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The Influence of Three-Phase Auto-Reclosure of Transmission Line on the Dynamic Stability of Power Systems.

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Research Article

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ABSTRACT

For a functional power system, the influence of automatic re-closure on the dynamic stability was ascertained by comparing calculated coefficients of system reserves during auto re-closure and without auto re-closure. It is only successful re-closure that was considered using double circuit power line and unsymmetrical short circuit. At the end of the work, a diagram was drawn to illustrate the pick-up area A_p and the retardation area A_r. For the calculation of the pick-up, retardation and then the coefficient of dynamic stability, there is also the need to find the re-closure angle δ_r and the re-closure time t_r of the affected part. The dependence of re-closure angle on the re-closure time was tabulated. At the end of the investigation, coefficient of reserve of static stability k_{st} at both normal regime and after short circuit regime was compared and found to have ensured higher stability when equipped with auto-re-closure. Lastly, the graph of switch-off angle limit δ_{lim} versus switch off time limit t_{lim} was plotted and the result corresponded to the expected parameters.

INTRODUCTION

The paper examines the need to install automatic re-closure switchgears on the transmission lines. Two generator power station, double circuit transmission line with load was chosen to carry out this research. A complex parametric analysis of the system was carried out in per unit for normal system regime, faulty regime and post fault regime. In each stage of the calculation, the impedances, the admittances and the various self- and mutual angles for both generator and load were clearly stated. The system power was calculated for the conditions of absence of auto re-closure system, presence of semi auto re-closure and presence of automatic re-closure. The dependence of switch off angle on the switch off time was also investigated for $0 \leq t \leq 0.15$ second. This clearly showed the transient behavior of the system, the speed up and the retardation angles and consequently the coefficient of dynamic stability for power system that is not equipped with automatic re-closure system as $K_r = 1.4136$. The result changed appreciably when the system was equipped with automatic re-closure system as the retardation angle increased 103.83^0 thereby raising the coefficient of dynamic stability to 1.5599. The fact that the coefficient of dynamic stability of the power system increased by 9.38 per cent when an automatic re-closure system was installed in the system shows that the installation of automatic re-closure system positively affects the dynamic stability of the power system.

Assumed input parameters used in the research work

Generator parameters Table 1.0

	Generator	S, MVA	V_{rated}, KV	Cosϕ	Reactance (%)			Moment
1.	-	-	-	-	X_d	X'_d	X	CD^2
2.	G_1	62.5	10.5	0.8	184	30	17.5	13.5
3.	G_2	75	10.5	0.8	161	28	18	8.85

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Transformer parameters Table 2.0

Serial No.	Transformer	S_{rated}, MVA	V_{rated}, KV	Short circuit voltage, % of V_{rated}
1.	T_1	63	121/10.5	10.5
2.	T_2	80	121/10.5	10.5
3.	T_3	40	115/38.5	17
4.	T_4	40	115/38.5	17
5.	T_5	63	121/10.5	10.5

Transmission line parameters: Voltage = 110KV,
Cosϕ = 0.90, System voltage V_s = 35KV, line length = 50km,
Short circuit line length (from source) = 15km,
System power = 50.4 MW, Short circuit switch off time t_{sw} = 0.15 sec., re-closure time t_r = 0.1 sec.

Problem statement:

(1) To find static stability of the power system.
(2) To calculate dynamic stability of power system.
(3) To find the influence of auto re-closure on dynamic stability of transmission lines.

Calculation of system parameters

There are four sub-divisions of voltage level as can be seen from Fig.1.0. The calculation is done in per unit value taking the base values as S_b = 100 MVA and V_b = V_{bII} = 115 KV. The base values of the remaining sections are: $V_{bi} = \frac{V}{n_1} = \frac{115}{\frac{121}{10.5}} = 9.98KV, V_{biii} = 38.5KV, V_{biv}\ 9.98KV$.

$$Generator\ G1: X_1^{'} = X_{*d}^{'} = \frac{X_d^{'}\% * S_b * (V_{rated}/V_{bi})^2}{100 * S_{rated}}$$

$$= \frac{184 * 100 * (10.5/9.98)^2}{100 * 62.5} = 3.10$$

Similarly, $X_1 = 0.531,\ X_1^{''} = 0.310$

$Generator\ G2: X_3^{'} = 2.376, X_3 = 0.413, X_3^{''} = 0.266$

$$Transformers: X_2 = X_{*T2} = \frac{V_{sc}\% * S_b * (V_{rated}/V_{bi})^2}{100 * S_{rated}}$$
$$= \frac{10.5 * 100 * (121/115)^2}{100 * 63} = 0.185$$

Similarly, $X_4 = X_{*T2}$ =0.145, $X_7 = X_8 = X_{*T3} = 0.425, X_2 = X_9 = 0.185$, Fig. 2.0.

$Line\ parameters\ X_{*L1} = X_5 = X_6 = X_{1L}*(S_b/V_{bii}^{\ 2})$ = 0.4*50*(100/115^2) = 0.151, where per unit reactance of aluminium conductor is 0.4 ohm/km [1].

Short circuit inductances X_{1k}=(35/50)*0.151=0.1057; X_{2k}=(15/50)*0.151=0.0453, where 50km = total line length and 15km=short circuit line length.

Conversion of system and load parameters to base values

$$V_{*s} = \frac{V_s}{V_{biii}} = \frac{35}{38.5} = 0.909;\ P_{*s} = P_s/S_b = \frac{50.4}{100} = 0.504$$

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Calculation of equivalent moment of inertia for the two generators

$G_1: T_{e*1} = 2.74 * \frac{CD^2 n^2}{S_b} * 100 = 2.74 * \frac{13.5*3000^2}{100*10^6} = 3.33$

Similarly, $T_{e*2} = 2.18, and\ T_{e*eq} = T_{e*1} + T_{e*2} = 3.33 + 2.18 = 5.51$

Determination of reactive power of system and load

Load power is 54MW =(0.54+j0.235)

$Q_{*s} = P_{*s} sin\varphi_L = 0.504 * sin25.84$=0.220 or
$Q_{*L} = 0.235, where\ cos\varphi_L = 0.9\ or\ 25.84°$

The next step is to simplify Fig. 2.0.

$X_{10} = \frac{X_5}{2} + \frac{X_7}{2} = \frac{j0.151}{2} + \frac{j0.425}{2} = j0.288$

$X_{11} = (X_1 + X_2) * \frac{X_3 + X_4}{X_1 + X_2 + X_3 + X_4} =$

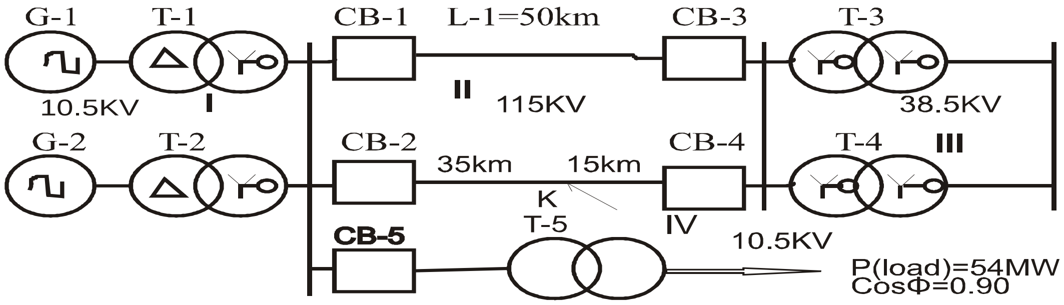

Figure 1.0 Circuit diagram of transmission lines

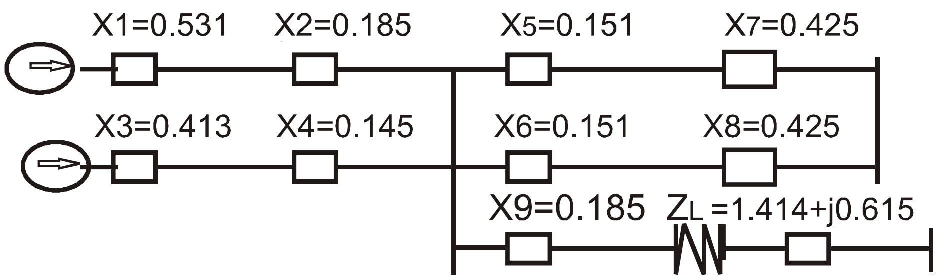

Figure 2.0 Impedance diagram of the transmission lines shown in figure 1

$= (j0.531 + j0.185) * \frac{j0.413 + j0.145}{j0.531 + j0.185 + j0.413 + j0.145}$

$= j0.716 * \frac{j0.558}{j1.274} = j0.314$

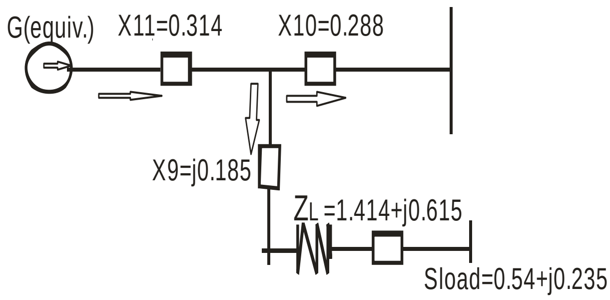

Figure 3.0 Simplified impedance diagram

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The total voltage at the system bus bar is $\acute{V_a} = V_a \angle\delta_a$; $V_a = \sqrt((V_s + (Q_s * \frac{X_{10}}{V_s}))^2 + j\frac{(P_s*X_{10})^2}{V_s})$

$= \sqrt((0.909 + (0.22 * \frac{0.288}{0.909}))^2 + j(0.504 * \frac{0.288}{0.909})^2) = 0.992 \angle 9.28°$, where $\delta_a = \arctan(\frac{X}{R})$

Voltage at the load bus bar

$V_L = \sqrt((V_a - (Q_L * \frac{X_9}{V_a}))^2 + j\frac{(P_L*X_9)^2}{V_s})$

$$= \sqrt((0.992 - (0.235 * \frac{0.185}{0.992}))^2 + j(0.54 * \frac{0.185}{0.992})^2)$$

$= 0.953 \angle 6.08°$

$Load\ impedance\ Z_{Load} = \frac{V_L^2(P_L + jQ_L)}{S_L^2} =$

$0.953^2 * \frac{0.54 + j0.235}{(0.54 + j0.235)^2} = 1.414 + j0.615$

Loss of reactive power in the inductances of X_9 and X_{10}

$\Delta Q_1 = (P_L^2 + Q_L^2) * \frac{X_9}{V_L^2} = 0.54^2 + j0.235^2) * \frac{0.185}{0.953^2} = 0.07065$

$\Delta Q_2 = (P_S^2 + Q_S^2) * \frac{X_{10}}{V_S^2} = (0.504^2 + j0.22^2) * \frac{0.288}{0.909^2} = 0.1054$

Over all power available in the system

$S_0 = P_0 + jQ_0 = P_S + jQ_S + P_L + jQ_L + j\Delta Q_1 + j\Delta Q_2$

$= 0.504 + j0.22 + 0.54 + j0.235 + j0.07065 + j0.105 = 1.044 + j0.6307$

The power generated by the turbine is $P_0 = 1.044$

$The\ e.m.f.: \grave{E} = E^{'}\angle\delta_0;\ E^{'} = \sqrt((V_a + Q_0 * \frac{X_{11}}{V_a})^2 + j(P_0 * \frac{X_{11}}{V_a})^2) = \sqrt((0.992 + 0.6311 * \frac{0.314}{0.992})^2 + j(1.044 * \frac{0.314}{0.992})^2) = \sqrt(1.192)^2 + j(0.33)^2 = 1.237$
$\arctan(\delta_0^{'} - \delta_a) = \frac{0.33}{1.192} = 15.5°$

$The\ angle\ between\ emf\ E^{'}\ and\ system\ voltage\ (V_S)$ is $\delta_0^{'}$, where $\delta_0^{'} = 9.28° + 15.5° = 24.78°$

The synchronous emf $E_q \angle \delta_0^{'}$ will be defined. For this purpose, the schematic impedance diagram of Fig. 2.0 will be adjusted by replacing the transient reactance $X_d^{'}$ of the generator with the synchronous reactance X_d value. Therefore Fig. 3.0 will express X_{12} as:

$X_{12} = X_1^{'} + X_2 * \frac{X_3^{'} + X_4}{X_1^{'} + X_2 + X_3^{'} + X_4}$

$= 3.10 + 0.185 * \frac{2.376 + 0.145}{3.10 + 0.185 + 2.376 + 0.145} = j1.456$

$E_q = \sqrt((V_a + (Q_0 * \frac{X_{12}}{V_a}))^2 + j\frac{(P_0*X_{12})^2}{V_a})$

$$= \sqrt((0.992 + (0.631 * \frac{1.456}{0.992}))^2 + j(1.044 * \frac{1.456}{0.992}))^2$$

$= \sqrt{1.9182 + j1.532} = 2.455$

$\arctan(\delta_0^{'} - \delta_a) = 38.63°$

The angle between emf E_q and system voltage V_s is $\delta_1^{'}$=38.63°+9.28°= 47.91°. Voltage V_G on the busbar of the equivalent diagram of generator excluding the generator resistance is represented by Fig. 2.0.

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$X_{13} = X_2 * \frac{X_4}{X_2+X_4} = 0.185 * \frac{0.145}{0.185+0.145} = j0.081$

$V_G = \sqrt{((V_a + (Q_0 * \frac{X_{13}}{V_a}))^2 + j\frac{(P_0 * X_{13})^2}{V_a}\Big)}$

$= \sqrt{((0.992 + (0.6307 * \frac{0.081}{0.992}))^2 + j(1.044 * \frac{0.081}{0.992})^2)} = 1.047\angle 4.65°$

$\delta_S' - \delta_a = 4.65°$; $\delta_S = 4.65 + 9.28 = 13.93°$

Calculation of self and mutual conductance at normal regime applying Fig. 3.0

Mutual impedance $Z_{12} = j0.185 + 1.414 + j0.615 =$ 1.414+j0.80

a) Without auto regulation of excitation system the self inductance Z_{11}' will be:

$$Z_{11}' = jX_{12} + jX_{10} * \frac{Z_{12}}{jX_{10} + Z_{12}}$$

$= (j1.456 + j0.288) * (1.414 + j0.80)/(j0.288 + 1.414 + j0.80) =$ 1.717$\angle 89.07°$

The corresponding self impedance angle $\alpha_{11}' = 90° - 89.07° = 0.93°$

Self admittance of the circuit $y_{11}' = \frac{1}{1.717}\angle 89.07° = 0.58\angle -89.07°$

Mutual impedance of the current

$Z_{12}' = jX_{12} + jX_{10} + \frac{X_{10} * jX_{12}}{Z_{12}}$

$j1.456 + j0.288 + \frac{j0.288 * j1.456}{1.414 + j0.80} = 1.633\angle 82.08°$

The corresponding mutual admittance angle

$\alpha_{12}' = 90° - 82.08° = 7.92°$

Mutual admittance $y_{12}' = \frac{1}{1.633}\angle 82.08° = 0.612\angle -82.08°$

b) With the presence of semi-automatic excitation regulator, the impedance becomes:

$Z_{11}' = jX_{11} + jX_{10} * \frac{Z_{12}}{jX_{10}+Z_{12}} = j0.314 + (j0.288 * (1.414 + j0.80))/(j0.288 + 1.414 + j0.80) =$ 0.575$\angle 86.32°$

The corresponding angle $\alpha_{11}' = 90° - 86.32° = 3.68°$

Self admittance $y_{11}' = \frac{1}{0.575}\angle 86.32 = 1.739\angle -86.32°$

Mutual impedance $Z_{12}' = jX_{11} + jX_{10} + \frac{jX_{10} * X_{11}}{Z_{12}}$

$= (j0.314 + j0.288) + \frac{j0.288 * j0.314}{(1.414 + j0.80)} = 0.577\angle 85.18°$

$\alpha_{12}' = 90° - 85.18° = 4.42°$; $y_{12}' = \frac{1}{0.577}\angle 85.18° = 1.733\angle -85.18°$

c) With the presence of automatic excitation regulator:

$Z_{11}' = jX_{13} + jX_{10} * \frac{Z_{12}}{jX_{10}+Z_{12}} = (j0.081 + j0.288) * (1.414 + j0.80)/(j0.288 + (1.414 + j0.80) =0.342\angle 85.34°$

The corresponding self impedance angle $\alpha_{11}' = 90° - 85.34° = 4.66°$

Self admittance of the circuit $y_{11}^{'} = \frac{1}{0.342} \angle 85.34° = 2.924 \angle -85.34°$

Mutual impedance

$Z_{12}^{'} = jX_{13} + jX_{10} + \frac{X_{10} * jX_{13}}{Z_{12}}$

$j0.081 + j0.288 + \frac{j0.288 * j0.081}{1.414 + j0.80} = 0.362 \angle 88.02°$

The corresponding mutual admittance angle

$\alpha_{12}^{'} = 90° - 88.02° = 1.98°$

Mutual admittance $y_{12}^{'} = \frac{1}{0.362} \angle 88.02° = 2.761 \angle -88.02°$

Short circuit condition

In determining the shunt resistance created by one phase short circuit to ground, the diagram of Fig. 4.0 will be applied for reverse and zero sequences.

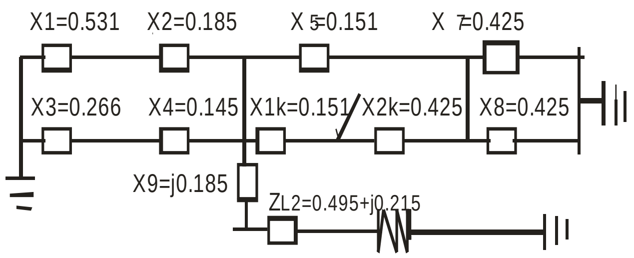

Figure 4.0 System reverse sequence impedance diagram

For reverse sequence, load resistance is taken as $0.35Z_{load}$ [2], therefore:

$Z_{load\,2} = 0.35 * Z_{load} = 0.35 * (1.414 + j0.615) = 0.495 + j0.215$

Rearranging the diagram of Fig. 4.0, it becomes:

$$X_{14} = \frac{jX_8}{2} = \frac{j0.425}{2} = j0.213$$

$$X_{15} = (X_1^{''} + X_2) * \frac{X_3^{''} + X_4}{X_1^{''} + X_2 + X_3^{''} + X_4} = \frac{(0.31 + 0.185)(0.266 + 0.145)}{0.31 + 0.185 + 0.266 + 0.145} = j0.225$$

$Z_{13} = jX_9 + Z_{load\,2} = j0.185 + 0.495 + j0.215 = 0.495 + j0.40$

Impedance transformation of figures 5 and 6

$Z_{14} = \frac{jX_{15} * Z_{13}}{jX_{15} + Z_{13}} = \frac{j0.225(0.495 + j0.40)}{j0.225 + 0.495 + j0.40} = 0.039 + j0.175$

$X_{16} = X_5 * \frac{X_{1k}}{X_5 + X_{1k} + X_{2k}}$
$= j0.151 * \frac{j0.045}{j0.151 + j0.106 + j0.045} = j0.053$

$$X_{17} = X_5 * \frac{X_{2k}}{X_5 + X_{1k} + X_{2k}} = j0.023$$

$X_{18} = X_{1k} * \frac{X_{2k}}{X_5 + X_{1k} + X_{2k}} = j0.016$

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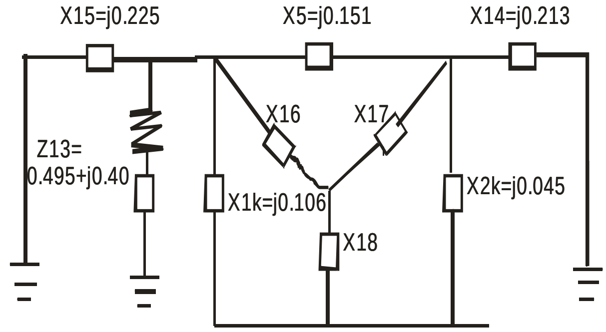

Figure 5.0 Δ/Y impedance conversion

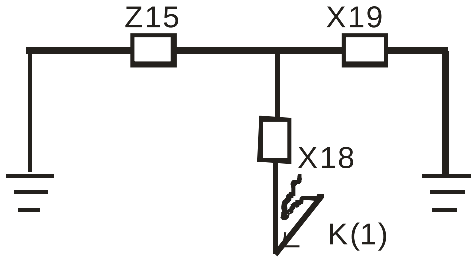

Figure 6.0 Resultant impedance from Figure 5

$Z_{15} = Z_{14} + jX_{16} = 0.039 + j0.288$

$X_{19} = X_{17} + jX_{14} = j0.236$

The equivalent impedance of the reverse sequence relative to the short circuit is Z_{eq}.

$Z_{eq} = jX_{18} + jX_{19} * \frac{Z_{15}}{jX_{19}+Z_{15}} = j0.016 + \frac{j0.236*(0.039+j0.228)}{j0.236+0.039+j0.228} = 0.01 + j0.133$

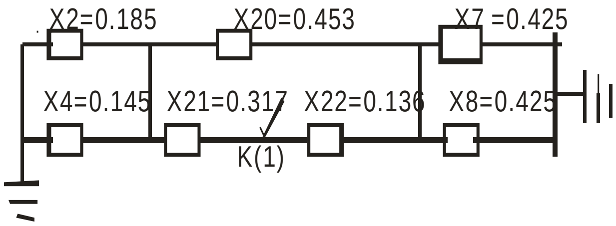

Figure 7.0 Zero sequence impedance diagram

For transmission lines, zero sequence reactance is defined as $X_0 = 3X_1$ [3]. Similarly, $X_{20}=3X_5$; $X_{21}=3X_{1k}$; $X_{22}=3X_{2k}$; $X_{23}=X_2*X_4/(X_2+X_4)$ = 0.0185*0.145/(0.0185+0.145) = j0.081

$X_{24} = jX_7/2 = j0.425/2 = j0.213$ (Fig. 7.0).

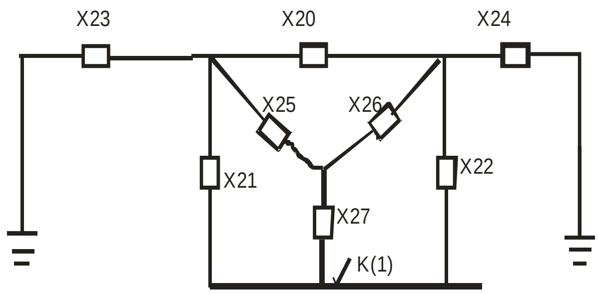

Figure 8.0 Conversion of Δ/Y impedance diagram

$$X_{25} = X_{20} * \frac{X_{21}}{X_{20} + X_{21} + X_{22}}$$

$$= j0.453 * \frac{j0.317}{j0.453 + j0.317 + j0.136} = j0.159$$

$$X_{26} = X_{20} * \frac{X_{22}}{X_{20} + X_{21} + X_{22}}$$

$$= j0.453 * \frac{j0.081}{j0.453 + j0.317 + j0.136} = j0.068$$

$$X_{27} = X_{21} * \frac{X_{22}}{X_{20} + X_{21} + X_{22}}$$

$$= j0.317 * \frac{j0.136}{j0.453 + j0.317 + j0.136} = j0.048$$

$$X_{28} = X_{23} + X_{25} = j0.081 + j0.159 = j0.240$$

$$X_{29} = X_{24} + X_{26} = j0.213 + j0.068 = j0.281$$

The equivalent reactance of the zero sequence relative to the point of short circuit $K^{(1)}$ is defined as:

$$X_{eq\,(0)} = X_{27} + X_{28} * \frac{X_{29}}{X_{28} + X_{29}} = j0.048 + j0.24 * \frac{j0.281}{j0.24 + j0.281} = j0.177$$

The impedance of the power line at the point of short circuit is:

$$Z_{sh}^{(1)} = jX_{eq\,(0)} + Z_{eq} = j0.177 + 0.01 + j0.133 = 0.01 + j0.31$$

Abnormal regime

Calculation of system reactance for single line-to-ground short circuit at15km distance from source.

$$X_{33} = (X_1 + X_2) * \frac{X_3 + X_4}{X_2 + X_2 + X_3 + X_4} =$$

$$(0.531 + 0.185) * \frac{0.413 + 0.145}{0.531 + 0.185 + 0.413 + 0.145} = j0.80$$

$$Z_{16} = jX_9 + Z_{load} = j0.185 + 1.414 + j0.625 = 1.414 + j0.80$$

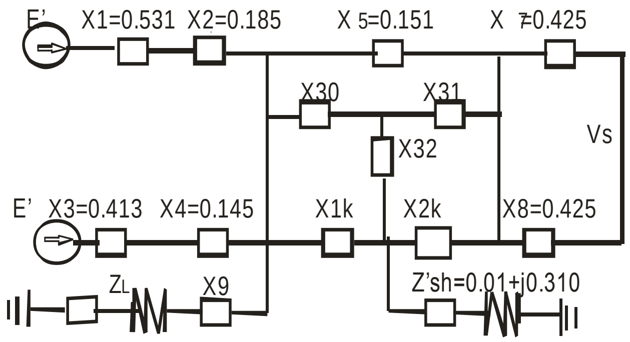

Figure 9.0 Abnormal regime impedance diagram

$$X_{30} = X_5 * \frac{X_{1k}}{X_5 + X_{1k} + X_{2k}} = j0.151 * \frac{j0.1057}{j0.151 + j0.1057 + j0.045} = j0.053$$

$$X_{31} = X_5 * \frac{X_{2k}}{X_5 + X_{1k} + X_{2k}} = j0.027$$

$X_{32} = X_{1k} * \frac{X_{2k}}{X_5+X_{1k}+X_{2k}} = j0.016$

$Z_{17} = Z_{sh}^{(1)} + X_{32} = 0.01 + j0.31 + j0.016 = 0.01 + j0.326$

$X_{34} = jX_{31} + jX_{24} = j0.027 + j0.213 = j0.240$

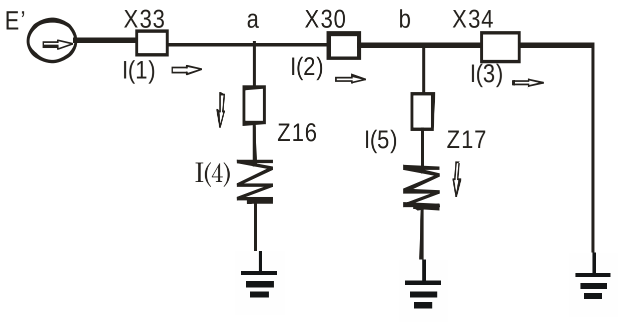

Figure 10.0 Equivalent generator circuit

Current quantity and its flow during abnormal regime Fig. 10

$V_s = 0, and\ \acute{I}_3 = 1.0\angle 0°$

$\acute{V}_b = \acute{I}_3 * jX_{34} = j0.240;\ \acute{I}_5 = \frac{\acute{V}_b}{Z_{17}} = 0.24\angle 90°/0.326\angle 88.24° = 0.736\angle 1.76°$

$\acute{I}_2 = \acute{I}_3 + \acute{I}_5 = 1.0 + 0.7357 + j0.0226 = 1.736 + j0.0226$

$\acute{V}_a = \acute{V}_b + \acute{I}_2 * jX_{30} = j0.24 + (1.736 + j0.0226) * j0.053 = 0.332\angle 89.8°$

$\acute{I}_4 = \frac{\acute{V}_a}{Z_{16}} = (0.332\angle 89.8°)/(1.414 + j0.8) = 0.101 + j0.177 = 0.204\angle 60.3°$

$\acute{I}_1 = \acute{I}_4 + \acute{I}_2 = 0.101 + j0.177 + 1.736 + j0.0226 = 1.848\angle 6.21°$

Input emf $E' = \acute{V}_a + jX_{33} * I_1 = 0.332\angle 89.8° + 0.314\angle 90° * 1.848\angle 6.21° = 0.911\angle 85.97°$

Self impedance: $Z_{11}''' = \frac{E'}{I_1} = 0.911\angle 85.97°/1.848\angle 6.21° = 0.493\angle 79.76°$

Self admittance angle: $\alpha_{11}''' = 90° - 79.76° = 10.24°$

Self admittance: $y_{11}''' = \frac{1}{0.493\angle 79.76°} = 2.028\angle -79.76°$

Mutual impedance $Z_{12}''' = \frac{E'}{I_3} = 0.911\angle 85.97° * \frac{1}{1.0}\angle 0° = 0.911\angle 85.97°$

Mutual impedance angle: $\alpha_{12}''' = 90° - 85.97° = 4.03°$

Mutual admittance: $y_{12}''' = \frac{1}{0.911\angle 85.97°} = 1.098\angle -85.97°$

Self and mutual reactance after accidental regime

$X_{35}=(X_1+X_2)(X_3+X_4)/(X_1+X_2+X_3+X_4)$

$(j0.531 + j0.185) * \frac{j0.266+j0.145}{j0.531+j0.185+j0.0.266+j0.145}$ $X_{36}=jX_5+X_7/2 = j0.151+j0.425/2 = j0.364$

$Z_{18}=jX_9+Z_{load}=1.414+j0.80$, Fig. 11(b)

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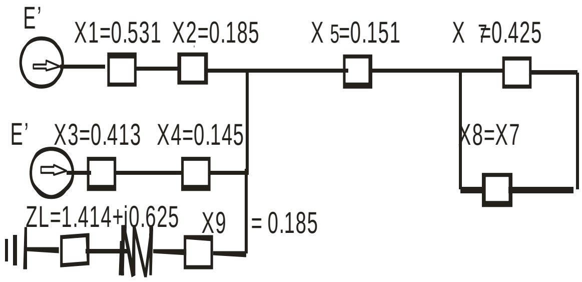

Figure11(a) Reactances after accidental regime

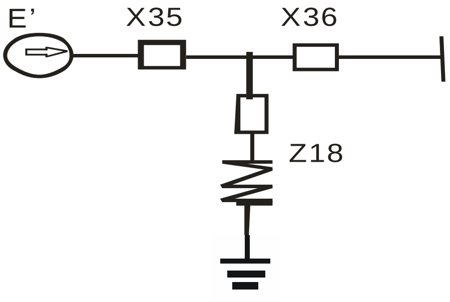

Figure11(b) Equivalent diagram after accidental regime

Self impedance: $Z''_{11} = jX_{35} + \frac{jX_{36} * Z_{18}}{X_{36} + Z_{18}} = 0.634\angle 85^\circ$

Self admittance angle: $\alpha''_{11} = 90^\circ - 85^\circ = 5^\circ$

Self admittance: $y''_{11} = \frac{1}{0.634\angle 85^\circ} = 1.577\angle - 85^\circ$

Mutual impedance: $Z''_{12} = jX_{35} + \frac{jX_{35} * X_{36}}{Z_{18}} = 0.646\angle 84.6^\circ$

Self admittance angle: $\alpha''_{12} = 90^\circ - 84.6^\circ = 5.4^\circ$

Self admittance: $y''_{12} = \frac{1}{0.646\angle 84.6^\circ} = 1.548\angle - 84.6^\circ$

Determination of maximum power at normal regime

(a) Without automatic excitation regulator on generator

$P_{m1} = E_q^2 * y'_{11} * sin\alpha'_{11} + E_q * V_{*s} * y'_{12} = 2.455^2 * 0.58 * sin0.93^\circ + 2.455 * 0.909 * 0.612 = 1.4225$

(b) With semi-automatic excitation regulator

$P_{m2} = (E')^2 * y'_{11} * sin\alpha'_{11} + E' * V_{*s} * y'_{12} = 1.237^2 * 1.739 * sin3.68^\circ + 1.237 * 0.909 * 1.733 = 2.1194$

(c) With automatic excitation regulator

$P_{m3} = V_G^2 * y'_{11} * sin\alpha'_{11} + V_G * V_{*s} * y'_{12} = 1.047^2 * 2.942 * sin4.66^\circ + 1.047 * 0.909 * 2.761 = 2.8881$

6. Calculation of power characteristics at different regimes:

1) Maximum power at normal regime

$P'_m = (E')^2 * y'_{11} sin\alpha'_{11} + E' * V_{*s} * y'_{12} \sin(\delta' - \alpha'_{11})$

$= 1.237^2 * 1.739 sin3.68^\circ + 1.237 * 0.909 * 1.733 * \sin(\delta' - 4.42^\circ) = 0.171 + 1.949 * \sin(\delta' - 4.42^\circ) = 2.12$

2) Maximum power at faulty regime

$P_m''' = (E')^2 * y_{11}''' sin\alpha_{11}''' + E' * V_{*s} * y_{12}''' \sin(\delta' - \alpha_{12}''')$

$= 1.237^2 * 2.028 sin 10.24 + 1.237 * 0.909 * 1.098 * \sin(\delta' - 4.03^\circ) = 0.552 + 1.235 * \sin(\delta' - 4.03^\circ) = 1.787$

3) Maximum power after fault clearance

$P_m'' = (E')^2 * y_{11}'' sin\alpha_{11}'' + E' * V_{*s} * y_{12}'' \sin(\delta' - \alpha_{12}'')$

$= 1.237^2 * 1.577 sin 5^\circ + 1.237 * 0.909 * 1.548 * \sin(\delta' - 5.4^\circ) = 0.210 + 1.741 * \sin(\delta' - 5.4^\circ) = 1.951$

Taking values of δ' from 0° to 180°, the values of P_m', P_m''', and P_m'' will be calculated as shown in Table 3.

Values of P_m', P_m''', and P_m'' for δ′ from 0° to 180° Table 3.0

δ′ degree	0°	30°	60°	90°	120°	150°	180°
P_m'	0.021	1.013	1.779	2.114	1.929	1.273	0.321
P_m'''	0.465	1.093	1.575	1.784	1.662	1.243	0.639
P_m''	0.0.046	0.935	1.629	1.943	1.793	1.219	0.374

Static stability at normal regime without auto-regulation of excitation

$K_{st} = \left[\frac{P_{m1} - P_0}{P_0}\right] * 100\% = \left[\frac{(1.4225 - 1.044)}{1.044}\right] * 100\% = 36.25\%$

Static stability at normal regime with semi-automatic regulation of excitation

$K_{st} = \left[\frac{P_{m2} - P_0}{P_0}\right] * 100\% = \left[\frac{(2.1194 - 1.044)}{1.044}\right] * 100\% = 103\%$

Static stability at normal regime with automatic regulation of excitation

$K_{st} = \left[\frac{P_{m3} - P_0}{P_0}\right] * 100\% = \left[\frac{(2.8881 - 1.044)}{1.044}\right] * 100\% = 176.64\%$

Static stability regime after fault clearance

$K_{st} = \left[\frac{P_m'' - P_0}{P_0}\right] * 100\% = \left[\frac{(1.951 - 1.044)}{1.044}\right] * 100\% = 86.9\%$

For three phase short circuit $P_m''' = 0$ [4]. The limit of switch off angle δ_{lim} of the short circuit is defined thus:

$\delta_{lim} = (P_0 * \frac{\delta_k' - \delta_0'}{57.3^\circ} + P_m'' cos\delta_k')/P_m''$

$$\frac{1.044 * \frac{147.65^\circ - 24.78^\circ}{57.3^\circ} + 1.951 * cos 147.65^\circ}{1.951} = 0.2543\, rad.\ or\ 14.57^\circ$$

where $\delta_k' = 180^\circ - \arcsin\left(\frac{P_0}{P_m''}\right) = 180^\circ - \arcsin\left(\frac{1.044}{1.951}\right) = 147.65^\circ$

The coefficient 57.3° converts degrees to radians.

Determination of switch off angle as a function of switch off time δ′=f(t) can be drawn by taking intervals of t=0.15 at ∆t=0.05 second.

First interval ∆t=0 to 0.05 second

Electrical power given out at the first moment after the short circuit is $P_m''' = 0$, this is because there will be no system voltage V_s during three phase short circuit. Power at the initial interval is P_0 =1.044. Increase in angle for this interval is:

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$\Delta\delta_1' = \frac{K*P_0}{2} = 8.17 * \frac{1.044}{2} = 4.27,\ where\ K = \frac{45}{T_{e*eq}} = \frac{45}{5.51} = 8.17$ [5]. Angle at the first interval,

$\delta_1' = \delta_0' + \Delta\delta_1' = 24.78 + 4.27 = 29.05°$

Second interval Δt=0.05 to 0.1 second, $\Delta P_1 = P_0 = 1.044$

$\Delta\delta_2' = \Delta\delta_1' + K * \Delta P_1 = 4.27 + 8.17 * 1.044 = 12.799°$

$\delta_2' = \delta_1' + \Delta\delta_2' = 29.05° + 12.799° = 41.85°$

Third interval Δt=0.1 to 0.15 second, $\Delta P_2 = 1.044$ (switch off time)

$\Delta\delta_3' = \Delta\delta_2' + K * \Delta P_2 = 12.799 + 8.17 * 1.044 = 21.328°$

$\delta_3' = \delta_2' + \Delta\delta_3' = 41.85 + 21.328 = 63.18°$

Forth interval Δt=0.15 to 0.20 second, $\Delta P_3 = 1.044$ (first power imbalance)

For this interval, the switch off of the short circuit begins. The electrical power given out after the accident in the beginning of the forth interval will be:

$\Delta_1 P_3'' = C + D * \sin(\delta_3' - \alpha_{12}'') = 0.21 + 1.741 * \sin(63.18 - 5.4) = 1.689$

Where $C = (E')^2 * y_{11}'' * sin\alpha_{11}'' = 1.237^2 * 1.577 * sin5° = 0.21$, and

$D = E' * V_{*s} * y_{12}'' * \sin(\delta' - \alpha_{12}''') = 1.237 * 0.909 * 1.548 sin 84.6 = 1.7329$

Second power imbalance at the beginning of the forth interval

$\Delta_2 P_3'' = P_0 - \Delta_1 P_3'' = 1.044 - 1.689 = -0.645$

Increase in angle for this interval:

$\Delta\delta_4' = \Delta\delta_3' + K * \frac{\Delta P_3 + \Delta_2 P_3''}{2} = 21.328° + 8.17 * \frac{1.044 - 0.645}{2} = 22.958°$

Angle at the end of the forth interval

$$\delta_4' = \delta_3' + \Delta\delta_4' = 63.18° + 22.958° = 86.14°$$

Fifth interval at Δt = 0.2 to 0.25 second

$P_4 = C + D * \sin(\delta_4' - \alpha_{12}'') = 0.21 + 1.7329 * \sin(86.14° - 5.4°) = 1.9203$

$$\Delta P_4 = P_0 - P_4 = 1.044 - 1.930 = -0.886$$

$\Delta\delta_5' = \Delta\delta_4' + K * \Delta_2 P_3'' = 22.958° + 8.17 * (-0.645) = 15.72°$

$\delta_5' = \delta_4' + \Delta\delta_5' = 86.14° + 15.72° = 103.83°$

Results of $\delta' =$ f(t) Table 4.0

t, second	0	0.05	0.10	0.15	0.20	0.25
δ' degree	24.78	29.05	41.85	63.18	86.14	103.83

Table 4.0 is illustrated in Fig. 12.0, showing ($\delta_0' = 24.78°$) angle between the emf and the system voltage. $\delta_{sw}' = \delta_3' = 63.18°$– the switch off angle at t=0.15 second. $\delta_r' = \delta_5' = 103.83°$– retardation angle at the elapsed time (re-closure angle).

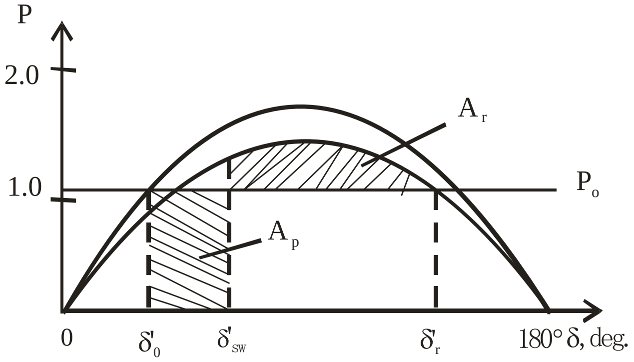

Figure 12.0 Generator swing curve

Speed up area A_p and possible retardation area A_r are defined in Fig. 13.0

$$A_p = P_0 * \frac{\delta_{sw}' - \delta_0'}{57.3^\circ} = 1.044 * \frac{63.18^\circ - 24.78^\circ}{57.3^\circ} = 0.70$$

$$A_r = P_0 * \frac{\delta_k' - \delta_{sw}'}{57.3^\circ} + P_m''(cos\delta_k' - cos\delta_{sw}') = 1.044 * \frac{147.65^\circ - 63.18^\circ}{57.3^\circ} + 1.951 * (cos147.65^\circ - cos63.18^\circ) = -0.9895$$

Reserved coefficient of dynamic stability of the power system (K_r) is defined as $K_r = |A_r|/A_p = \frac{-0.9895}{0.7} = 1.4136$

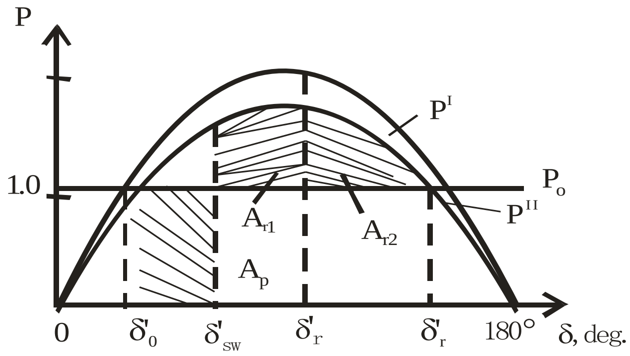

Figure 13.0 Dynamic stability curve

The influence of a successful auto-reclosure on the dynamic stability of the system has been presented. From table 4, it is seen that reclosure angle $\delta_r'$is equal to 103.83⁰ and reclosure time is 0.1second. Therefore, the retardation areas before A_{r1} and A_{r2} can be defined as stated below. These parameters can be used to define the coefficient of dynamic stability of the system through the influence of auto-reclosure equipment installed on the power system.

$$A_{r1} = P_0 * (\delta_r' - \delta_{sw}') * \frac{1}{57.3} + P_m''(cos\delta_r' - cos\delta_{sw}') = 1.044 * \frac{103.83^\circ - 63.18^\circ}{57.3} + 1.951 * (cos103.83^\circ - cos63.18^\circ) = -0.606$$

$$\delta_k' = 180^\circ - \arcsin(P_0 / P_m'') = 180^\circ - \arcsin(1.044/1.951) = 147.65^\circ$$

$$A_{r2} = P_0 * \frac{\delta_k' - \delta_r'}{57.3} + P_m' * (cos\delta_k' - \delta_r') = 1.044 * \frac{147.65^\circ - 103.83^\circ}{57.3^\circ} + 2.12 * (cos147.65^\circ - cos103.83^\circ) = -0.4858$$

Finally, the coefficient of dynamic stability of the system $K_r = (|A_{r1} + A_{r2}|) * \frac{1}{A_p} = \frac{0.606 + 0.4858}{0.70} = 1.5597$

CONCLUSION

As a result of the presence of automatic re-closure system on the power line, the re-closure angle was improved to 147.65⁰. Consequently, the coefficient of dynamic stability was raised to 1.5597 as compared with the 1.4136 earlier obtained after fault clearance. This result proves that the reserve of dynamic stability with auto re-closure in the system is more than when there is no

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auto re-closure system on the transmission line. Therefore, a successful automatic re-closure of transmission lines positively influences the dynamic stability of power systems.

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