Compensation

Now let's try a 300 mile line. Both voltage drop and rise problems will be exacerbated and we will need to compensate the line to make it work

Long line

$z := 0.017 + 0.483i \quad \frac{ohm}{mi} \qquad y := 8.59i \times 10^{-6} \quad \frac{mho}{mi} \qquad l := 300\ mi$

$\gamma := \sqrt{z \cdot y} \qquad Zc := \sqrt{\frac{z}{y}} \qquad \gamma = 3.584 \times 10^{-5} + 2.037i \times 10^{-3} \qquad Zc = 237.118$

$Z := 300 \cdot z$ ohm $\qquad Y := 300 \cdot y$ mho

$A := \cosh(\gamma \cdot l) \qquad B := Zc \cdot \sinh(\gamma \cdot l) \qquad C := \frac{\sinh(\gamma \cdot l)}{Zc} \qquad D := A$

$A = 0.819 + 6.17i \times 10^{-3}$ $B = 4.483 + 136.06i$ $\qquad C = -5.437 \times 10^{-6} + 2.42i \times 10^{-3}$

$B = 4.483 + 136.06i$

$Y' := \frac{2 \cdot \tanh\left(\gamma \cdot \frac{l}{2}\right)}{Zc} \qquad Z' := Zc \cdot \sinh(\gamma \cdot l)$

$Y' = 3.046 \times 10^{-6} + 2.66i \times 10^{-3} \qquad Z' = 4.483 + 136.06i$

Step 3 Performance of uncompensated line

Full and no load ABCD matrix $\qquad ABCDline := \begin{pmatrix} A & B \\ C & D \end{pmatrix} \quad ABCD := ABCDline$

Step 3A Full Load Conditions

$VRfl := \frac{500000}{\sqrt{3}}$ V $\qquad IRfl := IR \qquad IR = 692.82 - 22\,A719i$

$|VRfl| = 2.887 \times 10^{5}$

$Vs := A \cdot VRfl + B \cdot IRfl \qquad |Vs| = 2.867 \times 10^{5}$ l − n $\qquad \arg(Vs) = 19.355\ deg$

$Is := C \cdot VRfl + D \cdot IRfl \qquad |Is| = 767.01 \qquad \arg(Is) = 42.303\ deg$

$Vrnl := \frac{Vs}{A} \qquad |Vrnl| = 3.501 \times 10^{5}$ Vl − n $\qquad \sqrt{3} \cdot |Vs| = 4.966 \times 10^{5}$ V l-l

$SSfl := 3 \cdot Vs \cdot \overline{Is}$ $SSfl = 6.075 \times 10^{8} - 2.572i \times 10^{8}$ Sending end power

Losses $Sloss := \left(Vs \cdot \overline{Is} - VRfl \cdot \overline{IRfl}\right) \cdot 3$ $Sloss = 7.548 \times 10^{6} - 4.545i \times 10^{8}$

Step 3b No load analysis

$VRnl := \frac{Vs}{A}$ $|VRnl| = 3.501 \times 10^{5}$ $\sqrt{3} \cdot |Vrnl| = 6.063 \times 10^{5}$

$Isnl := C \cdot VRnl$ $|Isnl| = 847.03$

Step 3c Voltage regulation

$Reg := \frac{(||VRnl|| - |VRfl|) \cdot (100)}{|VRfl|}$ $Reg = 21.268$ percent

Step 3d Loadability at δ=35 deg Remember, we use rated valuesfor voltages

$Vs := \frac{500000}{\sqrt{3}}$ $Vr := \frac{500000}{\sqrt{3}}$

$$Pmax := \left[|Vs| \cdot \frac{|Vr| \cdot \cos\left(\arg(B) - 90 \cdot \frac{3.14}{180}\right)}{|B|} - (|Vr|)^{2} \cdot Re\left(\frac{A}{B}\right)\right] \cdot 3 \qquad Pmax = 1.775 \times 10^{9}$$

$$Pmaxpractical := \left[|Vs| \cdot \frac{|Vr| \cdot \cos\left(\arg(B) - 35 \cdot \frac{3.14}{180}\right)}{|B|} - (|Vr|)^{2} \cdot Re\left(\frac{A}{B}\right)\right] \cdot 3$$

$Pmaxpractical = 1.041 \times 10^{9}$

Regulation is unacceptable

- Full Load VS is OK
- No Load voltage jumps to 600 kV -- this is a problem

Practical Pmax at δ=35deg is to close to the desired power transfer of 600 MW

Sending end reactive power at full load is 257 MVAR leading -- this is bad

Compensation

Series compensation

Reduce overal series inductive impedance

Reduce full load drop

Increase loadability

Definition

% Compensation = 100 Xc/Xl

Limits

Voltage across capacitor during short circuit
Subsynchronous resonance

Keep < 70 %

Connection

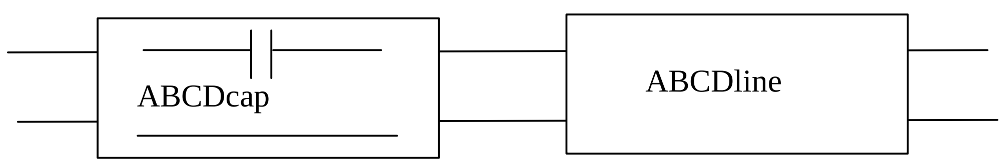
One end or other
Middle

Split each end
Often dictated by substation availability

Example

50 % compensation at sending end

$Xc := 0.5 \cdot Im(Z)$ $Xc = 72.45$ ohm



ABCD = ABCDcap ABCDline

$$ABCDcap := \begin{pmatrix} 1 & -iXc \\ 0 & 1 \end{pmatrix}$$

$ABCD := ABCDcap \cdot ABCDline$

$$ABCD = \begin{pmatrix} 0.994 + 6.564i \times 10^{-3} & 4.93 + 76.721i \\ -5.437 \times 10^{-6} + 2.42i \times 10^{-3} & 0.819 + 6.17i \times 10^{-3} \end{pmatrix}$$

Step 3 Performance of compensated line

Full and no load ABCD matrix

$A := ABCD_{1,1}$ $\quad B := ABCD_{1,2}$

$C := ABCD_{2,1}$ $\quad D := ABCD_{2,2}$

Step 3A Full Load Conditions

$VRfl := \frac{500000}{\sqrt{3}}$ V $\quad IRfl := IR \quad IR = 692.82 - 22\,A719i$

$Vs := A \cdot VRfl + B \cdot IRfl \quad |Vs| = 3.126 \times 10^5$ l – n $\quad \arg(Vs) = 9.933\,deg$

$Is := C \cdot VRfl + D \cdot IRfl \quad |Is| = 767.01 \quad \arg(Is) = 42.303\,deg$

$Vrnl := \frac{Vs}{A} \quad |Vrnl| = 3.144 \times 10^5$ Vl – n $\quad \sqrt{3} \cdot |Vs| = 5.415 \times 10^5$ V ll

$SSfl := 3 \cdot Vs \cdot \overline{Is} \quad SSfl = 6.075 \times 10^8 - 3.851i \times 10^8$ Sending end power

Losses $\quad Sloss := \left(Vs \cdot \overline{Is} - VRfl \cdot \overline{IRfl}\right) \cdot 3 \quad Sloss = 7.548 \times 10^6 - 5.823i \times 10^8$

Step 3b No load analysis

$VRnl := \frac{Vs}{A} \quad |VRnl| = 3.144 \times 10^5 \quad \sqrt{3} \cdot |Vrnl| = 5.445 \times 10^5$

$Isnl := C \cdot VRnl \quad |Isnl| = 760.688$

Step 3c Voltage regulation

$Reg := \frac{(||VRnl|| - |VRfl|) \cdot (100)}{|VRfl|} \quad Reg = 8.907$ percent

Step 3d Loadability at δ=35 deg Remember, we use rated valuesfor voltages

$$Vs := \frac{500000}{\sqrt{3}} \qquad Vr := \frac{500000}{\sqrt{3}}$$

$$Pmax := \left[|Vs| \cdot \frac{|Vr| \cdot \cos\left(\arg(B) - 90 \cdot \frac{3.14}{180}\right)}{|B|} - (|Vr|)^2 \cdot \mathrm{Re}\left(\frac{A}{B}\right) \right] \cdot 3 \qquad Pmax = 3.017 \times 10^9$$

$$Pmaxprac := \left[|Vs| \cdot \frac{|Vr| \cdot \cos\left(\arg(B) - 35 \cdot \frac{3.14}{180}\right)}{|B|} - (|Vr|)^2 \cdot \mathrm{Re}\left(\frac{A}{B}\right) \right] \cdot 3 \qquad Pmaxprac = 1.803 \times 10^9$$

Regulation and Loadability OK

Sending end reactive power at full load is bad; no load is bad as well

Shunt Compensation

Reduce overal shunt charging current

Reduce no load voltage rise

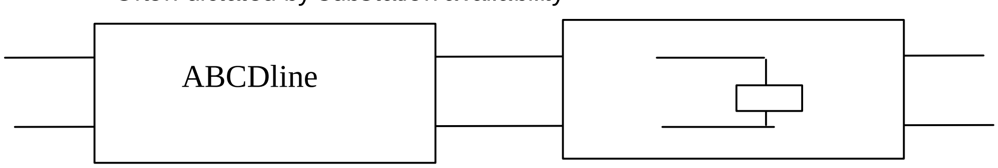
Definition

% Compensation = 100 Br/Bc

Connection

One end or other
Middle

Split each end
Often dictated by substation availability



ABCD = ABCDline ABCDr

Example

Receiving end 50 %

$Br := 0.5 \cdot Im(Y)$ $Br = 1.288 \times 10^{-3}$

$ABCDr := \begin{pmatrix} 1 & 0 \\ -i \cdot Br & 1 \end{pmatrix}$ $ABCD := ABCDline \cdot ABCDr$

$$ABCD = \begin{pmatrix} 0.994 + 3.939i \times 10^{-4} & 4.483 + 136.06i \\ 2.513 \times 10^{-6} + 1.364i \times 10^{-3} & 0.819 + 6.17i \times 10^{-3} \end{pmatrix}$$

Step 3 Performance of compensated line

Full and no load ABCD matrix

$A := ABCD_{1,1}$ $B := ABCD_{1,2}$

$C := ABCD_{2,1}$ $D := ABCD_{2,2}$

Step 3A Full Load Conditions

$VRfl := \frac{500000}{\sqrt{3}}$ V $IRfl := IR$ $IR = 692.82 - 22\,A719i$

$Vs := A \cdot VRfl + B \cdot IRfl$ $|Vs| = 3.344 \times 10^5$ l – n $arg(Vs) = 16.21\ deg$

$Is := C \cdot VRfl + D \cdot IRfl$ $|Is| = 607.604$ $arg(Is) = 20.38\ deg$

$SSfl := 3 \cdot Vs \cdot \overline{Is}$ $SSfl = 6.08 \times 10^8 - 4.433i \times 10^7$ Sending end power

Losses $Sloss := \left(Vs \cdot \overline{Is} - VRfl \cdot \overline{IRfl}\right) \cdot 3$ $Sloss = 7.981 \times 10^6 - 2.415i \times 10^8$

Step 3b No load analysis

$VRnl := \frac{Vs}{A}$ $|VRnl| = 3.363 \times 10^5$ $\sqrt{3} \cdot |Vrnl| = 5.445 \times 10^5$

$Isnl := C \cdot VRnl$ $|Isnl| = 458.844$

Step 3c Voltage regulation

$Reg := \frac{(||VRnl|| - |VRfl|) \cdot (100)}{|VRfl|}$ $Reg = 16.508$ percent

Step 3d Loadability at δ=35 deg Remember, we use rated values for voltages

$$Vs := \frac{500000}{\sqrt{3}} \qquad Vr := \frac{500000}{\sqrt{3}}$$

$$Pmax := \left[|Vs| \cdot \frac{|Vr| \cdot \cos\left(\arg(B) - 90 \cdot \frac{3.14}{180}\right)}{|B|} - (|Vr|)^2 \cdot \mathrm{Re}\left(\frac{A}{B}\right) \right] \cdot 3 \qquad Pmax = 1.775 \times 10^9$$

$$Pmax := \left[|Vs| \cdot \frac{|Vr| \cdot \cos\left(\arg(B) - 35 \cdot \frac{3.14}{180}\right)}{|B|} - (|Vr|)^2 \cdot \mathrm{Re}\left(\frac{A}{B}\right) \right] \cdot 3 \qquad Pmax = 1.041 \times 10^9$$

Regulation Improved a little; Loadability did not

Sending end reactive power at full load is good

Final Example

A. 30 % series compensation at each end

B. 50 % shunt compensation at sending end

C. 50 % SWITCHED (no load) compensation at receiving end

Sending and Receiving end 30 % series compensation

$Xc := 0.3 \cdot Im(Z)$ $\qquad Xc = 43.47$ ohm

$$ABCDc := \begin{pmatrix} 1 & -i \cdot Xc \\ 0 & 1 \end{pmatrix}$$

Sending and Receiving end 50 % Shunt Compensation

$Br := 0.5 \cdot Im(Y)$ $\qquad Br = 1.288 \times 10^{-3}$

$$ABCDr := \begin{pmatrix} 1 & 0 \\ -i \cdot Br & 1 \end{pmatrix}$$

Step 3 Performance of compensated line

Full and no load ABCD matrix

Step 3A Full Load Conditions

$ABCD\_FL := ABCDr \cdot ABCDc \cdot ABCDline \cdot ABCDc$

$$ABCD\_FL = \begin{pmatrix} 0.924 + 6.406i \times 10^{-3} & 5.029 + 60.281i \\ 2.818 \times 10^{-6} + 1.229i \times 10^{-3} & 1.002 - 7.417i \times 10^{-5} \end{pmatrix}$$

$A := ABCD\_FL_{1,1}$ $B := ABCD\_FL_{1,2}$

$C := ABCD\_FL_{2,1}$ $D := ABCD\_FL_{2,2}$

$VRfl := \frac{500000}{\sqrt{3}}$ V $IRfl := IR$ $IR = 692.82 - 22\,A719i$

$Vs := A \cdot VRfl + B \cdot IRfl$ $|Vs| = 2.872 \times 10^{5}$ l − n $\arg(Vs) = 8.505\,deg$

$Is := C \cdot VRfl + D \cdot IRfl$ $|Is| = 706.34$ $\arg(Is) = 10.318\,deg$

$\sqrt{3} \cdot |Vs| = 4.974 \times 10^{5}$ VLL

$SSfl := 3 \cdot Vs \cdot \overline{Is}$ $SSfl = 6.082 \times 10^{8} - 1.925i \times 10^{7}$ Sending end power

Sending end reactive power is 19 MVAR leading

Losses $Sloss := \left(Vs \cdot \overline{Is} - VRfl \cdot \overline{IRfl}\right) \cdot 3$ $Sloss = 8.204 \times 10^{6} - 2.165i \times 10^{8}$

Step 3b No load analysis

We now switch in the no-load reactor

$$ABCD\_NL := ABCDr \cdot ABCDc \cdot ABCDline \cdot ABCDc \cdot ABCDr$$

$$ABCD\_NL = \begin{pmatrix} 1.002 - 7.417i \times 10^{-5} & 5.029 + 60.281i \\ 2.722 \times 10^{-6} - 6.218i \times 10^{-5} & 1.002 - 7.417i \times 10^{-5} \end{pmatrix}$$

$$A := ABCD\_NL_{1,1} \quad B := ABCD\_NL_{1,2}$$
$$C := ABCD\_NL_{2,1} \quad D := ABCD\_NL_{2,2}$$

$$VRnl := \frac{Vs}{A} \qquad |VRnl| = 2.866 \times 10^{5} \qquad \sqrt{3} \cdot |Vrnl| = 5.445 \times 10^{5}$$

$$Isnl := C \cdot VRnl \qquad |Isnl| = 17.838$$

Step 3c Voltage regulation

$$Reg := \frac{(||VRnl|| - |VRfl|) \cdot (100)}{|VRfl|} \qquad Reg = -0.71 \qquad \text{percent}$$

Step 3d Loadability at δ=35 deg Remember, we use rated valuesfor voltages

$$A := ABCD\_FL_{1,1} \quad B := ABCD\_FL_{1,2}$$
$$C := ABCD\_FL_{2,1} \quad D := ABCD\_FL_{2,2}$$

$$Pmax := \left[|Vs| \cdot \frac{|Vr| \cdot \cos\left(\arg(B) - 35 \cdot \frac{3.14}{180}\right)}{|B|} - (|Vr|)^2 \cdot Re\left(\frac{A}{B}\right) \right] \cdot 3 \qquad Pmax = 2.285 \times 10^{9}$$