EE4-48
EE9-CS6-2

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2013

MSc and EEE PART IV: MEng and ACGI

POWER SYSTEM CONTROL, MEASUREMENT AND PROTECTION

Monday, 29 April 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 a power system lead to dynamic response of the network quantities such as voltage, current and frequency. Associate the approximate time scales of these events in appropriate unit.

i) Network switching surges

ii) Transient stability

iii) Fast primary frequency control

Ans: i) 200 to 2000 micro seconds; ii) 1 to 10 seconds iii) 0-10 seconds [3]

b)

i) Why does the output power from a standard hydro turbine suddenly drop before rising to a new value in response to water gate opening command?

[2]

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.

ii) How is the above phenomenon characterised from system theory perspective?

[3]

This is characterized by non-minimum phase zero. The open loop transfer function has poor phase margin. This poses control problem needs careful control approach. Typically water inertia constant is few seconds.

iii) Describe briefly any practical measure to overcome this?

[2]

In practice governor gain is high at low frequency and made to drop at high frequency so that suddenly the closed loop system after the gate position opening command does not change. This is realised through large transient governor droop compensation.

c) In a salient pole synchronous generator, the voltage-current relationship along the generator **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 generator 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 expression of the generator.

[5]

The terminal power output expression can be written as usual $V_t I_t^* = (\bar{V}_q + j\bar{V}_d)(\bar{I}_q - j\bar{I}_d)$. *The students will be required to derive the expression from the given algebraic relationship between various variables. The final form should look like:*

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

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

ii) For the following values of the variables in per unit, obtain the per unit real power output of the generator.

$X_d = 2.2$, $X_q = 1.6$, $V_t = 1.05$, $E_{fd} = 3.5$ and $\delta = 20$ degrees

[3]

```
a1=sin(20/180*pi)

a1 =

  0.3420

>> a2=sin(40/180*pi)

a2 =

  0.6428

>> b1 = 3.5*1.05/2.2

b1 =

  1.6705

>> b2 = 1.05*1.05/2*(1/1.6-1/2.2)

b2 =

  0.0940
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*>> p= a1*b1+a2*b2*

p =

0.6317

0.6317 p.u.

iii) Suddenly the generator loses excitation. What percentage of power obtained in (ii) can still be produced with the loss of excitation? [2]

*>> pr= a2*b2/p*

pr =

0.0956

Approximately 10%

2.

a)

i) Why does energy conversion in a steam turbine take place in multiple stages? [3]

The efficiency of steam turbine (steam energy to mechanical energy) depends on the temperature and pressure differences between inlet steam and outlet water. Dropping the pressure produces work but expands the steam thus introducing moisture content. The moisture is detrimental to the working life of turbine blade so they need drying again. This is done in stages in intermediate and low pressure section after mechanical energy is produced at the high pressure stages. Such pressure compounding at different stages help extracts more energy from the steam thus improving the efficiency.

ii) Why is the rotor of a synchronous generator made of solid steel where as its stator is of thin laminations? [3]

Rotor carries DC current at synchronous speed so there is no chance of induced eddy current. It also rotates at synchronous speed so the induced EMF because of stator magnetic flux is also nil. So the solid construction is fine and less expensive. When rotor is subject to deviation from synchronous speed (accelerates or decelerate because of fault) eddy current is set up. This introduces damping against the rotor mechanical oscillation- the damping is very effective with solid rotor construction.

iii) Why is the X/R (reactance to resistance) ratio of a synchronous generator deliberately kept high? [3]

High X/R ratio primarily results in very low air gap machine so it is very economic as overall stator diameter is less for given shaft length and power capacity. It is required for limiting fault current. The downside is poor output power versus voltage characteristic. This is addressed through automatic voltage controller in excitation system at marginal cost.

iv) Why is the short term real power capacity of a synchronous generator higher in lagging power factor operation than that in leading power factor operation?

[3]

The heating and temperature rise of the stator body due to hysteresis and eddy current loss particularly at the ends of the stator (conductor overhang, collar binding the conductors) are higher in leading power factor operation than that in lagging power factor operation. The reason is the additive nature of the stator and rotor magnetic field during leading power factor operation. Because of this situation lower limit of leading current can be allowed compared to lagging current. Overall real power capacity is less.

v) The potential source controlled solid state excitation system is a very effective technology for enhancing transient stability of large power generator. Nevertheless, the industry trend is increasingly towards the brushless excitation system- Justify this statement with reasons.

[3]

The potential source controlled solid state excitation system is very fast and can provide adequate reactive power through synchronous generator. They also have fast capability of field forcing. The primary disadvantages are the maintenance of brush for slip ring, thyristor circuit and control failure. The brushless excitation on the contrary employs rotating diodes inside the generator shaft. The DC field for main generator is controlled through pilot excitation system which is easy to control. There is no brush arrangement required. In dusty power plant environment, the maintenance cost is always less.

vi) Describe the function of the closed circuit rotor windings of a synchronous generator.

[3]

The additional closed circuit rotor winding provides damping against electromechanical oscillation thus offer dynamic stability to power system.

vii) How does the inertia constant (H) of a synchronous generator influence the system frequency change?

[2]

The synchronous generator stores energy in its inertial field which is function of the square of the velocity and also directly linear to the magnitude of the inertia constant H. The generator with higher inertia constant H stores more energy and very quickly (rather instantly) releases when the system frequency starts falling. Generally within the first 5 to 10 seconds primary frequency response through governor droop or other means do not appear because of slower dynamics they have to overcome (turbine power reference to power output response time, water starting time constant, turbine time constant etc.). In the first 10 seconds thus this temporary source of energy is very useful. The rate of decline is contained by the amount of kinetic energy in the inertial field which is proportional inertia constant H.

3

a)

i) How much excitation power is approximately required to operate a 500 MW synchronous machine?

[2]

Generally 200 to 350 KW per MVA of the machine rating is required. So for 500 MW machine, typically on a 0.85 pf, 1.2 to 2.0 MW excitation power is required.

ii) What is the purpose of field forcing in excitation system control?

[3]

Field forcing is done to suddenly boost the excitation voltage (EFD) for 5 to 10 seconds to make sure the synchronous generator following terminal short circuit stay connected to the system and transiently stable. The field forcing helps to produce electrical torque that is function of terminal voltage and excitation voltage (EFD). In the presence of reduced terminal voltage because of short circuit, high EFD helps to produce higher electrical torque thus slowing down the pace of acceleration of the rotor.

iii) Why is it so important to have the power system stabilizer (PSS) in a large synchronous generator with fast acting voltage control?

[4]

The synchronous generators with fast acting voltage control mechanism are prone to low frequency electromechanical oscillations. The oscillations set in following the clearance of fault while the system tends to reach another post fault equilibrium. Depending on the operating conditions, pre disturbance conditions etc. the oscillations may be poorly damped or can even grow. Power system stabiliser under this condition is must to dampen these oscillations. Usually the feedback signal for PSS is synthesized generator speed, line power flow or frequency.

iv) Why is the voltage rise problem in a 400 kV cable network more severe than that of an overhead line of similar rating?

[2]

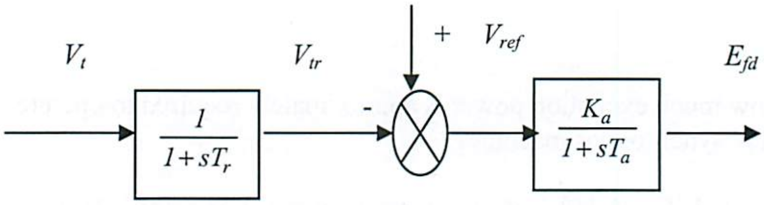
The phase to phase and phase to ground capacitance of a 400 kV cables are much higher (10-20 times) than that of a 400 kV overhead line. The reactive generated by a 400 kV cable is about 20 MVAR per km where it is about 50 MVAR per 100km for overhead line. Higher reactive power generated by the cable system increases the receiving voltage. It can become dangerous during switching potentially damaging plant insulation. So this is very severe problem compared to that in over head line of similar voltage rating.

v) Why are the fixed shunt capacitors not as effective as the automatic voltage control in synchronous generators?

[3]

Fixed capacitor is a passive source of reactive power and is proportional to square of the voltage across it. The voltage is smoothly not controllable except for the fact that some reactive power is generated that indirectly improve the voltage. When system operates under severe loading voltage is below nominal so, a 10% drop in voltage leads to about 20% drop in reactive power. The AVR equipped with synchronous generator produces smooth voltage control. The source is also active (can create its own reactive power through magnetisation).

b) A simplified model of a fast excitation system is shown in Figure 3.1. It is required to produce a 4.5 p.u. of E_{fd} in the steady state. The voltage regulator has a gain of 450 and time constant of 0.02 s. Compute the reference voltage V_{ref} that needs to be set in order to maintain a terminal voltage of 1.06 p.u.



3.1 Block Diagram of a Fast Excitation System

[6]

A set of differential equation can be written as follows:
dVtr / dt = 1/Tr [-Vtr + Vt]
dEfd / dt = 1/TA [(Vref-Vtr)-Efd]
At steady state
Vtr = Vt ; Efd = KA (Vref-Vtr)
Vref = Efd/KA + Vtr
Vref = Efd / KA + Vt
4.5/450 + 1.06 = 1.07 pu

4.

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

[4]

Sudden load-generation imbalance is immediately picked up by the inertial response of synchronous generator following which the droop control takes effect. This is primary frequency response but mainly works on the produced steam. Droop control without change of load reference point will not be able to sustain permanent change in demand beyond 30 seconds. The secondary frequency control has to take effect as early as 30 seconds as up to 30 mins. Generally some units are synchronised to system and remain part loaded (gas turbines, hydro unit and fast response thermal units). They provide additional demand. This can be automatic or semi automatic. They are required to maintain the frequency within tolerable limit. In the UK contexts these are contracted out to many independent small generator or large generator. Generally they are expensive so the grid operator has to eventually switch to comparably cheaper generation.

b) Including the effect of the governor droop characteristic, develop the following load frequency control characteristic:

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

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]

Let us establish the load frequency characteristics without droop. 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*

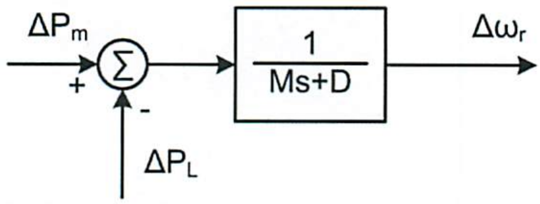
$$\Delta P_m - \Delta P_L - D\Delta\omega_r = Ms\Delta\omega_r \ .$$

Rearranging the term, the following expression is obtained.

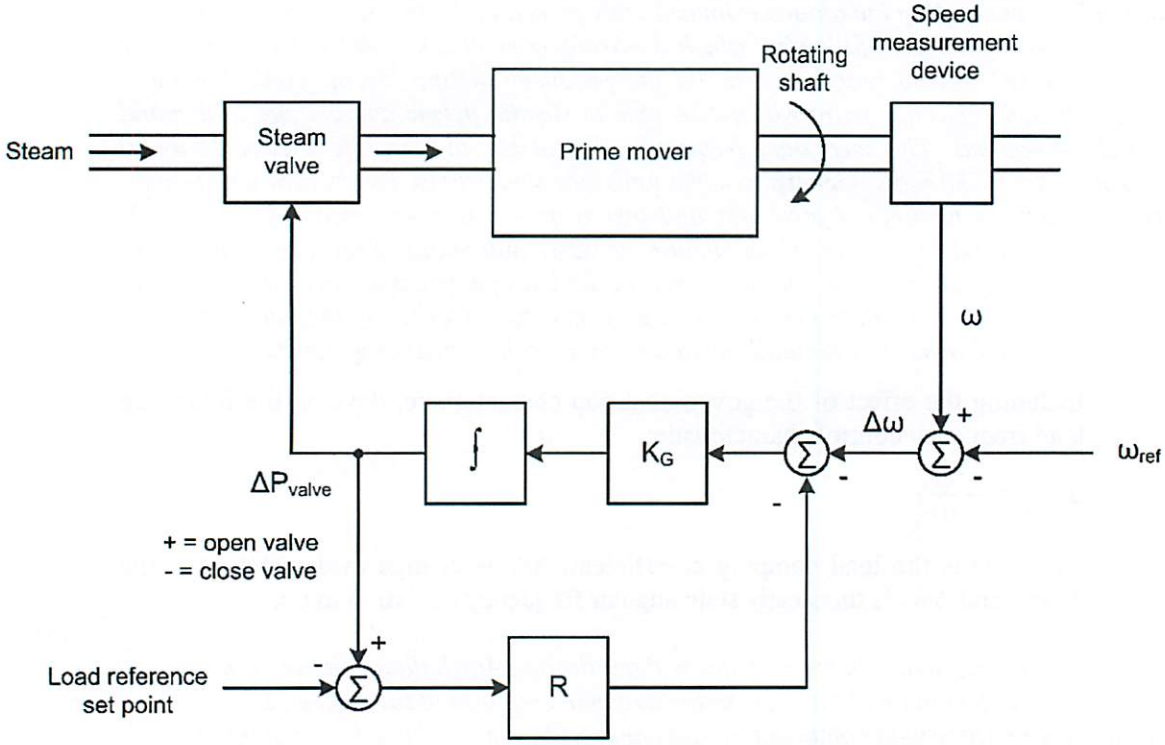
$$\Delta\omega_r = \frac{\Delta P_m - \Delta P_L}{Ms + D}$$

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*

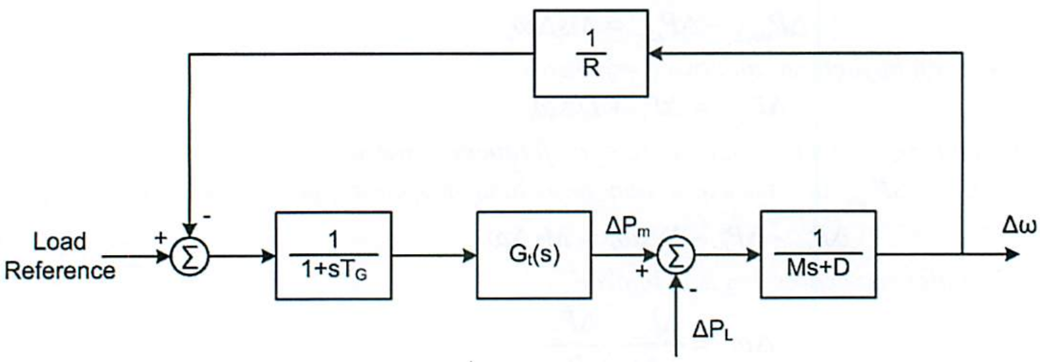
$$\Delta\omega_r = \frac{-\Delta P_L}{Ms + D}$$



Let us now include with the system a governor droop control in the following block diagram.



The prime mover is subjected to the difference between generation demand which can be modelled by M and D constant. The influence of the droop on the load change and hence frequency can be modelled by further simplified model of the system.



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

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

c) A small 50 Hz system consists of 4 identical 588 MVA, 500 MW units feeding a total load of 1700 MW. The H constant of each unit is 6.5 sec on their own base MVA. Each unit has 4% governor droop mechanism fitted. The load varies by 2% for 1% change in frequency. For a sudden increase of 100 MW of load find the steady state frequency deviation in Hz:

i) without droop [3]

With increase of 100 MW load, total load is 1800MW. D = 2%of 1800 for 1% of 50= 36MW/0.5 Hz = 72 MW/Hz. The frequency deviation without droop is -100/72 = -1.38 Hz

ii) with droop. [3]

4% governor droop R means: change in 4% frequency for full change in unit output. i.e. 4% of 50 Hz/500MW; 1/R = 500/2 MW/Hz = 250 MW/Hz. With 4 identical units, the combined droop of the system is 4/R = 1000 MW/Hz. The frequency deviation is -100/(72+1000) = -0.093Hz

iii) comment on the effectiveness of droop control in steady state frequency deviation in view of the results obtained above. [2]

It is very obvious that with droop control in action the deviation is frequency is comparably insignificant (0.093 Hz) to that with out droop (1.38 Hz)

5.

a) What are the fundamental differences between apparatus protection and system protection?

[3]

Apparatus protection focuses on individual components. It takes input from within the component or from input output terminal. The inputs signal need not be always electrical. Temperature protection of transformer assess the condition of (temperature level) the transformer. In system protection a large area is protected e.g. wide area protection of a system. Frequency, power flow, electromechanical swings of two or more areas is used as signals. The protection is coordinated.

b) Discuss the various components and functionalities of electromechanical relays.

[5]

When the principle of electromechanical energy conversion is used for decision making, the relay is referred as an electromechanical relay. These relays represent the first generation of relays. Let us consider a simple example of an over current relay, which issues a trip signal if current in the apparatus is above a reference value. By proper geometrical placement of current carrying conductor in the magnetic field, Lorentz force $F = Bil \sin\theta$ *is produced in the coil.*
This force is used to create the operating torque. If constant 'B' is used (for example by a permanent magnet), then the instantaneous torque produced is proportional to instantaneous value of the current. Since the instantaneous current is sinusoidal, the instantaneous torque is also sinusoidal which has a zero average value. Thus, no net deflection of operating coil is perceived.
On the other hand, if the B is also made proportional to the instantaneous value of the current, then the instantaneous torque will be proportional to square of the instantaneous current (non-negative quantity). The average torque will be proportional to square of the rms current. Movement of the relay contact caused by the operating torque may be restrained by a spring in the over current relay. If the spring has a spring constant 'k', then the deflection is proportional to the operating torque (in this case proportional to I_{rms}^2*). When the deflection exceeds a preset value, the relay contacts closes and a trip decision is issued. Electromechanical relays are known for their ruggedness and immunity to Electromagnetic Interference (EMI).*

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

[4]

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.
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 the dependability, security and reliability of the relay as a percentage of its ideal performance.

[6]

Number of correct trips = 12; Number of desired trips = 12 + 3 = 15

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

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

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

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

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

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

e) A power transformer, when energised, usually draws huge amount of inrush current. The transformer invariably has over current protection that operates thus not letting the transformer circuit breaker to connect the transformer to the rest of the system. What additional protection can you suggest to solve this problem?

[2]

The inrush current should not be confused as over current is the key. There are differences between the inrush current and over current in view of the nature of the waveform. Inrush current usually has very high second harmonic current. There has to be a detection circuit which will measure the percentage of second harmonic of the total current and once it exceeds a set threshold, it should block the tripping signal. After few tens of milliseconds the harmonics will subside and *the overcurrent element will be allowed to monitor the circuit. This is known a second harmonic restraints protection of power transformer.*

6

a) A 1200/5 C400 current transformer (CT) is connected to a relay with a burden of 2.75 Ω. The secondary resistance of the CT is 0.75 Ω. A secondary current of 110 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]

*Total impedance in the secondary circuit: 3.5 ohm. The secondary excitation voltage is 110*3.5 = 385 volts.. Since the secondary voltage does not exceed 400V, it will behave linearly as per the CT specification (C400).*

ii) A new generation capacity came up that increased the fault level of the substation where the CT remains connected. It was decided not to replace the CT rather upgrade some of the relays with lower burden so that when primary fault current is 30 kA, the CT could faithfully reflect the primary current to the relay input terminal. Find the upper limit of the relay burden to realise this. [3]

*30kA on the primary will be reflected as 30000/1200*5 = 125A. In order for the excitation voltage not to exceed 400V (CT remaining unchanged); 400/125 = 3.2 ohm total secondary circuit impedance. With a secondary resistance of 0.75 ohm, the allowed relay burden will be 3.2-0.75 =2 .45 ohm.*

b) In what ways does a high ratio error affect the quality of CT's measurement? [3]

High ratio error means higher magnetising current. CT performance is usually gauged from the ratio error. The ratio error is the percentage deviation in the current magnitude in the secondary from the desired value. In other words, if the current measured in the secondary is I_s, true or actual value is I_p/N, where N is nominal ratio (e.g. N for a 100:5 CT is 20) and I_p is the primary current then ratio error is given by $\dfrac{\left|\frac{I_P}{N}\right| - |I_S|}{|I_S|}\times 100$ *. When the CT is not saturated ratio error* $\dfrac{\frac{I_P}{N} - I_S}{I_S}\times 100$ *is a consequence of magnetizing current I_E since* $\frac{I_P}{N} - I_S = I_E$ *. Therefore, % ratio error is equal to* $\frac{I_E}{I_S}\times 100$ *. When the CT is saturated, coupling between primary and secondary is reduced. Hence large ratio errors are expected in saturation. The current in the secondary is also phase shifted. For measurement grade CTs, there are strict performance requirements on phase angle errors also. Error in phase angle measurement affects power factor calculation and ultimately real and reactive power measurements. It is expected that the ratio error for protection grade CTs will be maintained within* $\pm 10\%$.

c)

i) What are the performance requirements of a measurement grade CT?

[2]

A measurement grade CT has much lower VA capacity than a protection grade CT. A measurement CT has to be accurate over its complete range e.g. from 5% to 125% of normal current. In other words, its magnetizing impedance at low current levels (and hence low flux levels) should be very high. Note that due to non-linear nature of B-H curve, magnetizing impedance is not constant but varies over the CT's operating range. It is not expected to give linear response (secondary current a scaled replica of the primary current) during large fault currents as it is not designed to operate accurately at abnormal condition.

ii) How do they differ from a protection grade CT?

[1]

In contrast, for a protection grade CT, linear response is expected up to 20 times the rated current. Its performance has to be accurate in the range of normal currents and up to fault currents. Specifically, for protection grade CT's magnetizing impedance should be maintained to a large value in the range of the currents of the order of fault currents.

d)

i) Draw the equivalent circuit of a capacitive coupled voltage transformer (CCVT).

[3]

ii) Briefly describe the purpose of the tuning inductor in a CCVT.

[2]

iii) Derive the required expression for the tuning inductor in this circuit?

[3]

Typically, the secondary voltage of the VT is standardized to 110 V (ac). Hence, as the primary voltage increases, the turns ratio N1:N2 increases and transformer becomes bulky. A capacitance potential divider is used (Fig 10.8) **to cut down the cost**. *Thus, a reduced voltage is fed to primary of the transformer. This reduces the size of VT. This leads to development of coupling capacitor voltage transformers (CCVT) or simply as capacitive voltage transformer (CVT).*

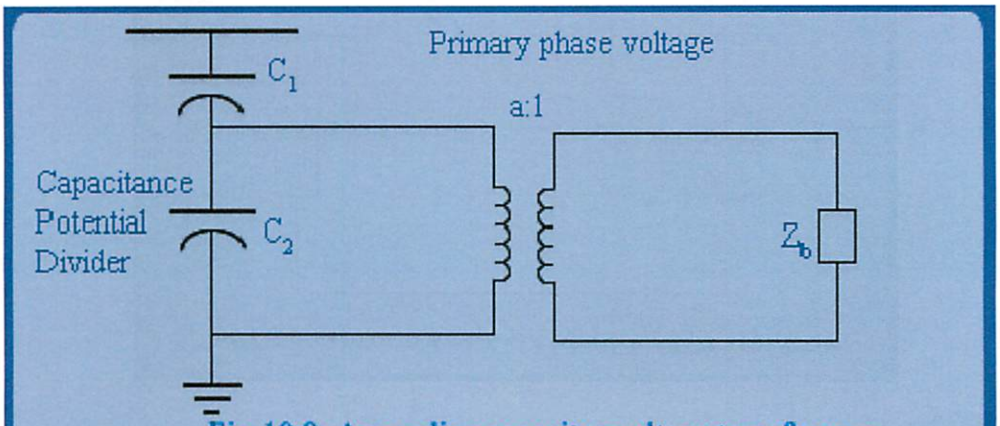


Fig 10.8: A coupling capacitor voltage transformer

Role of Tuning Reactor L: *Assuming, the transformer to be ideal, and source with negligible reactance, the Thevenin's equivalent circuit of CCVT is shown in Fig 10.9.*

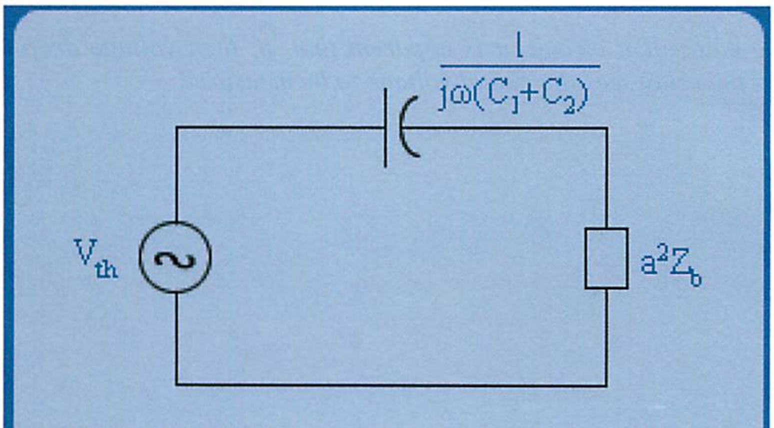


Fig 10.9: CCVT as seen from primary of VT

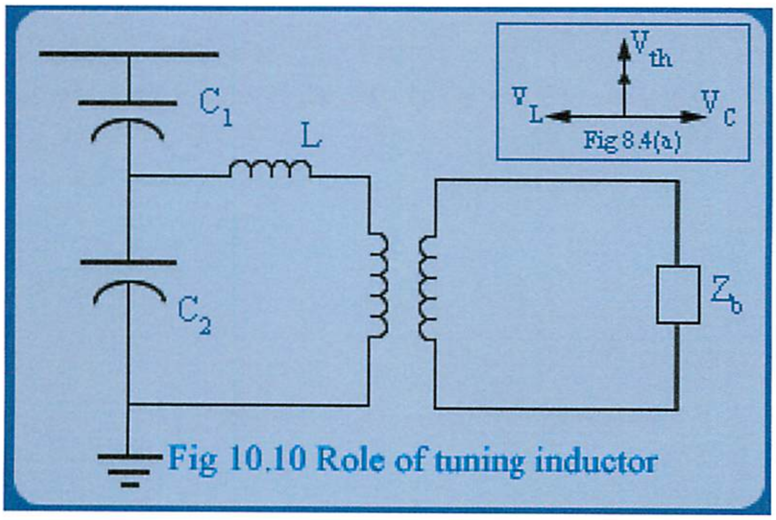


Fig 10.10 Role of tuning inductor

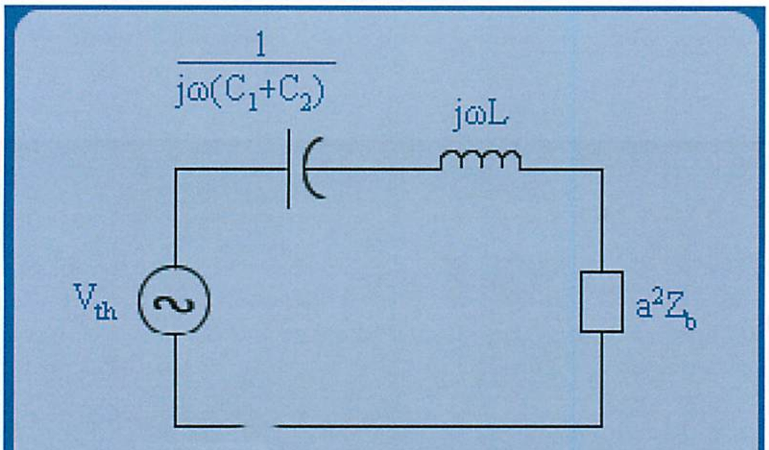


Fig 10.11: Final equivalent circuit of CCVT

It is now obvious that Z_{th} due to the capacitance divider affects the voltage received by the relay. To achieve high level of accuracy, it is therefore necessary to compensate for this voltage drop by connecting a tuning inductor. The tuning inductor's value is so chosen that it compensates for the 'net C' at power frequency (50/60Hz). $\omega L = \frac{1}{\omega(C_1 + C_2)}$ *The phasor diagram across resistive load, is as shown in Fig 10.10.*

From the corresponding equivalent circuit, it is apparent that, if, then voltage drop across C is neutralized and the relay sees the actual voltage to be measured.