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1.

a)

To limit the angle difference to 45° from the generator to the load we need to identify the phase angle difference across each transformer.

The angle difference across each transformer is estimated from:

$$P = \frac{V_1 V_2}{X} \sin \delta_T \Rightarrow \sin \delta_T = \frac{PX}{V_1 V_2}$$

Each transformer should have a rating greater than $\frac{350}{0.95} = 368$ MVA. The transformer rating is estimated at 400 MVA and its reactance $X_T = 10\%$ on rating. Therefore:

$$P = \frac{350}{400} = 0.875 \quad X_T = 0.1 \text{ and } V_1 \cong V_2 \cong 1.0 \text{ p.u}$$

$$\sin \delta = \frac{350}{400} \times 0.1 = 0.0875 \Rightarrow \delta \simeq 5^\circ$$

So $5 \times 2 = 10°$ should be allowed for the transformer and hence 35° should be used for the transmissi line. So:

$$P = P_{SIL} \frac{\sin 35^\circ}{\sin\left(\frac{2\pi 250}{6000}\right)} = P_{SIL} \times 2.2$$

$$\text{At } 132\,kV \quad P_{SIL} = \frac{(132)^2}{325} = 53.6\ MW \Rightarrow P_{132} = 118\,MW$$

$$275\,kV \quad P_{SIL} = \frac{(275)^2}{300} = 252\ MW \Rightarrow P_{275} = 554\,MW$$

$$400\,kV \quad P_{SIL} = \frac{400^2}{275} = 582\ MW \Rightarrow P_{400} = 1280\,MW$$

At 132 kV the number of circuits is 350/118 = 2.97, an to transmit the power with one circuit on outage:

$$n-1 = 2.97 \Rightarrow n = 2.97+1 = 3.97 \simeq 4$$

So we need 4 circuits on 2 towers each carrying a double circuit.

At 275 kV $n-1 = 350/554 = 0.63 \Rightarrow n = 1.63$ so 2 circuits are needed. At 400 kV also 2 circuits are needed.

So in conclusion 400 kV is not likely to be the selected voltage its capacity is much higher than that requir by the load. The selection is between 4 circuits (2x2) at 132 kV or 2 circuits at 275 kV and should be based on economics and environmental. It is likely

that 2 circuits at 275 kV are cheaper than 4 circui
of 132 kV. Check this on the Internet!

So the selected voltage is 275 kV.

b) The required current at 275 kV in one circuit is calculated from:

$$\frac{P}{2} = \sqrt{3} V I \cos\theta \Rightarrow I = \frac{P}{2\sqrt{3} V \cos\theta} = 0.387 \text{ kA}$$

To reduce corona losses and reduce line series reactance 4 bundles per phase will be considered so the current in each conductor of the bundle will be

$$I_b = \frac{I}{4} = 0.0966 \text{ kA}$$

P_{loss} in one circuit is given by:

$$P_{loss} = 4 \times 3 I_b^2 \times R < 0.025 \times \frac{350}{2} = 4.375 \text{ M}$$

$$\therefore \quad 4 \times 3 \times (0.0966)^2 \times R < 4.375 \Rightarrow$$

$$R < 39 \, \Omega$$

$$\text{So} \quad r = \frac{R}{l} < \frac{39}{250} = 0.156 \, \Omega/\text{km} \rightarrow 0.25\overline{0} \, \Omega/\text{mi}$$

So a suitable conductor is 300 000 cmils with $r = 0.213 \, \Omega/\text{mile}$.

c) Line parameters

* $R = \frac{0.213 \times 250}{4 \times 1.604} = 8.3\,\Omega$

$l = 2\times10^{-7} \ln \frac{10\times0.305}{\sqrt[4]{0.01987\times1\times1\times\sqrt{2}}} = 2\times10^{-7}\ln\frac{32.786}{0.41}$

0.0281

$= 2\times10^{-7} \times 4.382 = 8.76\times10^{-7}$ H/m. $L = 0.219$ H

$x = \omega l = 0.2753\ \Omega/\text{km}$

* $X = x l = 0.2755\times250 = 68.8\ \Omega$

$c = \frac{2\pi\varepsilon}{\ln\frac{D}{R_b^c}} = \frac{2\pi\times8.854\times10^{-12}}{\ln\left(\frac{10/0.305}{\sqrt[4]{0.0262\times\sqrt{2}}}\right)} = \frac{2\pi\times8.854\times10^{-12}}{\ln\frac{32.786}{0.439}}$

4.314

$c = 12.9\times10^{-12}$ F/m

$y = \omega c = 314\times12.9\times10^{-12}\times10^{3} = 4.052\times10^{-6}$ S/km

$Y = y l = 1013\times10^{-6}$ S $\quad C = 3.2\ \mu$F $\quad (Y \sim 10\times10^{-4}$

* $Z_c = \sqrt{\frac{l}{c}} = \sqrt{\frac{8.76\times10^{-7}}{12.9\times10^{-12}}} = 260.6\ \Omega$

Let us re-calculate P_{SIL} based on the actual Z_c:

$P_{SIL} = \frac{(275)^2}{261} = 289.7$ MW

It is higher than the estimated $P_{SIL} = 252$ MW and hence the power that can be transmitted

$P = 2.2 \times P_{SIL} = 637$ mW is higher. So the design is very likely to work. So the choice still stands correct.

d) Transformer should have an mVA rating such that :

$$S_T \geq \frac{350}{0.95} = 368 \text{ mVA}.$$

So a 400 mVA transformer or 2×200 mVA transfor are selected on the generator side and 2×200 mVA on the load side.

Each 200 mVA generator transformer has a voltage rating of 13/220 kV with ΔY connection the Δ is on the generator side.

The 200 mVA load transformers has voltage rating of 220/66 kV with YΔ connection the Δ on the load side.

Both transformer should have a standard ΔY connection.

e) $S_B = 100$ mVA

generator region 1 : $V_{B1} = 13$ kV $Z_{B1} = 1.69\ \Omega$

Line region 2 : $V_{B2} = 275$ kV $Z_{B2} = 756.25\ \Omega$

load region 3 : $V_{B3} = 66$ kV $Z_{B3} = 43.56\ \Omega$

$$Z_{load} = \frac{66^2}{\frac{350}{0.95}\angle -\cos^{-1}0.95} = 11.8\angle 18.2^\circ\ \Omega$$

$$= 11.23 + j3.69\ \Omega$$

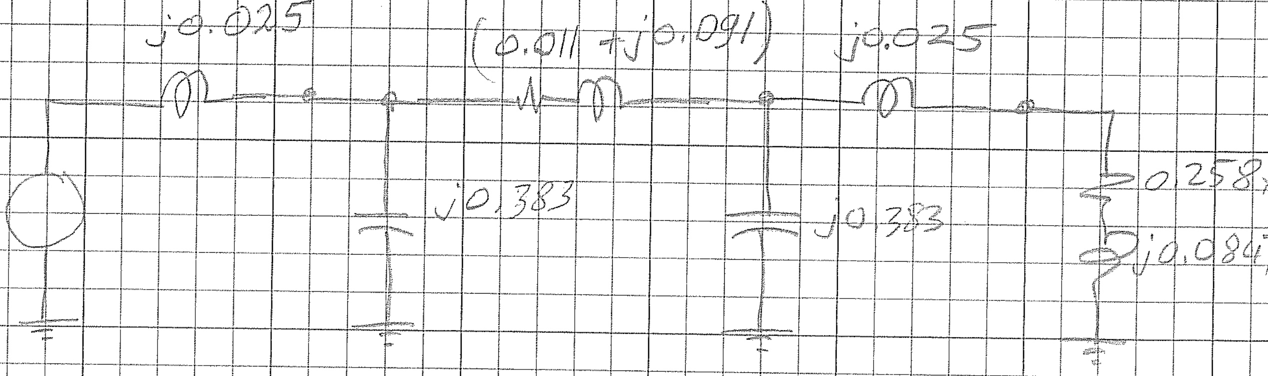
$$= 0.271\angle 18.2^\circ = 0.258 + j0.0847\ \Omega$$

$$X_{TG} = 0.1 \times \frac{100}{400} = 0.025\ p.u.$$

$$Z_{line} = (8.3 + j68.8)/756 = 0.011 + j0.091\ p.u.$$

$$Y_{line} = 1013 \times 10^{-6} \times 756 = 0.766\ p.u.$$

Equivalent Circuit of one circuit



FACULTY OF ENGINEERING & ARCHITECURE - AMERICAN UNIVERSITY OF BEIRUT

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b)

Transformer:

$A_T = 1 \quad B_T = jX_T = j0.025 \quad C_T = 0 \quad D_T = 1$

Line

$$A_L = 1 + \frac{(0.011 + j0.091)(j0.766)}{2} = 0.965 + j0.0042$$

$B = 0.011 + j0.091$

$$C = j0.766\left(1 + \frac{YZ}{4}\right) = -0.00161 + j0.75$$

The ABCD of the whole system is obtained by multiplying the matrices of the series system as follows:

$$\begin{bmatrix} 1 & j0.025 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0.965 + j0.0042 & 0.011 + j0.091 \\ -0.00161 + j0.75 & 0.965 + j0.0042 \end{bmatrix} \begin{bmatrix} 1 & j0. \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 0.946 + j0.00416 & 0.0109 + j0.115 \\ -0.00161 + j0.75 & 0.965 + j0.0042 \end{bmatrix} \begin{bmatrix} 1 & j0.025 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 0.946 + j0.00416 & 0.0109 + j0.139 \\ -0.00161 + j0.75 & 0.946 + j0.00416 \end{bmatrix}^{*}$$

Voltage Regulation:

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}}$$

The sending end voltage is:

$$V_R = 1\angle 0 \qquad I_R = \frac{1}{2Z_L} = 1.75 - j0.575$$

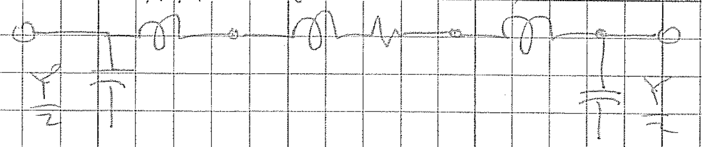
$$V_s = (0.946 + j0.00416)(1\angle 0) + (0.0109 + j0.139)(1.75 - j0.575)$$

$$= 1.045 + j0.241 = 1.072\angle 13.0^\circ$$

$$V_{nl} = \frac{V_s}{A} = 1.10 + j0.254 = 1.13\angle 13^\circ$$

$$VR = \frac{1.13 - 1}{1} = 13\,\%$$

* Note that this matrix can be approximated by shifting the transformer reactances in towards the center of line:



Then $Z = jX_{T1} + jX_{T2} + jX_L + R_L$

9)

$S_g = 2V_s I_s^*$ 2 because we have 2 circuits of 275kV.

$I_s = CV_R + DI_R = (-0.00102 + j0.48)(1\angle 0)$

$+ (0.993 + j0.0042)(1.75 - j0.5$

$= 1.67 - j0.061$

$S_g = (1.09 + j0.327) \times (1.67 + j0.061) \times 2$

$= (1.8 + j0.613) \times 2 = 3.6 + j1.23$

$= 3.8 \angle 18.9^\circ$

$|S_g| = 380$ MVA.