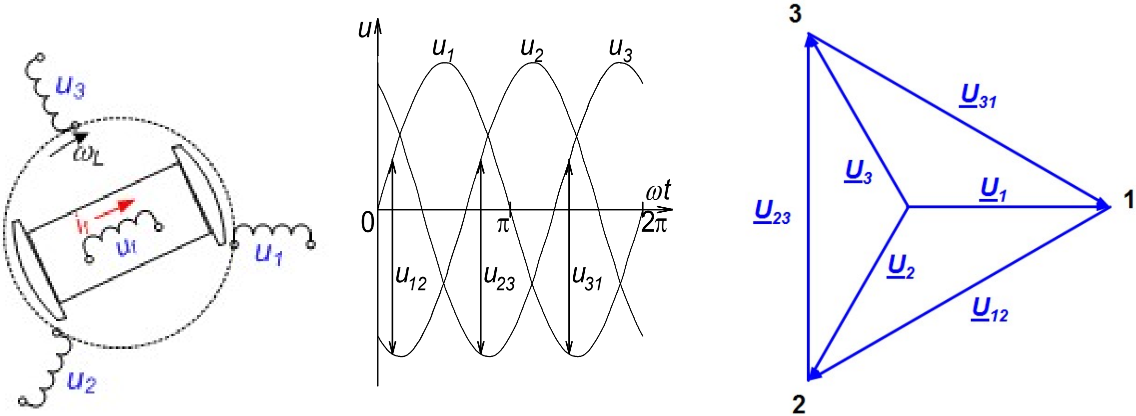

Erzeugung dreiphasiger Wechselspannung

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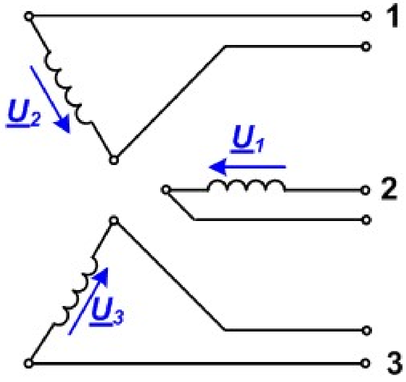
<td>
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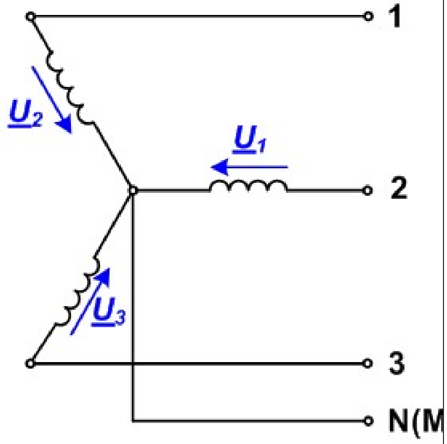
<td>
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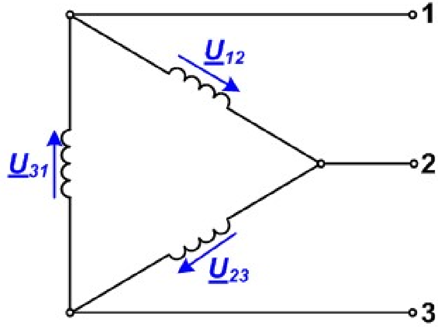
<td>
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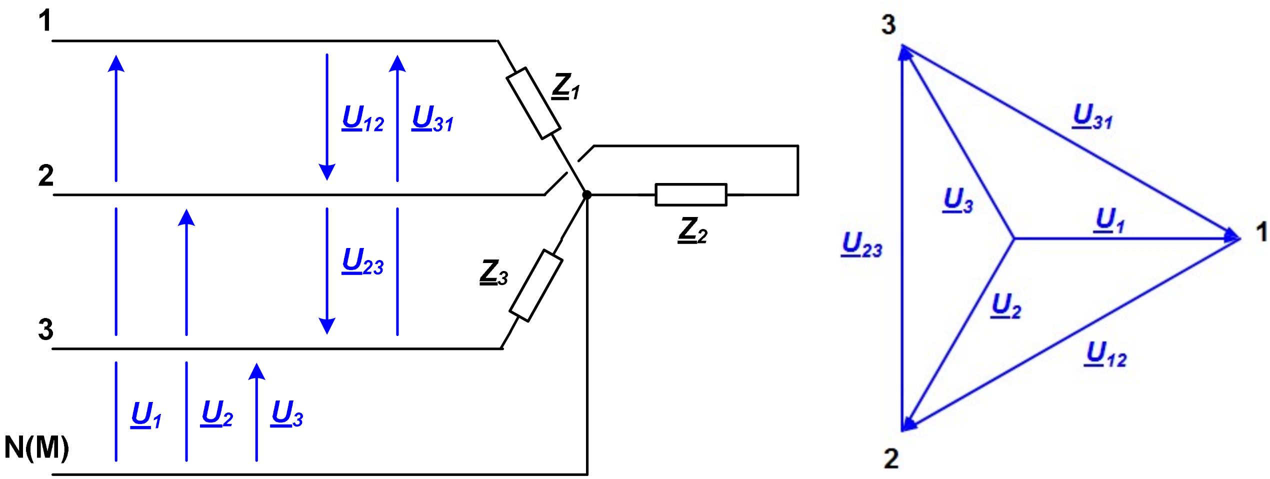
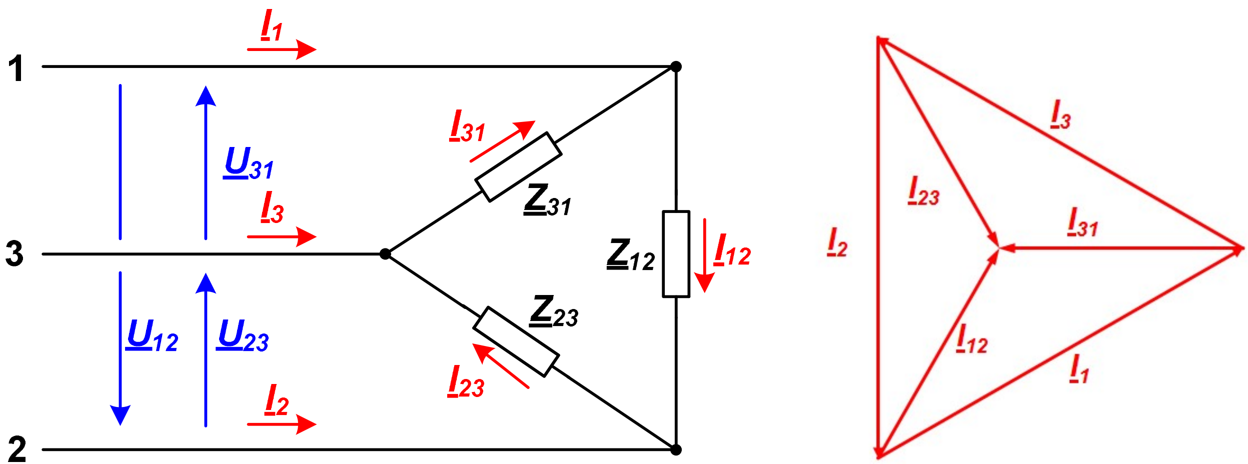
<tr>
<td>offenes</td>
<td colspan="2">verkettetes Dreiphasensystem in</td>
</tr>
<tr>
<td>Dreiphasensystem
(Sechsleitersystem)</td>
<td>Sternschaltung
(Vierleitersystem)</td>
<td>Dreieckschaltung
(Dreileitersystem)</td>
</tr>
</table>

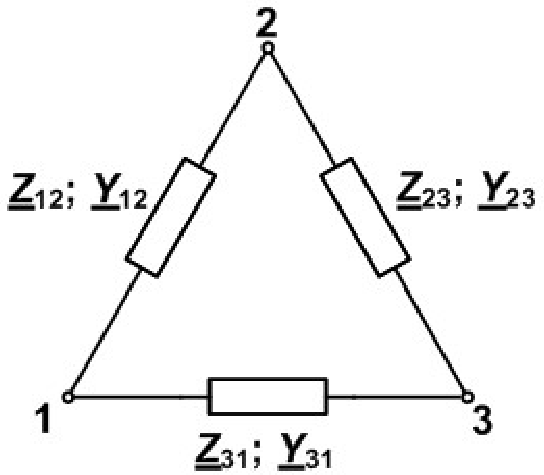
Mehrleitersysteme

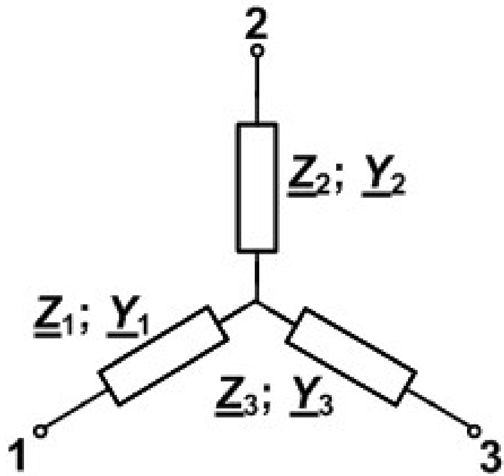


Sternschaltung



Dreieckschaltung

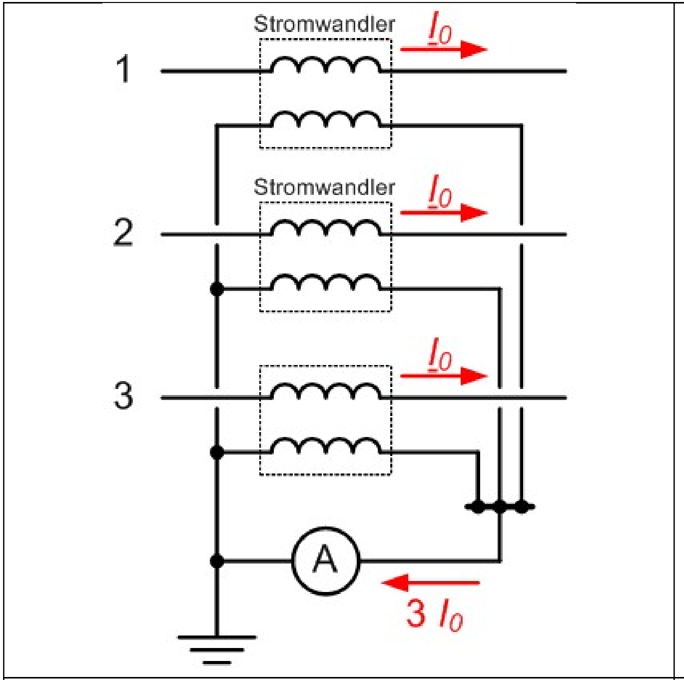
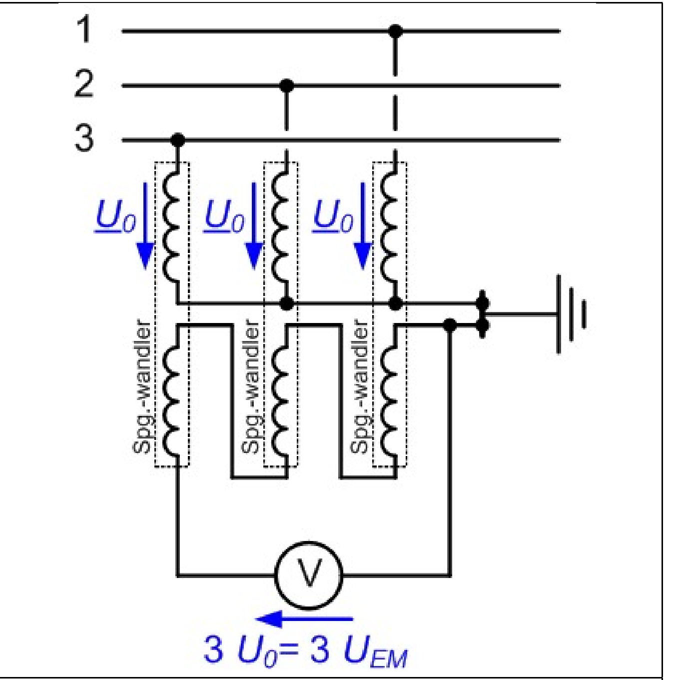




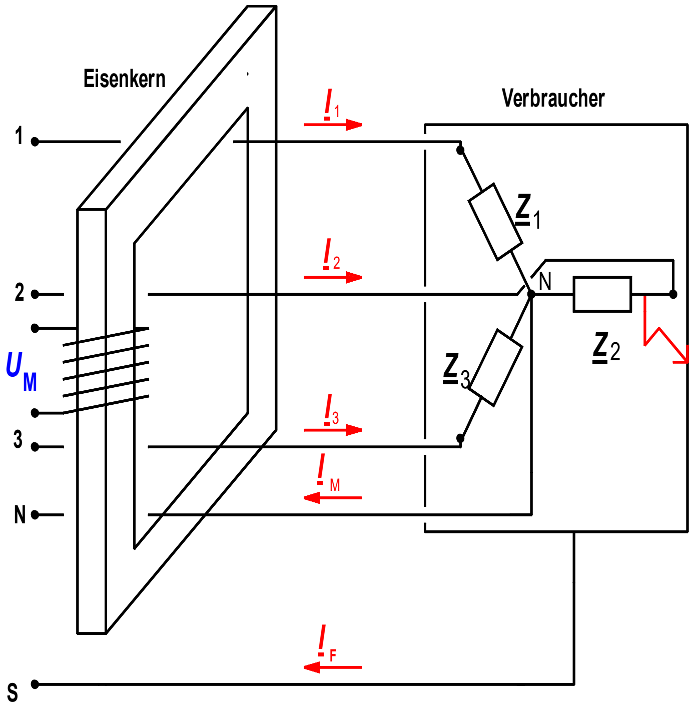
$\underline{\mathbf{Z}}_{12} = \underline{\mathbf{Z}}_1 + \underline{\mathbf{Z}}_2 + \frac{\underline{\mathbf{Z}}_1 \cdot \underline{\mathbf{Z}}_2}{\underline{\mathbf{Z}}_3}$	$\underline{\mathbf{Z}}_1 = \frac{\underline{\mathbf{Z}}_{12} \cdot \underline{\mathbf{Z}}_{13}}{\underline{\mathbf{Z}}_{12} + \underline{\mathbf{Z}}_{23} + \underline{\mathbf{Z}}_{31}}$
$\underline{\mathbf{Y}}_{12} = \frac{\underline{\mathbf{Y}}_1 \cdot \underline{\mathbf{Y}}_2}{\underline{\mathbf{Y}}_1 + \underline{\mathbf{Y}}_2 + \underline{\mathbf{Y}}_3}$	$\underline{\mathbf{Y}}_1 = \underline{\mathbf{Y}}_{21} + \underline{\mathbf{Y}}_{31} + \frac{\underline{\mathbf{Y}}_{12} \cdot \underline{\mathbf{Y}}_{31}}{\underline{\mathbf{Y}}_{32}}$

- weiter mit zyklischer Vertauschung der Indizes

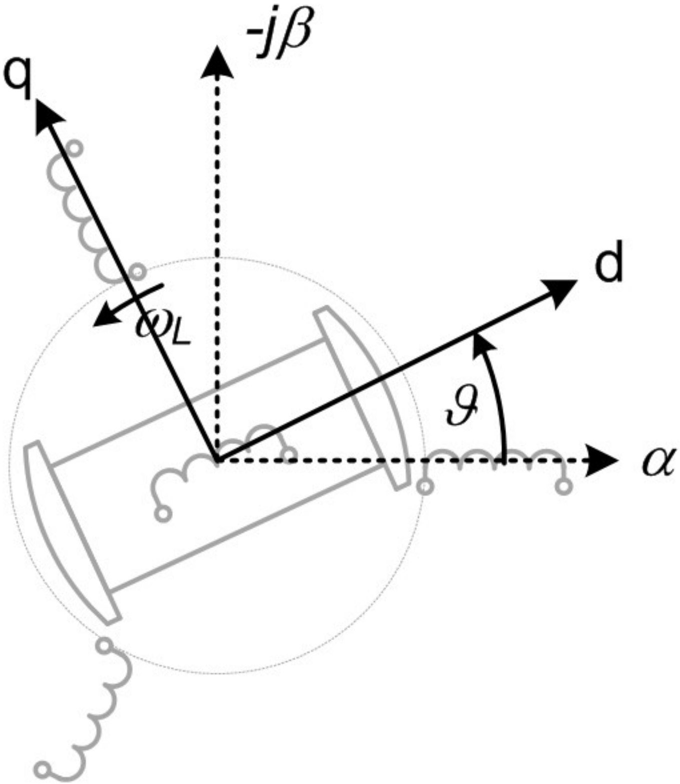
Stern-Dreieck-Umrechnung

	
Nullströmen	**Nullspannungen**

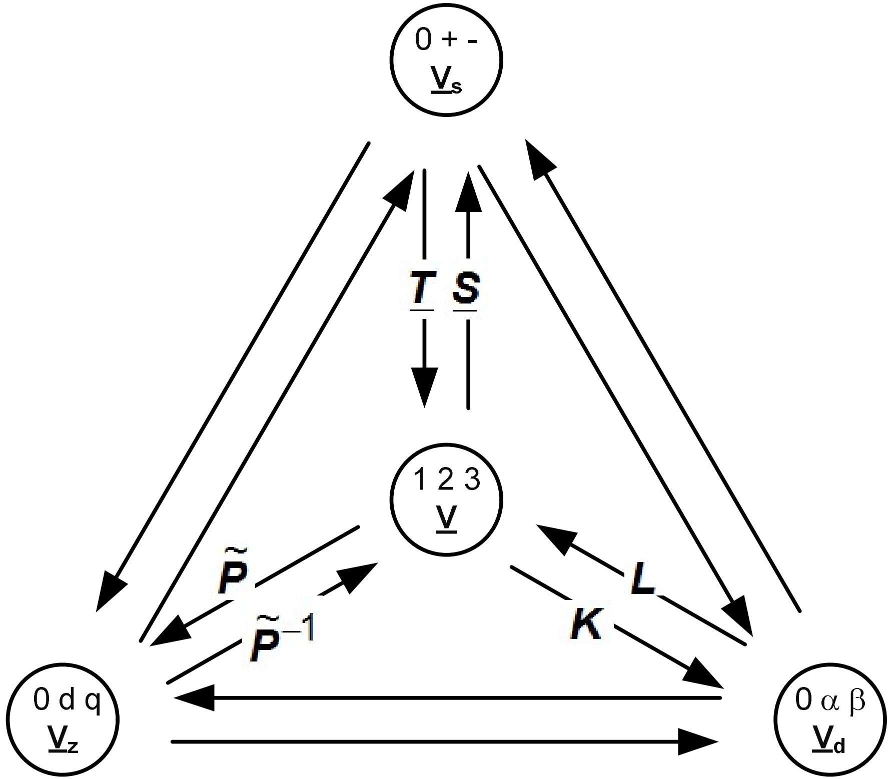
Messung von Nullgrößen



FI-Schutzschaltung - Prinzip



Zweiachsenkomponenten



Umrechnung der Komponentensysteme

$$\begin{pmatrix} \underline{\boldsymbol{U}}_{10} \\ \underline{\boldsymbol{U}}_{1+} \\ \underline{\boldsymbol{U}}_{1-} \end{pmatrix} = \begin{pmatrix} \underline{\boldsymbol{Z}}_{00} & \underline{\boldsymbol{Z}}_{0+} & \underline{\boldsymbol{Z}}_{0-} \\ \underline{\boldsymbol{Z}}_{+0} & \underline{\boldsymbol{Z}}_{++} & \underline{\boldsymbol{Z}}_{+-} \\ \underline{\boldsymbol{Z}}_{-0} & \underline{\boldsymbol{Z}}_{-+} & \underline{\boldsymbol{Z}}_{--} \end{pmatrix} \cdot \begin{pmatrix} \underline{\boldsymbol{I}}_{10} \\ \underline{\boldsymbol{I}}_{1+} \\ \underline{\boldsymbol{I}}_{1-} \end{pmatrix}$$

bzw.

$$\begin{aligned} \underline{\boldsymbol{U}}_{10} &= \underline{\boldsymbol{Z}}_{00} \cdot \underline{\boldsymbol{I}}_{10} + \underline{\boldsymbol{Z}}_{0+} \cdot \underline{\boldsymbol{I}}_{1+} + \underline{\boldsymbol{Z}}_{0-} \cdot \underline{\boldsymbol{I}}_{1-} \\ \underline{\boldsymbol{U}}_{1+} &= \underline{\boldsymbol{Z}}_{+0} \cdot \underline{\boldsymbol{I}}_{10} + \underline{\boldsymbol{Z}}_{++} \cdot \underline{\boldsymbol{I}}_{1+} + \underline{\boldsymbol{Z}}_{+-} \cdot \underline{\boldsymbol{I}}_{1-} \\ \underline{\boldsymbol{U}}_{1-} &= \underline{\boldsymbol{Z}}_{-0} \cdot \underline{\boldsymbol{I}}_{10} + \underline{\boldsymbol{Z}}_{-+} \cdot \underline{\boldsymbol{I}}_{1+} + \underline{\boldsymbol{Z}}_{--} \cdot \underline{\boldsymbol{I}}_{1-} \end{aligned}$$

Der erste Index der Elemente der Matrix der symmetrischen Impedanzen gibt das symmetrische System des Spannungsabfalls an, der zweite das symmetrische System des Stroms, der den Spannungsabfall über der Impedanz verursacht.

Der Spannungsabfall im Nullsystem setzt sich also aus drei Spannungsabfällen zusammen, von denen der erste durch den Strom im Nullsystem, der zweite durch den Strom im Mitsystem und der dritte durch den Strom im Gegensystem bedingt ist. Das gilt analog für die Spannungsabfälle im Mit- und Gegensystem.

Die symmetrischen Selbstimpedanzen verknüpfen Spannungen und Ströme des gleichen symmetrischen Systems. Die symmetrischen gegenseitigen Impedanzen sind Koppelimpedanzen, die Spannungen und Ströme verschiedener symmetrischer Systeme verknüpfen.

Beschreibung der Matrix der symmetrischen Impedanzen

$$\underline{Z}\cdot\underline{T}=\begin{pmatrix}\underline{Z}_1 & 0 & 0\\ 0 & \underline{Z}_2 & 0\\ 0 & 0 & \underline{Z}_3\end{pmatrix}\cdot\begin{pmatrix}1 & 1 & 1\\ 1 & \underline{a}^2 & \underline{a}\\ 1 & \underline{a} & \underline{a}^2\end{pmatrix}=\begin{pmatrix}(\underline{Z}_1\cdot 1+0\cdot 1+0\cdot 1) & (\underline{Z}_1\cdot 1+0\cdot\underline{a}+0\cdot\underline{a}^2) & (\underline{Z}_1\cdot 1+0\cdot\underline{a}+0\cdot\underline{a}^2)\\ (0\cdot 1+\underline{Z}_2\cdot 1+0\cdot 1) & (0\cdot 1+\underline{a}^2\cdot\underline{Z}_2+0\cdot\underline{a}) & (0\cdot 1+\underline{a}\cdot\underline{Z}_2+0\cdot\underline{a}^2)\\ (0\cdot 1+0\cdot 1+\underline{Z}_3 1) & (0\cdot 1+0\cdot\underline{a}^2+\underline{a}\cdot\underline{Z}_3) & (0\cdot 1+0\cdot\underline{a}+\underline{a}^2\cdot\underline{Z}_3)\end{pmatrix}=\begin{pmatrix}\underline{Z}_1 & \underline{Z}_1 & \underline{Z}_1\\ \underline{Z}_2 & \underline{a}^2\cdot\underline{Z}_2 & \underline{a}\cdot\underline{Z}_2\\ \underline{Z}_3 & \underline{a}\cdot\underline{Z}_3 & \underline{a}^2\cdot\underline{Z}_3\end{pmatrix}$$

$$\underline{Z}_S=\underline{S}\cdot(\underline{Z}\cdot\underline{T})=\frac{1}{3}\cdot\begin{pmatrix}1 & 1 & 1\\ 1 & \underline{a} & \underline{a}^2\\ 1 & \underline{a}^2 & \underline{a}\end{pmatrix}\cdot\begin{pmatrix}\underline{Z}_1 & \underline{Z}_1 & \underline{Z}_1\\ \underline{Z}_2 & \underline{a}^2\cdot\underline{Z}_2 & \underline{a}\cdot\underline{Z}_2\\ \underline{Z}_3 & \underline{a}\cdot\underline{Z}_3 & \underline{a}^2\cdot\underline{Z}_3\end{pmatrix}$$

$$\underline{Z}_S=\frac{1}{3}\begin{pmatrix}(\underline{Z}_1+\underline{Z}_2+\underline{Z}_3) & (\underline{Z}_1+\underline{a}^2\cdot\underline{Z}_2+\underline{a}\cdot\underline{Z}_3) & (\underline{Z}_1+\underline{a}\cdot\underline{Z}_2+\underline{a}^2\cdot\underline{Z}_3)\\ (\underline{Z}_1+\underline{a}\cdot\underline{Z}_2+\underline{a}^2\cdot\underline{Z}_3) & (\underline{Z}_1+\underline{Z}_2+\underline{Z}_3) & (\underline{Z}_1+\underline{a}^2\cdot\underline{Z}_2+\underline{a}\cdot\underline{Z}_3)\\ (\underline{Z}_1+\underline{a}^2\cdot\underline{Z}_2+\underline{a}\cdot\underline{Z}_3) & (\underline{Z}_1+\underline{a}\cdot\underline{Z}_2+\underline{a}^2\cdot\underline{Z}_3) & (\underline{Z}_1+\underline{Z}_2+\cdot\underline{Z}_3)\end{pmatrix}=\begin{pmatrix}\underline{Z}_{00} & \underline{Z}_{0+} & \underline{Z}_{0-}\\ \underline{Z}_{+0} & \underline{Z}_{++} & \underline{Z}_{+-}\\ \underline{Z}_{-0} & \underline{Z}_{-+} & \underline{Z}_{--}\end{pmatrix}$$

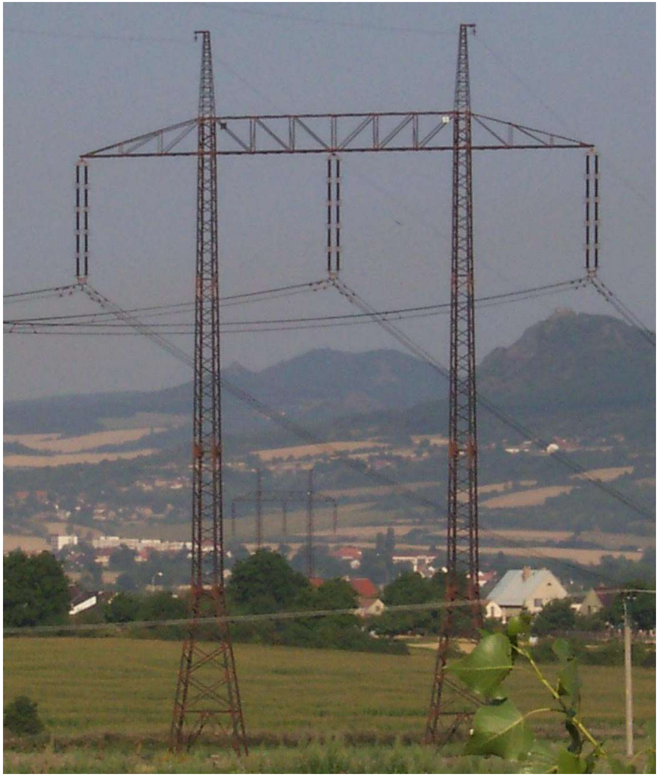
$$\underline{Z}_{00}=\underline{Z}_{++}=\underline{Z}_{--}=\frac{1}{3}(\underline{Z}_1+\underline{Z}_2+\underline{Z}_3)$$

$$\underline{Z}_{0+}=\underline{Z}_{+-}=\underline{Z}_{-0}=\frac{1}{3}\left(\underline{Z}_1+\underline{a}^2\cdot\underline{Z}_2+\underline{a}\cdot\underline{Z}_3\right)$$

$$\underline{Z}_{+0}=\underline{Z}_{-+}=\underline{Z}_{0-}=\frac{1}{3}\left(\underline{Z}_1+\underline{a}\cdot\underline{Z}_2+\underline{a}^2\cdot\underline{Z}_3\right)$$

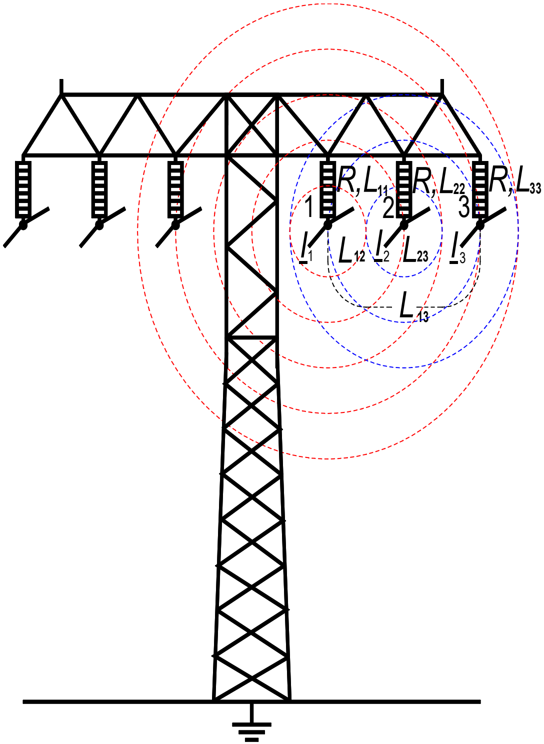
$$\underline{Z}_{0+}\neq\underline{Z}_{+0},\quad \underline{Z}_{+-}\neq\underline{Z}_{-+},\quad \underline{Z}_{0-}\neq\underline{Z}_{-0}$$

Matrix der symmetrischen Impedanzen $\underline{Z}_S=\underline{S}\cdot\underline{Z}\cdot\underline{T}$ für das gegenseitig unabhängige Dreileiter-Impedanzsystem



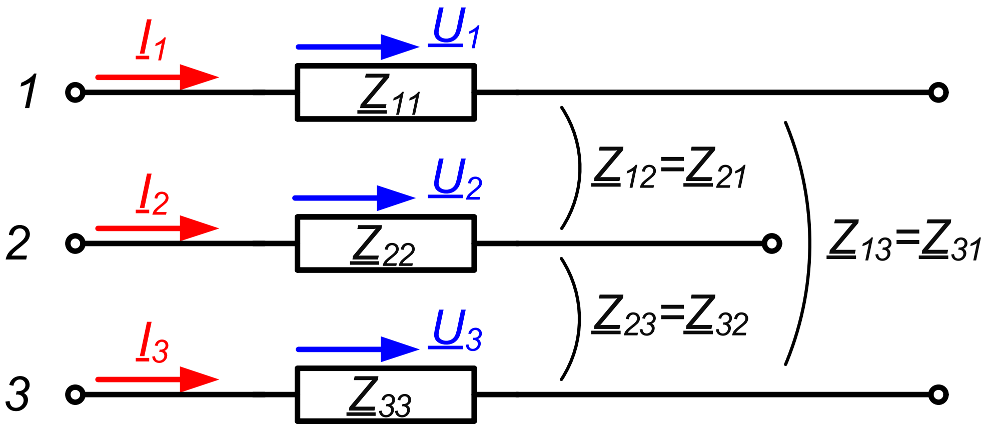
Gegenseitig abhängiges Dreileiter-Impedanzsystem - Beispiel 1

Gegenseitig abhängiges Dreileiter-Impedanzsystem - Beispiel 2



$$\underline{Z}_{11} = R_{11} + j\omega L_{11}$$
$$\underline{Z}_{22} = R_{22} + j\omega L_{22}$$
$$\underline{Z}_{33} = R_{33} + j\omega L_{33}$$
$$\underline{Z}_{12} = \underline{Z}_{21} = j\omega L_{12}$$
$$\underline{Z}_{23} = \underline{Z}_{32} = j\omega L_{23}$$
$$\underline{Z}_{13} = \underline{Z}_{31} = j\omega L_{13}$$

Impedanzsystem - Beispiel



Impedanzsystem - Schaltbild

$$\underline{Z}\cdot\underline{T}=\begin{pmatrix}\underline{Z}_{11} & \underline{Z}_{12} & \underline{Z}_{13}\\ \underline{Z}_{21} & \underline{Z}_{22} & \underline{Z}_{23}\\ \underline{Z}_{31} & \underline{Z}_{32} & \underline{Z}_{33}\end{pmatrix}\cdot\begin{pmatrix}1 & 1 & 1\\ 1 & \underline{a}^2 & \underline{a}\\ 1 & \underline{a} & \underline{a}^2\end{pmatrix}=\begin{pmatrix}(\underline{Z}_{11}+\underline{Z}_{12}+\underline{Z}_{13}) & (\underline{Z}_{11}+\underline{a}^2\cdot\underline{Z}_{12}+\underline{a}\cdot\underline{Z}_{13}) & (\underline{Z}_{11}+\underline{a}\cdot\underline{Z}_{12}+\underline{a}^2\cdot\underline{Z}_{13})\\ (\underline{Z}_{21}+\underline{Z}_{22}+\underline{Z}_{23}) & (\underline{Z}_{21}+\underline{a}^2\cdot\underline{Z}_{22}+\underline{a}\cdot\underline{Z}_{23}) & (\underline{Z}_{21}+\underline{a}\cdot\underline{Z}_{22}+\underline{a}^2\cdot\underline{Z}_{23})\\ (\underline{Z}_{31}+\underline{Z}_{32}+\underline{Z}_{33}) & (\underline{Z}_{31}+\underline{a}^2\cdot\underline{Z}_{32}+\underline{a}\cdot\underline{Z}_{33}) & (\underline{Z}_{31}+\underline{a}\cdot\underline{Z}_{32}+\underline{a}^2\cdot\underline{Z}_{33})\end{pmatrix}$$

$$\underline{Z}_S=\underline{S}\cdot\underline{Z}\cdot\underline{T}=\frac{1}{3}\begin{pmatrix}1 & 1 & 1\\ 1 & \underline{a} & \underline{a}^2\\ 1 & \underline{a}^2 & \underline{a}\end{pmatrix}\cdot\begin{pmatrix}(\underline{Z}_{11}+\underline{Z}_{12}+\underline{Z}_{13}) & (\underline{Z}_{11}+\underline{a}^2\cdot\underline{Z}_{12}+\underline{a}\cdot\underline{Z}_{13}) & (\underline{Z}_{11}+\underline{a}\cdot\underline{Z}_{12}+\underline{a}^2\cdot\underline{Z}_{13})\\ (\underline{Z}_{21}+\underline{Z}_{22}+\underline{Z}_{23}) & (\underline{Z}_{21}+\underline{a}^2\cdot\underline{Z}_{22}+\underline{a}\cdot\underline{Z}_{23}) & (\underline{Z}_{21}+\underline{a}\cdot\underline{Z}_{22}+\underline{a}^2\cdot\underline{Z}_{23})\\ (\underline{Z}_{31}+\underline{Z}_{32}+\underline{Z}_{33}) & (\underline{Z}_{31}+\underline{a}^2\cdot\underline{Z}_{32}+\underline{a}\cdot\underline{Z}_{33}) & (\underline{Z}_{31}+\underline{a}\cdot\underline{Z}_{32}+\underline{a}^2\cdot\underline{Z}_{33})\end{pmatrix}$$

$$\underline{Z}_S=\frac{1}{3}\begin{pmatrix}[(\underline{Z}_{11}+\underline{Z}_{22}+\underline{Z}_{33})+2(\underline{Z}_{12}+\underline{Z}_{23}+\underline{Z}_{31})] & [(\underline{Z}_{11}+\underline{a}^2\cdot\underline{Z}_{22}+\underline{a}\cdot\underline{Z}_{33})-(\underline{Z}_{23}+\underline{a}\cdot\underline{Z}_{12}+\underline{a}^2\cdot\underline{Z}_{31})] & [(\underline{Z}_{11}+\underline{a}\cdot\underline{Z}_{22}+\underline{a}^2\cdot\underline{Z}_{33})-(\underline{Z}_{23}+\underline{a}^2\cdot\underline{Z}_{12}+\underline{a}\cdot\underline{Z}_{31})]\\ [(\underline{Z}_{11}+\underline{a}\cdot\underline{Z}_{22}+\underline{a}^2\underline{Z}_{33})-(\underline{Z}_{23}+\underline{a}^2\cdot\underline{Z}_{12}+\underline{a}\cdot\underline{Z}_{31})] & [(\underline{Z}_{11}+\underline{Z}_{22}+\underline{Z}_{33})-(\underline{Z}_{23}+\underline{Z}_{12}+\underline{Z}_{31})] & [(\underline{Z}_{11}+\underline{a}^2\cdot\underline{Z}_{22}+\underline{a}\cdot\underline{Z}_{33})+2(\underline{Z}_{23}+\underline{a}\cdot\underline{Z}_{12}+\underline{a}^2\cdot\underline{Z}_{31})]\\ [(\underline{Z}_{11}+\underline{a}^2\cdot\underline{Z}_{22}+\underline{a}\cdot\underline{Z}_{33})-(\underline{Z}_{23}+\underline{a}\cdot\underline{Z}_{12}+\underline{a}^2\cdot\underline{Z}_{31})] & [(\underline{Z}_{11}+\underline{a}\cdot\underline{Z}_{22}+\underline{a}^2\cdot\underline{Z}_{33})+2(\underline{Z}_{23}+\underline{a}^2\cdot\underline{Z}_{12}+\underline{a}\cdot\underline{Z}_{31})] & [(\underline{Z}_{11}+\underline{Z}_{22}+\underline{Z}_{33})-(\underline{Z}_{23}+\underline{Z}_{12}+\underline{Z}_{31})]\end{pmatrix}$$

$$\underline{Z}_s=\begin{pmatrix}\underline{Z}_{00} & \underline{Z}_{0+} & \underline{Z}_{0-}\\ \underline{Z}_{+0} & \underline{Z}_{++} & \underline{Z}_{+-}\\ \underline{Z}_{-0} & \underline{Z}_{-+} & \underline{Z}_{--}\end{pmatrix}$$

$$\underline{Z}_{00}=\frac{1}{3}[(\underline{Z}_{11}+\underline{Z}_{22}+\underline{Z}_{33})+2(\underline{Z}_{12}+\underline{Z}_{23}+\underline{Z}_{31})]$$

$$\underline{Z}_{++}=\underline{Z}_{--}=\frac{1}{3}[(\underline{Z}_{11}+\underline{Z}_{22}+\underline{Z}_{33})-(\underline{Z}_{23}+\underline{Z}_{12}+\underline{Z}_{31})]$$

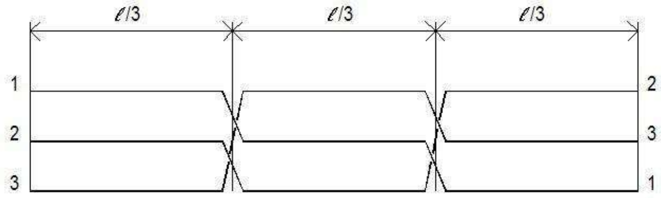
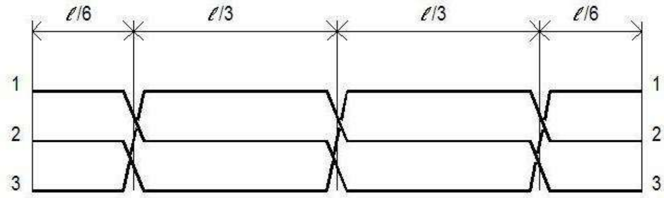
$$\underline{Z}_{0+}=\underline{Z}_{-0}=\frac{1}{3}[(\underline{Z}_{11}+\underline{a}^2\cdot\underline{Z}_{22}+\underline{a}\cdot\underline{Z}_{33})-(\underline{Z}_{23}+\underline{a}\cdot\underline{Z}_{12}+\underline{a}^2\cdot\underline{Z}_{31})]$$

$$\underline{Z}_{0-}=\underline{Z}_{+0}=\frac{1}{3}[(\underline{Z}_{11}+\underline{a}\cdot\underline{Z}_{22}+\underline{a}^2\cdot\underline{Z}_{33})-(\underline{Z}_{23}+\underline{a}^2\cdot\underline{Z}_{12}+\underline{a}\cdot\underline{Z}_{31})]$$

$$\underline{Z}_{+-}=\frac{1}{3}[(\underline{Z}_{11}+\underline{a}^2\cdot\underline{Z}_{22}+\underline{a}\cdot\underline{Z}_{33})+2(\underline{Z}_{23}+\underline{a}\cdot\underline{Z}_{12}+\underline{a}^2\cdot\underline{Z}_{31})]$$

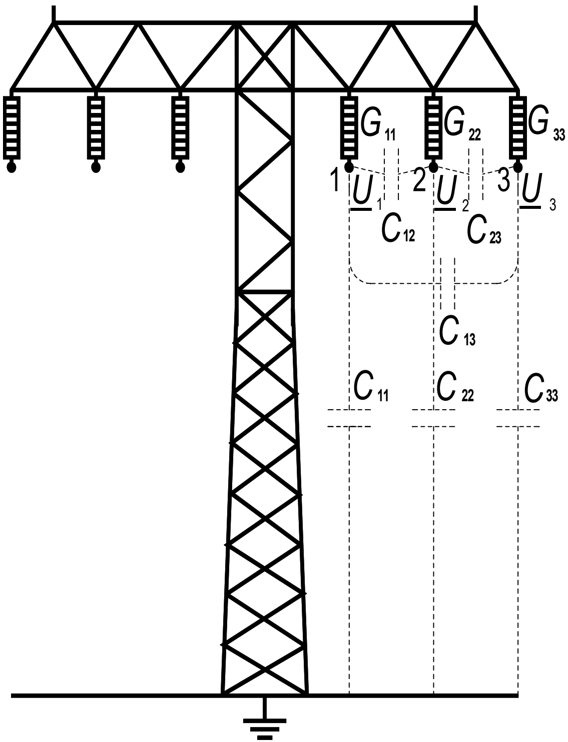
$$\underline{Z}_{-+}=\frac{1}{3}[(\underline{Z}_{11}+\underline{a}\cdot\underline{Z}_{22}+\underline{a}^2\cdot\underline{Z}_{33})+2(\underline{Z}_{23}+\underline{a}^2\cdot\underline{Z}_{12}+\underline{a}\cdot\underline{Z}_{31})]$$

Matrix der symmetrischen Impedanzen $\underline{Z}_S=\underline{S}\cdot\underline{Z}\cdot\underline{T}$ für das gegenseitig abhängige Dreileiter-Impedanzsystem

α_1 -Verdrillung	α_2 -Verdrillung
	

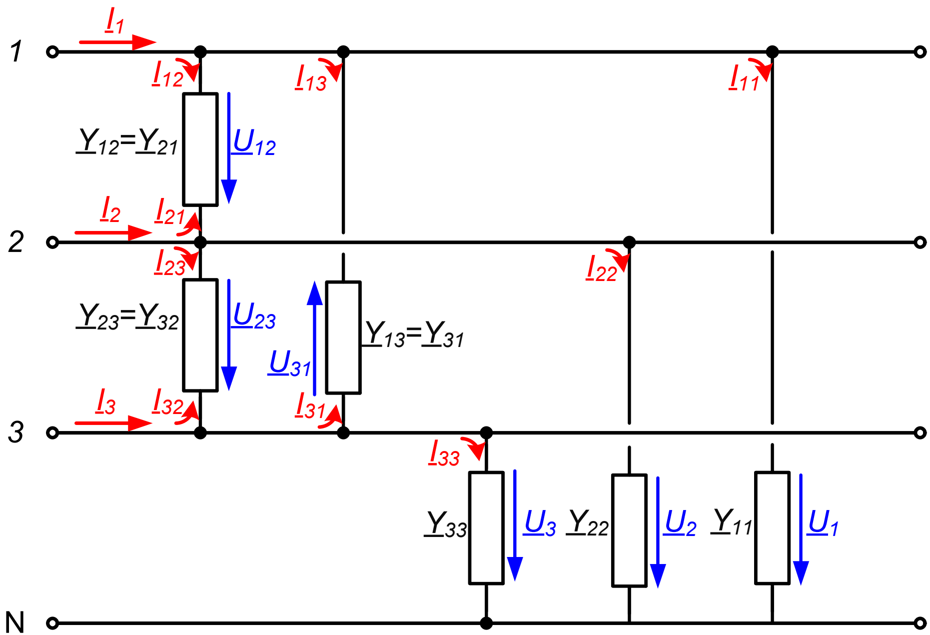
Verdrillung von Freileitungen zur Symmetrierung der Leitungsimpedanzen

Verdrillungsmast



$$\underline{Y}_{11} = (G_{11} +) j\omega\, C_{11}$$
$$\underline{Y}_{22} = (G_{22} +) j\omega\, C_{22}$$
$$\underline{Y}_{33} = (G_{33} +) j\omega\, C_{33}$$
$$\underline{Y}_{12} = \underline{Y}_{21} = j\omega\, C_{12}$$
$$\underline{Y}_{23} = \underline{Y}_{23} = j\omega\, C_{23}$$
$$\underline{Y}_{13} = \underline{Y}_{31} = j\omega\, C_{13}$$

Admittanzsystem - Beispiel



$$\underline{\boldsymbol{I}}_1 = \underline{\boldsymbol{I}}_{11} + \underline{\boldsymbol{I}}_{12} + \underline{\boldsymbol{I}}_{13} = \underline{\boldsymbol{Y}}_{11} \cdot \underline{\boldsymbol{U}}_1 + \underline{\boldsymbol{Y}}_{12} \cdot (\underline{\boldsymbol{U}}_1 - \underline{\boldsymbol{U}}_2) + \underline{\boldsymbol{Y}}_{13} \cdot (\underline{\boldsymbol{U}}_1 - \underline{\boldsymbol{U}}_3)$$

$$\underline{\boldsymbol{I}}_2 = \underline{\boldsymbol{I}}_{21} + \underline{\boldsymbol{I}}_{22} + \underline{\boldsymbol{I}}_{23} = \underline{\boldsymbol{Y}}_{12} \cdot (\underline{\boldsymbol{U}}_2 - \underline{\boldsymbol{U}}_1) + \underline{\boldsymbol{Y}}_{22} \cdot \underline{\boldsymbol{U}}_2 + \underline{\boldsymbol{Y}}_{23} \cdot (\underline{\boldsymbol{U}}_2 - \underline{\boldsymbol{U}}_3)$$

$$\underline{\boldsymbol{I}}_3 = \underline{\boldsymbol{I}}_{31} + \underline{\boldsymbol{I}}_{32} + \underline{\boldsymbol{I}}_{33} = \underline{\boldsymbol{Y}}_{13} \cdot (\underline{\boldsymbol{U}}_3 - \underline{\boldsymbol{U}}_1) + \underline{\boldsymbol{Y}}_{23} \cdot (\underline{\boldsymbol{U}}_3 - \underline{\boldsymbol{U}}_2) + \underline{\boldsymbol{Y}}_{33} \cdot \underline{\boldsymbol{U}}_3$$

Admittanzsystem - Schaltbild