Final

E4.48
CS6.2

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2010

MSc and EEE PART IV: MEng and ACGI

POWER SYSTEM CONTROL, MEASUREMENT AND PROTECTION

Friday, 21 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) The following events in power systems lead to dynamic response of the system quantities such as voltage, current and frequency. Associate the time scale of these events in appropriate unit.

i) Network switching surges

ii) Transient stability

iii) Boiler and long term dynamics

[3]

b) Why do hydro turbines have non-minimum phase transfer characteristic between the water gate position and power output? How can this be overcome?

[5]

c) In a salient pole synchronous generator, the voltage current relations along the **d** and **q** axis are as follows:

$$E_{fd} - V_q + I_d X_d = 0$$

$$V_d + I_q X_q = 0$$

where the symbols carry their usual meanings.

Taking the terminal voltage $\bar{V}_t$ as the reference vector, the **q**-axis is defined to lead $\bar{V}_t$ by an angle δ.

The terminal voltage and current vector of the machine are related by:

$$\bar{V}_q + j\bar{V}_d = \bar{V}_t e^{-j\delta};\ \bar{I}_q + j\bar{I}_d = \bar{I}_t e^{-j\delta}$$

i) Making use of the above information, derive the power angle relationship of the machine.

[6]

ii) For the following values of the variables in p.u. obtain the real and reactive power output of the machine in p.u.

$X_d = 2.0$, $X_q = 1.8$, $V_t = 1.05$, $E_{fd} = 3.0$ and $\delta = 20$ degrees

[3]

iii) Suddenly the machine loses excitation. Justify through load angle computation whether the stability will be maintained if the mechanical input was to remain unchanged.

[3]

a) Starting from the inertia constant J (Kg-m^2), rated VA as VA_{base}, basic torque and angle equations in a rotational system, derive the following swing equations of a synchronous generator connected to the grid:

$$\frac{d\delta}{dt} = \omega_r - \omega_s$$

$$\frac{2H}{\omega_s}\frac{d\omega_r}{dt} = P_{mech} - P_{elec} - D(\omega_r - \omega_s)$$

$\delta =$ is the angle of the rotor with respect to a synchronously rotating reference frame;

ω_r, ω_s: speed of the rotor and synchronous reference frame respectively in rad/sec.

P_{mech}, P_{elec}: mechanical power input and electrical power output in p.u. respectively

$H =$ H-constant in seconds

D: mechanical damping co-efficient in p.u.-sec/rad

[8]

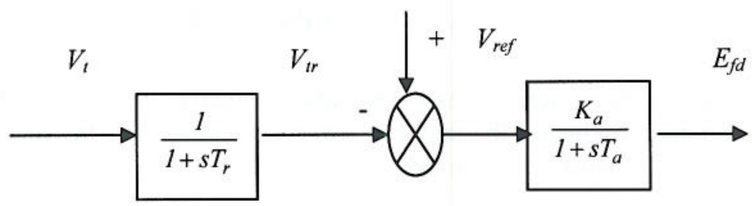
b) The moment of inertia of a generator-turbine mass is 30,000 Kg-m^2. The generator has a rating of 600 MVA and operates at 3000 RPM. Find the

i) stored energy [3]

ii) H-constant (H) [2]

iii) mechanical starting time (T_M) [1]

c) A simplified model of a fast excitation system is shown in Figure 2.1. It is required to produce a 4.0 p.u. of E_{fd} in the steady state. The voltage regulator has a gain of 400 and time constant of 0.03 s. Compute the reference voltage V_{ref} that needs to be set in order to maintain a terminal voltage of 1.05 p.u.



2.1 Block Diagram of a Fast Excitation System

[6]

3.

a) Briefly describe the nature and importance of the primary frequency control in power systems.

[3]

b) Including the effect of the governor droop characteristic, establish the following relationship:

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

where, D is the load damping co-efficient, ΔP_L is change in demand, R is the droop and $\Delta\omega_{ss}$ is the steady state angular frequency deviation in p.u.

[8]

c) A small 50 Hz system consists of 5 identical 600 MVA units feeding a total load of 1550 MW. The H constant of each unit is 6.0 sec on their own base MVA. Each unit has 5% governor droop mechanism fitted. The load varies by 2% for 1% change in frequency. For a sudden increase of 50 MW of load find the steady state frequency deviation in Hz. Obtain the frequency deviation

i) without droop

[4]

ii) with droop.

[4]

iii) comment on the effectiveness of droop control in view of the results obtained above.

[1]

4

a) List the various frequency control regimes with their associated time scales of operation.

[3]

b) A power system has combined generation inertia constant M (= 2H) (sec) and load damping co-efficient of D (p.u power per p.u change in frequency). It is equipped with a primary frequency control feature. For an increase in system load (ΔP_L in p.u), derive an expression for the steady state frequency deviation in p.u for the following two situations

i) without governor droop control

[5]

ii) with governor droop control having droop R

[4]

c) A small 60 Hz system consists of 4 identical 500 MVA generating units feeding a total load of 1,020 MW. The H constant of each unit is 5.0 seconds on a 500 MVA base. The load varies by 1.5% for 1% change in frequency. For a sudden drop in load by 20 MW answer the following

i) Compute the equivalent M, D and express load variation on 2000 MVA base

[6]

ii) Find the frequency deviation in the steady state assuming no speed governing option.

[2]

5.

a) Describe the purpose of the protection systems. [4]

b) Discuss the various components and functionalities of numerical relays. [5]

c) Distinguish between the dependability and security of a relay. [4]

d) The performance of an over current relay was monitored for a period of one year. It was found that the relay operated 14 times, out of which 12 were correct trips. If the relay failed to issue trip decisions on 3 occasions, compute the dependability, security and reliability of the relay as a percentage of ideal performance [7]

6

a) A 1200/5 C400 current transformer (CT) is connected to a relay with a burden of 0.7 Ω. The secondary resistance of the CT is 0.61 Ω. A secondary current of 105 A flows through the relay coil.

i) For this secondary current, is the CT still expected to behave in a linear manner? Justify your answer.

[3]

ii) The magnetising impedance (as referred to the secondary of the CT) is 5 k Ω. Calculate the % ratio error.

[4]

b) In what ways does a high ratio error affect the quality of CT's measurement?

[3]

c) What are the performance requirements of a protection grade CT? How do they differ from a measurement grade CT?

[4]

d) Draw the equivalent circuit for a capacitively coupled voltage transformer (CCVT). Briefly describe the purpose of the tuning inductor in a CCVT. Derive the required expression for the tuning inductor in this circuit?

[6]

The Solutions 2010

1.

a) *The following events in power systems lead to dynamic response of the system quantities such as voltage, current and frequency. Associate the time scale of these events in appropriate unit.*

i) *Network switching surges*

ii) *Transient stability*

iii) *Boiler and long term dynamics*

[3]

Answer

i) Network switching surge in the range of a few microseconds to few hundred micro seconds

[1]

ii) Transient stability in the range of first few seconds (5 seconds) after the initiating event

[1]

iii) Boiler and long term dynamics: few tens of seconds to few tens of minutes

[1]

b) *Why do hydro turbines have non-minimum phase transfer characteristic between the water gate position and power output? How can this be overcome?*

[5]

The Mechanics of power production in hydro turbine is characterised by the following relation

$$\Delta P_m = \left[\frac{1 - T_w s}{1 + 0.5 T_w s}\right] \Delta G$$

$\Delta P_m, T_w, \Delta G$ are respectively mechanical power, water inertia constant and gate opening.

In water turbine it is the potential energy of water head when converted to kinetic energy at the lower elevation (end of penstock) hits the turbine blade. Kinetic energy is converted to mechanical energy that rotates the shaft. The mechanical power produced is proportional to the pressure and amount of water discharged. The amount of water admitted is governed by the gate opening. There is a reverse relationship between the power production and gate opening because of drop of pressure due to sudden gate opening. This is characterized by non-minimum phase zero.

This poses control problem and needs large transient governor droop compensation. Typically water inertia constant is few seconds.

[5]

c) *In a salient pole synchronous generator, the voltage current relations along the **d** and **q**-axis are as follows:*

$$E_{fd} - V_q + I_d X_d = 0$$

$$V_d + I_q X_q = 0$$

where the symbols carry their usual meanings.

*Taking the terminal voltage $\bar{V}_t$ as the reference vector, the **q**-axis is defined to lead $\bar{V}_t$ by an angle δ.*

The terminal voltage and current vector of the machine are related by:

$$\bar{V}_q + j\bar{V}_d = \bar{V}_t e^{-j\delta};\ \bar{I}_q + j\bar{I}_d = \bar{I}_t e^{-j\delta}$$

i) Making use of the above information, derive the power angle relationship of the machine.

[6]

ii) For the following values of the variables in p.u. obtain the real and reactive power output of the machine in p.u.

$X_d = 2.0$, $X_q = 1.8$, $V_t = 1.05$, $E_{fd} = 3.0$ and $\delta = 20$ degrees

[3]

iii) Suddenly the machine loses excitation. Justify through load angle computation whether the stability will be maintained if the mechanical input was to remain unchanged.

[3]

i) Algebraic summation of voltage along q-axis

$$E_{fd} - V_q + I_d X_d = 0;$$

Along d-axis

$$V_d + I_q X_q = 0$$

From the relation: $V_d = -V_t \sin\delta; V_q = V_t \cos\delta; V_t = V_q + jV_d; I_t = I_q + jI_d$

The currents in the voltage equations can be solved as function of voltage and substituted in the complex expression for power $V_t I_t^*$. On simplification the real and reactive power will be

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

$$Q = \frac{E_{fd}V_t}{X_d}\cos\delta + \frac{V_t^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\cos 2\delta - \frac{V_t^2}{2}\left[\frac{1}{X_q} + \frac{1}{X_d}\right]$$

ii)

Ans: Real power = 0.56; reactive power 0.92 p.u.

iii)

The maximum power due to saliency that could be developed is 0.0306 p.u. (the student has to apply the understanding of the saliency power concept with the help of power angle relation and compute the maximum power from it under loss of excitation. which is far too lower than the input power 0.56. The machine will loose the stability immediately following loss of excitation.

2

a) *Starting from the inertia constant J (Kg-m^2), rated VA as VA_{base}, basic torque and angle equations in a rotational system, derive the following swing equations of a synchronous generator connected to the grid:*

$$\frac{d\delta}{dt} = \omega_r - \omega_s$$

$$\frac{2H}{\omega_s}\frac{d\omega_r}{dt} = P_{mech} - P_{elec} - D(\omega_r - \omega_s)$$

δ = is the angle of the rotor with respect to a synchronously rotating reference frame;

ω_r, ω_s: speed of the rotor and synchronous reference frame respectively in rad/sec.

P_{mech}, P_{elec}: mechanical power input and electrical power output in p.u. respectively

H = H-constant in seconds

D: mechanical damping co-efficient in p.u.-sec/rad

[8]

It is known that the balance of torque (mechanical input (T_{mech}) – electrical output (T_{elec})) drive the generator dynamics. Let's assume that the combined inertia of the generator and prime mover is J (Kg-m$^{2)}$. If the rotational speed is ω_m (rad/sec); the following equation of motion can be written

$$J\frac{d\omega_m}{dt} = T_a = T_{mech} - T_{elec}$$

Generator manufacturers provide machine inertia constant as H that is related to J as

$$H = \frac{1}{2}\frac{J\omega_{0m}^2}{VA_{base}}$$ (Stored energy per rated VA at rated speed)

The substitution of this into above will yield following set of equations

$$\frac{2H}{{\omega_{0m}}^2} VA_{base} \frac{d\omega_m}{dt} = T_{mech} - T_{elec}$$

$$\frac{2H}{\omega_{0m}} VA_{base} \frac{d\omega_m}{dt} = P_{mech0} - P_{elec0}$$

Multiplying ω_m by number of pole pairs will result electrical speed ω_r ; ω_{0m} accordingly will correspond to synchronous speed ω_s

The final equation will appear as:

$$\frac{2H}{\omega_s}\frac{d\omega_r}{dt} = P_{mech} - P_{elec}$$

The mechanical damping effect is to retard the acceleration; this can be included as a term proportional to speed deviation on the right side of the above equation

The resulting equation can be written as:

$$\frac{2H}{\omega_s}\frac{d\omega_r}{dt} = P_{mech} - P_{elec} - D(\omega_r - \omega_s)$$

The angle equation: The rotor rotates at speed ω_r ; the angle (δ) of the rotor at any point of time t with respect to a synchronously rotating reference speed ω_s is

$$\delta(t) = (\omega_r - \omega_s)t + \delta_0$$

The initial rotor position at time t = 0 is δ_0

The rate of change of angle is therefore

$$\frac{d\delta}{dt} = \omega_r - \omega_s$$

These two differential equations are known as swing equations

$$\frac{d\delta}{dt} = \omega_r - \omega_s$$

$$\frac{2H}{\omega_s}\frac{d\omega_r}{dt} = P_{mech} - P_{elec} - D(\omega_r - \omega_s)$$

Sometime another constant $M = \dfrac{2H}{\omega_s}$ is also used in swing equation.

[8]

b) *The moment of inertia of a generator-turbine mass is 30,000 Kg-m^2. The generator has a rating of 600 MVA and operates at 3000 RPM. Find the*

i) stored energy [3]

ii) H-constant (H) [2]

iii) mechanical starting time (T_M) [1]

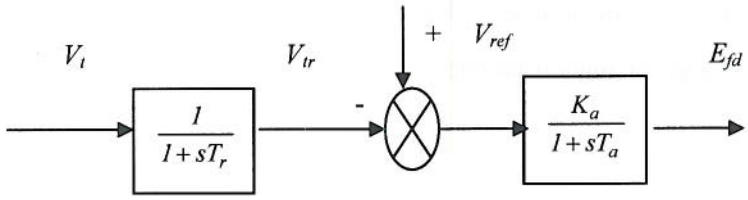
Answer:

i) The stored energy = ½ J ω^2= 0.5*30,000*($2\pi N/60$)^2 = 1480 Mega Joules [3]

ii) H = Stored Energy(MJ)/rated MVA = 2.46 seconds [2]

iii) Mechanical starting time T_M= 2H = 4.92 seconds [1]

c) *A simplified model of a fast excitation system is shown in Figure 2.1. It is required to produce a 4.0 p.u. of E_{fd} in the steady state. The voltage regulator has a gain of 400 and time constant of 0.03 s. Compute the reference voltage V_{ref} that needs to be set in order to maintain a terminal voltage of 1.05 p.u.*



2.1 Block Diagram of a Fast Excitation System [6]

The differential equations describing the excitation system dynamics are:

$$T_r \frac{dV_{tr}}{dt} = -V_{tr} + V_t$$

$$T_a \frac{dE_{fd}}{dt} = -E_{fd} + K_a(V_{ref} - V_{tr})$$

At steady state the time derivative term will be zero. So $V_{tr} = V_t$; so $V_{ref} = \frac{E_{fd}}{K_a} + V_t$

For $E_{fd} = 4.0, K_a = 400, V_t = 1.05; V_{ref} = 1.06$

3.

a) *Briefly describe the nature and importance of the primary frequency control in power systems.*

[3]

The primary frequency response is automatic, online and real-time in less than 30 seconds time frame. The generator slows down initially to produce extra MW (release of stored kinetic energy) when meets sudden increase in demand. This is not enough to sustain the demand for more than few seconds and the decline in frequency can not be prevented. When frequency drops, in the absence of any other control, rate of frequency fall is limited by the inertia of the machines and frequency sensitive component of the load (motor load) also releases some demand. The combined action results in settling at a frequency at lower than the earlier steady state value.

Load generation dynamic response: Any balance between the generation and demand will give rise to the dynamic response of the system. The primary response can improve the frequency deviation through governor droop characteristic. It is very important to maintain the system frequency deviation within the prescribed tolerance as specified in the network operator's grid code.

b) *Including the effect of the governor droop characteristic, establish the following relationship:*

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

where, D is the load damping co-efficient, ΔP_L is change in demand, R is the droop and $\Delta\omega_{ss}$ is the steady state angular frequency deviation in p.u.

[8]

The student is expected to draw the governor control loop to establish the relation between the change in demand to the change in frequency in transfer function domain. They are expected to derive the steady state condition there upon.

Let's consider a generator with combined inertia constant M. The balance between input mechanical power and output electrical power (in p.u) will govern the drive the turbine governed by the following equation:

$$P_{mech} - P_{elec} = Ms\omega_r$$

The perturbation of the above equation will result in

$$\Delta P_{mech} - \Delta P_{elec} = Ms\Delta\omega_r$$

Change in electrical power can be factored into two components as

$$\Delta P_{elec} = \Delta P_L + D\Delta\omega_r$$

D is known as load damping constant that represents frequency sensitivity component of load. Substituting the expression for ΔP_{elec} into the expression for dynamic response equation one gets

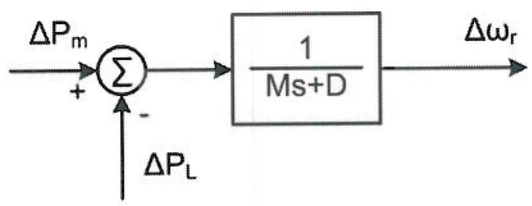
$$\Delta P_m - \Delta P_L - D\Delta\omega_r = Ms\Delta\omega_r\ .$$

Rearranging the term, the following expression is obtained.

$$\Delta\omega_r = \frac{\Delta P_m - \Delta P_L}{Ms + D}$$

This is shown in the following block diagram. The perturbation in mechanical input (ΔP_m) will be zero when governor action is not represented. This will further simplify the above expression to

$$\Delta\omega_r = \frac{-\Delta P_L}{Ms + D}$$



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 $G_t(s)$.

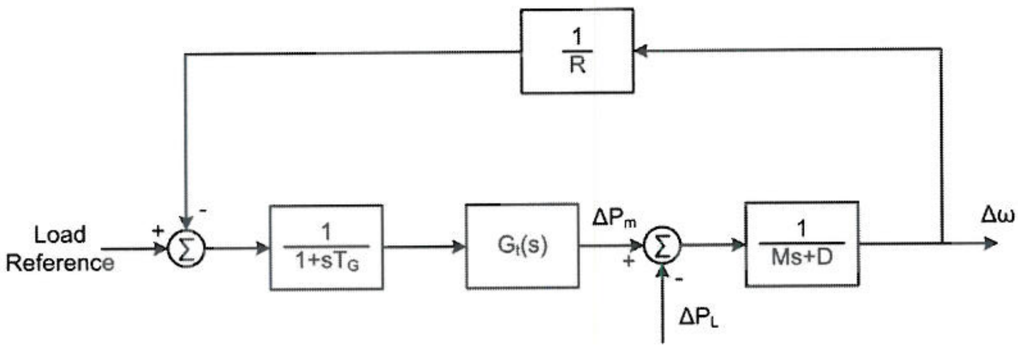


Fig: Block diagram of governor with droop for generator speed control

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.

c) *A small 50 Hz system consists of 5 identical 600 MVA units feeding a total load of 1550 MW. The H constant of each unit is 6.0 sec on their own base MVA. Each unit has 5% governor droop mechanism fitted. The load varies by 2% for 1% change in frequency. For a sudden increase of 50 MW of load find the steady state frequency deviation in Hz. Obtain the frequency deviation*

i) *without droop*

[4]

ii) *with droop.*

[4]

iii) *comment on the effectiveness of droop control in view of the results obtained above.*

[1]

It is will be convenient to lump all the units into one equivalent one. Let's choose base MVA as the combined MVA of all the 5 units, i.e. 3000 MVA. The damping co-efficient will be computed on 1600 MW (1550+50) loads. Change in load = 50 MW = 50/3000 p.u. D = 2% of 1600 per 1% of frequency change i.e. 64 MW/ Hz i.e 64/3000 p.u load/ 1 Hz = 0.0213/Hz. The droop of all the units combined will be equivalent R/5 and on 3000 MVA it will be R again i.e. 5% or 0.05.

The steady state frequency deviation without droop will be 0.01666/0.0213 = 0.78 Hz and with governor droop will be 0.01666/ (0.0213+1/0.05) =0.00083 Hz. It is very clear that with governor droop the frequency deviation is comparably smaller than without governor droop action.

4

a) *List the various frequency control regimes with their associated time scales of operation.*

[3]

Answer:

Primarily major power system adopts to frequency control regimes; Primary frequency control with governor (10 seconds to 30 seconds); Secondary control with load reference point activated by AGC/LFC (30 seconds to 30 minutes). Some grid operators also have tertiary control which is manual and mainly to ensure enough margin for secondary control.

[3]

a) *A power system has combined generation inertia constant M (= 2H) (sec) and load damping co-efficient of D (p.u power per p.u change in frequency). It is equipped with a primary frequency control feature. For an increase in system load (ΔP_L in p.u), derive an expression for steady state frequency deviation in p.u for the following two situations*

i) *without governor droop control*

[5]

Answer

Any balance between the generation and demand will give rise to the dynamic response of the system. Let's consider a generator with combined inertia constant M. The balance between input mechanical power and output electrical power (in p.u) will govern the drive the turbine governed by the following equation:

$$P_{mech} - P_{elec} = Ms\omega_r$$

The perturbation of the above equation will result in

$$\Delta P_{mech} - \Delta P_{elec} = Ms\Delta\omega_r$$

Change in electrical power can be factored into two components as

$$\Delta P_{elec} = \Delta P_L + D\Delta\omega_r$$

D is known as load damping constant that represents frequency sensitivity component of load. Substituting the expression for ΔP_{elec} into the expression for dynamic response equation one gets

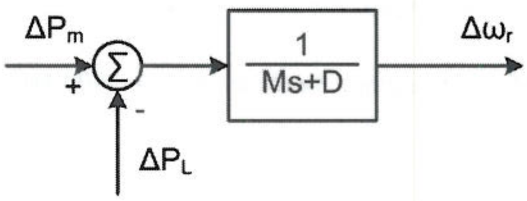
$$\Delta P_m - \Delta P_L - D\Delta\omega_r = Ms\Delta\omega_r \ .$$

Rearranging the term, the following expression is obtained.

$$\Delta\omega_r = \frac{\Delta P_m - \Delta P_L}{Ms + D}$$

This is shown in the following block diagram. The perturbation in mechanical input (ΔP_m) will be zero when governor action is not represented. This will further simplify the above expression to

$$\Delta \omega_r = \frac{-\Delta P_L}{Ms + D}$$



[5]

ii) *with governor droop control having droop R.*

[4]

Through governor droop control, mechanical power output ΔP_m is influenced through governor dynamics and control. 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 $G_t(s)$ as shown.

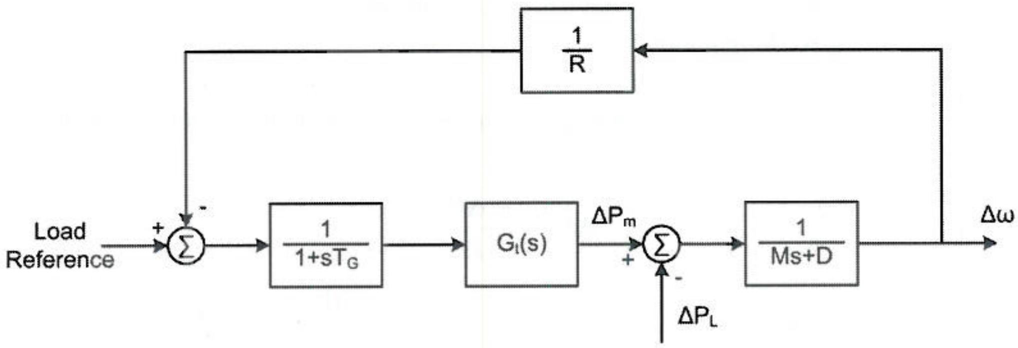


Fig: Block diagram of governor with droop for generator speed control

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.

b) *A small 60 Hz system consists of 4 identical 500 MVA generating units feeding a total load of 1,020 MW. The H constant of each unit is 5.0 seconds on 500 MVA base. The load varies by 1.5% for 1% change in frequency. For a sudden drop in load by 20 MW answer the following*

i) *Compute equivalent M, D and express load variation on 2000 MVA base*

[6]

Answer:

H on 500 MVA is 5 seconds: Combined H for four units = 4x5 = 20 seconds and on 2000 MVA it will be 20x500/2000= 5 seconds. M = 2H = 10 seconds.

D = 1.5 % change in load for 1% change is frequency: Since 20 MW load will be dropped, D has to be calculated on the remaining 1000 MW.

Change in load = 1000*1.5/100= 15 MW; Change in frequency is 1/100x60 = 0.6 Hz. On 2000 MVA base this is 15/2000/(0.6) = 0.0125 p.u/Hz or 0.0075 pu per 1% change in frequency.

ii) Find the frequency deviation in the steady state assuming no speed governing option

[2]

In the absence of speed governor the steady state frequency deviation is expressed as

$$\Delta f_{ss} = \frac{-\Delta P_L}{D}$$

On substituting the values $\Delta f_{ss} = \frac{-(-20)}{.0125x2000} = 0.8Hz$

[2]

5.

a) *Describe the purpose of the protection systems.*

[4]

Electrical power system operates at various voltage levels from 440 V to 765 kV or even more. Electrical apparatus used may be enclosed (e.g., motors) or placed in open (e.g., transmission lines). They meet uncertain operating circumstances (both internal and external) because of various reasons. For example, a worn out bearing may cause overloading of a motor. A tree falling or touching an overhead line may cause a fault. A lightning strike (act of nature) can cause insulation failure. Pollution may result in degradation in performance of insulators which may lead to breakdown. Under or over speeding of generators may result in mechanical shaft damage that must be prevented through generator protection. When a part of the system is subjected to such abnormal situations, it should be taken off the system to minimize the impact of such events on the overall system operation. This is achieved through properly planned, designed and implemented protection strategy.

b) *Discuss various components and functionalities of numerical relays.*

[5]

The block diagram of a numerical relay is shown in Fig below. It involves analogue to digital (A/D) conversion of analogue voltage and currents obtained from secondary of CTs and VTs. These current and voltage samples are fed to the microprocessor or Digital Signal Processors (DSPs) where the protection algorithms or programs process the signals and decide whether a fault exists in the apparatus under consideration or not. In case, a fault is diagnosed, a trip decision is issued. Numerical relays provide maximum flexibility in defining relaying logic. The hardware comprising of numerical relay can be made scalable i.e., the maximum number of v and i input signals can be scaled up easily. A generic hardware board can be developed to provide multiple functionalities. Changing the relaying functionality is achieved by simply changing the relaying program or software. Also, various relaying functionalities can be multiplexed in a single relay. It has all the advantages of solid state relays like self checking etc. Enabled with communication facility, it can be treated as an Intelligent Electronic Device (IED) which can perform both control and protection functionality. Also, a relay that communicates can be made adaptive i.e. it can adjust to changing apparatus or system conditions. For example, a differential protection scheme can adapt to transformer tap changes. An overcurrent relay can adapt to different loading conditions. Numerical relays are both "the present and the future".

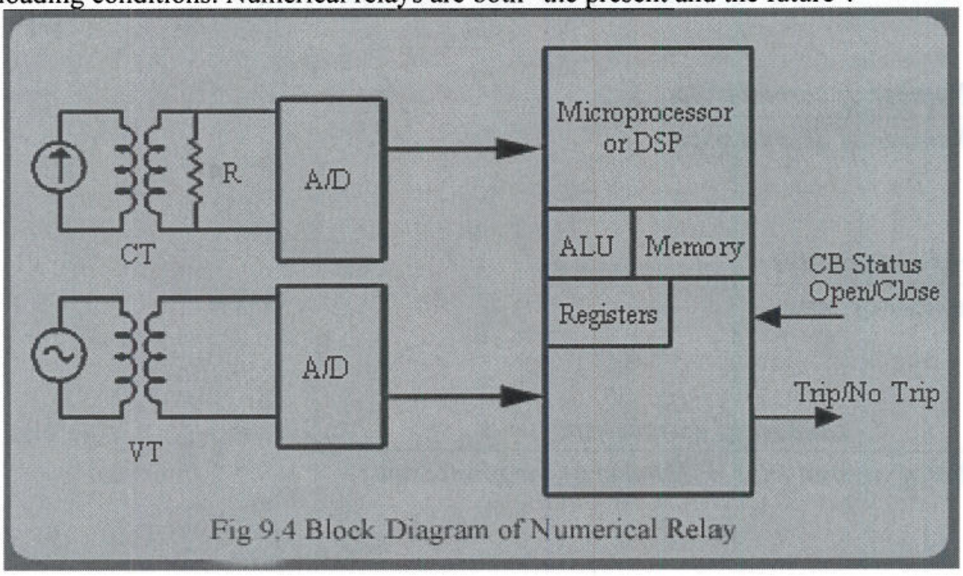


Fig 9.4 Block Diagram of Numerical Relay

c) Distinguish between the dependability and security of a relay.

[4]

Dependability

A relay is said to be dependable if it trips only when it is expected to trip. This happens either when the fault is in its primary jurisdiction or when it is called upon to provide the back-up protection. However, false tripping of relays or tripping for faults that is either not within its jurisdiction, or within its purview, compromises system operation. Power system may get unnecessarily stressed or else there can be loss of service. Dependability is the degree of certainty that the relay will operate correctly:

$$\% \, Dependability = \frac{Number\ of\ correct\ trips}{Number\ of\ desired\ trips} \times 100$$

Dependability can be improved by increasing the sensitivity of the relaying system.

Security

On the other hand, security is a property used to characterize false tripping of the relays. A relay is said to be secure if it does not trip when it is not expected to trip. It is the degree of certainty that the relay will not operate incorrectly:

$$\% \, Security = \frac{Number\ of\ correct\ trips}{Total\ number\ of\ trips} \times 100$$

False trips do not just create nuisance. They can even affect system security. For example, tripping of a tie-line in a two area system can result in load-generation imbalance in each area which can be dangerous. Even when multiple paths for power flow are available, under peak load conditions, overloads or congestion in the system may result. Dependability and security are contrasting requirements. Typically, a relay engineer biases his setting towards dependability. This may cause some nuisance tripping, which can in the worst case, trigger partial or complete blackout! Security of the relaying system can be improved by improving selectivity of the relaying system

d) The performance of an over current relay was monitored for a period of one year. It was found that the relay operated 14 times, out of which 12 were correct trips. If the relay failed to issue trip decisions on 3 occasions, compute dependability, security and reliability of the relay as a percentage of ideal performance.

[7]

$$\% \, Dependability = \frac{Number\ of\ correct\ trips}{Number\ of\ desired\ trips} \times 100$$

$$= \frac{12}{15} \times 100 = 80\%$$

$$\% \, Security = \frac{Number\ of\ correct\ trips}{Total\ number\ of\ trips} \times 100$$

$$= \frac{12}{14} \times 100 = 85.71\%$$

$$\% \, \mathrm{Re}\,liability = \frac{Number\ of\ correct\ trips}{Number\ of\ desired\ trips\ +\ Number\ of\ incorrect\ trips} \times 100$$

$$= \frac{12}{15+2} = 70.59\%$$

Note that even though dependability and security are individually above 80%, overall reliability much poor (only 70.55%).

6

a) *A 1200/5 C400 current transformer (CT) is connected to a relay with a burden of 0.7 Ω. The secondary resistance of the CT is 0.61 Ω. A secondary current of 105 A. flows through the relay coil.*

i) *For this secondary current, is the CT still expected to behave in a linear manner? Justify your answer.*

[3]

Answer

The rating of a relay defines the secondary voltage up to which linear operation is to be expected. In this case the relay is described as a C400 type relay, indicating it is a C class relay (low leakage reactance) in which saturation sets in if the secondary voltage exceeds 400 V.

In this case, we have been told that the relay is measuring a secondary current of 105 A (e.g. 21 time nominal). The burden on the secondary of the relay is 0.61 + 0.7 = 1.31 Ω. The secondary voltage that results from the particular burden is then: 1.31 x105 = 138 V. This is well below the "knee-point" in the operating curve for the CT, implying that the response of the device is still linear.

ii) The magnetising impedance (as referred to the secondary of the CT) is 5 k Ω. Calculate the % ratio error

[4]

Answer

The ratio error is summarises the comparative amount of current required to establish flux inside the CT as compared with the current being observed in the relay coil. In this case, the secondary current (measured current) is 105 A. For this current load and the given burden of 1.31 Ω, as calculated previously, the required secondary voltage of the relay is 138 V. Consequently, the magnetising or excitation current for the relay is 138 / 5 k Ω = 27.6 mA. The ratio error is determined by Ie/Is = excitation current / magnetising current = 27.6 mA / 105 A = 0.026% - very low

b) *In what ways does a high ratio error affect the quality of CT's measurement?*

[3]

Answer

A high ratio error indicates that the excitation current (Ie) of the relay is significant (i.e > 10%) of the secondary current (Is) that is following in the measurement winding of the relay. This has two impacts. First and foremost, as measured current (referred to the secondary winding) consists of the sum of the excitation current and the secondary current, e.g. Ip/N = Ie + Is, a significant excitation current will result in an error in the magnitude of the current seen by the relay. Additionally, the current in the secondary winding is usually a predominantly resistive current. This contrasts with the excitation current which is predominantly inductive. Consequently, the need to supply a large, out-of-phase current will lead to an appreciable divergence between the phase angle of the referred secondary current (Ip/N) and the secondary current Is which is the measured current. This error in phase angle could in turn affect the quality of the power flow measurements that can be derived from the system.

c) *What are the performance requirements of a protection grade CT? How do they differ from a measurement grade CT?*

[4]

Answer

A protection grade relay is must be designed to handle large fault current (i.e. up to 20 times rated currents without the transformer going into saturation. In this way, the magnetising reactance of the transformer remain large from the normal pre-fault low flux condition up to the high current fault conditions during which there is a large amount of flux inside the transformer.

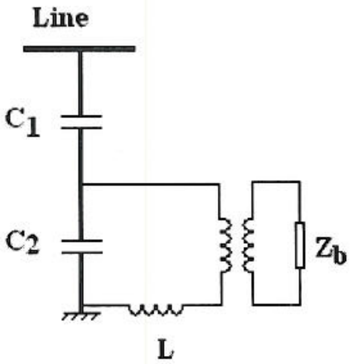
This is necessary so that it can accurately measure all fault currents, i.e. from low current faults, up to very severe faults. Accurate measurement of the fault current magnitudes over the full range of fault current is essential for coordination of the protective devices. For example, many relays are designed to trip faster for higher fault current (e.g inverse time over-current relays). Without the ability to accurately distinguish between the severities of different faults such basic functionality would not be possible.

In contrast a measurement grade CT can be designed with a much lower VA rating. Generally it is designed to handle current only in the range of 5% to 125% of the rated voltage. To achieve this requires a very high magnetising reactance so that the device will operate correctly even at very low flux level (e.g. due to low measured currents). Operation of a measurement CT at currents well above the rated current though are likely to result in saturation of the transformer and large errors in the measured current (resulting from distortion in the waveshapes)

d) *Draw the equivalent circuit for a capacitively coupled voltage transformer (CCVT). Briefly describe the purpose of the tuning inductor in a CCVT. Derive the required expression for the tuning inductor in this circuit?*

[6]

Answer



A capacitively coupled voltage transformer essentially uses a capacitive voltage divider to ensure that the voltage being measured is a scaled version of the line voltage to be observed. This offers economic voltage measurement scheme for protection and metering purpose. The presence of the capacitors however will affect the voltage that appears across the relay burden (and hence can be measured). Consider the Thevenin's equivalent impedance as determined at the point of the connection of the relay burden (i.e. the meter) While the Thevenins equivalent voltage is the voltage across C2, the Thevenin's impedance is $-j/(\omega C_1 + \omega C_2)$. When this is placed in the series with relay burden it will mean that the measured voltage is not correct. The purpose of the tuning inductor, shown as L on the primary side of the voltage transformer is to cancel out the apparent impedance of the capacitive divider. Consequently, it must have the value of $\omega L = 1/(\omega C_1 + \omega C_2)$.

In the diagram above it is drawn in the ground path of the primary side. This is where it is usually placed physically so that the voltage gradient across the inductor is smaller than if it were placed on the line-side of the capacitor, thereby reducing the physical requirements (in terms of insulation) on the device's construction.