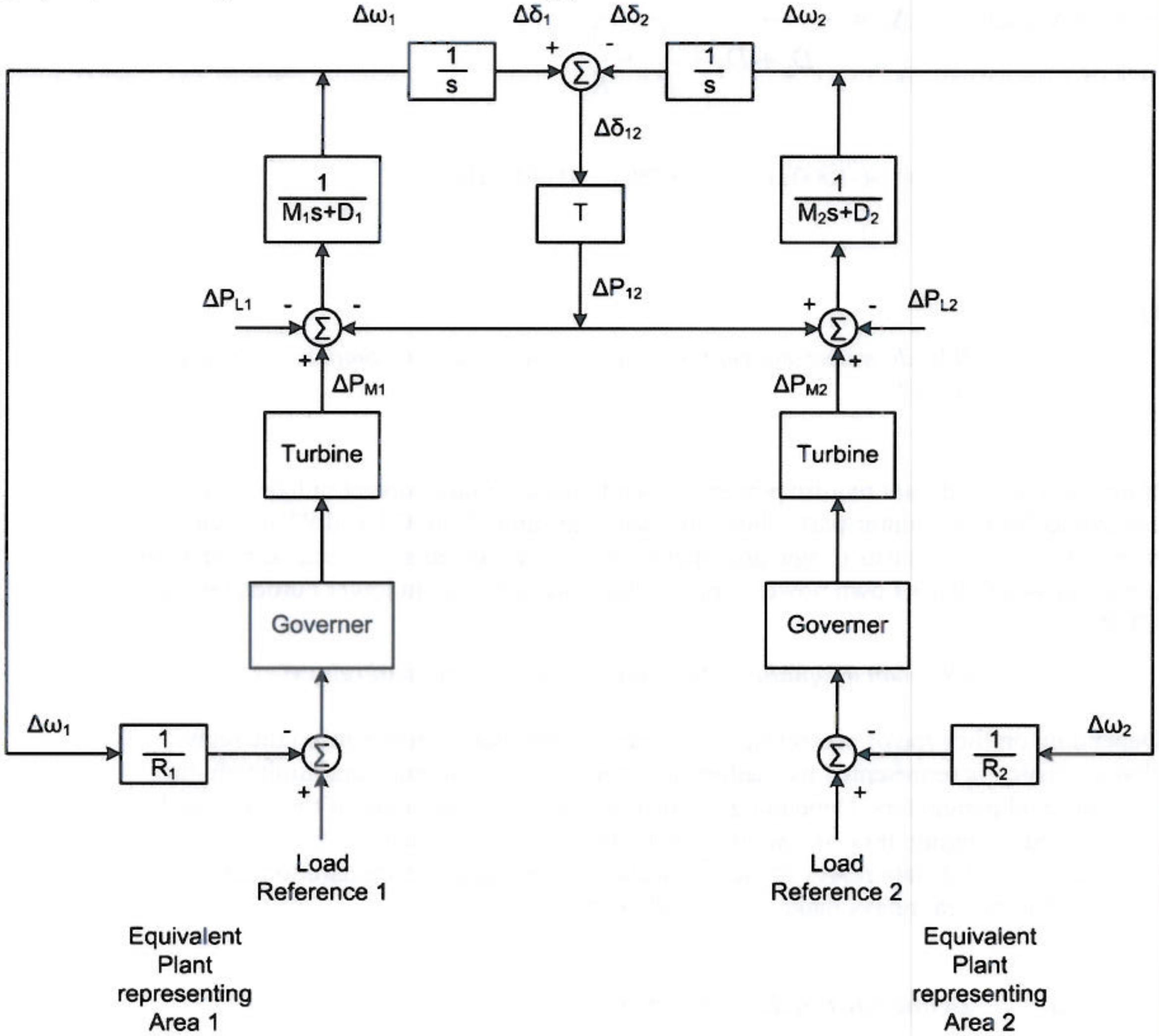


In an interconnected system operation as shown in the figure, it is important to consider the scheduled interchange power. These two areas can be modelled as two equivalent voltage sources behind source reactance and tie line reactance.

$$P_{12} = \frac{E_1 E_2}{X_T} sin(\delta_1 - \delta_2)$$

The linearized form of the above equation is:

$\Delta P_{12} = T(\Delta\delta_1 - \Delta\delta_2)$ where $T = \frac{E_1 E_2}{X_T} cos(\delta_{10} - \delta_{20})$ is the synchronising power co-efficient. The block diagram below shows this. Note each area is represented by its composite load damping and frequency characteristic. The frequency deviation $\Delta\omega_1 = \Delta\omega_2 = \Delta\omega = \Delta f$ is common in both area connected by tie. The tie power deviation ΔP_{12} will be seen as load in area 1 and generation in area 2 (import) and its sign will be assumed accordingly.



This two area system with primary governor control can easily be characterised by the following equation or relation:

$$\Delta f = -\frac{\Delta P_L}{D_1 + D_2 + \frac{1}{R_1} + \frac{1}{R_2}}$$

c) *Area 1 has Gen 9,000 MW, Load 10,000 MW; Area 2 has Gen 31,000 MW and Load 30,000 MW. The load in each area varies 1% with 1% change in the frequency. The composite droop is 4% for both areas. Area 1 is importing 1000 MW from Area 2. For the loss of 1000 MW load in Area 1, find the change in the system frequency when there is no tie-line supplementary control. Assume the nominal system frequency to be 50 Hz.*

[6]

First step is to obtain droop and frequency sensitivity co-efficient of the loads.

$1/R_1$ = 1/0.04*9000/50 = 4500 MW/Hz, $1/R_2$ = 1/0.04*31000/50 = 15500 MW/Hz:
Combined droop: $1/R_1+1/R_2$ = 20000 MW/Hz
D_1 = (10000- loss of 1000)*1/100/(50/100) = 180 MW/Hz
D_2 = (30000)*1/100/(50/100) = 600 MW/Hz
Total effective damping = D_1+D_2 = 780 MW/Hz. Change in frequency due to loss of 1000 MW load is = $\Delta f = -\frac{\Delta P_L}{D_1 + D_2 + \frac{1}{R_1} + \frac{1}{R_2}}$

= -(-1000)/(20000+780) = 0.0481 Hz

5.

a)

i) *Why do numerical relays require a lower burden compared to other types?*

[3]

Numerical relays do not require power to operate the auxiliary contact unlike their electromechanical counter-part. They only need the signal from CT and PT in digital form. The rest of the tasks (logic and operation) are processed and executed by the mini computer which has its own power supply. This always results in lower burden on the CT/PT.

ii) *How can adaptability be implemented in numerical relays?*

[3]

Depending on the type of protection (over current, distance or differential) the relay characteristic is represented by mathematical equations with range and limits on the variables and parameters. Depending on the operating circumstances, if the limits and ranges need changing, they are easily done by modifying the equation through software. In the case of solid state relays or electromechanical relays these are hard to realise. This feature of numerical relays makes it very adaptable.

b)

i) *Define any two desirable attributes of a relay.*

[6]

The students are expected to write very short descriptions (5-6 sentences each) of any two of the desirable attributes: dependability, sensitivity, security, selectivity and reliability.

ii) *You are asked to design protection system for a network which is likely to operate under stressed operating condition frequently. Which attribute of the relay should you be giving higher consideration and why?*

[2]

The dependability is a property that guarantees operation whenever there is fault. The security is an attribute when the relay should not operate when it is not expected to operate. In the case of stressed operation, there can be many situation when normal (but stressed) operation will be seen as fault by some relays (load encroachment under poor voltage condition). Under such condition it is best not to operate the relay in anticipation that the situation will change. If the relay operates undesirably, it will make the system vulnerable/weaker resulting in increased risk for likelihood of further bigger disturbance. So it is best to offer higher consideration to security over dependability.

c) *The performance of an over current relay was monitored for a period of three years. It was found that the relay operated 38 times, out of which 34 were correct trips. If the relay failed to issue trip decisions on 5 occasions, compute dependability, security and reliability of the relay as percentages.*

[6]

Correct trips: 34, total trip 38, number of desired trips: 34+5 = 39

Dependability (%): Number of correct trip/Number of desired trip*100 = 34/39*100

Security (%): Number of correct trip/Number of total trips*100 = 34/38*100

Reliability(%): Number of correct trip/(Number of desired trip+number of incorrect trip)=34/(39+4)*100 =

6

a) *A 1000/5 C400 current transformer (CT) is connected to a relay with a burden of 1.0 Ω. The secondary resistance of the CT is 0.51 Ω. The total lead (connecting the CT to the relay room) resistance is 1.0 Ω. For a secondary current of 110 A flowing through the relay coil;*

i) *Is the CT still expected to behave in a linear manner? Justify your answer.*

[4]

The fault current is 110/5= 22 times the normal current. The secondary voltage is 110*(1.0+1.0+0.51) = 276 volt. Since the voltage is less than 400 V (C400 spec allows that much), the CT will behave linearly.

ii) *The magnetising impedance (as referred to the secondary of the CT) is 3 kΩ. Calculate the % ratio error.*

[4]

Exciting current is 276/3000 A. Secondary current is 110 A. The ratio error (%) = Exciting current/Secondary current *100 = 276/(3000*110) = 0.0837%

b) *The secondary of a CT accidentally gets disconnected from the relay and other connected burden. Describe in details possible consequences.*

[5]

The primary current of the CT is the load current. This acts like a current source. If the secondary current is interrupted, the entire primary current will flow through the magnetising branch (no secondary current to balance large part of primary current). This will produce very high voltage and will stress the insulation. After few cycles of high voltage, the insulation will burn and will damage the CT permanently. The mechanism of failure is through puncture of insulation because of very high voltage due to secondary remaining open.

c)

i) *Why are capacitive coupled voltage transformer (CCVT) used for metering and protection?*

[3]

There are three distinct features of CCVT that the students should point on: economy, size, features of carrier line communication.

ii) *What are the possible limitations of using CCVT in system protections and how are they overcome?*

[4]

The major problem is phase shift because of capacitive voltage divider action. This is compensated by a tuning inductor, but with time the value of the capacitance changes. The capacitances of two sections are also not fixed as they have tolerance, so exact phase compensation is not achieved. This introduces phase angle error. The electromagnetic transformer has non linearity as well. During fault with Dc offset is system voltage, the transient behaviour of the CCVT is poor. There is also risk of ferro resonance. Usually with good tuning circuit for phase compensation and ferro resonance damper circuit these problems are overcome. Some of these problems can be overcome by software algorithm in numerical relays as well.