Sample problem Reactive power compensations

A 350 km, 500 kV, 60 Hz uncompensated three-phase line has a positive-sequence series impedance $\bar{z} = 0.032 + j0.40\ \ \Omega/\text{km}$ and a positive-sequence shunt admittance $\bar{y} = j4.8 \times 10^{-6}$ S/km.

At full load, the line delivers 650 MVA at 0.98 power factor lagging and at 95% of the rated voltage.

a) Percent voltage regulation of the uncompensated line.

b) Percent voltage regulation after line compensation. Assume 75% shunt reactive compensation is used.

c) Find the maximum loadability of the uncompensated line.

d) Find the maximum loadability of the line after series capacitive compensation. Assume only 30% series capacitive compensation. There is no shunt reactive compensation in this part.

Solution

a) $\bar{Z}_c = \sqrt{\dfrac{\bar{z}}{\bar{y}}} = 289.14\angle{-2.287}\ \Omega$

$\bar{\gamma} l = \sqrt{\bar{z}\cdot\bar{y}}\cdot l = \alpha l + j\beta l$

$\alpha l = 0.0194$

$\beta l = 0.4854$

$\cosh(\bar{\gamma} l) = 0.8847 + j0.009$

$\sinh(\bar{\gamma} l) = 0.0171 + j0.4666$

$\bar{A} = \cosh(\bar{\gamma} l) = 0.8847 + j0.009$

$\bar{A} = 0.88472\angle 0.5857^\circ$ per unit

$\bar{B} = \bar{Z}_c \sinh(\bar{\gamma} l) = 10.337 + j134.61$

$\bar{B} = 135\angle 85.6086^\circ\ \Omega$

$\bar{C} = \dfrac{\sinh(\bar{\gamma} l)}{\bar{Z}_c} = -5.15\times 10^{-6} + j1.615\times 10^{-3}$

$\bar{C} = 0.001615\angle 90.183^\circ$ S

$\bar{D} = \bar{A}$

$\bar{Z}' = \bar{B}$

$\bar{V}_s = \bar{A}\,\bar{V}_{RFL} + \bar{B}\,\bar{I}_{RFL}$

$\bar{V}_{RFL} = \dfrac{0.95\times 500}{\sqrt{3}}\angle 0^\circ = 274241.38\ V_{LN}$

$\bar{I}_{RFL} = \dfrac{650\times 10^6}{\sqrt{3}(0.95\times 500000)}\angle{-\cos^{-1}(0.98)} = 790\angle{-11.478}$ A

$\bar{V}_s = (0.88472\angle 0.5857^\circ)(274241.38) + (135\angle 85.61^\circ)(790\angle{-11.478^\circ})$

$\bar{V}_s = 291386.6\angle 21.14^\circ\ V_{LN}$

$V_s = 504696.4\ V_{LL}$

$V_{RNL} = \dfrac{V_s}{A} = \dfrac{504696.4}{0.88472} = 570459\ V_{LL}$

$$\% VR = \frac{V_{RNL} - V_{RFL}}{V_{RFL}} \times 100 = \frac{570.5 - 475}{475} \times 100 = 20.1\,\%$$

This voltage regulation is not acceptable since it is too larger than 10 % criterion.

We should reduce $V_{RNL} = 570.5\ kV_{LL}$ at the light load condition by adding shunt reactors.

b) We are going to provide 75 % shunt reactive compansation.

First find $\bar{Y}'$

$$\bar{Y}' = 2\left(\frac{\bar{Y}}{2}\right) F_2 = 2\left(j8.4\times10^{-4}\right) \frac{\tanh\left(\frac{\bar{\gamma}l}{2}\right)}{\left(\frac{\bar{\gamma}l}{2}\right)} = 2\left(j8.4\times10^{-4}\right)\left(1.02\angle -0.09237\right)$$

$$\bar{Y}' = 2.7627\times10^{-6} + j\,0.0017137$$

$$\bar{Y}_{eq} = 2.7627\times10^{-6} + j\,0.0017137\,(1-0.75)$$

$$\bar{Y}_{eq} = 2.7627\times10^{-6} + j\,0.000428429 = 0.00042844\angle 89.63^\circ$$

$\bar{Z}_{eq} = \bar{Z}'$ since there is no series capacitive compensation.

$$\bar{A}_{eq} = \left(1 + \frac{\bar{Z}_{eq}\cdot\bar{Y}_{eq}}{2}\right) = 0.9712\angle 0.1416^\circ$$

$$V_{RNL-compansated} = \frac{504.7\ kV_{LL}}{0.9712} = 519.672\ kV_{LL}$$

$$\% VR_{compansated} = \frac{519.672 - 475}{475} \times 100 = 9.4\,\%$$

This number is less than 10 %, so it is acceptable.

c) $V_S = V_R = V_{rated} = 500 \text{ kV}_{LL}$ $\delta = \theta_Z$

$$P_{max} = \frac{V_S V_R}{Z'} - \frac{A V_R^2}{Z'} \cos(\theta_Z - \theta_A)$$

$$P_{max} = \frac{(500)(500)}{135} - \frac{(0.88472)(500)^2}{135} \cos(85.6 - 0.5857)$$

$P_{max} = 1709$ MW uncompansated line

d) We are now going to provide 30% series capacitive compensation to increase the loadability of the line.

First find X'

$$X' = Z' \sin(\theta_Z) = 135 \sin(85.6) = 134.6 \ \Omega$$

$$X_{cap} = -j\left(\tfrac{1}{2}\right)(0.3)(134.6) = -j20.19 \ \Omega$$

$$\begin{bmatrix} \bar{A}_{eq} & \bar{B}_{eq} \\ \bar{C}_{eq} & \bar{D}_{eq} \end{bmatrix} = \begin{bmatrix} 1 & -j20.19 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0.88472\angle 0.5857^\circ & 135\angle 85.6^\circ \\ 0.001615\angle 90.183^\circ & 0.88472\angle 0.5857^\circ \end{bmatrix} \begin{bmatrix} 1 & -j20.19 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \bar{A}_{eq} & \bar{B}_{eq} \\ \bar{C}_{eq} & \bar{D}_{eq} \end{bmatrix} = \begin{bmatrix} 0.91728 + j0.0091474 & 10.704 + j98.226 \\ -5.1456\times 10^{-6} + j0.001615 & 0.91728 + j0.0091474 \end{bmatrix}$$

$\bar{A}_{eq} = 0.91733\angle 0.57135^\circ$ $\bar{B}_{eq} = 98.8\angle 83.78^\circ \ \Omega$

$$P_{max\text{-}compansated} = \frac{(500)(500)}{98.8} - \frac{(0.91733)(500)^2}{98.8} \cos(83.78 - 0.57135)$$

$P_{max\text{-}compansated} = 2255$ MW

32% increase in maximum loadability