(a) In synchronism - All machines in a network are operating at the same frequency.

Losing synchronism - One or more machines undergoes a deviation in synchronous frequency and power angles change leading to instability - pole slipping.

Consequences - Large mechanical forces on rotor leading to possible damage.
- Possible system blackouts / islanding

(b)(i) Before the fault:

Total system reactance $= 0.15 + 0.35 + \frac{0.2}{2} = 0.6pu$

Now $P_{eb} = \frac{V_1 V_2 \sin\delta}{X} = \frac{1.1 \times 1.0 \times \sin\delta}{0.6} = \underline{\underline{1.833 \sin\delta}}$

The generator is delivering 180MW or $\frac{180}{200} = 0.9pu$

Hence:

$$1.8333 \sin\delta_0 = 0.9$$

$$\therefore \underline{\underline{\delta_0 = 29.4^\circ}} \quad (0.513 \text{ rads})$$

(ii) During the fault the power-load angle equation is:

$$P_{ed} = \frac{1.1 \times 1.0 \times \sin\delta}{1.9} = \underline{\underline{0.5789 \sin\delta}}$$

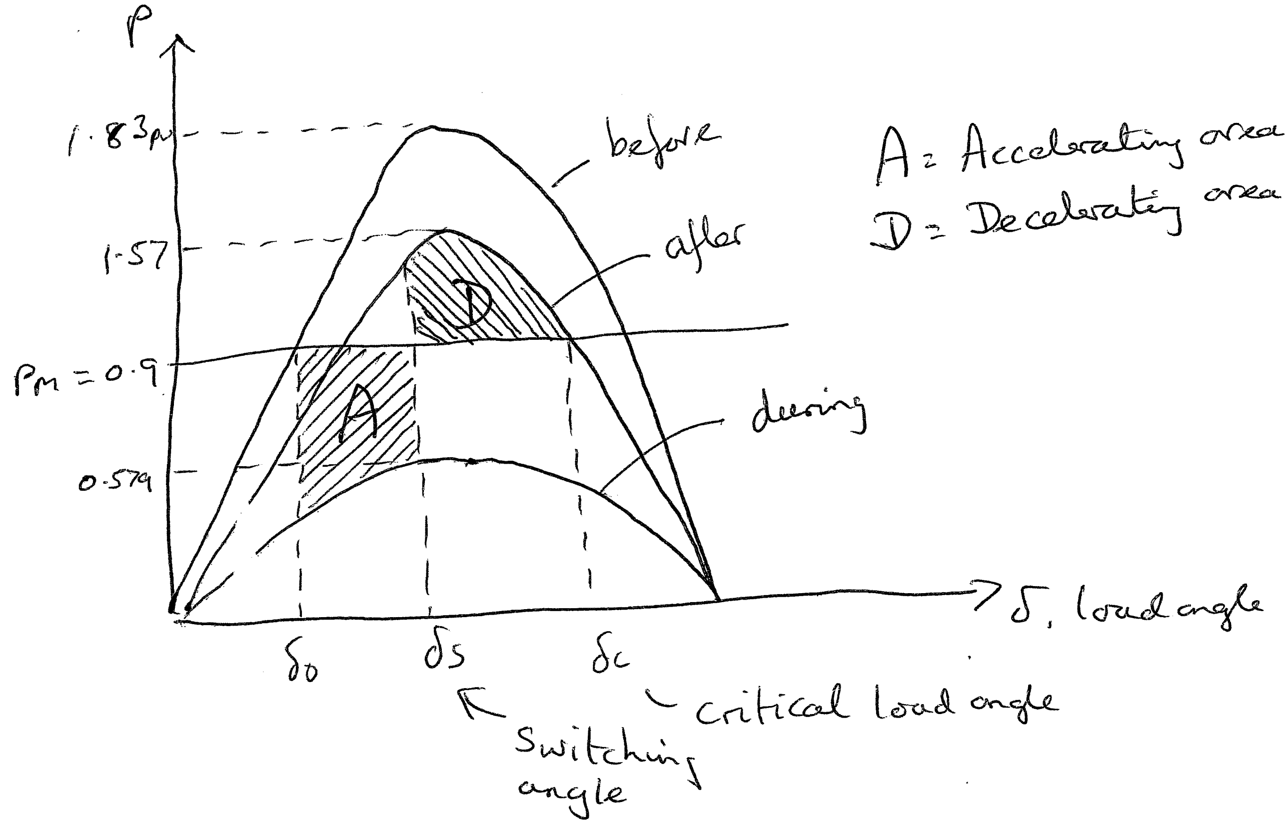
(iii) After the circuit breakers are opened the system reactance is:

$$X_A = 0.15 + 0.35 + 0.2 = 0.7\text{pu}$$

Hence:

$$P_{ea} = \frac{1.1 \times 1.0 \times \sin\delta}{0.7} = \underline{\underline{1.57 \sin\delta}}$$

(iv)



(v) Equal area criteria → Accelerating area = Decelerating area

$$\text{Acc\_area} = P_m(\delta_s - \delta_o) - \int_{\delta_0}^{\delta_s} P_{ed} \sin\delta \, d\delta$$

$$= 0.9\delta_s - 0.4617 + 0.5789\cos\delta - 0.5043$$

$$= 0.9\delta_s - 0.966 + 0.5789\cos\delta$$

$$\text{Dec\_area} = \int_{\delta_s}^{\delta_c} P_{ea} \sin\delta \, d\delta - P_m(\delta_c - \delta_s)$$

First find δ_c:

$$\delta_c = 180 - \sin^{-1}\frac{0.9}{1.57} = 145° \quad (= 2.531\,\text{rad})$$

$\therefore$ Dec-area $= -1.57\cos 145° + 1.57\cos\delta_s - 2.2779 + 0.9\delta_s$

$= 0.9\,\delta_s + 1.57\cos\delta_s - 0.9918$

Equating areas:

$$\cancel{0.9\delta_s} - 0.966 + 0.5789\cos\delta_s = \cancel{0.9\delta_s} + 1.57\cos\delta_s - 0.9918$$

$$\cos\delta_s = \frac{0.0258}{0.9911} \Rightarrow \underline{\underline{\delta_s = 88.5°}}$$

(c)

$$\frac{(\Delta t)^2}{M} = \frac{(0.05)^2}{2.5\times10^{-4}} = 10$$

Continued next page.

QUESTION 1 (CONTINUED)

t	C	$C\sin\delta$	$P_a = P_m - P_e$	$10P_a$	$\Delta\delta$	δ
0−	1.833	0.9	0			29.4
0+	0.5789	0.284	0.616			
0 Ave			0.31	3.1		
					3.1	
0.05	0.5789	0.311	0.579	5.9		32.5
					9.0	
0.1	0.5789	0.384	0.516	5.2		41.5
					14.2	
0.15	0.5789	0.478	0.422	4.2		55.7
					18.4	
0.2−	0.5789	0.557	0.343			74.1 *
0.2+	1.57	1.51	−0.608			
			−0.133	−1.3		
					17.1	
0.25	1.57	1.57	−0.67	−6.7		91.2
					10.4	
0.3	1.57	1.54	−0.64	−6.4		101.6
					4.0	
0.35	1.57	1.51	−0.61	−6.1		105.6
					−2.1	
						103.5

* Switching occurs before the critical switching angle of 88.5°, therefore machine is stable

QUESTION 2   301

(a) Choose a base of 120MVA:

Generator G1:

$$X_+ = X_- = 0.1 \times \frac{120}{100} = 0.12\,pu$$

$$X_0 = 0.08 \times \frac{120}{100} = 0.096\,pu$$

Generator G2:

No change $X_+ = 0.15\,pu$ $X_- = 0.18\,pu$ $X_0 = 0.14\,pu$

Generator G3:

$$X_+ = X_- = 0.08 \times \frac{120}{80} \times \left(\frac{19.5}{20}\right)^2 = 0.1141\,pu$$

$$X_0 = 0.06 \times \frac{120}{80} \times \left(\frac{19.5}{20}\right)^2 = 0.0856\,pu$$

Transformers T1/T2 No change.

$$X_+ = X_- = X_0 = 0.12\,pu$$

Transformer T3:

$$X_+ = X_- = X_0 = 0.06 \times \frac{120}{80} = 0.09\,pu$$

Lines L1 and L2:

Calculate base impedance:

$$Z_B = \frac{V_B^2}{MVA_B} = \frac{132000^2}{120 \times 10^6} = 145.2\,\Omega$$

$$\therefore X_+ = X_- = \frac{8}{145.2} = 0.0551\,pu$$

$$X_0 = \frac{30}{145.2} = 0.207\,pu.$$

QUESTION 2 (CONTINUED)

Earthing reactor:

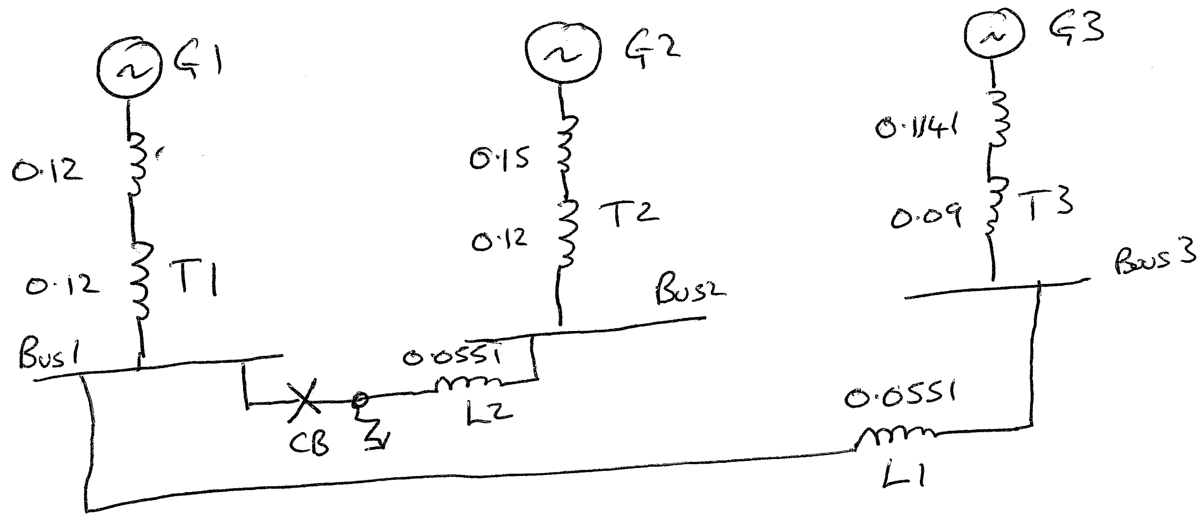
$$Z_{base} = \frac{25000^2}{120 \times 10^6} = 5.208\,\Omega$$

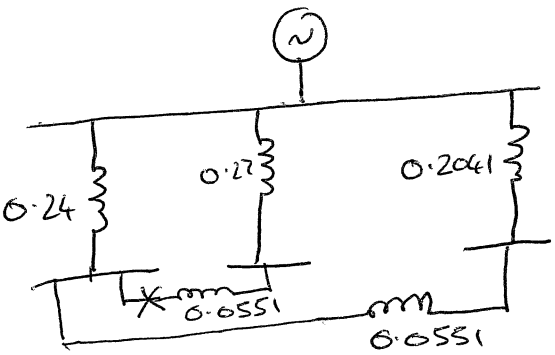
$$\therefore X_{pu} = \frac{0.3}{5.208} = 0.0576\,pu$$

Multiply by 3 to include in zero sequence network

$$X_{puER} = 0.1728\,pu.$$

(b) Positive sequence:





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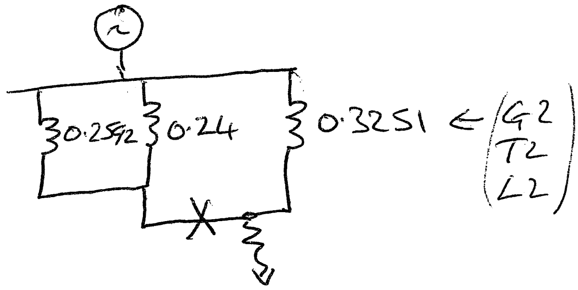

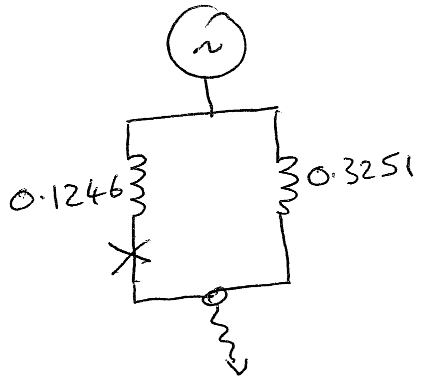

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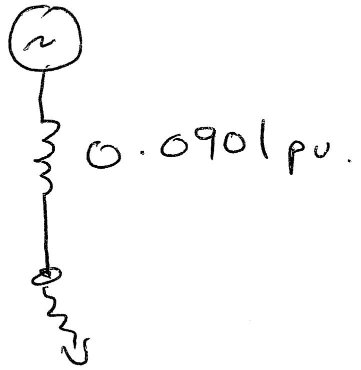
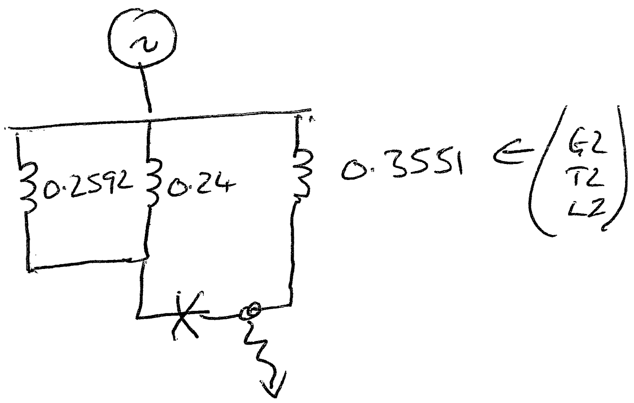


Negative Sequence – Same form as positive, but different values for G2 only. (G2 changes from 0.15 to 0.18)

Using intermediate diagram from positive sequence



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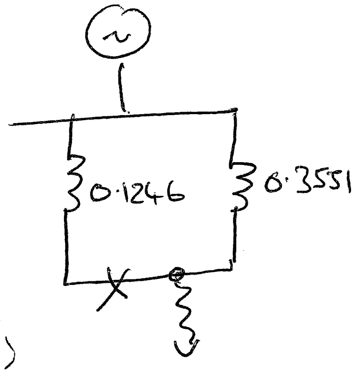

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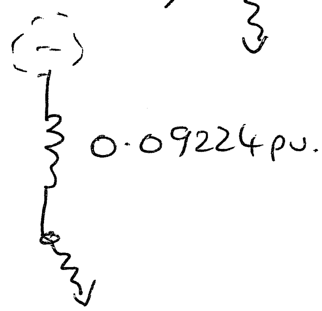
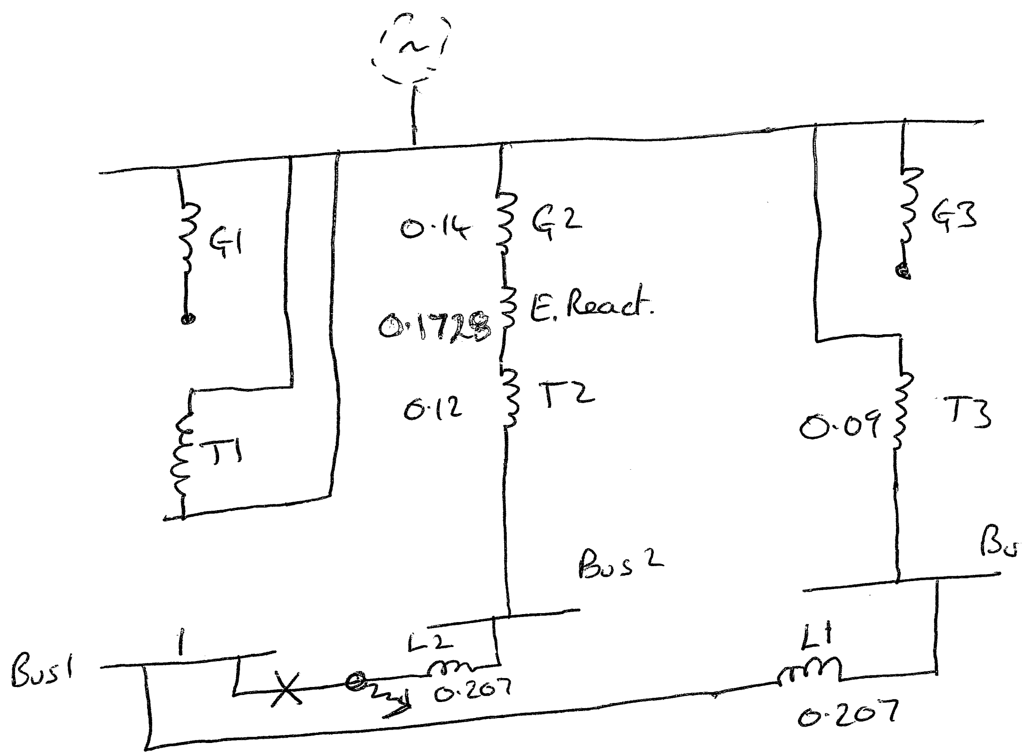


Zero Sequence



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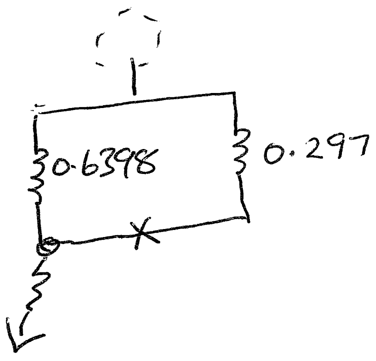

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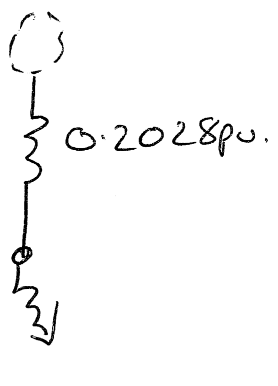


(c) For a single line to earth fault the sequence networks are connected in series:

$$I_+ = I_- = I_0 = \frac{1.0}{Z_+ + Z_- + Z_0} = \frac{1}{0.0901 + 0.09224 + 0.2028}$$

$$= 2.5964 \text{ pu}$$

Now actual pu fault current is $3I_+ = 7.789 \text{pu}$

$$I_B \text{ at fault} = \frac{MVA_B}{\sqrt{3}\, V_B} = \frac{120 \times 10^6}{\sqrt{3} \times 132 \times 10^3} = 524.9 \text{A}$$

$\therefore$ Total fault current $= 524.9 \times 7.789 = \underline{\underline{4088 \text{A}}}$

(d) First find the sequence current flowing through CB.

Refer back to sequence diagrams.

$$I_{CB+} = \quad \times \frac{0.3251}{(0.3251 + 0.1246)} = 1.877 \text{pu}$$

$$I_{CB-} = \quad \times \frac{0.3551}{(0.3551 + 0.1246)} = 1.922 \text{pu}$$

$$I_{CB0} = \quad \times \frac{0.6398}{(0.6398 + 0.297)} = 1.773 \text{pu}$$

$\therefore$ Total pu current through CB $= 1.877 + 1.922 + 1.773 = 5.572 \text{pu}$

Hence actual fault current through CB is 5.572×524.9

$= \underline{\underline{2924.5 \text{A}}}$

$\therefore$ CB is properly rated to clear this type of fault.

Question 3

(a) Students should give 2 of the following:

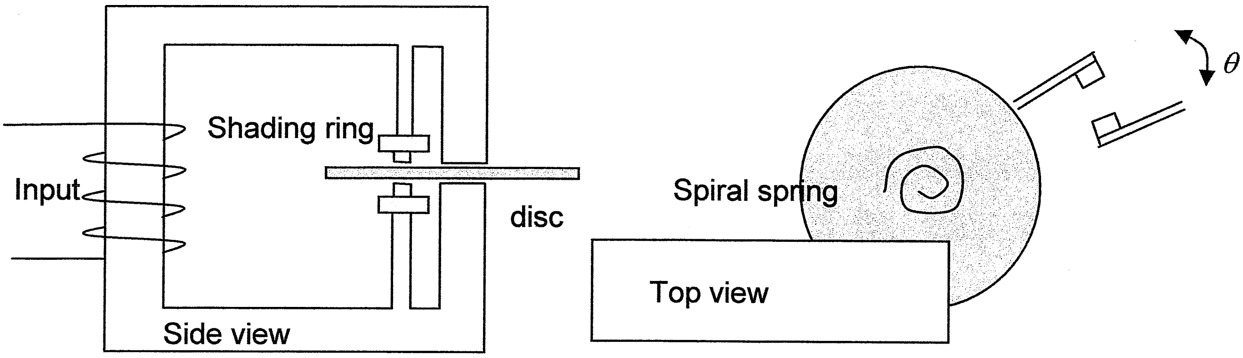
- Equipment insulation faults
- System over-voltages due to lightning or other surges
- Physical or natural damage (mechanical digger through cable, tree touching overhead line)

Protection is required to save personnel from risk of electrocution and to help prevent the risk of fire and explosion and damage to equipment.

(b) ***The following descriptions are from the course notes; the students do not need to provide quite as much detail provided they cover the main points.***

(i) Induction relays

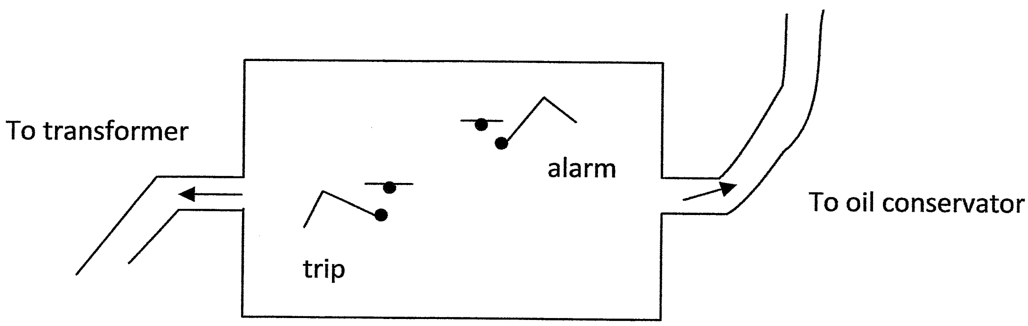
In an induction relay eddy currents are induced in a conducting rotor (disc), which in turn produced a flux which interacts with the stator flux to develop a torque (Similar to induction motor operation). If the input current exceeds the pickup current, the disc rotates through an angle θ to close the relay contacts. The larger the input current the faster the contact closes. After the current is removed or reduced below the pickup the spring provides resets of the contacts.



A permanent magnet may be used to produce a breaking torque. This configuration results in the operating time being dependent on operating current and distance that the disc is required to travel before closing the relay contacts. Consequently the relay exhibits an inverse definite minimum time (IDMT) characteristic – the higher the current above pickup the faster the relay will operate:

(ii) Buccholz relays

In oil immersed transformers (the vast majority) an internal fault is always accompanied by the release of gas, since oil temperature is increased to vaporising point in the vicinity of a fault. Since some faults e.g. an earth fault close to the neutral involving only a few turns produce insufficient fault current to operate the protection relays, a gas operated relay is used.



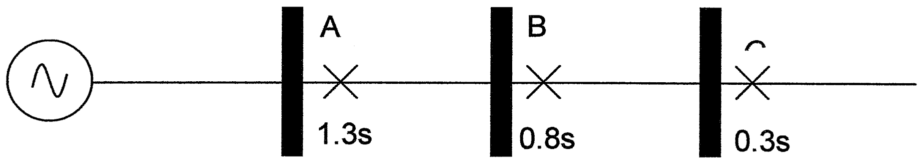
This consists of 2 pivoted buckets carrying mercury switches. When a slight fault occurs gas is trapped in the relay housing. As the gas accumulates the oil level in the relay falls. This causes the bucket to tilt and complete the alarm circuit. When a serious fault occurs a sudden surge of gas impinges on the lower bucket causing it to tilt and close the mercury switch which in turn trips the circuit breaker.

(c) ***The following descriptions are from the course notes; the students do not need to provide quite as much detail provided they cover the main points.***

(i) There are a number of different types of protection; Over-current is one of the most important. It is the cheapest and simplest means of protecting a wire and plant. Over-current protection may be time graded, current graded or time and current graded.

Time grading

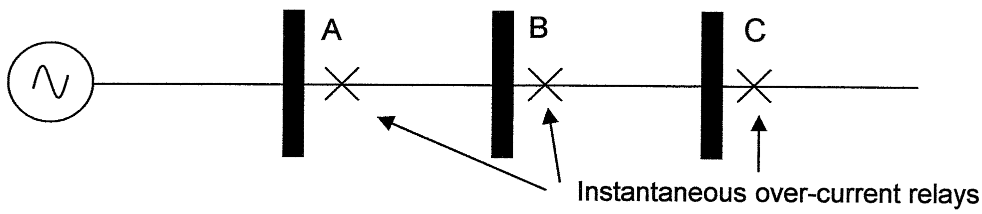
For example consider a radial feeder with time grading:



Protection is graded such that A operates after 1.3 seconds, B after 0.8s and C after 0.3s. This is to ensure selectivity of operation from the far end of the protected circuit to the generator. This is done by using an overcurrent relay followed by a timing relay which trips the circuit breaker. For a fault beyond C – Circuit breaker C trips first and the circuit up to C remains in operation. Relays A and B also provide back-up protection. For a fault between B and C – Circuit breaker B trips first and A provides back-up. Time setting of successive relays differ by a time delay in the order of 0.3-0.6s to allow for fault clearance time of the circuit breakers.

Current grading

Since the short circuit current decreases as distance from the source to the fault increases, relays can be set to pick-up at progressively higher currents towards the source. This overcomes the disadvantage of the time delays which occur with time grading.



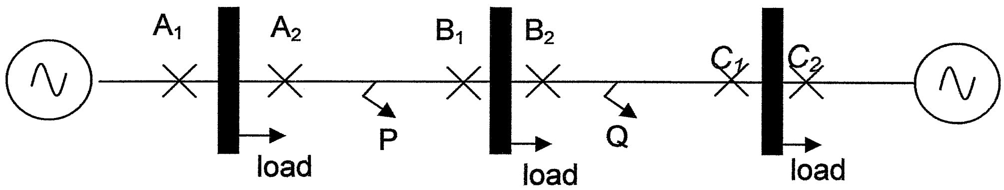
A is set to operate for faults between A and B
B is set to operate for faults between B and C
C is set to operate for faults after C where the current settings of C are less than the settings of B which are less than the settings of A

This has several associated difficulties:

- The fault currents need to be known accurately
- It is difficult to differentiate between faults either side of the circuit breakers
-

(ii) **Protection of 2 source system**

It becomes more difficult to co-ordinate over-current relays when there are two or more sources at different locations. Consider the system below.



Suppose there is a fault at Q, it would be desirable for B_2 and C_1 to clear the fault to minimise disruption. Using time delay over-current relays, we would set B_2 faster than B_1. However, consider a fault at P, if B_2 operates faster than B_1 then the load at bus B would be disconnected (which is not desirable). When a fault can be fed from two directions then it is necessary to use directional relays.

What this means is that for a fault at Q only B_2 should operate, ie. The current is flowing from bus B towards B_2. (Whereas it is flowing from B_1 towards the bus). For a fault at P only B_1 should operate (ie the current is flowing from bus B towards B_1, but from B_2 towards the bus). The directional relays are set so that only currents greater than the specified amount and in the direction flowing away from the bus will trip the relay. For a fault on bus B (currents flowing inward from B_1 and B_2), then A_2 and C_1 will trip (by the directional relay) to ensure that the bus is isolated.

(d)

(i) Current transformers must have a load in the form of an ammeter or short circuit connected across them whenever a current is flowing through the primary conductor. In normal operation the mmf of the primary is balanced by that of the secondary. The secondary current I_2 itself produces a 'back' flux to oppose the 'forward' flux (Lenz's law) and the two are almost equal. If the ammeter is removed, there is no 'back' flux produced since $I_2 = 0$, therefore the current through the busbar produces the 'forward', unopposed flux. This cuts the secondary windings and the high flux value and the high number of turns on the secondary produce very high induced voltages.

(ii) The turns ratio is given by:

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} = \frac{5}{15000} = \frac{1}{3000}$$

Assume:

$$I_1 = 15000 \sin \omega t$$

then:

$$\phi_{1CORE} = \frac{mmf}{reluctance} = \frac{N_1 I_1}{S_{CORE}} = \frac{15000 \sin \omega t}{3 \times 10^5}$$

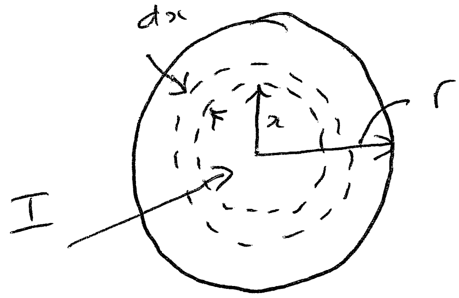
If there is no secondary load, then there is no 'back' flux to oppose this and the emf is:

$$V_2 = N_2 \frac{d\phi}{dt} = \frac{3000 \times \omega \times 15000 \cos \omega t}{3 \times 10^5} = \frac{3000 \times 2\pi \times 50 \times 15000 \cos \omega t}{3 \times 10^5}$$

ie a maximum induced emf of 47kV.

QUESTION 4 301

(a)



Assume uniform current density

i.e. $J = \frac{I}{\pi r^2}$

Consider elemental flux path of radius x linking current, I_x:

Using Ampere's law:

$$\oint H_x \, dx = I_x = 2\pi x H_x$$

$$\therefore 2\pi x H_x = \frac{\pi x^2}{\pi r^2} \cdot I$$

$$\therefore H_x = \frac{xI}{2\pi r^2} \quad A/m$$

$$\therefore B_x = \mu_0 H_x = \frac{\mu_0 x I}{2\pi r^2} \quad T$$

Flux enclosed per metre length of tubular elemental flux path

$$d\phi = \frac{\mu_0 x I}{2\pi r^2} \cdot 1 \cdot dx$$

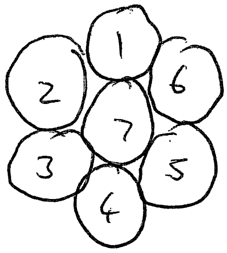
Elemental flux linkage with conductor:

$$d\lambda = \frac{\mu x I}{2\pi r^2} \cdot dx \times \frac{x^2}{r^2} = \frac{\mu_0 I x^3}{2\pi r^4} dx$$

$\therefore$ Total flux linkage due to all internal elemental flux paths

$$\lambda_{int} = \int_0^r d\lambda = \int_0^r \frac{\mu_0 I x^3 dx}{2\pi r^4} = \frac{\mu_0 I r^4}{8\pi r^4} = \frac{\mu_0 I}{8\pi}$$

$$\therefore L_{int} = \frac{\lambda_{int}}{I} = \frac{\mu_0}{8\pi} = \underline{\underline{\frac{1}{2} \times 10^{-7} \ H/m}} \quad \text{(independent of r)}$$



Let radius $= r$

$\therefore r' = 0.778\,r$ (to account for internal flux linkages)

$d_{12} = 2r = d_{16}$ etc.

$d_{14} = 4r$

$d_{13} = \sqrt{d_{14}^2 - d_{34}^2} = \sqrt{16r^2 - 4r^2} = 2\sqrt{3}\,r$

$d_{16} = d_{12}$; $d_{13} = d_{15}$; $d_{17} = d_{12}$

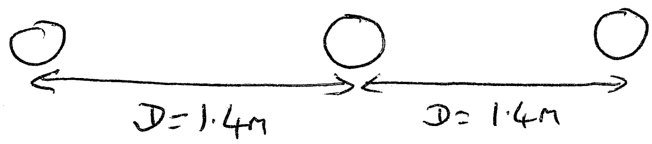
$$GMR = \sqrt[7\times7]{(r'.d_{12}.d_{13}.d_{14}.d_{15}.d_{16}.d_{17})(d_{21}.r'.d_{23}\ldots)\ldots(d_{71}.d_{72}.d_{73}.d_{74}.d_{75}.d_{76}.r')}$$

$$= \sqrt[49]{(r'.2r.2\sqrt{3}r.4r.2\sqrt{3}r.2r.2r)^6 . r'(2r)^6}$$

$$= \sqrt[49]{r'^7 (3\times3\times3\times5.2\times5.2\times6.0)\times3^6}$$

$$= \sqrt[49]{(0.778\times1.5)^7(4380.48)^6\times729} = \underline{\underline{3.265\,mm}}$$

(c)(i)



Assume fully transposed line $\therefore L = \frac{\mu_0}{2\pi} \ln \frac{D_g}{R_g}$ $D_g = GMD$ $R_g = GMR$

$D_g = \sqrt[3]{D.D.2D} = \sqrt[3]{1.4\times1.4\times2.8} = 1.76\,m$

(i) For the single conductor, radius 4mm

$$GMR = 0.7788 \times 4 = 3.11\,mm$$

$$\therefore L = \frac{\mu_0}{2\pi} \ln\left(\frac{1.76}{3.11\times10^{-3}}\right) = 1.27\times10^{-6}\ H/m.$$

$$\therefore X_L = 2\pi f L = \underline{\underline{0.399\,\Omega}}$$

(ii) For the 7-strand conductor

GMD is unchanged from above

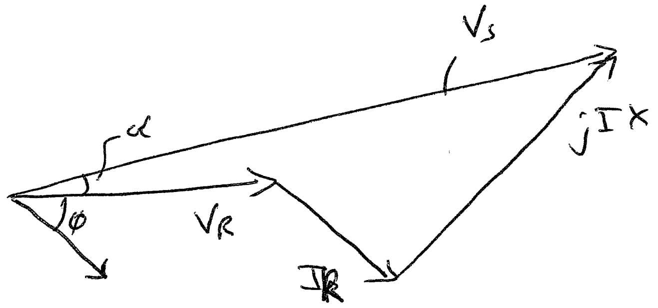
$$\therefore L = \frac{\mu_0}{2\pi} \ln\frac{1.76}{3.27\times10^{-3}} = 1.258\times10^{-6}\ H/m$$

$$\therefore X_L = 2\pi f L = \underline{\underline{0.395\,\Omega}}$$

(d) For a 10km long line:

$R = 5\,\Omega \qquad X = 7.9\,\Omega$

Phasor diagram:



$$V_S^2 = (V_R + IR\cos\phi + IX\sin\phi)^2 + (IX\cos\phi - IR\sin\phi)^2$$

$$\text{Now } I_{ph} = \frac{P}{\sqrt{3}\,V_L \times \cos\phi} = \frac{400\times10^3}{\sqrt{3}\times11\times10^3\times0.8} = 26.24A$$

$$V_S^2 = \left(\frac{11000}{\sqrt{3}} + (26.24 \times 5 \times 0.8) + (26.24 \times 7.9 \times 0.6) \right)^2 + \left((26.24 \times 7.9 \times 0.8) - (26.24 \times 5 \times 0.6) \right)^2$$

$$= (6351 + 104.96 + 124.4)^2 + (165.84 - 78.72)^2$$

$$= (6580.4)^2 + (87.12)^2 \Rightarrow V_S = 6580.5 \quad \underline{\underline{(V_{S\,LINE} = 11400\,V)}}$$

e. The voltage at the receiving end could be regulated using any of the following methods:

- Tap changing transformers
- Shunt reactors
- Synchronous compensators
- Static VAR compensation
- FACTS, FADS
- Shunt/series capacitors.