References

ENG125/243 Txtbk → Electrical Engineering – Fourth Ed. By Allan R. Hambley
Other reference → Alexander, Fundamentals of Electric Circuits, 3rd Edition. McGraw Hill, 2007.
Calculator used → Casio fx – 9860G AU
Calculator book → Mathematics with a graphics calculator - Casio fx – 9860G Auby Barry Kissane & Marian Kemp

Radial System = Generator at one end and current can only go one way around.

ENG455 Lect 2 p3.
Voltage is defined in terms of Line to Line.

ENG455 Lect 2 p7 : Per Unit analysis.
All the same except in current.

$$I_{3\phi,base} = \frac{S_{3\phi,base}}{\sqrt{3}\,V_{3\phi,base}} \qquad (15)$$

Per unit calculations – ENG347 P7L3
S_{base} is continuous across the whole circuit.

$$V_{pu}=\frac{V}{V_{base}} \quad I_{pu}=\frac{I}{I_{base}} \quad Z_{base}=\frac{(V_{base})^2}{S_{base}} \quad P_{pu}=|I_{pu}|^2\times R_{pu}$$

$$I_{base}=\frac{S_{base}}{V_{base}} \quad I_{3\phi base}=\frac{S_{3\phi base}}{\sqrt{3}V_{3\phi base}} \quad S_{pu}=V_{pu}\times I^*_{pu} \quad S_{pu}=\frac{S}{S_{base}}$$

$$X_{pu}=\frac{X}{Z_{base}} \quad Z_{pu}=\frac{Z}{Z_{base}} \quad Z_{pu}=\frac{V_{pu}}{I_{pu}} \quad R_{pu}=\frac{R}{Z_{base}}$$

Fault Level
$VA_{SC} = \frac{S_{base}}{Z_{pu}} = \sqrt{3}V_{base}I_{SC}$ See ENG455 SG3 Q2 for the derivation.

When X is given as a percentage (ie 10%) you can convert it straight across (ie 0.10pu). So the actual reactance is the X * Sbase.
When converting power bases (ie KVA) it is a ratio thing.
Say $2\times S_{baseOld}=S_{baseNew}$ therefore
$2 = \frac{S_{baseNew}}{S_{baseOld}}$ see **ENG348 Lect 18 pages 4 to 7**
This is only if the voltage bases are the same. The actual equation is
$X_{pu\_new} = X_{pu\_old}\times\frac{Z_{base\_old}}{Z_{base\_new}}$ better to get in the habit of using this.
The Voltage on Generators just becomes 1pu and the (X) reactance is calculated to allow for the difference in voltages.
Transformers just become reactances.

Fault Level pu : ENG348 Lect18 p9
$FL_{pu}=\frac{FL}{S_{base}}$
where
$FL = \sqrt{3}V_{nominated}I_f$

WYE circuits
Line to line voltages – pg 248 Hamb

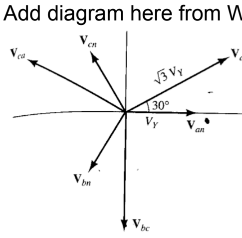
$$V_L=\sqrt{3}V_Y \qquad (5.96)$$

$$V_{ab}=V_{an}\times\sqrt{3}\angle 30^o \qquad (5.97)$$

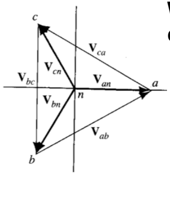
The line to line voltage is $\sqrt{3}$ x the line to neutral voltage.
This is only for positive sequence phasors. For negative sequence use

$$V_{ab}=V_{an}\times\sqrt{3}<-30^o$$

Add diagram here from WSAC-19 or page 249. hambley.



(a) All phasors starting from the origin



(b) A more intuitive way to draw the phasor diagram

Wye to Delta load conversion hamb pg 251

$$Z_\Delta=3Z_Y \qquad (5.100)$$

$$V_L=\sqrt{3}V_Y \angle 30^o$$
(5.96) pg 248
Phase Voltage = Line to Neutral Voltage – p245 Hamb

Figuring out 3 phase systems using PU analysis : ENG455 PracTest 1
1. All generators become 1pu
2. Calculated the reactance $X_{pu}=\frac{X}{Z_{base}}$
3. If the Sbase is different to the component then
When converting power bases (ie KVA) it is a ratio thing.
Say $2\times S_{baseOld}=S_{baseNew}$ therefore
$2 = \frac{S_{baseNew}}{S_{baseOld}}$ see **ENG348 Lect 18 pages 4 to 7**
4. Transformers just become reactive impedances : again $X_{pu}=\frac{X}{Z_{base}}$
5. You should end up with a circuit where Generators are 1.0pu and everything else is a reactance. Ie j0.65
6. Calculate the current in this PU circuit.
7. Convert the Ipu back to the time domain I Amps. This is the current at the original Sbase point.
8. Find the current for all other sections of the circuit using the turns ratios on the transformers. (remember in transformers that when voltage goes up current goes down)

Symmetrical Components : ENG348 Lect19 p3

$$\begin{bmatrix}\mathbf{V}_a\\\mathbf{V}_b\\\mathbf{V}_c\end{bmatrix} = \begin{bmatrix}1&1&1\\1&a^2&a\\1&a&a^2\end{bmatrix}\begin{bmatrix}\mathbf{V}_0\\\mathbf{V}_1\\\mathbf{V}_2\end{bmatrix} \qquad (9)$$

$$\begin{bmatrix}V_0\\V_1\\V_2\end{bmatrix} = \frac{1}{3}\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\begin{bmatrix}V_a\\V_b\\V_c\end{bmatrix}$$

ENG348 Lect19 p4 : the first one is the base equation we use.
The current I_a I_b I_c are the line to neutral currents.

$$\mathbf{I}_p = \begin{bmatrix}\mathbf{I}_a\\\mathbf{I}_b\\\mathbf{I}_c\end{bmatrix} = \begin{bmatrix}1&1&1\\1&a^2&a\\1&a&a^2\end{bmatrix}\begin{bmatrix}\mathbf{I}_0\\\mathbf{I}_1\\\mathbf{I}_2\end{bmatrix} = \mathbf{A}\,\mathbf{I}_s$$

and

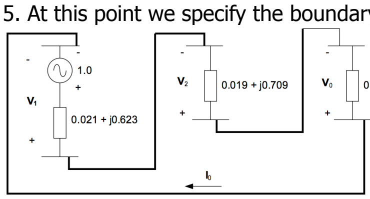
$$\mathbf{I}_s = \begin{bmatrix}\mathbf{I}_0\\\mathbf{I}_1\\\mathbf{I}_2\end{bmatrix} = \frac{1}{3}\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\begin{bmatrix}\mathbf{I}_a\\\mathbf{I}_b\\\mathbf{I}_c\end{bmatrix} = \mathbf{A}\,\mathbf{I}_p$$

Where $a = 1\angle 120^o$ and
$a^2 = 1\angle 240^o$
NB :
$a-a^2 = j\sqrt{3}$ & $a^2-a = -j\sqrt{3}$

Identity for a : **ENG348 lect19 p2**

$$1+a+a^2=0$$

ENG455 Lect 5 p8 and self notes 455-3
Method to Calculate Unbalanced circuits – for single ground to phase fault.
1. Make a Positive Sequence Network
If the Generator is abc then the positive network has a generator in it. Else the Negative network will if acb rotation.
2. Make negative sequence Network
3. Make Zero sequence network.
4. Each one will have a Voltage across it V1, V2, V0 with an I1, I2, I0
5. At this point we specify the boundary conditions.



For a single ground to phase fault Va = 0 and Ib = Ic = 0 and therefore I0 = If (fault current)

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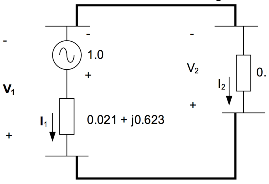
6. Now apply the matrices to get the voltages and currents using the boundary conditions.
7. Run the 3 sequence networks in series (don't know why – ask Greg) and do KVL to give the overall current.
8. Convert it from sequence to phasor PU current using the equation derived from step 6.
9. Remember your sqrt(3) multiples at this stage for Delta-Y changes.
10. Apply this current (as a sequence current) back to the original network to get currents at breaker points. (start at the fault and work back to the breaker)
11. Use PU rules to get back to phase voltages (check this last step as vague and tired whilst writing at 10:50pm)

For Phase to Phase (Line to Line) fault : ENG455 Lect 5 p11



1. Boundary conditions
Ia = 0
Ib = -Ic
Vb = Vc
Outcomes
I_0 = 0 and $I_1 = I_2$
V_0 = 0 and $V_1 = V_2$

2. Convert these boundary conditions to Sequences using matrices.
3. Draw sequence diagrams. There will be no I0 sequence as Ia has no current.
4. Convert sequence currents back to phase currents using :

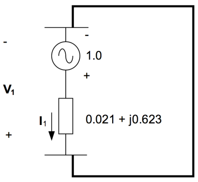
$$I_b = -j\sqrt{3}I_1$$

this is because

$$a-a^2 = j\sqrt{3} \quad \& \quad a^2-a = -j\sqrt{3}$$

Balanced Three-phased faults :

1. Boundary Conditions are :



$$V_a = V_b = V_c = 0 \text{ and}$$
$$I_a = I_b = I_c = 0$$

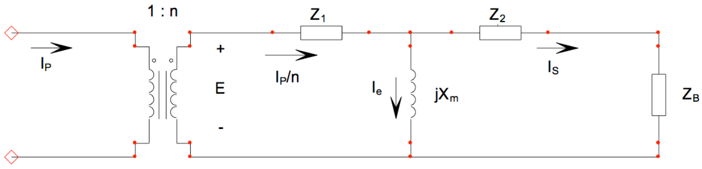
2. This implies that I0 = I2 = 0 when the calcs are done.
So If = Ia = I1
3. Only the positive sequence is used to calculate the current.

Method to Calculate Unbalanced circuits – for various faults.

1. Make a Positive Sequence Network
If the Generator is abc then the positive network has a generator in it. Else the Negative network will if acb rotation.
2. Make negative sequence Network
3. Make Zero sequence network. Remember that the **zero** sequence network can not go past Delta connections.
4. Each one will have a Voltage across it V1, V2, V0 with an I1, I2, I0
4.5 Draw the fault as it physically appears as phases.
5. At this point we specify the boundary conditions.
For a single ground to phase fault
Va = 0 and
Ib = Ic = 0 and therefore I0 = If (fault current)
or whatever combination for each type of fault.
6. Now apply the matrices to get the voltages and currents using the boundary conditions.
7. Run the 3 sequence networks so that they satisfy the current equation produced from the matrix.
7.5. Do KVL to give the overall current.
8. Convert it from sequence to phasor PU current using the equation derived from step 6.
9. Remember your sqrt(3) multiples at this stage for Delta-Y changes.
10. Apply this current (as a sequence current) back to the original network to get currents at breaker points. (start at the fault and work back to the breaker)
11. Use PU rules to get back to phase voltages (check this last step as vague and tired whilst writing at 10:50pm)

ENG455 Lect 6 p6 Current transformers

1. Move everything to the RHS of the transformer.
Z1 = Impedance through primary coil.



Z2 = Impedance through secondary coil.
Jxm = The magnetising impedance of the core

2. Use the current divider rule to find the currents.
3. To find Ie you'll need to use the magnetisation curve.
4. The magnetisation curve equation will need the need E (secondary voltage.
5 Will need to be iterated. Assume jXm not there to estimate E.
6. Insert into magnetisation curve equation and iterate to find Ie.
7. CT_error is the difference between the primary and secondary currents. The difference will be what is lost in Ie.

$$CT_{error}\% = \frac{I_e}{\frac{I_P}{n}} = \frac{I_P - I_S}{\frac{I_P}{n}}$$

Secondary coil current :

$$\mathbf{I_S} = \frac{jX_m}{jX_m + Z_2 + Z_B} \times \left(\frac{\mathbf{I_P}}{n}\right) \qquad (9)$$

ENG455 Lect 7 p9 Tap setting

$$\text{Current\_multiplier} = \frac{\text{fault\_current}}{\text{Current\_tap\_setting}}$$

ENG455 Lect 7 p6 Tap setting

Curves are usually given by a formula something like

$$t = TD\left(\frac{A}{M^P - 1} + B\right)$$

Where TD = Time dial setting
M = ????

Curve description	Standard	P	A	B
Moderate Inverse	IEEE	0.02	0.0104	0.0226
Inverse	IEEE	2.0	5.95	0.18
Very Inverse	IEC	1.0	13.5	0

Equal area Calculations :

When a fault occurs in a circuit the overall power expelled by the circuit changes as there is now less components for the current to pass through between the generator and ground. Usually a breaker cuts the circuit where the fault is.

So when the power goes from it's old power level to the new power level there is an element of overshoot past the new power level. Then the power in the circuit has a reducing oscillatory motion until it settles to steady state again. This is because the generator speeds up or slows down to compensate for the power increase.

If the overshoot is too great then the circuit can become unstable and can go out of control. This is quite a complex set of equations to calculate out so it is simplified using the equal area method.

The power area in A_1 is a good indicator of the power area of the overshoot A_2. By using the equal areas we can estimate the maximum power angle the machine will go to and whether it becomes unstable.

The actual reason for doing the equal area calculations is to find out how long you can let a fault run for before it causes damages. But the equal area calc only gives you angle. If you want the exact time you will have to do a non linear DE.

Method :

1. Redraw the circuit with the tripped breaker.
2. Calculate the overall reactance of the new circuit.
3. Apply $P_e = \frac{E' \times V_{bus}}{X_{eq}} \sin\delta$

where :
E' = The generator voltage
V_{bus} = is the voltage on the infinite bus.
X_{eq} = The reactance in the circuit as a whole.
And this will give you something like $P_e = 1.8303 \sin\delta$ which will let you draw the graph :

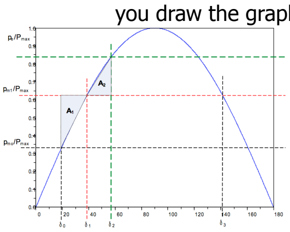


figure 1.

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4. Set P_e = 1.0 to find the new power angle (in this case δ_1)

5. Integrate to find A_1 where δ_0 is the initial power angle.

6. Then use the same integration equation again to find δ_2

7. An example of this is in Study guide 13 Question 2.

Equal Area – 3 types.

1. (Figure 1) The first type (p705 Glover) is when the load jumps up suddenly.

δ_0 is the normal operating condition.

δ_1 is the new operating condition with the new load value. When the new larger load happens then the physical rotor of the generator spins faster to supply more power to keep the output voltage / current the same. Because it spins up o much it overshoots the point it needs to be at because it has inertia due to it's mass. If it goes past δ_2 it will go out of control until physical damage to the rotor occurs.

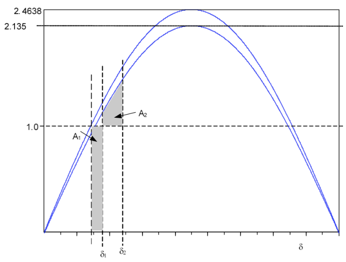


Figure 2

2. The second (page 711 Glover) is when there is an actual fault.

δ_0 is the normal operating condition.

When the fault occurs the breaker trips but the rotor of the generator spins faster now as there is no load to slow it down. When the fault is cleared and the breaker recontacts the power angle is now at δ_{cr} (or maybe δ_1 on other drawings). The load is reapplied but because of inertia the rotor speed will keep growing for a while. If it goes past δ_3 it will become unstable.

3. The third (page 713 Glover) is when a branch disappears. *Have not looked closely at this one yet.*

ENG455 Lect 12 p2

What is Pe = Real Power → lect 11 page 8 or active power → see **ENG455 Lect 11 p8**

Pm = Mechanical power?

Pmo = Mechanical power steady state value → Lect13 p1

Pm1 = Mechanical power at a new value → Lect13 p1

δ = The machine power angle

Real Power

$$P_e = \frac{E' \times V_{bus}}{X_{eq}} \sin\delta \quad \textbf{ENG455 Lect 11 p8} \qquad (3)$$

Reactive Power

$$Q_e = \frac{V_{bus}}{X_{eq}}(E' \cos\delta - V_{bus}) \quad \text{Glover pg 323}$$

where :

E' = The generator voltage

Pe = Real Power

Qe = Imaginary Power Var

V_{bus} = is the voltage on the infinite bus.

X_{eq} = The reactance in the circuit as a whole.

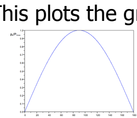
δ = The machine power angle

$$H = \frac{KE_{stored}}{S_{rated}}$$ **SG12 q1 WTF is H???**

ENG455 Lect 11 p8

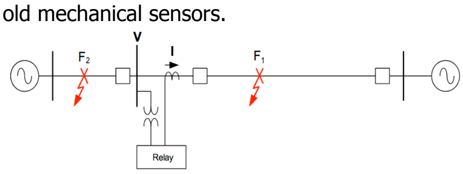
Power is a function of machine angle : This plots the graph :

$$P_e(\delta) = P_{max} \sin\delta \quad \text{where} \quad P_{max} = \frac{E' V_{bus}}{X_{eq}}$$



Directional Relays Lect9 Page 5

Directional Relays sense both the current and the voltage. The do a calculation for Power. Except they call it torque (Something to do with the old mechanical sensors.



The equation of Power is $P = V I \cos\theta$

The equation for Torque in a directional relay is

$T = V I \cos(\theta_m - \theta)$ for

where θ_m is the maximum angle difference between the current and voltage.

$\theta = \angle I_a - \angle V_a$ = The operating angle difference between voltage and current.

Fault condition is when T > 0. → to work this out you ignore the VI section and just do the $T = \cos(\theta_m - \theta)$ section.

If finding the torque using Line to Line voltages instead of line to Neutral

SG9 Q3 – 90° Phase direction or Quadrature connection.

$$T_a = k V_{bc} I_a \cos(\theta - \theta_{MT})$$
$$\theta = \angle I_a - \angle V_{bc}$$
$$T_b = k V_{ca} I_b \cos(\theta - \theta_{MT})$$
$$\theta = \angle I_b - \angle V_{ca}$$
$$T_c = k V_{ab} I_c \cos(\theta - \theta_{MT})$$
$$\theta = \angle I_c - \angle V_{ab}$$

Fault condition is when T > 0. → to work this out you ignore the VI section and just do the $T = \cos(\theta - \theta_{MT})$ section.

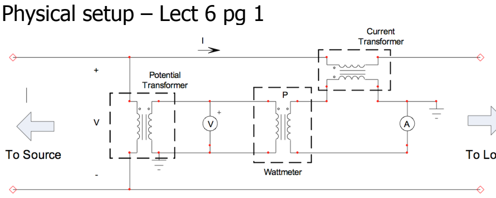
K is a left over spring constant from the old mechanical relays.

Mho = the reciprocal of the ohm.

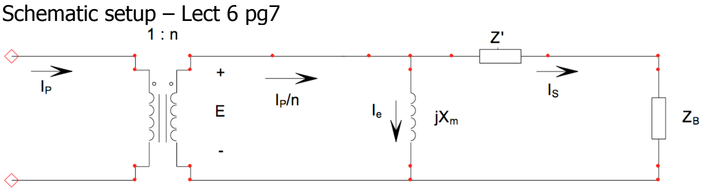
ENG455 Current Transformer – SG06 lect6

Used for detecting the current in a high current line by stepping it down with a transformer and reading the current as a voltage then doing a conversion.

Physical setup – Lect 6 pg 1



Schematic setup – Lect 6 pg7



Current divider rule used to find I_S

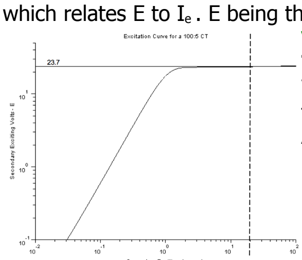
$$\mathbf{I_S} = \frac{j X_m}{j X_m + Z_2 + Z_B} \times \left(\frac{\mathbf{I_P}}{n}\right)$$

I_e is the error between I_s and I_P/n

$$CT\_error = \left|\frac{I_e}{I_P/n}\right| \times 100\,\%$$

$$= \left|\frac{Z_2 + Z_B}{j X_m + Z_2 + Z_B}\right| \times 100\%$$

Sometimes I_e can not easily be found so we use a magnetisation curve which relates E to I_e. E being the vertical axis below.



Voltage Quality :

Thompsons Formula From Lab5 week 5

This is used to find the resonant frequency of an RLC circuit.

Applies to series and parallel circuits – p16 2010-07-Filters_Resonance.pdf

$$f_0 = \frac{1}{2\pi\sqrt{LC}} (Hz)$$

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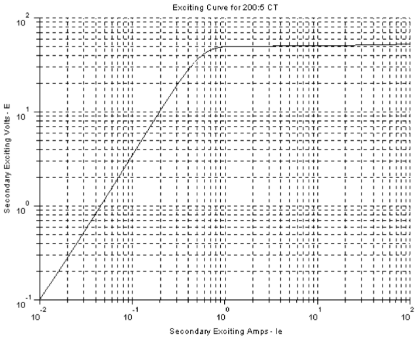
Covered in ENG455 exam S1 2011

1. Current Transformer 14min 8

SG6Q4

An overcurrent relay set to operate at 10A is connected to the CT in the figure below with a 200:5 CT ratio. The secondary resistance is 0.125 Ω. Determine the minimum primary fault current that the relay will detect if the burden Z_B is (a) 1.0Ω, (b) 4.0Ω, and (c) 5.0Ω.



4. ANS:

(a) With a current of 10A in the relay, $E = 10 \times (0.125 + 1.0) = 11.25\,V$

Reading from the graph, when $E = 11.25$, the exciting current is about 0.21A.

Hence the primary current that will be detected as a fault current is

$$I_P = \frac{200}{5} \times (10 + 0.21) = 408.4\ A$$

SG6Q2

2. A type of transformer where the magnetizing component of a transformer can become important is a current transformer (CT). These transformers can be modeled as conventional transformers, but it is the transformation of their input current that is important, and not voltage, and the load (also called the ***burden***) of a CT is ideally a short-circuit.

A 200-A:5-A, 60-Hz current transformer has the following parameters as referred to the 200-A (primary) winding:

$X_1 = 745\ \mu\Omega$ $X_2' = 813\ \mu\Omega$ $X_m = 307\ m\Omega$

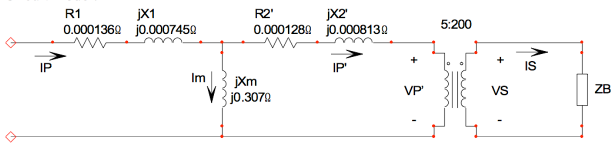
$R_1 = 136\ \mu\Omega$ $R_2' = 128\ \mu\Omega$

(a) Assuming a current of 200 A in the primary and that the secondary is short-circuited, find the magnitude and phase angle of the secondary current.

(b) Repeat the calculation of part (a) if the CT is shorted through a purely resistive 250 mΩ burden. (The load element of a CT is called a ***burden***.)

2. ANS:

Circuit model:



(a) When $Z_B = 0$ (a short-circuit), $V_S = 0$ and also $V_P' = 0$. Hence the impedance $R_2' + jX_2'$ appears in parallel to jX_m. We can use the current divider rule to find I_P', and then multiply this by the turns ratio to find I_S:

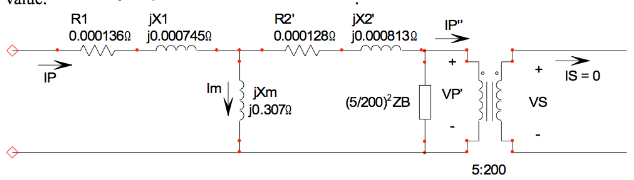
$$I_S = \left(\frac{5}{200}\right) \times \frac{jX_m}{jX_m + R_2' + jX_2'} \times I_P$$

$$= \left(\frac{5}{200}\right) \times \frac{j0.307}{j0.307 + 0.000128 + j0.000813} \times (200\angle 0°)$$

$$= 4.9868 \angle 0.0238°\ A$$

(b) For $Z_B = 0.250\Omega$: this impedance can be referred across to the primary side, where it has the value:

$$Z_B' = \left(\frac{5}{200}\right)^2 \times 0.25 = 0.00015625\ \Omega$$



jXm is now in parallel with (R2' + jX2' + (5/200)²ZB). Using the current divider rule:

$$I_S = \left(\frac{5}{200}\right) \times \frac{jX_m}{jX_m + R_2' + jX_2' + \left(\frac{5}{200}\right)^2 Z_B} \times I_P$$

$$= \left(\frac{5}{200}\right) \times \frac{j0.307}{j0.307 + 0.000128 + j0.000813 + 0.00015625} \times (200\angle 0°)$$

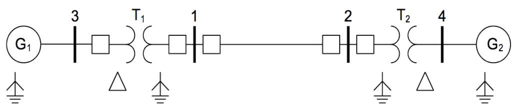
$$= 4.9868 \angle 0.0528°\ A$$

There is little change from the ideal short-circuit.

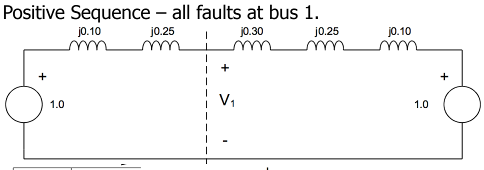
2. Non -Symmetric Faults 25min 16

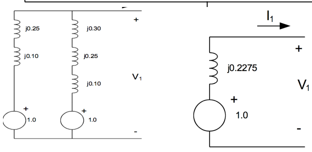
SG5Q5

Item	X_1	X_2	X_0
G_1	0.10	0.10	0.05
G_2	0.10	0.10	0.-05
T_1	0.25	0.25	0.25
T_2	0.25	0.25	0.25
Line 1-2	0.30	0.30	0.50

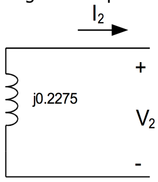


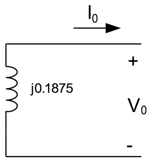
Positive Sequence – all faults at bus 1.





Negative Sequence and Zero Sequence

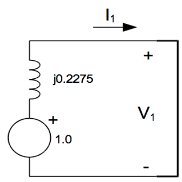




a) 3 phase bolted

$$\mathbf{I}_a + \mathbf{I}_b + \mathbf{I}_c = 0$$

$$\mathbf{V}_a = \mathbf{V}_b = \mathbf{V}_c = 0$$



From the voltage sequence transformation:

$$\begin{bmatrix}\mathbf{V}_0\\ \mathbf{V}_1\\ \mathbf{V}_2\end{bmatrix} = 1/3\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\begin{bmatrix}\mathbf{V}_a\\ \mathbf{V}_b\\ \mathbf{V}_c\end{bmatrix}$$

$$= 1/3\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\begin{bmatrix}0\\ 0\\ 0\end{bmatrix}$$

$$[0]$$

Using KVL:

$$\mathbf{I}_1 = \frac{1.0}{j0.2275} = -j4.396$$

$$\begin{bmatrix}\mathbf{I}_0\\ \mathbf{I}_1\\ \mathbf{I}_2\end{bmatrix} = 1/3\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\begin{bmatrix}\mathbf{I}_a\\ \mathbf{I}_b\\ \mathbf{I}_c\end{bmatrix}$$

$$= 1/3\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\begin{bmatrix}\mathbf{I}_a\\ a^{-1}\mathbf{I}_a\\ a^{-2}\mathbf{I}_a\end{bmatrix}$$

$$= 1/3\begin{bmatrix}0\\ 3\mathbf{I}_a\\ 0\end{bmatrix}$$

i.e.

$$\mathbf{I}_a = \mathbf{I}_1 = -j4.396$$

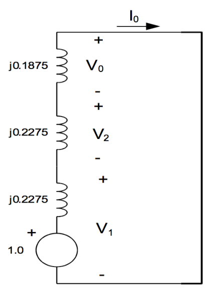
b) Single line to ground fault at bus 1

Ib – Ic = 0

Va = 0

$$I_o = I_1 = I_2 = \frac{1}{3} I_a$$

$$V_0 + V_1 + V_2 = 0$$



c) Bolted Line to Line fault at bus 1

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(c) Assume a bolted line-to-line fault between phases *b* and *c*:

$$\mathbf{I}_a = 0$$
$$\mathbf{I}_b = -\mathbf{I}_c$$
$$\mathbf{V}_b = \mathbf{V}_c$$

From the sequence current transformation:

$$\begin{bmatrix}\mathbf{I}_0\\\mathbf{I}_1\\\mathbf{I}_2\end{bmatrix} = 1/3\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\begin{bmatrix}\mathbf{I}_a\\\mathbf{I}_b\\\mathbf{I}_c\end{bmatrix}$$
$$= 1/3\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\begin{bmatrix}0\\\mathbf{I}_b\\-\mathbf{I}_b\end{bmatrix}$$
$$= 1/3\begin{bmatrix}0\\(a-a^2)\mathbf{I}_b\\(a^2-a)\mathbf{I}_b\end{bmatrix}$$

$$\therefore\ \mathbf{I}_0 = 0$$
$$and\ \mathbf{I}_1 = -\mathbf{I}_2$$

If the zero-sequence current is zero, then so must be the zero-sequence voltage:

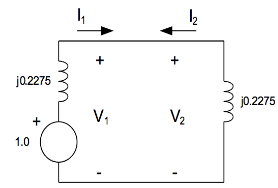
$$\mathbf{V}_0 = 0 \qquad (3a)$$

From the sequence voltage transformation:

$$\begin{bmatrix}\mathbf{V}_0\\\mathbf{V}_1\\\mathbf{V}_2\end{bmatrix} = 1/3\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\begin{bmatrix}\mathbf{V}_a\\\mathbf{V}_b\\\mathbf{V}_c\end{bmatrix}$$
$$= 1/3\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\begin{bmatrix}\mathbf{V}_a\\\mathbf{V}_b\\\mathbf{V}_b\end{bmatrix}$$

$$\therefore\ \mathbf{V}_1 = \mathbf{V}_2 \qquad (4)$$

Equations (3),(3a) and (4) have a circuit interpretation as shown below:



Using KVL:

$$\mathbf{I}_1 = \frac{1.0}{j0.2275 + j0.2275} = -j2.198$$

Recall that

$$\mathbf{I}_1 = \frac{1}{3}\left(a - a^2\right)\mathbf{I}_b$$

Now

$$a - a^2 = \cos 120^\circ + j\sin 120^\circ - \left(\cos 240^\circ + j\sin 240^\circ\right)$$
$$= -\frac{1}{2} + j\frac{\sqrt{3}}{2} - \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)$$
$$= j\sqrt{3}$$

Therefore

$$\mathbf{I}_1 = \frac{1}{3}j\sqrt{3}\mathbf{I}_b$$
$$\therefore\ \mathbf{I}_b = -j\sqrt{3}\mathbf{I}_1 = \left(-j\sqrt{3}\right)\times\left(-j2.198\right) = -3.807$$

For phase c: $\mathbf{I}_c = 3.807$

d) Double line to ground fault.

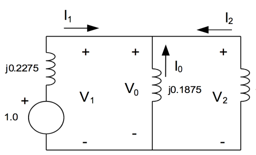
Boundary Conditions :

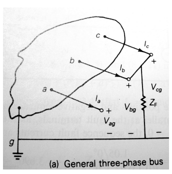
Ia = 0

Vb = Vc = Zf (Ia + Ib)

Sequence outcomes :

$$I_0 + I_1 + I_2 = 0$$
$$V_0 = V_1 = V_2 = \frac{1}{3}V_a$$





(a) General three-phase bus

Combining R_0 and R_2 in parallel, then KVL gives:

$$\mathbf{I}_1 = \frac{1.0}{j0.2275 + j0.1028} = -j3.028$$

Now using the current divider rule:

$$\mathbf{I}_0 = -\frac{j0.2275}{j0.2275 + j0.1028}\times\left(-j3.028\right) = j1.660$$
$$\mathbf{I}_2 = -\frac{j0.1875}{j0.2275 + j0.1028}\times\left(-j3.028\right) = j1.368$$

The phase currents can be found by substituting these sequence values into the matrix equation:

$$\begin{bmatrix}\mathbf{I}_0\\\mathbf{I}_1\\\mathbf{I}_2\end{bmatrix} = 1/3\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\begin{bmatrix}\mathbf{I}_a\\\mathbf{I}_b\\\mathbf{I}_c\end{bmatrix}$$
$$= 1/3\begin{bmatrix}1&1&1\\1&a&a^2\\1&a^2&a\end{bmatrix}\begin{bmatrix}0\\\mathbf{I}_b\\\mathbf{I}_c\end{bmatrix}$$

t flows into ground,

This equation shows that

$$\mathbf{I}_0 = \frac{1}{3}\times\left(\mathbf{I}_b + \mathbf{I}_c\right)$$
$$\therefore\ \mathbf{I}_b + \mathbf{I}_c = 3\times I_0 = 3\times j1.660 = j4.98$$

3. Over-current Relays 25min 14

there is no SG7

4. Distance Relays - SG10Q1 20min 12

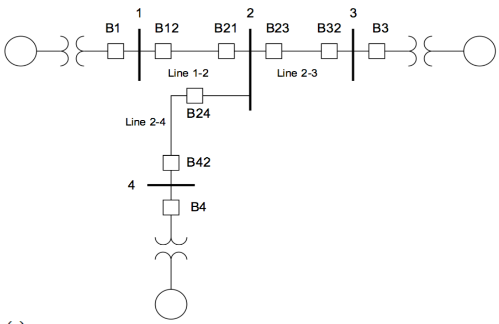
1. [Glover, P10.20]
Three-zone mho relays are used for transmission line protection of the power system shown in the figure below. Positive-sequence line impedances are given as follows:

Line	Positive-sequence impedance Ω
1-2	6 + j 60
2-3	4 + j 40
2-4	5 + j 50

Rated voltage for the high-voltage buses is 500 kV. Assume a 1500:5 CT ratio and a 4500:1 VT ratio at B12.

(a) Determine the setting Z_{r1}, Z_{r2}, and Z_{r3} for the mho relay at B12.

(b) Maximum current for line 1-2 under emergency loading conditions is 1400 A at 0.90 power factor lagging. Verify that B12 does not trip during emergency loading conditions.



(a)

$$Z' = \frac{Z}{15}$$

Set the B12 Zone 1 relay for 80% reach of Line 1-2:

$$Z_{r1} = \frac{0.8\times\left(6 + j60\right)}{15} = 0.32 + j3.2\ \Omega$$
secondary

Set the B12 Zone 2 relay for 120% reach of Line 1-2:

$$Z_{r2} = \frac{1.2\times\left(6 + j60\right)}{15} = 0.48 + j4.8\ \Omega$$
secondary

Set the B12 Zone 3 relay for 100% reach of Line 1-2 and 120% reach of line 2-4:

$$Z_{r3} = \frac{1.0\times\left(6 + j60\right)}{15} + \frac{1.2\times\left(5 + j50\right)}{15} = 0.8 + j8.0\ \Omega$$

(b)

Secondary impedance viewed by B12:

$$Z' = \left(\frac{\frac{500}{\sqrt{3}}\angle 0^\circ}{1.4\angle -\cos^{-1}0.9}\right)\times\frac{1}{15} = 13.7\angle 25.8^\circ\ \Omega$$

Z' exceeds the Zone 3 setting of $\left(0.8 + j8.0\right) = 8.04\angle 84.3^\circ\ \Omega$ for B12. Hence, the impedance

5. Stability SG11 Q2 25min 16

2. [Glover 13.4]
A three-phase, 60-Hz, 500-MVA, 13.8-kV, 4-pole steam turbine-generating unit has an H constant of 5.0 p.u.-s.

This generating unit is initially operating at $p_{m,pu} = p_{e,pu} = 0.7$ per unit, $\omega = \omega_{syn}$, and $\delta = 12^\circ$ when a fault reduces the generator electrical power output by 70%. Determine the power angle δ five cycles after the fault commences. Assume that the accelerating power remains constant during the fault. Also assume that $\omega_{pu} =$

Swing equation:

$$p_{m,pu} - p_{e,pu} = 2H\frac{\omega_{pu}(t)}{\omega_{sync}}\frac{d^2\delta(t)}{dt^2}$$

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With the fault: $P_{e,pu} = 0.3 \times 0.7 = 0.21$

Swing equation becomes:

$$0.7 - 0.21 = 2 \times 5 \times \frac{1}{377} \frac{d^2\delta(t)}{dt^2}$$

$$\therefore \frac{d^2\delta(t)}{dt^2} = 18.473$$

$$\therefore \frac{d\delta(t)}{dt} = 18.473\,t + K$$

If the fault occurs at $t = 0$ then K will be zero, hence

$$\frac{d\delta(t)}{dt} = 18.473\,t$$

$$\therefore \delta(t) = \frac{1}{2} \times 18.473 t^2 + K_2$$

At $t = 0$, the power angle is 12°, which corresponds to $12 \times \frac{\pi}{180} = 0.2094\,rad$. 5 cycles corresponds to a time period of $5 \times \frac{1}{60} = \frac{1}{12}$ sec. Hence the power angle after 5 cycles will be

$$\delta\left(\frac{1}{12}\right) = \frac{1}{2} \times 18.473 \times \left(\frac{1}{12}\right)^2 + 0.2094$$

$$= 0.2735\,rad$$

$$= 15.7°$$

6. Voltage Quality Test2Q2 15min 10

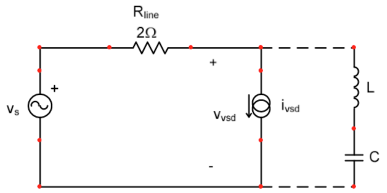
A simple power system consists of a 50Hz source supplying power to a variable speed drive through a resistive line, as shown in figure 5. The voltage supply is given by

$$v_S = 120\cos(2\pi 50 t) \quad V$$

The variable speed drive generates a significant 5th harmonic component. This drive can be modeled as a current source with a current waveform given by

$$i_{VSD} = 8\cos(2\pi 50 t) + 1.5\cos(2\pi 250 t) \quad A$$

An *LC* filter is placed in parallel with this VSD drive in order to eliminate the 5th harmonic in the voltage v_{vsd}, as shown in figure 2.



(a) Find an expression for the voltage across the VSD drive before the filter is added, $v_{VSD}(t)$.

(b) If $C = 0.2\ mF$, then find a suitable value for inductor L.

(c) Find a new expression for the voltage across the VSD after the filter is added, $v_{VSDnew}(t)$

(a)

$$v_{vsd} = v_s - R_{line}\, i_{vsd}$$
$$= 120\cos(2\pi 50 t) - 2.0 \times [8\cos(2\pi 50 t) + 1.5\cos(2\pi 250 t)]$$
$$= 104\cos(2\pi 50 t) - 3.0\cos(2\pi 250 t) \quad V$$

(b) Require:

$$\frac{1}{2\pi\sqrt{LC}} = 250$$

$$\therefore \frac{1}{2\pi\sqrt{L \times 0.2 \times 10^{-3}}} = 250$$

$$\therefore L = \frac{1}{0.2\times10^{-3} \times (2\pi\times250)^2} = 2.026\,mH$$

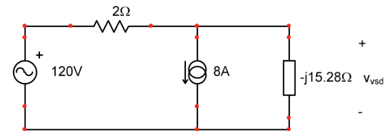
(c) The *LC* circuit acts as a short circuit to the 250 Hz component, so only the 50 Hz component needs to be considered. If we assume that the LC circuit acts like an open circuit at 50 Hz then

$$v_{vsd} = 120\cos(2\pi 50 t) - 2.0 \times [8\cos(2\pi 50 t) + 0]$$
$$= 104\cos(2\pi 50 t) \quad V$$

This answer would score most of the marks, but it is only an approximation. At 50Hz, the LC circuit has an impedance given by

$$Z = j\omega L + \frac{1}{j\omega C}$$
$$= j\left(2\pi 50 \times 2.026\times10^{-3} - \frac{1}{2\pi 50 \times 0.2 \times 10^{-3}}\right)$$
$$= -j15.28\,\Omega$$

This leads to the phasor circuit shown below:



Using phasor analysis gives

$$\mathbf{V}_{vsd} = 103.2\angle 7.45°$$

or

$$v_{vsd} = 103.2\cos(2\pi 50 t + 7.45°) \quad V$$

Notice that this answer is close to the approximate answer.

7. Safe work practises20min 12

NO	Network Operator
IMO	independent Market Operator
SWS	South West Interconnected Service
WAER	WA Electrical Requirements
SA	Standards Australia
PPE	Personal Protective Equipment
NOLA	National Occupational Licencing Authority
AER	Aust. Energy Regulator – part of the ACCC.

WorkSafe and its inspectors administer the following legislation: • *Occupational Safety and Health Act 1984; and* • *Occupational Safety and Health Regulations 1996*

- Also covers mine sites

- The Energy Coordination Act 1994

- Infringments individuals $500 corps $4000

- Prosecution $50k and $250k for corps

- In HV an Access permit may need to be written by the HV operator.

- HV switching operators need NOT be licenced but trained and authorised. Often done by electrical engineers.

- NOTICE OF COMPLETION issued to NO when job completed.

- Working on Live LV is banned apart from testing and fault finding.

- Full covered clothing for working near live equipment.

- When HV switching, overalls should be flame resistant and non- synthetic, shoes or boots should have insulated soles, and gloves should be voltage rated and a full face shield plus safety helmet should be used;

• For more general electrical work shoes/boots, cotton type overalls or trousers with long sleeved shirt, safety glasses and safety helmet.

• Safety belts, harnesses and noise protection may also be required at times.

- Conductive ladders NOT to be used.

- A Professionally qualified Electrical Engineer is not required to have a licence but : Such engineers can be expected to have –

• received basic electrical safety instruction in an "off job" environment,

• spent a considerable amount of time working with the Wiring Rules so as to understand electrical installation components and requirements, and also

• spent a reasonable amount of time on site inspecting electrical installations under the guidance of a person substantially experienced in such work.

- Accidents are reported to the NO or to Energy/ Safety WA.

8. Electricity Regulation. 20Min 12

- Developed by standards Australia

Regulations are split into

1. Acts

2. Regulations (subsidiary or subordinate)

• **Acts** – each commences life as a "Bill" that is ultimately passed by Parliament as an Act.

• **Regulations** – are referred to as subsidiary or subordinate legislation, and are limited in their powers according to provisions in the parent Act.

Regulators :

1. Economic Reg Auth
2. IMO
3. Office of Energy and Safety WA
4. Resources Safety Div & Dept of Mines and Petrol.
5. Worksafe WA.

Key electrical safety statistics to end of June 2010

• 28 deaths due to electricity in Australia and New Zealand in 2009- 10. 25 occurred in Australia, a high number due in part to bushfires in VIC, some of which were electricity caused.

• Typically, 65% of deaths each year are electricity network related deaths (electrocution due to accidental contact with live parts or fires) and 35% of deaths involve consumers' installations, appliances or equipment.

• Typically, 65% of deceased are either non-electrical workers or members of the general public.

• Typically, 75% are workplace related accidents

– ***Electrical contractor licences***, for those carrying out electrical installing work (HV and LV fixed wiring, switchboards, wiring of mechanical equipment etc) for clients for gain or reward.

– ***Electrician licences*** (and related trainee licences for apprentice electricians) for tradespersons carrying out electrical installing work, whether for an electrical contractor or another employer.

- ***Restricted electrical licences***

A summary of electrical workers" accident causes is as follows:

– 60% - Incorrect work practices causing a flashover (phase to phase, or phase to earth)

– 15% - Inadvertent body contact with live parts – 14% - Failure to isolate properly (parts were still live) – 11% - Defective or damaged wiring

• ***Preferred voltages for: – Transmission are 132, 220, 330 and 500 kV, – subtransmission typically 66 and/or 132 kV, and – distribution is generally at 33, 22, 11 or 6.6 kV.***

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