Modifications/Corrections to First Course on Power Systems, 2006 Edition

Page 4-5: $\rho = 2.65 \times 10^{-2} \mu\Omega - m$.

Eq. 4-44: replace 2 by Z_c.

Page 6-10: in the Solution section, Z_{base} =1190.25 is calculated in Eq. 5-1

Eq. 11-15: delete the subscript *system* for H.

Example 6-1 Consider that the 200-km long transmission line between buses "1" and "3" in the 3-bus power system of Chapter 5 in Fig. 5-1 is at 500 kV. Two 345/500 kV transformers are used at both ends, as shown in the one-line diagram of Fig. 6-11. In the per-unit study, if the system base voltage is 345 kV, then the line impedance and the transformer leakage impedances are all calculated on the 345-kV voltage base, and 100 MVA base. For this 500-kV transmission line, the series reactance is 0.326 Ω / km at 60 Hz and the series resistance is 0.029 Ω / km. Neglect line susceptances. Each of the transformers has a leakage reactance of 0.2 pu on the 1000-MVA base.

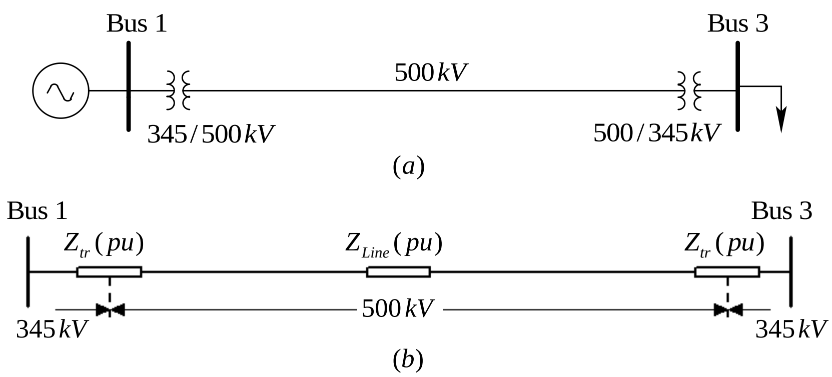


Fig. 6-11 Including nominal-voltage transformers in per-unit.

Calculate the per-unit series impedance of the transmission line and the transformers between buses 1 and 3 for the power flow study as discussed in Chapter 5, where the line-line voltage base is $345 kV$ and the three-phase MVA base is $100 MVA$.

Solution The 500-kV transmission line is 200-km long. From the given parameter values, the series impedance of the line is $Z_{Line} = (5.8 + j65.2)\Omega$. In a 3-phase system,

$$Z_{base}(\Omega) = \frac{kV_{base}^2 \text{(L-L)}}{MVA_{base} \text{(3-phase)}} \tag{6-19}$$

and therefore, at the 500-kV voltage and 1,000 MVA (3-phase) basis, the base impedance is $Z_{base} = 250.0\ \Omega$. Therefore, in per-unit, the series impedance of the transmission line is

$Z_{Line} = (0.0232 + j0.2608)\ pu$. Each of the transformer impedances are given as $Z_{tr} = j0.2\ pu$. All the impedances in per-unit, on a 1,000 MVA basis are shown in Fig. 6-11b.

Using Eq. 6-18, the transmission-line impedance can be represented on the 345-kV side of either transformer and its per-unit value will not change. Therefore, the impedance between buses 1 and 3 on a 345-kV and 1000-MVA base is as follows in the diagram of Fig. 6-11b:

$$Z_{13} = j0.2 + (0.0232 + j0.2608) + j0.2 = (0.0232 + j0.6608)\ pu$$

We now need to express this impedance on 345-kV and 100-MVA base for use in power-flow studies of Chapter 5. Making use of Eq. 6-19, the per-unit impedance from an original MVA base to a new MVA base is as follows:

$$Z_{pu}(\text{new}) = Z_{pu}(\text{original}) \times \frac{MVA_{base}(\text{new})}{MVA_{base}(\text{original})} \qquad (6\text{-}20)$$

Therefore, from Eq. 6-20, using 100-MVA as the new base and 1000 MVA as the original base, the series impedance between buses 1 and 3 is

$$Z_{13} = (0.00232 + j0.06608)\ pu\,. \qquad \#$$

6-8-1 Phase-Shift in Δ-Y Transformers

Transformers connected in Δ-Y, as shown in Fig. 6-13a, result in a 30^0 phase-shift that is shown by the phasor diagram of Fig. 6-13b. In order to boost the voltages produced by the generators, the low-voltage sides are connected in a delta and the high-voltage sides are connected in a grounded wye. On the Δ-connected side, the terminal voltages, although isolated from ground, can be visualized by hypothetically connecting very large, but equal, resistances from each terminal to a hypothetical neutral "n". Thus, $\bar{V}_{An}$ is the terminal-A voltage with respect to the hypothetical neutral "n". As shown in Fig. 6-13b, $\bar{V}_{An}$ leads $\bar{V}_a$ by 30^0 and the magnitude of the two voltages can be related as follows:

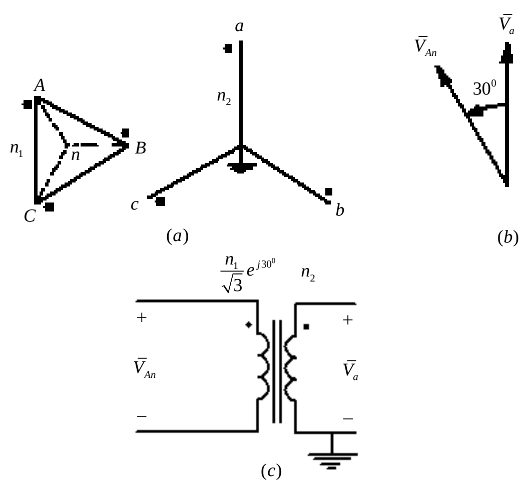


Fig. 6-13 Phase-shift in Δ-Y connected transformers.

$$\bar{V}_{AC} = \left(\frac{n_1}{n_2}\right)\bar{V}_a \text{ and thus,} \qquad \bar{V}_{An} = \frac{1}{\sqrt{3}}\left(\frac{n_1}{n_2}\right)\bar{V}_a e^{j30^0} \qquad (6\text{-}28)$$

Based on Eq. 6-28, the per-phase equivalent circuit is as shown in Fig. 6-13c.

\# **Example 11-1** Consider a simple system discussed earlier in Fig. 11-2b. The infinite-bus voltage is $\bar{V}_B = 1\angle 0\,\text{pu}$. The bus 1 voltage magnitude is $V_1 = 1.05\,\text{pu}$. The generator has a transient reactance $X_d^{'} = 0.28\,\text{pu}$ at a base of 22 kV (L-L) and its three-phase 1,500 MVA base. On the generator base, $H_{gen} = 3.5s$. The transformer steps up 22 kV to 345 kV, and has a leakage reactance of $X_{tr} = 0.2\,\text{pu}$ at its base of 1,500 MVA. The two 345-kV transmission lines are 100 km in length, and each has a series reactance of $0.367\Omega/km$, where the series resistance and the shunt capacitances are neglected. Initially, the three-phase power flow from the generator to the infinite-bus is 1500 MW.

A 3-phase to ground fault occurs on one of the lines, 20 percent of the distance away from bus-1. Calculate the maximum rotor-angle swing δ_m if the fault clearing is 40 ms after which the faulted transmission line is isolated from the system by the circuit breakers at both ends of the line.

Solution This example is solved using a program written in MATLAB which is verified by solving it in PowerWorld [1]. Both of these are attached. The plot of the rotor-angle oscillation is shown in Fig. 11-3; these oscillations continue since no damping is included in the model.

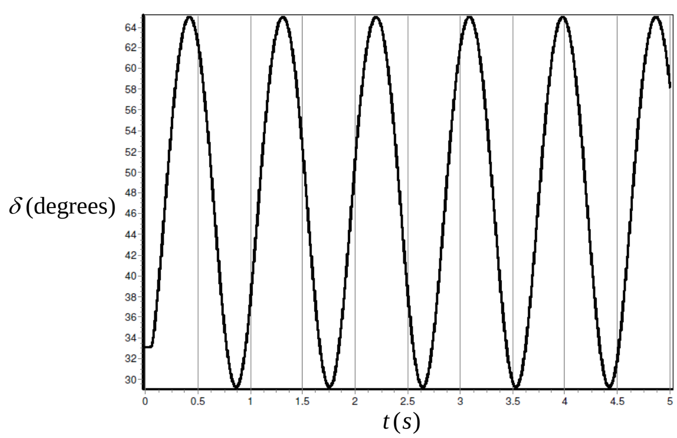


Fig. 11-3 Rotor oscillation in Example 11-1.

\# **Example 11-2** Consider a simple system discussed earlier in Fig. 11-4a. The infinite-bus voltage is $\bar{V}_B = 1\angle 0\,\text{pu}$. The voltage magnitude at Bus 1 is $V_1 = 1.05\,\text{pu}$. The generator has a transient reactance $X_d^{'} = 0.28\,\text{pu}$ at a base of 22 kV (L-L) and 1,500 MVA. On the generator base, $H_{gen} = 3.5s$. The transformer steps up 22 kV to 345 kV and has a leakage reactance of $X_{tr} = 0.2\,\text{pu}$ at its own base of 1,500 MVA. The two 345-kV transmission lines are 100 km in length, and each has a series reactance of

$0.367\,\Omega/km$, where the series resistance and the shunt capacitances are neglected. Initially, the three-phase power flow from the generator to the infinite-bus is 1500 MW.

A 3-phase to ground fault occurs on one of the lines, 20 percent of the distance away from bus-1. Calculate the maximum rotor-angle swing δ_m if the rotor angle at the time of fault clearing is 50^0.

Solution The solution to this example is carried out by a MATLAB program included on the accompanying website. The power angle curves for the pre-fault, during-fault and the post-fault conditions are as shown in Fig. 11-7, where initially $\delta_0 = 33.50^0$. The peak values of the power angle curves are calculated as follows on a system MVA base of 100 MVA: $\hat{P}_{e,pre-fault,pu} = 27.17$, $\hat{P}_{e,fault,pu} = 5.78$, and $\hat{P}_{e,post-fault,pu} = 20.51$. Using these values, the power-angle curves are as shown in Fig. 11-7.

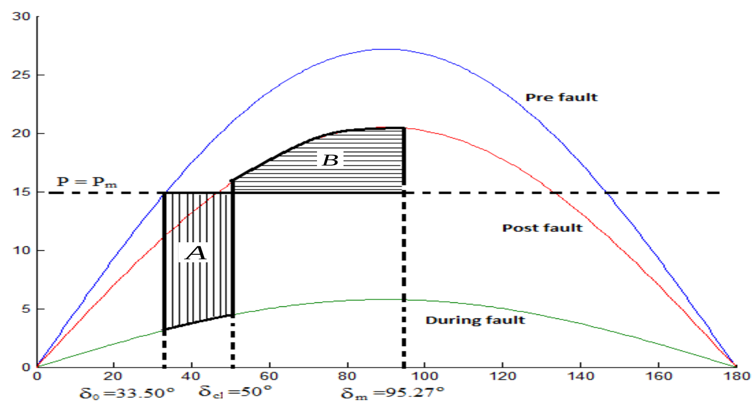


Fig. 11-7 Power angle curves and equal-area criterion in Example 11-2.

During the fault, the Area A in Fig. 11-7 can be calculated by using Eq. 11-16:

$$\begin{aligned} Area\ A &= \int_{\delta_0}^{\delta_{c\ell}} \left(P_{m,pu} - \hat{P}_{e,fault,pu} \sin\delta \right) d\delta \\ &= P_{m,pu}(\delta_{cl} - \delta_0) + \hat{P}_{e,fault,pu}(\cos\delta_{cl} - \cos\delta_0) \end{aligned} \qquad (11\text{-}17)$$

Similarly, the Area B in Fig. 11-7 can be calculated from Eq. 11-16:

$$\begin{aligned} Area\ B &= \int_{\delta_{cl}}^{\delta_m} \left(\hat{P}_{e,post-fault,pu} \sin\delta - P_{m,pu} \right) d\delta \\ &= \hat{P}_{e,post-fault,pu}(\cos\delta_{cl} - \cos\delta_m) - P_{m,pu}(\delta_m - \delta_{cl}) \end{aligned} \qquad (11\text{-}18)$$

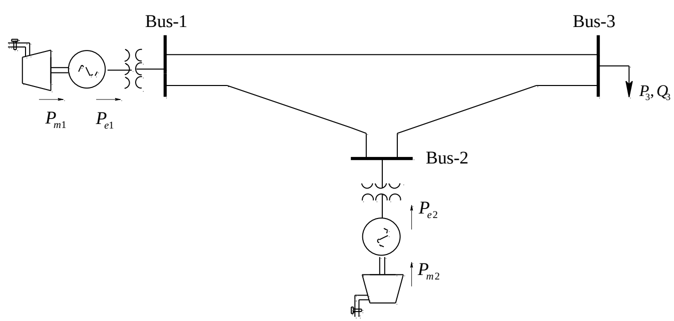
By applying equal-area criterion, the maximum rotor-angle swing $\delta_m = 95.27^0$, as shown in Fig. 11-7.

#

Example 11-3 Consider a three-bus system discussed earlier in chapter 5 and repeated in Fig. 11-9. These three buses are connected through three 345-kV transmission lines 200 km, 150 km and 150 km long, as shown in Fig. 5-1 of Chapter 5. These transmission lines, considered to consist of bundled conductors, have the line reactance of 0.367 Ω/km at 60 Hz. The line resistance is 0.0367 Ω/km. Ignore all the shunt susceptances. Bus-1 is a slack bus with $V_1 = 1.0\,pu$ and $\theta_1 = 0$. Bus-2 is a PV bus with $V_2 = 1.05\,pu$ and $P_2^{sp} = 4.0\,pu$. Bus-3 is a PQ bus with the injection of $P_3^{sp} = -5.0\,pu$ and $Q_3^{sp} = -1.0\,pu$.

Both the transformers and the generators have the three-phase MVA ratings of 500 MVA each. Both the generators have a transient reactance $X_d^{'} = 0.23\text{pu}$ at a base of 22 kV (L-L) and its own MVA base. Also, each generator has $H_{gen} = 3.5s$ on the generator base. Each 22-kV to 345-kV step-up transformer has a leakage reactance of $X_{tr} = 0.2\text{pu}$ at its own MVA base.

A 3-phase to ground fault occurs on line 1-2, 1/3rd of the distance away from bus-1. Calculate the rotor-angle swings if the fault-clearing time is 0.1 s after which the faulted transmission line is isolated from the



system by the circuit breakers at both ends of the line 1-2.

Fig. 11-9 A 345-kV test example system.

Solution The solution to this example using MATLAB and PowerWorld [1] are attached. #

Example 13-2 Consider a simple system with a 1 pu load at bus-3 being supplied by a single generator, as shown in Fig. 13-10, where all the quantities are in per unit. Calculate the fault current in per unit at Bus-2 for (a) three-phase fault, and (b) single-line to ground (SLG) fault with the fault impedance as zero.

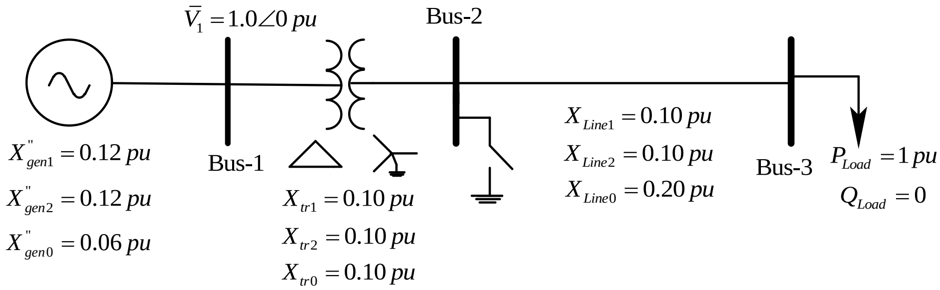


Fig. 13-10 One-line diagram of a simple power system.

Solution Bus-1 is assumed to be the slack bus with $\bar{V}_1 = 1.0\angle 0\ pu$. Using the MATLAB program developed in Chapter 5 on Power Flow or the *PowerWorld*, both of which are included on the accompanying website, the pre-fault voltage at bus-3 is calculated as $\bar{V}_3 = 0.98\angle -11.79^0\ pu$. Therefore, the load on bus-3 can be represented by $R_{Load} = 0.96\,pu$.

(a) In case of a three-phase fault on bus-2, the positive-sequence per-phase circuit is shown in Fig. 13-11, where $\bar{I}_{Load}$ and hence $\bar{E}''$ at the back of the sub-transient reactance can be calculated as follows:

$\bar{V}_3 \bar{I}^*_{Load} = 1.0\,pu$. Therefore, $\bar{I}_{Load} = 1.02\angle -11.79^0\ pu$ before the fault. Using $\bar{E}''$, with X''_{gen1} in series, to represent the generator, and given that $\bar{V}_1 = 1.0\angle 0^0\ pu$ prior to the fault, we can calculate $\bar{E}'' = 1.0\angle 0 + j(0.12\bar{I}_{Load}) = 1.03\angle 6.67^0\ pu$. For a three-phase to ground fault on bus-2, represented by closing the switch in Fig. 13-11, $\bar{I}_{fault} = 4.69\angle -83.32^0\ pu$.

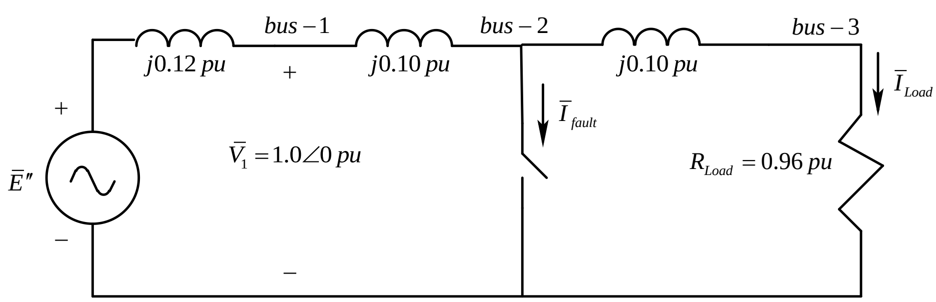


Fig. 13-11 Positive-sequence circuit for calculating a 3-phase fault on bus-2.

(b) In case of a single-line to ground (SLG) fault on bus-2, the sequence per-phase networks are connected in series as the analysis in Fig. 13-5 shows. With the fault impedance $Z_f = 0$, the circuit diagram is shown in Fig. 13-12. In the zero-sequence network, the generator zero-sequence impedance is shorted out because of the grounded-wye-delta connection. Also, the 30^0 phase shift introduced by the transformer connection has no effect on the fault current. From Fig.

13-12, $\overline{I}_{fault} = 5.71\angle -85.7^0\ pu$. The MATLAB and the PowerWorld files are included on the accompanying website.

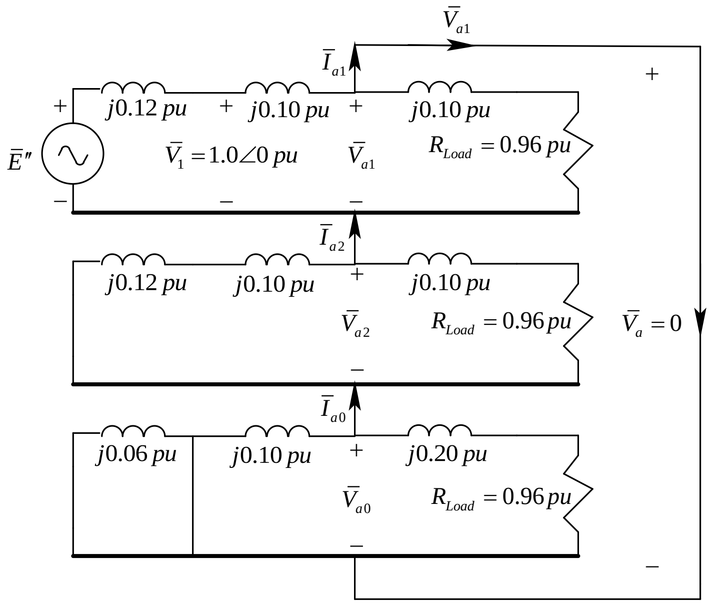


Fig. 13-12 Sequence networks for calculating the fault current due to SLG fault on bus-2.

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