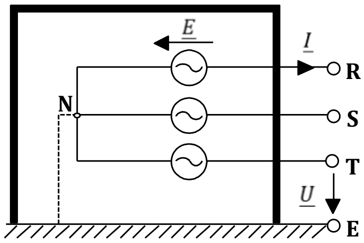
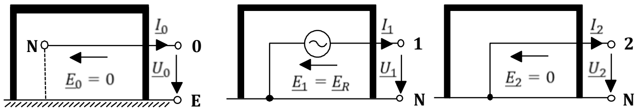
012-Modelle Symmetrischer Anlagen

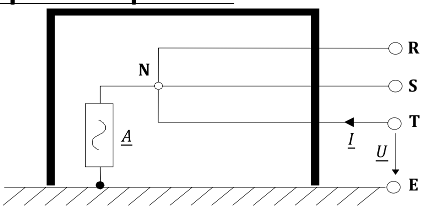
Symmetrische Spannungsquelle



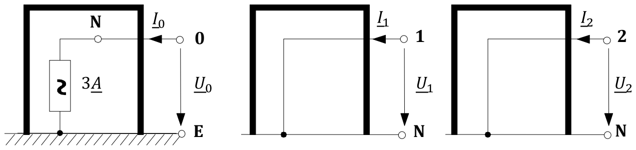
$$\begin{pmatrix} \underline{E}_0 \\ \underline{E}_1 \\ \underline{E}_2 \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \underline{a}^2 \\ \underline{a} \end{pmatrix} \cdot \underline{E}_R = \begin{pmatrix} 0 \\ \underline{E}_R \\ 0 \end{pmatrix}$$



Sternpunktimpedanz

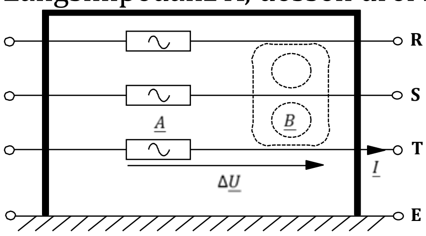


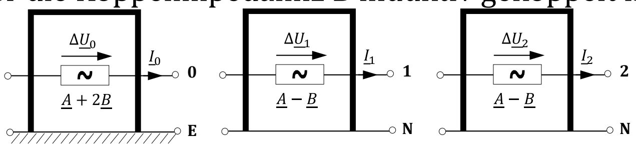
$$\underline{Z}_0 = 3\underline{A}$$



Symmetrische Längsimpedanzen

Längsimpedanz A, dessen drei Phasen zusätzlich über die Koppelimpedannz B induktiv gekoppelt ist



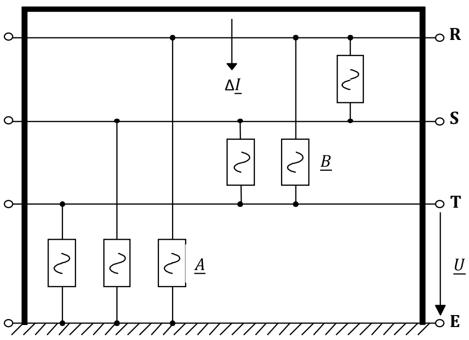


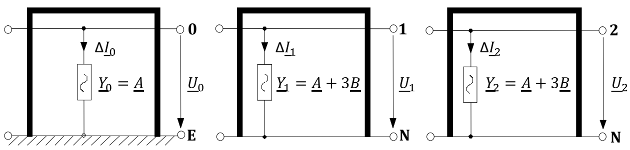
$$\underline{Z}_0 = \underline{A} + 2\underline{B} \qquad \underline{Z}_1 = \underline{Z}_2 = \underline{A} - \underline{B}$$

Sonderfall: Ohne Kopplung B=0 → $\underline{Z}_0 = \underline{Z}_1 = \underline{Z}_2 = \underline{A}$

4. Symmetrische Queradmittanzen

Querelemente ins 012-System → einfacher unter A und B nicht Impedanzen sondern Admittanzen zu verstehen





Knotenanalyse:

$$\begin{pmatrix} \Delta \underline{I}_R \\ \Delta \underline{I}_S \\ \Delta \underline{I}_T \end{pmatrix} = \begin{pmatrix} \underline{A} + 2\underline{B} & -\underline{B} & -\underline{B} \\ -\underline{B} & \underline{A} + 2\underline{B} & -\underline{B} \\ -\underline{B} & -\underline{B} & \underline{A} + 2\underline{B} \end{pmatrix} \cdot \begin{pmatrix} \underline{U}_R \\ \underline{U}_S \\ \underline{U}_T \end{pmatrix}$$

Nach Transformation :

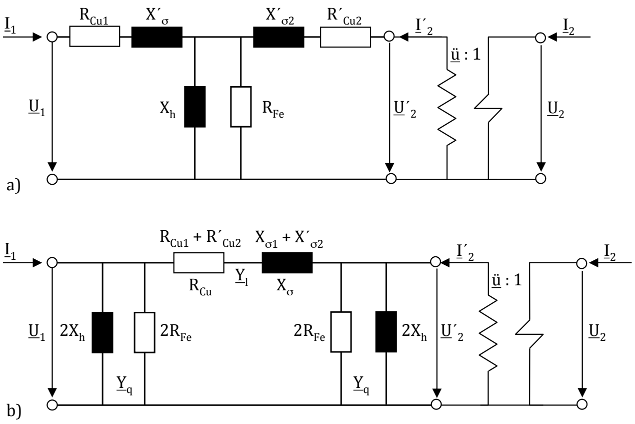
$$\begin{pmatrix} \Delta \underline{I}_0 \\ \Delta \underline{I}_1 \\ \Delta \underline{I}_2 \end{pmatrix} = \boldsymbol{T}_{012} \cdot \boldsymbol{Y}_{RST} \cdot \boldsymbol{T}_{012}^{-1} \cdot \begin{pmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \end{pmatrix} \begin{pmatrix} \underline{A} + 2\underline{B} & -\underline{B} & -\underline{B} \\ -\underline{B} & \underline{A} + 2\underline{B} & -\underline{B} \\ -\underline{B} & -\underline{B} & \underline{A} + 2\underline{B} \end{pmatrix} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \underline{a}^2 & \underline{a} \\ 1 & \underline{a} & \underline{a}^2 \end{pmatrix} \begin{pmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{pmatrix}$$

$$\underline{Y}_0 = \underline{A} \qquad \underline{Y}_1 = \underline{Y}_2 = \underline{A} + 3\underline{B}$$

Symmetrische Transformatoren

Mit- und Gegensystem

T- un TT ESB:



$$P_{Fe,r} \approx \frac{U_{r1}^2}{R_{Fe}} \quad \Rightarrow \quad R_{Fe} \approx \frac{U_{r1}^2}{P_{Fe,r}}$$

$$I_{01} \approx \frac{U_{r1}}{\sqrt{3}} \sqrt{\frac{1}{R_{Fe}^2} + \frac{1}{X_h^2}} \quad \Rightarrow \quad X_h \approx \frac{1}{\sqrt{\frac{3I_{01}^2}{U_{r1}^2} - \frac{1}{R_{Fe}^2}}} \approx \frac{U_{r1}}{\sqrt{3} I_{01}}$$

$$P_{Cu,r} \approx I_{r1}^2 \cdot (R_{Cu1} + R'_{Cu2}) = \left(\frac{S_r}{U_{r1}}\right)^2 \cdot (R_{Cu1} + R'_{Cu2})$$

$$\Rightarrow R_{Cu1} + R'_{Cu2} \approx P_{Cu,r} \cdot \left(\frac{U_{r1}}{S_r}\right)^2$$

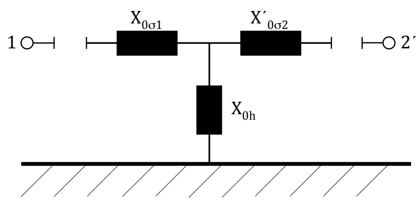
$$u_{kr} \cdot \frac{U_{r1}}{\sqrt{3}} \approx I_{r1} \cdot \sqrt{(R_{Cu1} + R'_{Cu2})^2 + (X_{\sigma 1} + X'_{\sigma 2})^2}$$

$$= \frac{S_r}{\sqrt{3} \cdot U_{r1}} \cdot \sqrt{(R_{Cu1} + R'_{Cu2})^2 + (X_{\sigma 1} + X'_{\sigma 2})^2}$$

$$\Rightarrow X_{\sigma 1} + X'_{\sigma 2} \approx \sqrt{(u_{kr} \cdot \frac{U_{r1}^2}{S_r})^2 - (R_{Cu1} + R'_{Cu2})^2} \approx u_{kr} \cdot \frac{U_{r1}^2}{S_r}$$

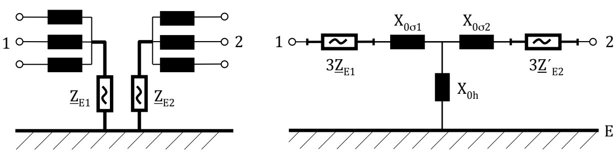
Null-System:

Ausgangsmodell des Zweiwicklungstrafo im Nullsystem

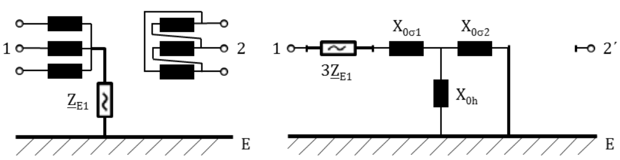


Bestimmt durch: (S. 46 Skript)
-Schaltungsart Stern- oder Dreieck der Wicklungen,
-Sternpunktbehandlung der Stern- oder Zickzack-Wicklungen und
-Art des Kernaufbaus, 3- oder 5- Schenklig

Yy-Trafo



Yd- bzw. Dy- Trafo



$$\underline{ü} = \frac{Uos}{Uus} e^{jx*30^\circ} \qquad \underline{Z}_{OS} = \underline{ü}^2 \cdot \underline{Z}_{US}$$

$$\underline{I}_{1,OS} = \frac{1}{\underline{ü}^*} \cdot \underline{I}_{1,US} \qquad \underline{I}_{2,OS} = \frac{1}{\underline{ü}} \cdot \underline{I}_{2,US} \qquad \underline{I}_{0,OS} = \frac{1}{\underline{ü}} \cdot \underline{I}_{0,US}$$

$$\underline{U}_{1,OS} = \underline{ü} \cdot \underline{U}_{1,US} \qquad \underline{U}_{2,OS} = \underline{ü}^* \cdot \underline{U}_{2,US} \qquad \underline{U}_{0,OS} = \underline{ü} \cdot \underline{U}_{0,US}$$

$$\underline{I}_{R,OS} = \underline{I}_0 + \underline{I}_1 + \underline{I}_2 =$$

$$\underline{I}_{S,OS} = \underline{I}_0 + \underline{a}^2 \cdot \underline{I}_1 + \underline{a} \cdot \underline{I}_2 =$$

$$\underline{I}_{T,OS} = \underline{I}_0 + \underline{a} \cdot \underline{I}_1 + \underline{a}^2 \cdot \underline{I}_2 =$$

Erst übertragen, dann Transformieren

.

$$\underline{U}_R = \underline{U}_0 + \underline{U}_1 + \underline{U}_2 \qquad \mathrm{I}_R = \underline{I}_0 + \underline{I}_1 + \underline{I}_2 \qquad (a^2 - a) = -j\sqrt{3}$$

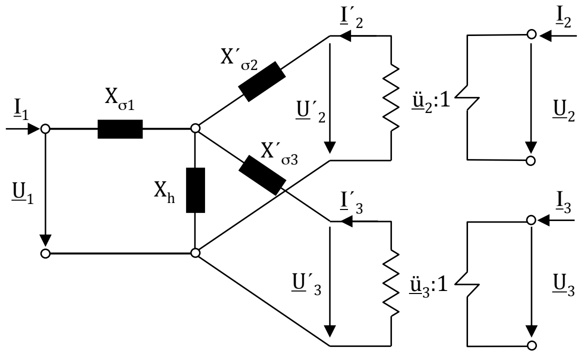
$$\underline{U}_S = \underline{U}_0 + \underline{a}^2\underline{U}_1 + \underline{a}\,\underline{U}_2 \qquad \underline{I}_S = \underline{I}_0 + \underline{a}^2\underline{I}_1 + \underline{a}\,\underline{I}_2 \qquad (a - a^2) = +j\sqrt{3}$$

$$\underline{U}_T = \underline{U}_0 + \underline{a}\,\underline{U}_1 + \underline{a}^2\underline{U}_2 \qquad \underline{I}_T = \underline{I}_0 + \underline{a}\,\underline{I}_1 + \underline{a}^2\underline{I}_2 \qquad (a + a^2) = -1$$

Symmetrische Dreiwcklungstrafos

Mit- und Gegensystem

ESB



Kurzschlussversuche beim 3W-Trafo

Test	Primary winding	Secondary winding	Tertiary winding
1.	Supply u_{kr12}	Short-circuit I_{r2}	Open-circuit
2.	Supply u_{kr13}	Open-circuit	Short-circuit I_{r3}
3.	Open-circuit	Supply u_{kr23}	Short-circuit I_{r3}

$$X_{k12} \approx \frac{u_{kr12} \cdot \frac{U_{r1}}{\sqrt{3}}}{I_{r2} \cdot \frac{U_{r2}}{U_{r1}}} = u_{kr12} \cdot \frac{U_{r1}^2}{S_{r2}}$$

$$X_{k13} \approx \frac{u_{kr13} \cdot \frac{U_{r1}}{\sqrt{3}}}{I_{r3} \cdot \frac{U_{r3}}{U_{r1}}} = u_{kr13} \cdot \frac{U_{r1}^2}{S_{r3}}$$

$$X'_{k23} \approx \left(\frac{U_{r1}}{U_{r2}}\right)^2 \cdot X_{k23} = \left(\frac{U_{r1}}{U_{r2}}\right)^2 \cdot \frac{u_{kr23} \cdot \frac{U_{r2}}{\sqrt{3}}}{I_{r3} \cdot \frac{U_{r3}}{U_{r2}}} = u_{kr23} \cdot \frac{U_{r1}^2}{S_{r3}}$$

Aus der ESB ergibt sich

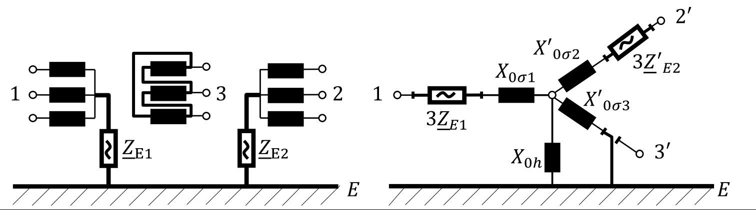
$$\begin{pmatrix} X_{k12} \\ X_{k13} \\ X'_{k23} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} X_{\sigma 1} \\ X'_{\sigma 2} \\ X'_{\sigma 3} \end{pmatrix}$$

und damit für die Streureaktanzen

$$\begin{pmatrix} X_{\sigma 1} \\ X'_{\sigma 2} \\ X'_{\sigma 3} \end{pmatrix} = \frac{1}{2} \cdot \begin{pmatrix} 1 & 1 & -1 \\ 1 & -1 & 1 \\ -1 & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} X_{k12} \\ X_{k13} \\ X'_{k23} \end{pmatrix}$$

Bezugsseite = 1 setzen.

Nullsystem



$$\underline{ü} = \frac{Uos}{Uus} e^{jx*30^\circ} \qquad \underline{Z}_{OS} = \underline{ü}^2 \cdot \underline{Z}_{US}$$

$$\underline{I}_{1,OS} = \frac{1}{\underline{ü}^*} \cdot \underline{I}_{1,US} \qquad \underline{I}_{2,OS} = \frac{1}{\underline{ü}} \cdot \underline{I}_{2,US} \qquad \underline{I}_{0,OS} = \frac{1}{\underline{ü}} \cdot \underline{I}_{0,US}$$

$$\underline{U}_{1,OS} = \underline{ü} \cdot \underline{U}_{1,US} \qquad \underline{U}_{2,OS} = \underline{ü}^* \cdot \underline{U}_{2,US} \qquad \underline{U}_{0,OS} = \underline{ü} \cdot \underline{U}_{0,US}$$

$$\underline{I}_{R,OS} = \underline{I}_0 + \underline{I}_1 + \underline{I}_2 =$$

$$\underline{I}_{S,OS} = \underline{I}_0 + \underline{a}^2 \cdot \underline{I}_1 + \underline{a} \cdot \underline{I}_2 =$$

$$\underline{I}_{T,OS} = \underline{I}_0 + \underline{a} \cdot \underline{I}_1 + \underline{a}^2 \cdot \underline{I}_2 =$$

Erst übertragen, dann Transformieren

.

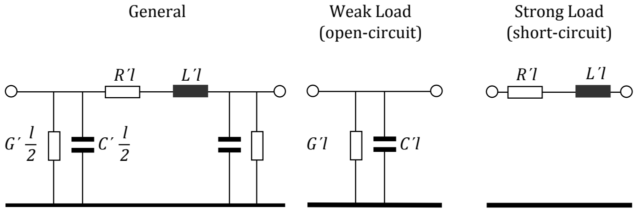
$$\underline{U}_R = \underline{U}_0 + \underline{U}_1 + \underline{U}_2$$
$$\underline{U}_S = \underline{U}_0 + \underline{a}^2\underline{U}_1 + \underline{a}\,\underline{U}_2$$
$$\underline{U}_T = \underline{U}_0 + \underline{a}\,\underline{U}_1 + \underline{a}^2\underline{U}_2$$

$$\mathrm{I}_R = \underline{I}_0 + \underline{I}_1 + \underline{I}_2$$
$$\underline{I}_S = \underline{I}_0 + \underline{a}^2\underline{I}_1 + \underline{a}\,\underline{I}_2$$
$$\underline{I}_T = \underline{I}_0 + \underline{a}\,\underline{I}_1 + \underline{a}^2\underline{I}_2$$

$$(a^2 - a) = -j\sqrt{3}$$
$$(a - a^2) = +j\sqrt{3}$$
$$(a + a^2) = -1$$

Symmetrische Freileitungen und Kabel

ESB-Allgemein



$C'_b = C'_E + 3C'_k$ $\quad C'_K = \frac{C'_b - C'_E}{3}$ $\quad L'_0 = L_1 + 3M' * l$

C'_E: *Erdungskapazitätsbelag = Zeilensumme*

C'_K: *Koppluingsskapazitätsbelag negatives Nebendiagonalelement*

$l * L'_b = L_1 = L_2$
$l * C'_b = C_1 = C_2$
$l * C'_E = C_0$

$X_C = \frac{1}{jwC}$ $\quad X_L = jwL$

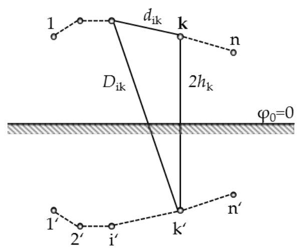
Erdstromtiefe: $\delta_E = \frac{1.85}{\sqrt{\mu_0 \cdot \omega \cdot \kappa_E}}$

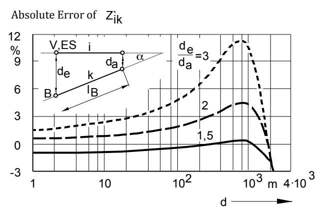
Bündelleiter: $\rho_B = \sqrt[n]{n\, \rho\, R^{n-1}} \cdot \frac{e^{-\frac{1}{4n}}}{e^{-\frac{1}{4}}}$

Hohlleiter: $\rho_H = \frac{\rho}{e^{-\frac{1}{4}}}$

Ersatzleiter: $\rho_B = \sqrt[n]{n\, \rho\, R^{n-1}}$

Geometrische Abstände





4-Bündelleiter: $R = \frac{d}{\sqrt{2}}$ $\quad$ 2-Bündel: $R = \frac{d}{2}$

Mittlere Höhe: $h_k = h_m - 0{,}7 f_m$

Kapazitätsbeläge von Freileitungen

Roh=Radius

$$p_{ii} = \frac{1}{2\pi\epsilon_0} \cdot \ln\frac{2h_i}{\rho_i} \qquad p_{ik} = \frac{1}{2\pi\epsilon_0} \cdot ln\frac{D_{ik}}{d_{ik}} = p_{ki}$$

Widerstands- und Induktivitätsbelag

$$\underline{Z}'_{ii} = (R'_i + \frac{\omega\mu_0}{8}) + j\frac{\omega\mu_0}{2\pi} \cdot ln\frac{\delta_E}{\rho e^{-\frac{1}{4}}} \quad \text{(Schleifenimpedanz)}$$

$$\underline{Z}'_{ik} = \frac{\omega\mu_0}{8} + j\frac{\omega\mu_0}{2\pi} \cdot ln\frac{\delta_E}{d_{ik}} \quad \text{(Koppelimpedanz)}$$

Bei verdirllten Freileitungen:

$$p_{ii} = \frac{1}{2\pi\epsilon_0} \cdot \ln\frac{2h}{\rho_i} \qquad p_{ik} = \frac{1}{2\pi\epsilon_0} \cdot ln\frac{D}{d} = p_{ki}$$

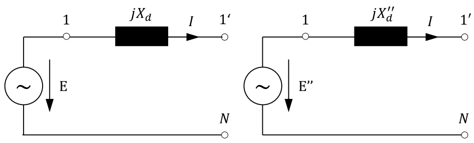
Schräger Leiter:

$d = \sqrt{d_e \cdot d_a}$ $\quad \frac{1}{3} \le \frac{d_e}{d_a} \le 3$ $\quad l_b * \cos\alpha \quad mit\ \alpha = \frac{d_e - d_a}{k}$

Symmetrische Generatoren

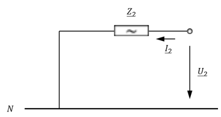
Mitsystem

Gilt immer bei Turbogeneratoren



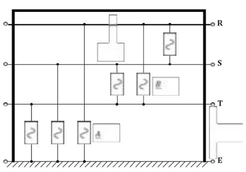
Gegensystem

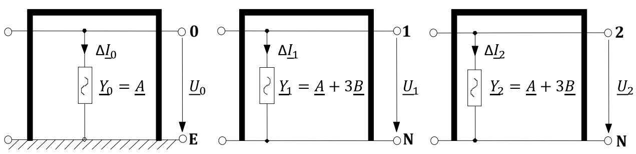
Bei rotierenden Maschinen entspricht das Gegen- nicht mehr dem Mitsystem



$\underline{Z}_2 = j\frac{1}{2}(X''_d + X''_q)$

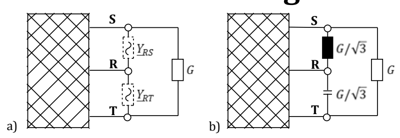
Symmetrische Verbraucher





Symmetrierung von unsymmetrischen Verbrauchern

Steinmetz-Schaltung

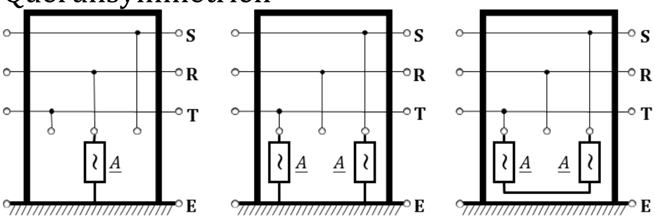
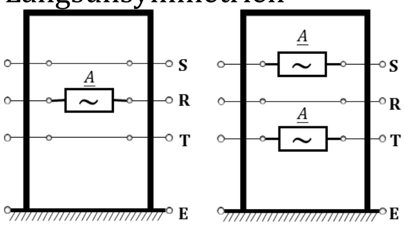


Forderung dass keine Null Ströme auftreten sollen

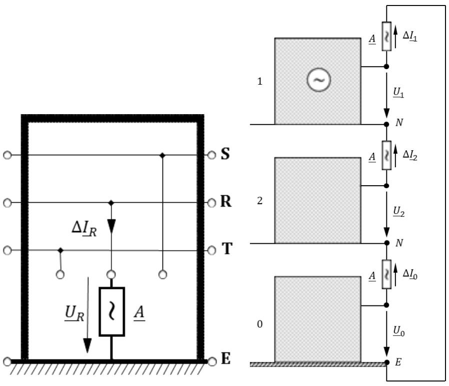
$$\underline{I}_0 = \frac{1}{3}(\underline{I}_R + \underline{a}^2 \cdot \underline{I}_S + \underline{a} \cdot \underline{I}_T) = 0$$

$$\underline{Y}_{RS} = -jG/\sqrt{3} \qquad \underline{Y}_{RT} = +jG/\sqrt{3}$$

012-Modell von Unsymmetrien

Querunsymmetrien	Längsunsymmetrien
	

Einphasige Querunsymmetrie



Knotenanalyse:

$$\begin{pmatrix}\Delta\underline{I}_R\\ \Delta\underline{I}_S\\ \Delta\underline{I}_T\end{pmatrix}=\begin{pmatrix}\underline{A}&0&0\\0&0&0\\0&0&0\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_R\\ \underline{U}_S\\ \underline{U}_T\end{pmatrix}$$

Transformation:

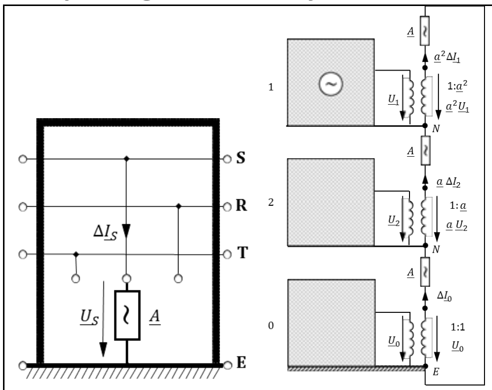
$$\begin{pmatrix}\Delta\underline{I}_0\\ \Delta\underline{I}_1\\ \Delta\underline{I}_2\end{pmatrix}=\underline{\boldsymbol{T}}_{012}\cdot\underline{\boldsymbol{Y}}_{RST}\cdot\underline{\boldsymbol{T}}_{012}^{-1}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}=\frac{1}{3}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}&\underline{a}^2\\1&\underline{a}^2&\underline{a}\end{pmatrix}\cdot\begin{pmatrix}\underline{A}&0&0\\0&0&0\\0&0&0\end{pmatrix}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}^2&\underline{a}\\1&\underline{a}&\underline{a}^2\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}$$

$$=\frac{1}{3}\cdot\begin{pmatrix}\underline{A}&\underline{A}&\underline{A}\\ \underline{A}&\underline{A}&\underline{A}\\ \underline{A}&\underline{A}&\underline{A}\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}$$

Unsymmetriebedingungen:

$$\Delta\underline{I}_0=\Delta\underline{I}_1=\Delta\underline{I}_2 \qquad \underline{U}_0+\underline{U}_1+\underline{U}_2=\frac{3}{\underline{A}}\Delta\underline{I}_0$$

Einphasige Querunsymmetrie in Phase S → Doppelerdschluss (R und S)



Knotenanalyse:

$$\begin{pmatrix}\Delta\underline{I}_R\\ \Delta\underline{I}_S\\ \Delta\underline{I}_T\end{pmatrix}=\begin{pmatrix}0&0&0\\0&\underline{A}&0\\0&0&0\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_R\\ \underline{U}_S\\ \underline{U}_T\end{pmatrix}$$

Transformation:

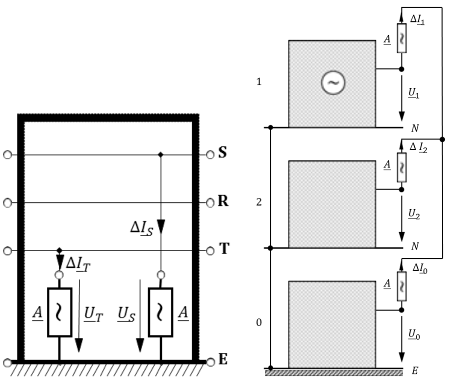
$$\begin{pmatrix}\Delta\underline{I}_0\\ \Delta\underline{I}_1\\ \Delta\underline{I}_2\end{pmatrix}=\underline{\boldsymbol{T}}_{012}\cdot\underline{\boldsymbol{Y}}_{RST}\cdot\underline{\boldsymbol{T}}_{012}^{-1}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}=\frac{1}{3}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}&\underline{a}^2\\1&\underline{a}^2&\underline{a}\end{pmatrix}\cdot\begin{pmatrix}0&0&0\\0&\underline{A}&0\\0&0&0\end{pmatrix}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}^2&\underline{a}\\1&\underline{a}&\underline{a}^2\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}$$

$$=\frac{1}{3}\cdot\begin{pmatrix}\underline{A}&\underline{a}^2\cdot\underline{A}&\underline{a}\cdot\underline{A}\\ \underline{a}\cdot\underline{A}&\underline{A}&\underline{a}^2\cdot\underline{A}\\ \underline{a}^2\cdot\underline{A}&\underline{a}\cdot\underline{A}&\underline{A}\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}$$

Unsymmetriebedingungen:

$$\Delta\underline{I}_0=\underline{a}^2\cdot\Delta\underline{I}_1=\frac{1}{\underline{a}^{2*}}\cdot\Delta\underline{I}_1=\underline{a}\cdot\Delta\underline{I}_2=\frac{1}{\underline{a}^{*}}\cdot\Delta\underline{I}_2 \qquad \underline{U}_0+\underline{a}^2\cdot\underline{U}_1+\underline{a}\cdot\underline{U}_2=\frac{3}{\underline{A}}\Delta\underline{I}_0$$

Zweiphasige Querunsymmetrie mit Erdberührung



Knotenanalyse:

$$\begin{pmatrix}\Delta\underline{I}_R\\ \Delta\underline{I}_S\\ \Delta\underline{I}_T\end{pmatrix}=\begin{pmatrix}0&0&0\\0&\underline{A}&0\\0&0&\underline{A}\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_R\\ \underline{U}_S\\ \underline{U}_T\end{pmatrix}$$

Transformation:

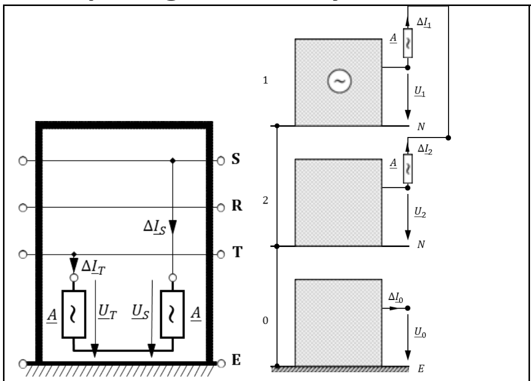
$$\begin{pmatrix}\Delta\underline{I}_0\\ \Delta\underline{I}_1\\ \Delta\underline{I}_2\end{pmatrix}=\underline{\boldsymbol{T}}_{012}\cdot\underline{\boldsymbol{Y}}_{RST}\cdot\underline{\boldsymbol{T}}_{012}^{-1}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}=\frac{1}{3}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}&\underline{a}^2\\1&\underline{a}^2&\underline{a}\end{pmatrix}\cdot\begin{pmatrix}0&0&0\\0&\underline{A}&0\\0&0&\underline{A}\end{pmatrix}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}^2&\underline{a}\\1&\underline{a}&\underline{a}^2\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}$$

$$=\frac{1}{3}\cdot\begin{pmatrix}2\underline{A}&-\underline{A}&-\underline{A}\\ -\underline{A}&2\underline{A}&-\underline{A}\\ -\underline{A}&-\underline{A}&2\underline{A}\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}$$

Unsymmetriebedingungen:

$$\Delta\underline{I}_0+\Delta\underline{I}_1+\Delta\underline{I}_2=0 \qquad \underline{U}_0-\underline{U}_1=\frac{1}{\underline{A}}\cdot(\Delta\underline{I}_0-\Delta\underline{I}_1) \qquad \underline{U}_1-\underline{U}_2=\frac{1}{\underline{A}}\cdot(\Delta\underline{I}_1-\Delta\underline{I}_2)$$

Zweiphasige Querunsymmetrie ohne Erdberührung



Knotenanalyse:

$$\begin{pmatrix}\Delta\underline{I}_R\\ \Delta\underline{I}_S\\ \Delta\underline{I}_T\end{pmatrix} = \begin{pmatrix}0&0&0\\0&\frac{\underline{A}}{2}&-\frac{\underline{A}}{2}\\0&-\frac{\underline{A}}{2}&\frac{\underline{A}}{2}\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_R\\ \underline{U}_S\\ \underline{U}_T\end{pmatrix}$$

Transformation:

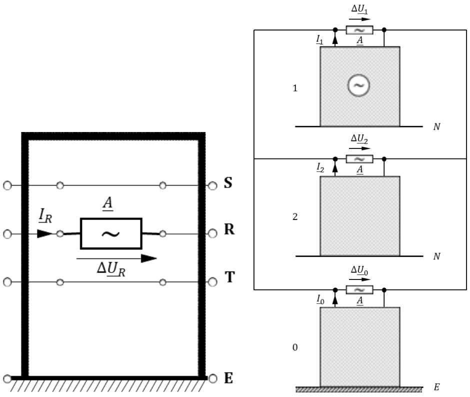
$$\begin{pmatrix}\Delta\underline{I}_0\\ \Delta\underline{I}_1\\ \Delta\underline{I}_2\end{pmatrix} = \boldsymbol{\underline{T}}_{012}\cdot\boldsymbol{\underline{Y}_{RST}}\cdot\boldsymbol{\underline{T}}_{012}^{-1}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix} = \frac{1}{3}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}&\underline{a}^2\\1&\underline{a}^2&\underline{a}\end{pmatrix}\cdot\begin{pmatrix}0&0&0\\0&\frac{\underline{A}}{2}&-\frac{\underline{A}}{2}\\0&-\frac{\underline{A}}{2}&\frac{\underline{A}}{2}\end{pmatrix}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}^2&\underline{a}\\1&\underline{a}&\underline{a}^2\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}$$

$$= \begin{pmatrix}0&0&0\\0&\underline{A}/2&-\underline{A}/2\\0&-\underline{A}/2&\underline{A}/2\end{pmatrix}\cdot\begin{pmatrix}\underline{U}_0\\ \underline{U}_1\\ \underline{U}_2\end{pmatrix}$$

Fehlerbedingungen:

$$\Delta\underline{I}_0 = 0 \quad \Delta\underline{I}_1 = -\Delta\underline{I}_2 \qquad \underline{U}_1 - \underline{U}_2 = \frac{2}{\underline{A}}\cdot\Delta\underline{I}_1$$

Einphasige Längsunsymmetrie



Maschenanalyse

$$\begin{pmatrix}\Delta\underline{U}_R\\ \Delta\underline{U}_S\\ \Delta\underline{U}_T\end{pmatrix} = \begin{pmatrix}1/\underline{A}&0&0\\0&0&0\\0&0&0\end{pmatrix}\cdot\begin{pmatrix}\underline{I}_R\\ \underline{I}_S\\ \underline{I}_T\end{pmatrix}$$

Transformation

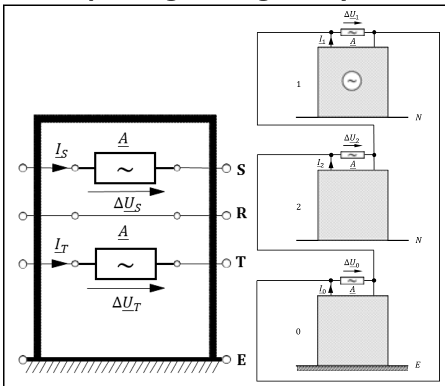
$$\begin{pmatrix}\Delta\underline{U}_0\\ \Delta\underline{U}_1\\ \Delta\underline{U}_2\end{pmatrix} = \boldsymbol{\underline{T}}_{012}\cdot\boldsymbol{\underline{Z}_{RST}}\cdot\boldsymbol{\underline{T}}_{012}^{-1}\cdot\begin{pmatrix}\underline{I}_0\\ \underline{I}_1\\ \underline{I}_2\end{pmatrix} = \frac{1}{3}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}&\underline{a}^2\\1&\underline{a}^2&\underline{a}\end{pmatrix}\cdot\begin{pmatrix}1/\underline{A}&0&0\\0&0&0\\0&0&0\end{pmatrix}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}^2&\underline{a}\\1&\underline{a}&\underline{a}^2\end{pmatrix}\cdot\begin{pmatrix}\underline{I}_0\\ \underline{I}_1\\ \underline{I}_2\end{pmatrix}$$

$$= \frac{1}{3}\cdot\begin{pmatrix}1/\underline{A}&1/\underline{A}&1/\underline{A}\\1/\underline{A}&1/\underline{A}&1/\underline{A}\\1/\underline{A}&1/\underline{A}&1/\underline{A}\end{pmatrix}\cdot\begin{pmatrix}\underline{I}_0\\ \underline{I}_1\\ \underline{I}_2\end{pmatrix}$$

Unsymmetriebedingungen

$$\Delta\underline{U}_0 = \Delta\underline{U}_1 = \Delta\underline{U}_2 \qquad \underline{I}_0 + \underline{I}_1 + \underline{I}_2 = 3\underline{A}\cdot\Delta\underline{U}_1$$

Zweiphasige Längsunsymmetrie



Maschenanalyse

$$\begin{pmatrix}\Delta\underline{U}_R\\ \Delta\underline{U}_S\\ \Delta\underline{U}_T\end{pmatrix} = \begin{pmatrix}0&0&0\\0&1/\underline{A}&0\\0&0&1/\underline{A}\end{pmatrix}\cdot\begin{pmatrix}\underline{I}_R\\ \underline{I}_S\\ \underline{I}_T\end{pmatrix}$$

Transformation

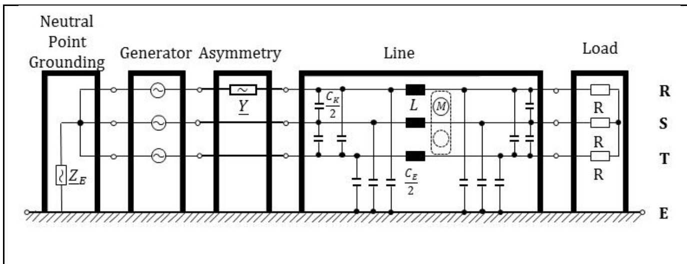
$$\begin{pmatrix}\Delta\underline{U}_0\\ \Delta\underline{U}_1\\ \Delta\underline{U}_2\end{pmatrix} = \boldsymbol{\underline{T}}_{012}\cdot\boldsymbol{\underline{Z}_{RST}}\cdot\boldsymbol{\underline{T}}_{012}^{-1}\cdot\begin{pmatrix}\underline{I}_0\\ \underline{I}_1\\ \underline{I}_2\end{pmatrix} = \frac{1}{3}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}&\underline{a}^2\\1&\underline{a}^2&\underline{a}\end{pmatrix}\cdot\begin{pmatrix}0&0&0\\0&1/\underline{A}&0\\0&0&1/\underline{A}\end{pmatrix}\cdot\begin{pmatrix}1&1&1\\1&\underline{a}^2&\underline{a}\\1&\underline{a}&\underline{a}^2\end{pmatrix}\cdot\begin{pmatrix}\underline{I}_0\\ \underline{I}_1\\ \underline{I}_2\end{pmatrix}$$

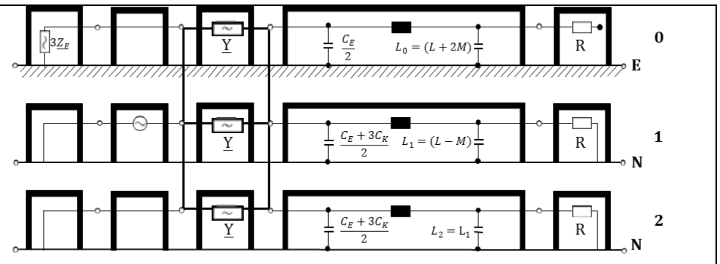
$$= \frac{1}{3}\cdot\begin{pmatrix}2/\underline{A}&-1/\underline{A}&-1/\underline{A}\\-1/\underline{A}&2/\underline{A}&-1/\underline{A}\\-1/\underline{A}&-1/\underline{A}&2/\underline{A}\end{pmatrix}\cdot\begin{pmatrix}\underline{I}_0\\ \underline{I}_1\\ \underline{I}_2\end{pmatrix}$$

Fehlerbedingungen

$$\Delta\underline{U}_0 + \Delta\underline{U}_1 + \Delta\underline{U}_2 = 0 \qquad \underline{I}_0 - \underline{A}\cdot\Delta\underline{U}_0 = \underline{I}_1 - \underline{A}\cdot\Delta\underline{U}_1 = \underline{I}_2 - \underline{A}\cdot\Delta\underline{U}_2$$

Beispiel



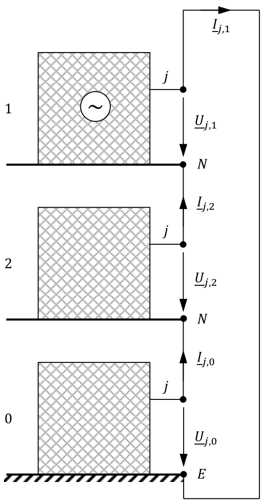
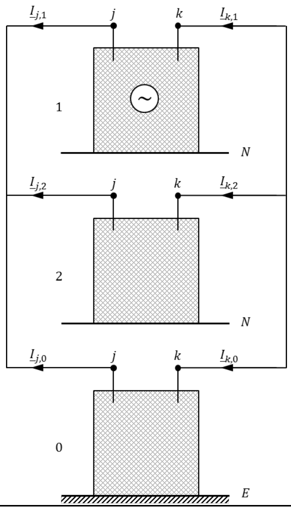
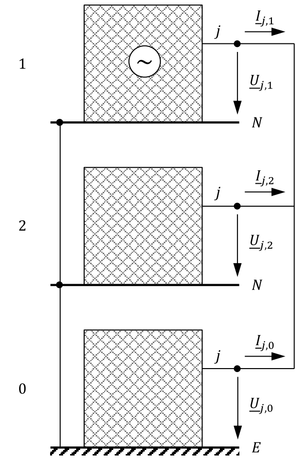
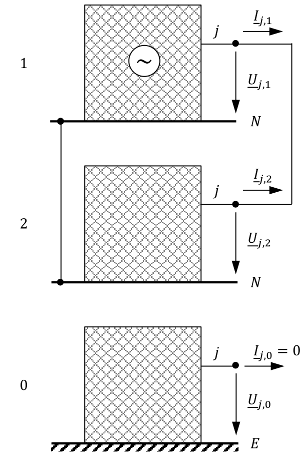


Unsymmetrische Kurzschlussberechnung

Vereinfachungen:

- Vernachlässigung der Querglieder aller Zweige in direkt geerdeten Netzen
- Stufensteller in Mittelstellung
- Vernachlässigung von Wirkwiderständen bei $R_k/X_k \leq 0{,}3$ (Gilt nicht im NS-Netz)
- Einheitliche Polradspannung $E'' = c \cdot U_n/\sqrt{3}$
- Verbraucher bleiben unberücksichtigt, Ausnahme große motorische. Beitrag von Async.M. zu $\underline{I}_k''$ darf vernachlässigt werden, wenn Beitrag nicht >5%

Kurzschlüsse (Doppelerdschluss – Skript)

Einpoliger Erd(kurz)schluss	**Einpolige Kurzunterbrechung**	**Zweipoliger Kurzschluss mit Erdberührung**	**Zweipoliger Kurzschluss ohne Erdberührung**
			
$\underline{U}_r = 0$ $\underline{I}_r = \underline{I}_s = 0$	$\underline{U}_s = 0$ $\underline{U}_t = 0$ $\underline{I}_r = 0$	$\underline{U}_s = 0$ $\underline{U}_t = 0$ $\underline{I}_r = 0$	$\underline{U}_b - \underline{U}_c = 0$ $\underline{I}_r = 0$ $\underline{I}_s + \underline{I}_t = 0$
$\underline{U}_1 + \underline{U}_2 + \underline{U}_0 = 0$ $\underline{I}_2 = \underline{I}_1$ $\underline{I}_0 = \underline{I}_2$	$\underline{U}_2 = \underline{U}_1$ $\underline{U}_0 = \underline{U}_2$ $\underline{I}_1 + \underline{I}_2 + \underline{I}_0 = 0$	$\underline{U}_2 = \underline{U}_1$ $\underline{U}_0 = \underline{U}_2$ $\underline{I}_1 + \underline{I}_2 + \underline{I}_0 = 0$	$\underline{U}_2 = \underline{U}_1$ $\underline{I}_1 + \underline{I}_2 = 0$ $\underline{I}_0 = 0$

Zusammenfassung

$$\underline{I}_{k1}'' = \frac{3}{\underline{Z}_{j,0} + \underline{Z}_{j,1} + \underline{Z}_{j,2}} \cdot \underline{E}_{j,L}$$

$$\underline{I}_{kE2E}'' = -\frac{3 \cdot \underline{Z}_{j,2}}{\underline{Z}_{j,0} \cdot \underline{Z}_{j,1} + \underline{Z}_{j,0} \cdot \underline{Z}_{j,2} + \underline{Z}_{j,1} \cdot \underline{Z}_{j,2}} \cdot \underline{E}_{j,L}$$

$$\underline{I}_{k2}'' = \frac{-j\sqrt{3}}{\underline{Z}_{j,1} + \underline{Z}_{j,2}} \cdot \underline{E}_{j,L}$$

Generatorferne Kurzschlüsse

$$\underline{I}_{k1}'' : \underline{I}_{kE2E}'' : \underline{I}_{k2}'' : \underline{I}_{k3}'' \approx \frac{3}{|2 + \underline{Z}_{j,0}/\underline{Z}_{j,1}|} : \frac{3}{|1 + 2\underline{Z}_{j,0}/\underline{Z}_{j,1}|} : \frac{\sqrt{3}}{2} : 1$$

3 Pol. KS: $\underline{I}_{k3}'' = \frac{1}{\underline{Z}_{j,1}} \cdot \underline{E}_{j,L}$

Leistung: $\left(\underline{U}_B = \frac{U_b}{\sqrt{3}}\right)$

$$S = \sqrt{P^2 + Q^2} = \underline{U} * \underline{I}^* = P + jQ$$

$$P = S\ \cos\varphi$$

$$Q = \sin\varphi = P * \tan\varphi$$

$$\cos\varphi = \frac{P}{S} \qquad \sin\varphi\ \frac{Q}{S}$$

$$\underline{S}_{RST} = 3 * \underline{S}_{012}$$

$$\underline{Z} = R \pm jX$$

+ind. –kap.

$$\underline{Z} = \frac{U^2}{S} e^{j\varphi}$$

$$\varphi = \tan^{-1}\frac{Q}{P}$$

$$R_L = \frac{U_b^2}{P_L}$$

$$X_L = 3\frac{U_b^2}{Q} = \frac{R_v}{\tan\cos^{-1}\varphi}$$

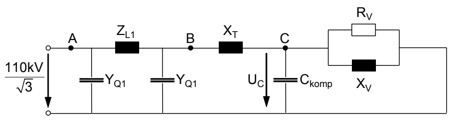
$$P_L = \sqrt{3}U_b I_b = \sqrt{3}U_b\frac{\frac{U_b}{\sqrt{3}}}{R_L} = \frac{U_b^2}{R_L}$$

Kompensation:

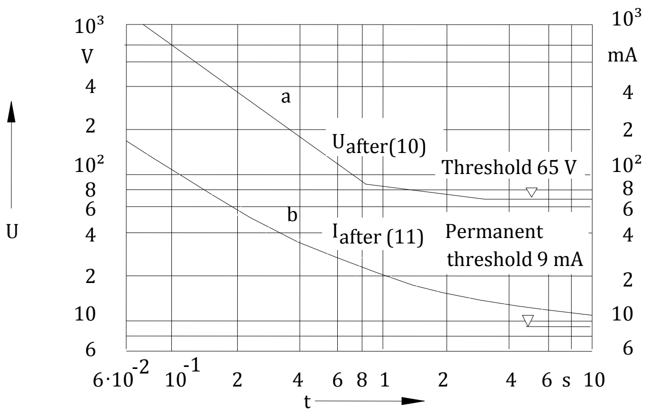
$$\cos\varphi_{komp} = \frac{P_V}{S_V} = \frac{P_V}{\sqrt{P_V^2 + (Q_V - Q_{komp})^2}} = \frac{\frac{3\cdot U_C^2}{R_V}}{\sqrt{\left(\frac{3\cdot U_C^2}{R_V}\right)^2 + \left(\frac{3\cdot U_C^2}{X_V} - 3\cdot U_C^2\cdot\omega\cdot C_{komp}\right)^2}} = \frac{1}{\sqrt{1 + R_V^2\cdot\left(\frac{1}{X_V} - \omega\cdot C_{komp}\right)^2}}$$

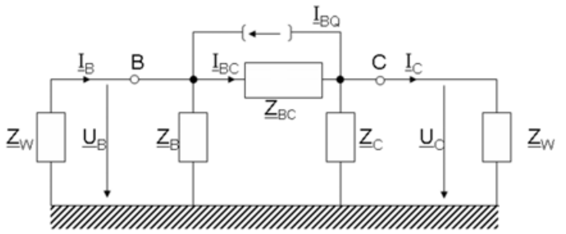
$$Q_{komp} = Q_V$$

$$\omega\cdot C_{komp} = \frac{1}{X_V}$$

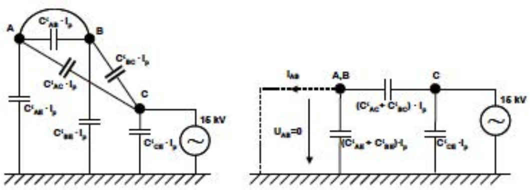


$$C_{komp} = \frac{1}{\omega\cdot X_V} = 149{,}2\ \mu F$$





$$\underline{Z}_P = \frac{\underline{Z}_B \underline{Z}_W}{\underline{Z}_B + \underline{Z}_W} \quad \underline{U}_B = \frac{\underline{Z}_{BC}}{\underline{Z}_{BC} + 2\underline{Z}_P}\cdot \underline{I}_{BQ}\cdot \underline{Z}_P \quad \underline{U}_{B,neu} = \underline{I}_{BQ}\frac{\underline{Z}_{BC}\underline{Z}_B}{\underline{Z}_{BC} + \underline{Z}_B} =$$



Berührungsspannung:

$$U_{AB} = \frac{(C'_{AC} + C'_{BC})\cdot l_p}{[(C'_{AC} + C'_{BC}) + (C'_{AE} + C'_{BE})]\cdot l_p}\cdot U_C \quad \text{(Spannungsteiler)}$$

$$U_{AB} = \frac{(0{,}18 + 0{,}29)\frac{nF}{km}}{[(0{,}18+0{,}29)+(5{,}34+5{,}24)]\frac{nF}{km}}\cdot 15kV = 638{,}01\,V$$

Berührungsstrom: $U_{A,B} = 0$

$$I_{AB} = U_C\cdot\omega\cdot(C'_{AC} + C'_{BC})\cdot l_p = 15\,kV\cdot 2\pi\cdot 16\tfrac{2}{3}Hz\cdot(0{,}18+0{,}29)\tfrac{nF}{km}\cdot 20km = 14{,}76mA > 9mA$$

$\Rightarrow$ maximal zulässiger Berührungsstrom überschritten

$$\begin{pmatrix}\Delta\underline{U}'_{ES}\\ \Delta\underline{U}'_K\end{pmatrix} = \begin{pmatrix}\underline{Z}'_{ES,V} & \underline{Z}'_{ES,ES} & \underline{Z}'_{ES,K}\\ \underline{Z}'_{K,V} & \underline{Z}'_{K,ES} & \underline{Z}'_{K,K}\end{pmatrix}\cdot\begin{pmatrix}\underline{I}_V\\ \underline{I}_{ES}\\ \underline{I}_K\end{pmatrix}$$

mit Kompensationsleiter:

$$\underline{Z}'_{ES,V}\cdot\underline{I}_V + \underline{Z}'_{ES,ES}\cdot\underline{I}_{ES_{mit}} + \underline{Z}'_{ES,K}\cdot\underline{I}_K \overset{!}{=} 0$$

$$\underline{Z}'_{K,V}\cdot\underline{I}_V + \underline{Z}'_{K,ES}\cdot\underline{I}_{ES_{mit}} + \underline{Z}'_{K,K}\cdot\underline{I}_K \overset{!}{=} 0$$

$$\Rightarrow \quad \underline{I}_K = \underline{I}_V\cdot\frac{\underline{Z}'_{K,V}\cdot\underline{Z}'_{ES,ES} - \underline{Z}'_{K,ES}\cdot\underline{Z}'_{ES,V}}{\underline{Z}'^{2}_{ES,K} + \underline{Z}'^{2}_{ES,ES}}$$

$$\underline{I}_{ES_{mit}} = -\frac{\underline{Z}'_{ES,V}\cdot\underline{I}_V + \underline{Z}'_{ES,K}\cdot\underline{I}_K}{\underline{Z}'_{ES,ES}} = -2{,}2$$

Ohne Kompensationsleiter:

$$\underline{Z}'_{ES,V}\cdot\underline{I}_V + \underline{Z}'_{ES,ES}\cdot\underline{I}_{ES_{ohne}} \overset{!}{=} 0$$

$$\Rightarrow \quad \underline{I}_{ES_{ohne}} = -\underline{I}_V\cdot\frac{\underline{Z}'_{ES,V}}{\underline{Z}'_{ES,ES}} = -$$

Beeinflussung - Kapazitive

$$\begin{pmatrix} \vec{Q}'_V \\ \vec{Q}'_B \end{pmatrix} = \begin{pmatrix} \boldsymbol{C'_{V,V}} & \boldsymbol{C'_{V,B}} \\ \boldsymbol{C'_{B,V}} & \boldsymbol{C'_{B,B}} \end{pmatrix} \cdot \begin{pmatrix} \vec{\underline{U}}_V \\ \vec{\underline{U}}_B \end{pmatrix} \quad \vec{Q} = C' * \vec{U}$$

$$\begin{pmatrix} \Delta\vec{\underline{I}}'_V \\ \Delta\vec{\underline{I}}'_B \end{pmatrix} = j\omega \cdot \begin{pmatrix} \boldsymbol{C'_{V,V}} & \boldsymbol{C'_{V,B}} \\ \boldsymbol{C'_{B,V}} & \boldsymbol{C'_{B,B}} \end{pmatrix} \cdot \begin{pmatrix} \vec{\underline{U}}_V \\ \vec{\underline{U}}_B \end{pmatrix}$$

$$\vec{I}' = jw\, C'\vec{U} = jwQ$$

$$\begin{pmatrix} \vec{\underline{U}}'_V \\ \vec{\underline{U}}'_B \end{pmatrix} = \begin{pmatrix} \boldsymbol{P'_{V,V}} & \boldsymbol{P'_{V,B}} \\ \boldsymbol{P'_{B,V}} & \boldsymbol{P'_{B,B}} \end{pmatrix} \cdot \begin{pmatrix} \vec{\underline{Q}}_V \\ \vec{\underline{Q}}_B \end{pmatrix} \quad \vec{U} = \underline{P} * \vec{Q}$$

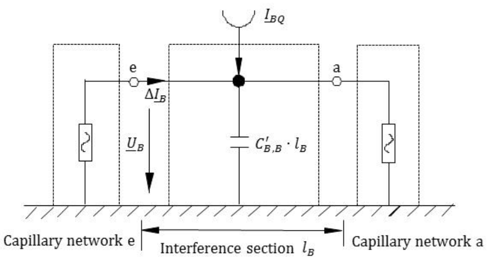
$\boldsymbol{C'_{V,B}} = \mathbf{0} \rightarrow \vec{\underline{I}}'_{BQ} = -j\omega \cdot \boldsymbol{C'_{B,V}} \cdot \vec{\underline{U}}_V \rightarrow \Delta\vec{\underline{I}}'_B + \vec{\underline{I}}'_{BQ} = j\omega \cdot \boldsymbol{C'_{B,B}} \cdot \vec{\underline{U}}_B$

-Isolierter Leiter $\Delta\vec{\underline{I}}'_B = \vec{0}$ → längenunabhängige Berührungsspannung: $\vec{\underline{U}}_B = -\boldsymbol{C'_{B,B}}^{-1} \cdot \boldsymbol{C'_{B,V}} \cdot \vec{\underline{U}}_V$

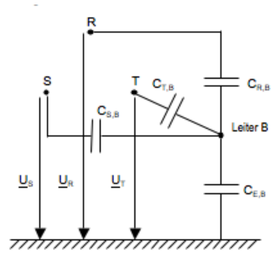
-widerstandslose Erdung ($\vec{\underline{U}}_B = \vec{0}$) längenproportionaler Quellenstrom: $\overrightarrow{\Delta \underline{I}'_B} = -\vec{\underline{I}}'_{BQ} = j\omega \cdot \boldsymbol{C'_{B,V}} \cdot \vec{\underline{U}}_V$

Mehrfachbeeinflussung:

$$\vec{\underline{I}}'_{BQ} \cdot l_B = \sum_{i=1}^{m} \vec{\underline{I}}'_{BQ,i} \cdot l_{B,i} = -j\omega \cdot \sum_{i=1}^{m} \boldsymbol{C'_{B,V,i}} \cdot \vec{\underline{U}}_V \cdot l_{B,i} = \vec{\underline{I}}_{BQ}$$



$C_{R,B} = -\ell_B \bullet c'_{RB}$ (Negative)



Berührungsstrom:

$$I_B = \omega \bullet \left| \sum_{i=R,S,T} C_{i,B} \bullet \underline{U}_i \right| = 2\pi \bullet f \bullet \left| \left(C_{R,B} + C_{S,B} \bullet \underline{a}^2 + C_{T,B} \bullet \underline{a} \right) \right| \bullet \frac{U_N}{\sqrt{3}}$$

$$I_B = 2\pi \bullet 50 \frac{1}{s} \bullet \sqrt{(1{,}4\,nF - 0{,}5 \bullet (1{,}0\,nF + 1{,}6\,nF))^2 + 0{,}5 \bullet \sqrt{3} \bullet (1{,}0\,nF - 1{,}6\,nF)^2} \bullet \frac{110kV}{\sqrt{3}}$$

Berührungsspannung:

$$U_B = \frac{\omega\ell \bullet \left| \sum_{i=R,S,T} C'_{i,B} \bullet \underline{U}_i \right|}{\omega\ell \bullet c'_{BB}} = \frac{-\left| \sum_{i=R,S,T} C'_{B,i} \bullet \underline{U}_i \right|}{c'_{BB}} = \frac{I_B}{\omega\ell \bullet c'_{BB}}$$

Beeinflussung - Induktive

$$\begin{pmatrix} \overrightarrow{\Delta \underline{U}'_V} \\ \overrightarrow{\Delta \underline{U}'_B} \\ \overrightarrow{\Delta \underline{U}'_{ES}} \end{pmatrix} = \begin{pmatrix} \boldsymbol{\underline{Z}'_{V,V}} & \cancel{\boldsymbol{\underline{Z}'_{V,B}}} & \boldsymbol{\underline{Z}'_{V,ES}} \\ \boldsymbol{\underline{Z}'_{B,V}} & \boldsymbol{\underline{Z}'_{B,B}} & \boldsymbol{\underline{Z}'_{B,ES}} \\ \boldsymbol{\underline{Z}'_{ES,V}} & \cancel{\boldsymbol{\underline{Z}'_{ES,B}}} & \boldsymbol{\underline{Z}'_{ES,ES}} \end{pmatrix} \cdot \begin{pmatrix} \vec{\underline{I}}_V \\ \vec{\underline{I}}_B \\ \vec{\underline{I}}_{ES} \end{pmatrix}$$

$$\vec{\underline{I}}_{ES} = -\boldsymbol{\underline{Z}'_{ES,ES}}^{-1} \cdot \boldsymbol{\underline{Z}'_{ES,V}} \cdot \vec{\underline{I}}_V$$

Induzierte Spannung im beeinflussten Leiter:

$$\vec{\underline{U}}'_{BQ} = \boldsymbol{\underline{Z}'_{B,V}} \cdot \vec{\underline{I}}_V + \boldsymbol{\underline{Z}'_{B,ES}} \cdot \vec{\underline{I}}_{ES}$$

(Leerlaufquellenspannung)

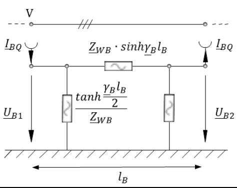
El. Kurze Leitung ohne Verluste($\underline{\gamma}' * l \ll 1$): $\quad Z_{qc} = 1/\underline{Y}_{q,C}$

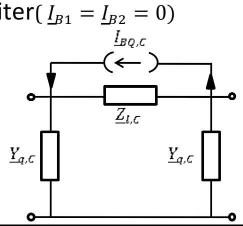
$$Z_L = \underline{Z}_W \sinh(\underline{\gamma}'\, l) = \underline{\gamma}' \cdot \underline{Z}_W * l \qquad Y_q = \frac{\tanh(\underline{\gamma}'\, l)}{\underline{Z}_W} = \frac{\underline{\gamma}'}{\underline{Z}_W} * l$$

Mehrfachbeeinflussung:

$$\underline{I}_{BQ} = \frac{\underline{U}'_{BQ} \cdot dx}{\underline{\gamma}_B \cdot \underline{Z}_{WB} \cdot dx} = \frac{\underline{U}'_{BQ}}{\underline{\gamma}_B \cdot \underline{Z}_{WB}} \quad \text{--} \quad \underline{I}_{BQ} = \frac{\sum Z_{BVi} * I_i}{Z_L}$$ (alle Beeinflussenden Ströme Länsind. Leiter)

Beidseitig isolierter Leiter($\underline{I}_{B1} = \underline{I}_{B2} = 0$)

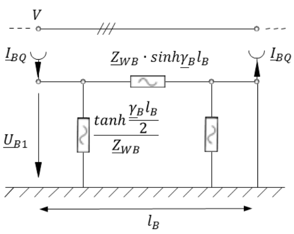




$$\underline{U}_{B1} = -\underline{U}_{B2} = \underline{I}_{BQ} \cdot \underline{Z}_{WB} \frac{\cosh \underline{\gamma}_B l_B - 1}{\sinh \underline{\gamma}_B l_B} = \underline{I}_{BQ} \cdot \underline{Z}_{WB} \cdot \tanh \frac{1}{2} \underline{\gamma}_B l_B$$

Für ($\boldsymbol{\underline{\gamma}_B l_B} \ll 1$) $\underline{U}_{B1} = -\underline{U}_{B2} = \frac{1}{2} \cdot \underline{I}_{BQ} \cdot \underline{Z}_{WB} \cdot \underline{\gamma}_B \cdot l_B = \frac{1}{2} \cdot \underline{U}'_{BQ} \cdot l_B$

Einseitig isolierter/geerdeter Leiter



($\underline{U}_{B2} = 0$ und $\underline{I}_{B1} = 0$)

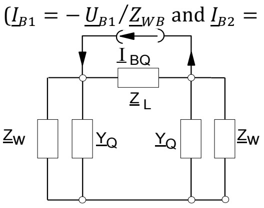
$$\underline{U}_{B1} = \underline{I}_{BQ} \cdot \underline{Z}_{WB} \cdot \tanh \underline{\gamma}_B\, I_B$$

Für el. Kurze Leutung ($\boldsymbol{\gamma_B \cdot l_B \ll 1}$) $\underline{U}_{B1} = \underline{I}_{BQ} \cdot \underline{Z}_{WB} \cdot \underline{\gamma}_B \cdot l_B = \underline{U}'_{BQ} \cdot l_B$

$$\underline{Z}_{l,C} \approx \underline{Z}_w \cdot \underline{\gamma} \cdot l \quad \underline{Y}_{q,C} \approx \frac{1}{2} \cdot \frac{\underline{\gamma} \cdot l}{\underline{Z}_w} \quad Z_{qc} = 1/\underline{Y}_{q,C}$$

Beidseitig unendlich lang fortgesetzter Leiter

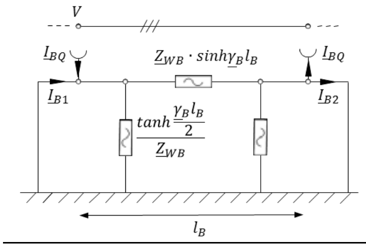
($\underline{I}_{B1} = -\underline{U}_{B1}/\underline{Z}_{WB}$ and $\underline{I}_{B2} = \underline{U}_{B2}/\underline{Z}_{WB}$)



$$\underline{U}_{B1} = -\underline{U}_{B2} = \frac{\underline{I}_{BQ} \cdot \underline{Z}_{WB}}{2} \cdot \left(1 + \sinh \underline{\gamma}_B\, I_B - \cosh \underline{\gamma}_B\, I_B\right) = \frac{\underline{I}_{BQ} \cdot \underline{Z}_{WB}}{2} \cdot \left(1 - e^{-\underline{\gamma}_B l_B}\right)$$

Für el. Lange Leitung ($\boldsymbol{\gamma_B \cdot l_B \gg 1}$) $\underline{U}_{B1} = -\underline{U}_{B2} = \frac{\underline{I}_{BQ} \cdot \underline{Z}_{WB}}{2} = \frac{\underline{U}'_{BQ}}{2 \cdot \underline{\gamma}_B}$

Beidseitig geerdeter Leiter ($\underline{U}_{B1} = \underline{U}_{B2} = 0$)



$$\underline{I}_{B1} = \underline{I}_{B2} = -\underline{I}_{BQ} = -\frac{\underline{U}'_{BQ}}{\underline{\gamma}_B \cdot \underline{Z}_{WB}}$$ (Berührungsstrom unabhängig von der Länge lb)

Reduktionswirkung von Kompensationsleiter:

$$\underline{p} = \frac{\underline{U}'_{BQ}\text{ (with shielding conductor)}}{\underline{U}'_{BQ}\text{ (without shielding conductor or)}} \quad \vec{\underline{U}}'_{BQ,mit} = \left(\underline{\boldsymbol{Z}}'_{\boldsymbol{B,V}} - \underline{\boldsymbol{Z}}'_{\boldsymbol{B,ES}} \cdot \underline{\boldsymbol{Z}}'^{\,-1}_{\boldsymbol{ES,ES}} \cdot \underline{\boldsymbol{Z}}'_{\boldsymbol{ES,V}}\right) \cdot \vec{\underline{I}}_V \quad \vec{\underline{U}}'_{BQ,ohne} = \left(\underline{\boldsymbol{Z}}'_{\boldsymbol{B,V}}\right) \cdot \vec{\underline{I}}_V$$

1Leiter $\underline{p} = 1 - \frac{\underline{Z}'_{B,ES} \cdot \underline{Z}'_{ES,V}}{\underline{Z}'_{B,V} \cdot \underline{Z}'_{ES,ES}}$

nahe Beeinflussung ($\underline{Z}'_{ES,V} \approx \underline{Z}'_{B,V}$):

$$\underline{p} \approx 1 - \frac{\underline{Z}_{B,ES}}{\underline{Z}'_{ES,ES}}$$

nahe Verursachendem($\underline{Z}'_{B,ES} \approx \underline{Z}'_{B,V}$) :

$$\underline{p} \approx 1 - \frac{\underline{Z}_{ES,V}}{\underline{Z}'_{ES,ES}}$$

Bsp.:

Abschnitte: A, E unendlich lange Leitungen
Abschnitte: B, C, D elektrisch kurze Leitungen
Symmetrie: A u. E