电力系统分析

—第10章— 电力系统故障分析
——不对称短路故障分析

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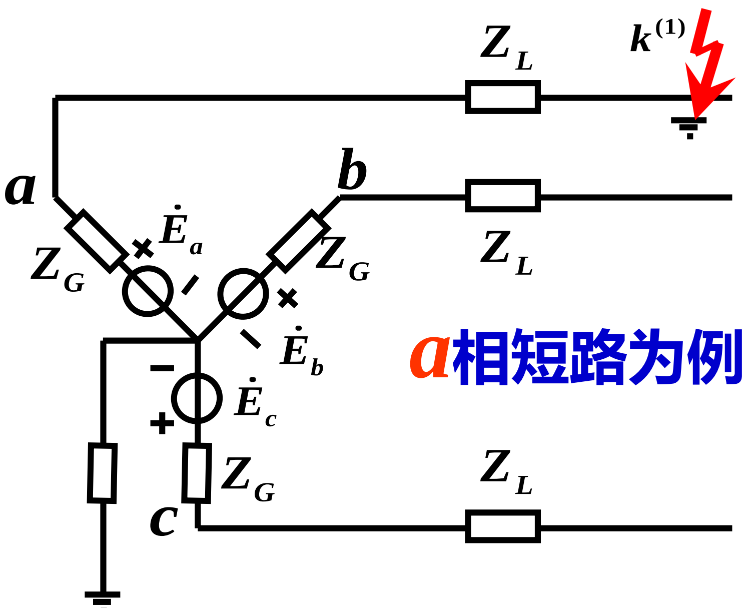
-第10章- 电力系统不对称短路故障分析

-第10.1节- 叠加原理的应用

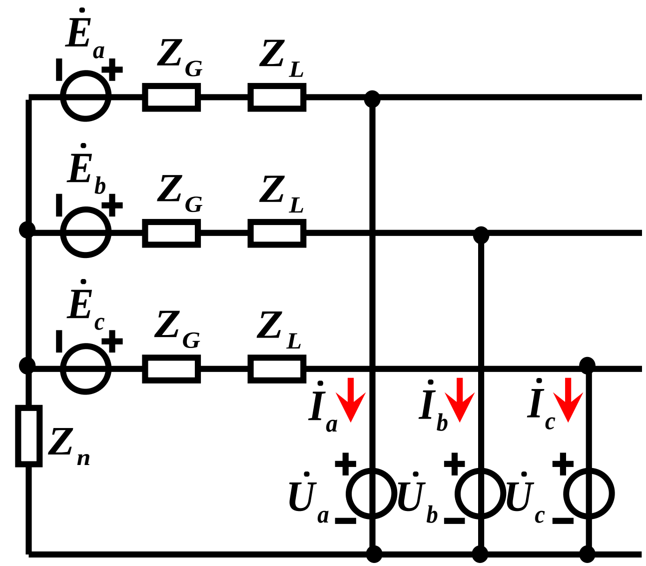
-第10.2节- 不对称短路故障复合序网

-第10.3节- 故障点电流和电压计算

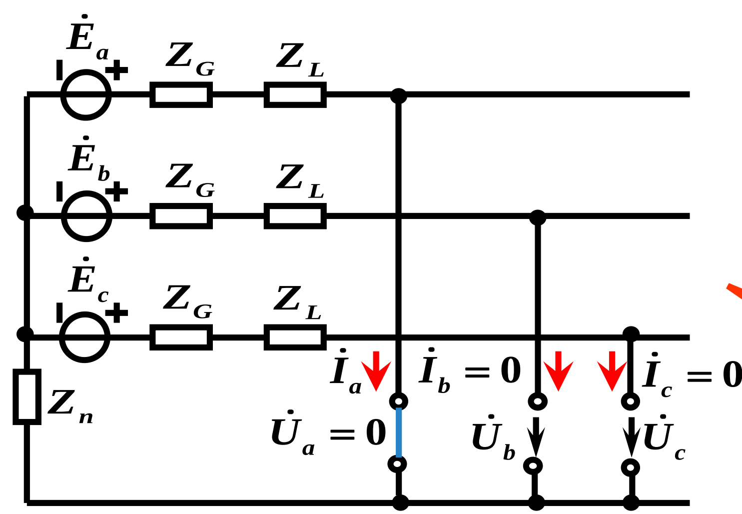
-第10.1节- 叠加原理的应用



a相短路为例



特殊相为a相



故障状态

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-第10.1节- 叠加原理的应用

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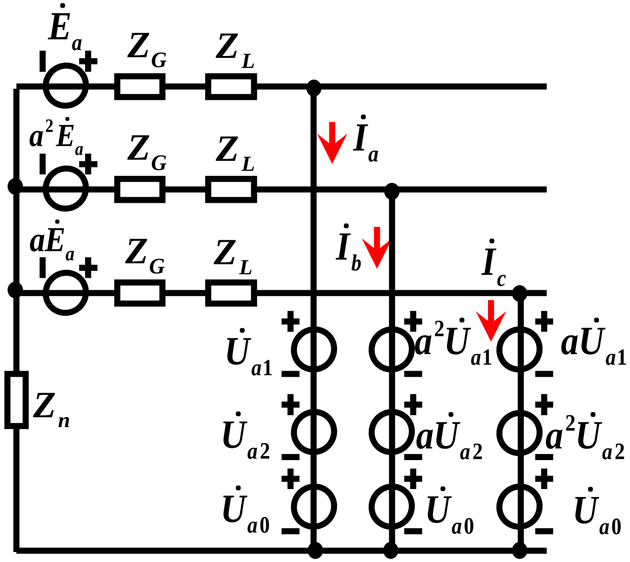

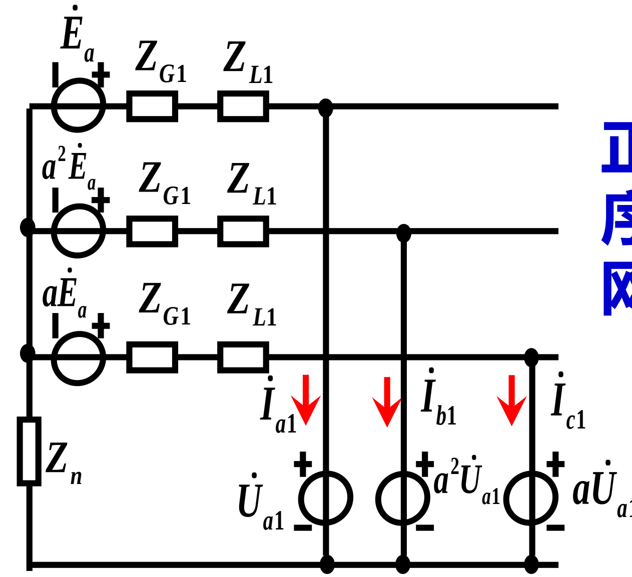

正序网

叠加定理

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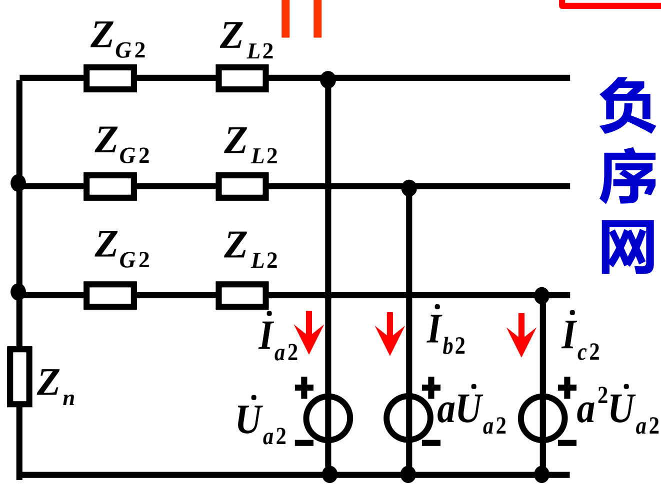

负序网

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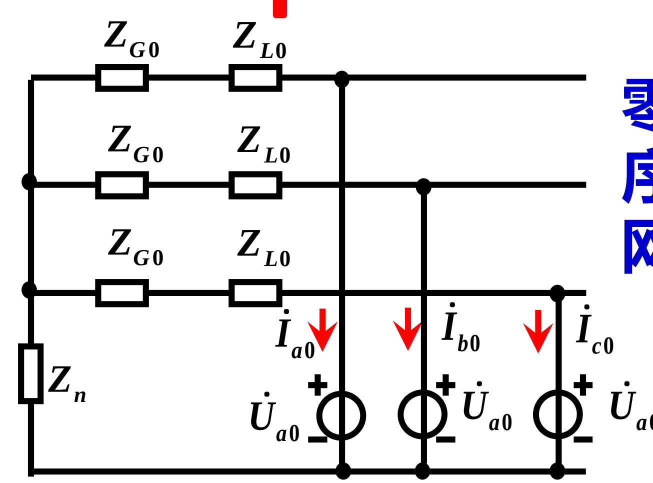
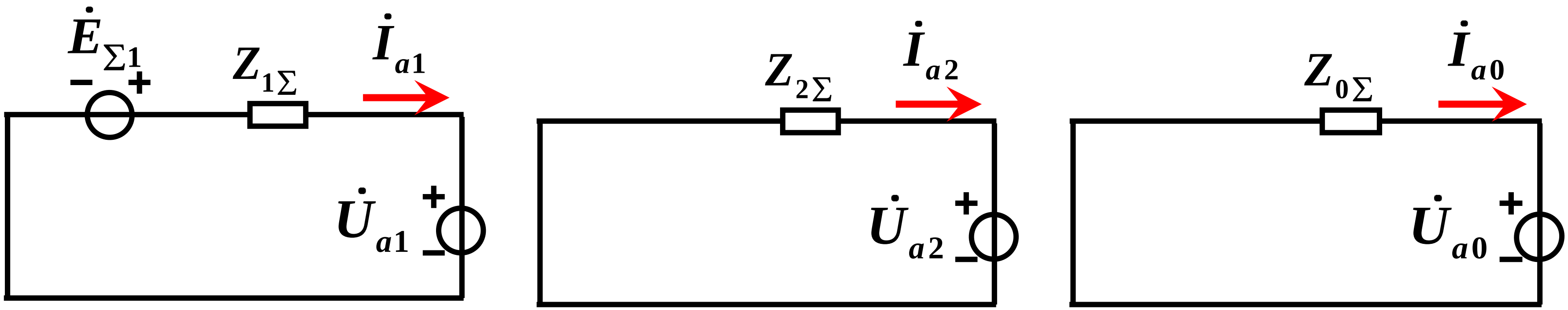


零序网

-第10.1节- 叠加原理的应用

- **各序分量三相对称**：大小、相位关系固定
- 因为三相电路对称，只需给出各序单相电路或序网



- **正序网**
- **负序网**
- **零序网**

- **序网基本方程**

$$\dot{U}_{a1} = \dot{E}_{\Sigma1} - \dot{I}_{a1}Z_{1\Sigma} \qquad \dot{U}_{a2} = -\dot{I}_{a2}Z_{2\Sigma} \qquad \dot{U}_{a0} = -\dot{I}_{a0}Z_{0\Sigma}$$

- **3个方程，6个变量，需补充3个方程。**

-第10.1节- 叠加原理的应用

- **边界条件**
  - **边界条件：短路点处的电压、电流方程**
  - a **相短路：** $\dot{U}_a = 0,\quad \dot{I}_b = 0,\quad \dot{I}_c = 0$
  - b、c **两相短路：** $\dot{U}_b = \dot{U}_c,\quad \dot{I}_a = 0,\quad \dot{I}_b = -\dot{I}_c$
  - b、c **两相接地短路：** $\dot{U}_b = 0,\quad \dot{U}_c = 0,\quad \dot{I}_a = 0$

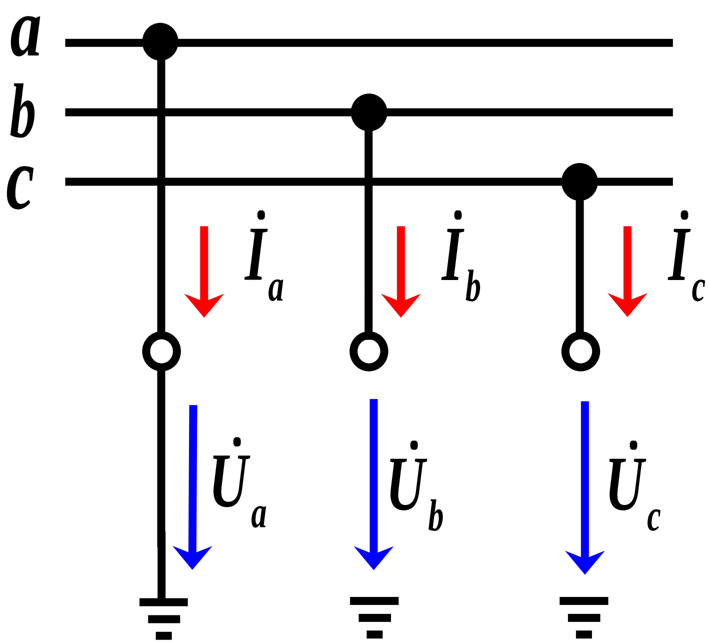
用序分量表示

- **边界条件：故障相的电压、非故障相的电流**

-第10.2节- 不对称短路故障复合序网

➢1. 单相接地短路

- *a* 相接地短路故障的3个边界条件



$$\dot{U}_a = 0,\quad \dot{I}_b = 0,\quad \dot{I}_c = 0$$

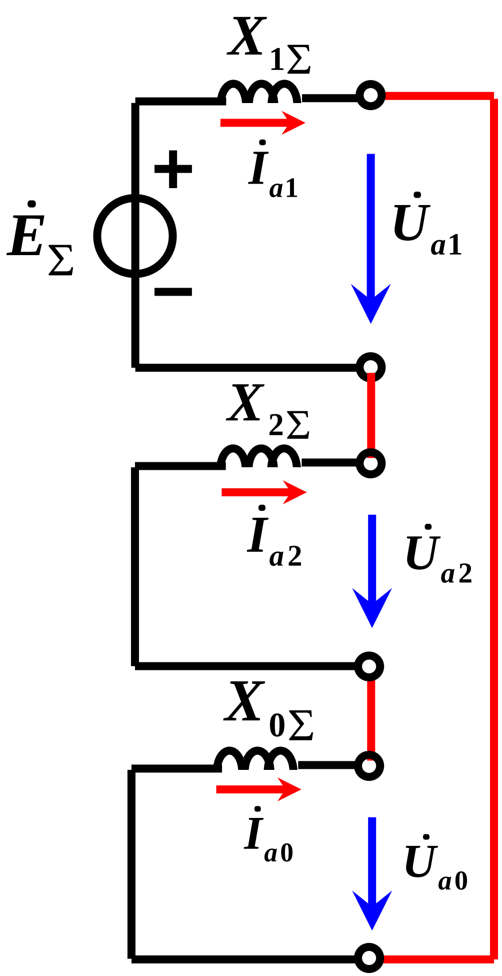
$$\begin{cases} \dot{U}_a = \dot{U}_{a1} + \dot{U}_{a2} + \dot{U}_{a0} = 0 \\ \dot{I}_b = a^2\dot{I}_{a1} + a\dot{I}_{a2} + \dot{I}_{a0} = 0 \\ \dot{I}_c = a\dot{I}_{a1} + a^2\dot{I}_{a2} + \dot{I}_{a0} = 0 \end{cases}$$

$$\left.\begin{aligned} \dot{U}_{a1} + \dot{U}_{a2} + \dot{U}_{a0} = 0 \\ \dot{I}_{a1} = \dot{I}_{a2} = \dot{I}_{a0} \end{aligned}\right\}$$

边界条件

-第10.2节- 不对称短路故障复合序网

• *a* 相接地短路故障的复合序网



$$\begin{cases} \dot{U}_{a1} + \dot{U}_{a2} + \dot{U}_{a0} = 0 \\ \dot{I}_{a1} = \dot{I}_{a2} = \dot{I}_{a0} \end{cases}$$

$$\begin{cases} \dot{I}_{a1} = \dfrac{\dot{E}_{\Sigma}}{j(X_{1\Sigma} + X_{2\Sigma} + X_{0\Sigma})} \\ \dot{I}_{a2} = \dot{I}_{a0} = \dot{I}_{a1} \end{cases}$$

短路点短路前电势

$$\dot{I}_a, \ \dot{I}_b = 0, \ \dot{I}_c = 0$$

• 短路点的短路电流为：

$$\dot{I}_d^{(1)} = \dot{I}_a = \dot{I}_{a1} + \dot{I}_{a2} + \dot{I}_{a0} = 3\dot{I}_{a1}$$

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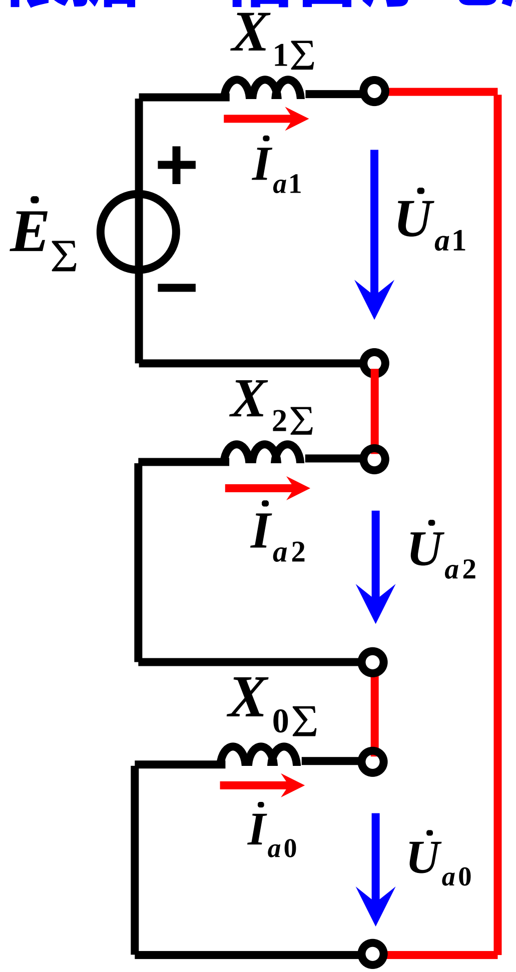
- **根据 *a* 相各序电流求 *a* 相各序电压**



$$\begin{cases}\dot{U}_{a1} = \dot{E}_{\Sigma} - jX_{1\Sigma}\dot{I}_{a1} \\ \dot{U}_{a2} = -jX_{2\Sigma}\dot{I}_{a2} \\ \dot{U}_{a0} = -jX_{0\Sigma}\dot{I}_{a0}\end{cases}$$

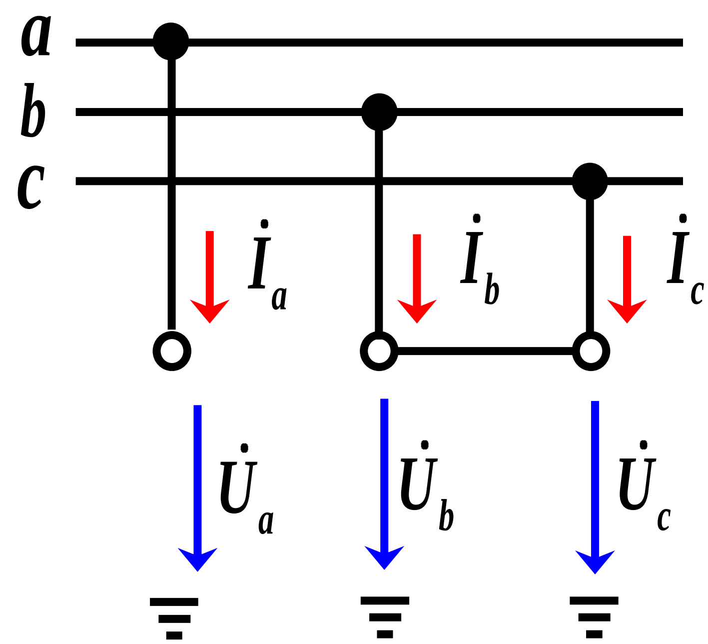
- 短路点的各相短路电压为：

$$\begin{cases}\dot{U}_{a} = \dot{U}_{a1} + \dot{U}_{a2} + \dot{U}_{a0} = 0 \\ \dot{U}_{b} = a^2\dot{U}_{a1} + a\dot{U}_{a2} + \dot{U}_{a0} \\ \dot{U}_{c} = a\dot{U}_{a1} + a^2\dot{U}_{a2} + \dot{U}_{a0}\end{cases}$$

➢2. 两相短路

- *b*、*c* 相短路故障的3个边界条件

$$\dot{U}_b=\dot{U}_c,\quad \dot{I}_a=0,\quad \dot{I}_b=-\dot{I}_c$$



$$\begin{cases}\dot{U}_b=a^2\dot{U}_{a1}+a\dot{U}_{a2}+\dot{U}_{a0}\\ \quad =a\dot{U}_{a1}+a^2\dot{U}_{a2}+\dot{U}_{a0}=\dot{U}_c\\ \dot{I}_a=\dot{I}_{a1}+\dot{I}_{a2}+\dot{I}_{a0}=0\\ \dot{I}_b=a^2\dot{I}_{a1}+a\dot{I}_{a2}+\dot{I}_{a0}\\ \quad =-(a\dot{I}_{a1}+a^2\dot{I}_{a2}+\dot{I}_{a0})=-\dot{I}_c\end{cases}$$

$$\dot{U}_{a1}=\dot{U}_{a2},\quad \dot{I}_{a0}=0,\quad \dot{I}_{a1}=-\dot{I}_{a2}$$

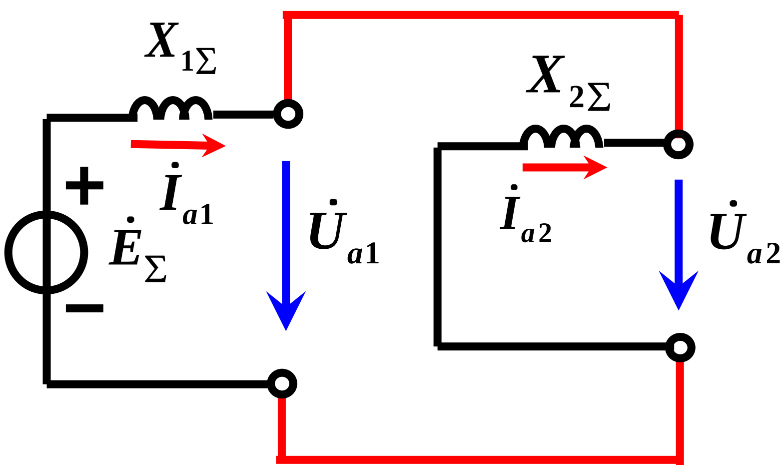
边界条件

-第10.2节- 不对称短路故障复合序网

- **b、c 相短路故障的复合序网**

$$\left.\begin{aligned}\dot{U}_{a1} &= \dot{U}_{a2}\\ \dot{I}_{a0} &= 0\\ \dot{I}_{a1} &= -\dot{I}_{a2}\end{aligned}\right\}$$

$$\begin{cases}\dot{I}_{a1} = \dfrac{\dot{E}_{\Sigma}}{j(X_{1\Sigma}+X_{2\Sigma})}\\ \dot{I}_{a2} = -\dot{I}_{a1}, \quad \dot{I}_{a0} = 0\end{cases}$$



- 短路点的短路电流为：

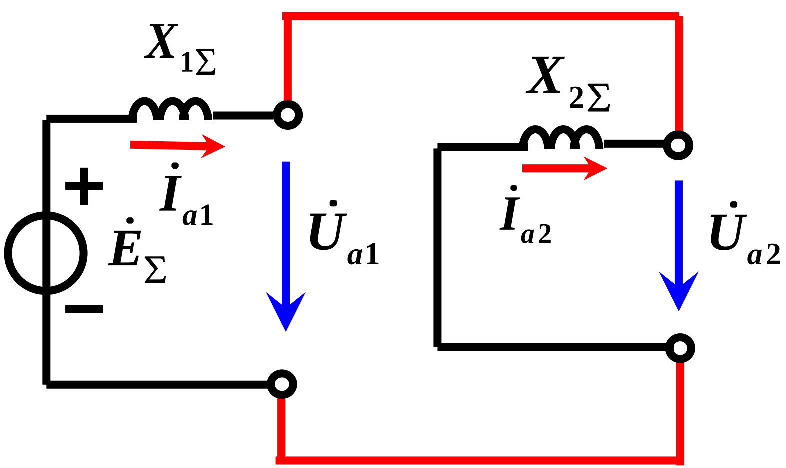
$$I_d^{(2)} = I_b = I_c$$
$$= \left|a^2\dot{I}_{a1} + a\dot{I}_{a2}\right|$$
$$= \left|a\dot{I}_{a1} + a^2\dot{I}_{a2}\right| = \sqrt{3}I_{a1}$$

-第10.2节- 不对称短路故障复合序网

- **根据 *a* 相各序电流求 *a* 相各序电压**

$$\begin{cases} \dot{U}_{a1} = \dot{E}_{\Sigma} - jX_{1\Sigma}\dot{I}_{a1} \\ \dot{U}_{a2} = -jX_{2\Sigma}\dot{I}_{a2} = \dot{U}_{a1} \\ \dot{U}_{a0} = 0 \end{cases}$$

a 相即非故障相电压等于故障前电压

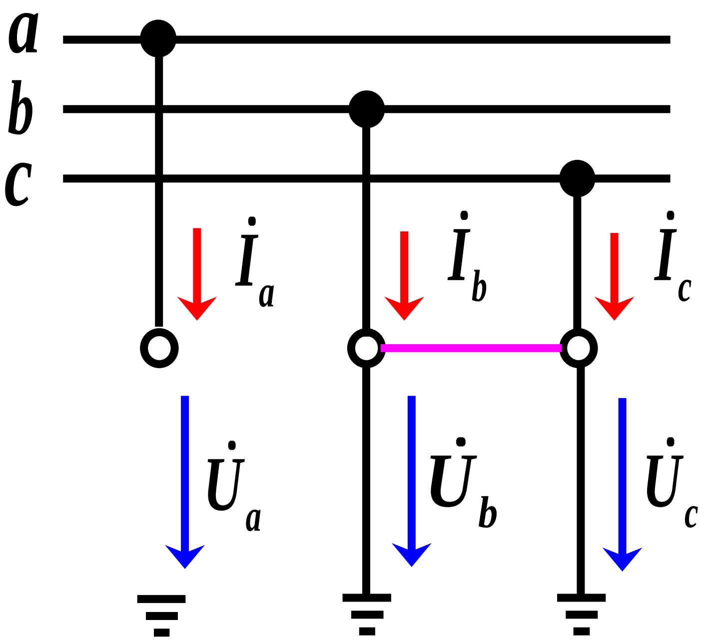


- 短路点的各相短路电压为：

$$\begin{cases} \dot{U}_{a} = \dot{U}_{a1} + \dot{U}_{a2} = \dot{E}_{\Sigma} \\ \dot{U}_{b} = a^2\dot{U}_{a1} + a\dot{U}_{a2} = -\frac{1}{2}\dot{E}_{\Sigma} \\ \dot{U}_{c} = a\dot{U}_{a1} + a^2\dot{U}_{a2} = -\frac{1}{2}\dot{E}_{\Sigma} \end{cases}$$

3. 两相接地短路

- *b*、*c* 相接地短路故障的3个边界条件



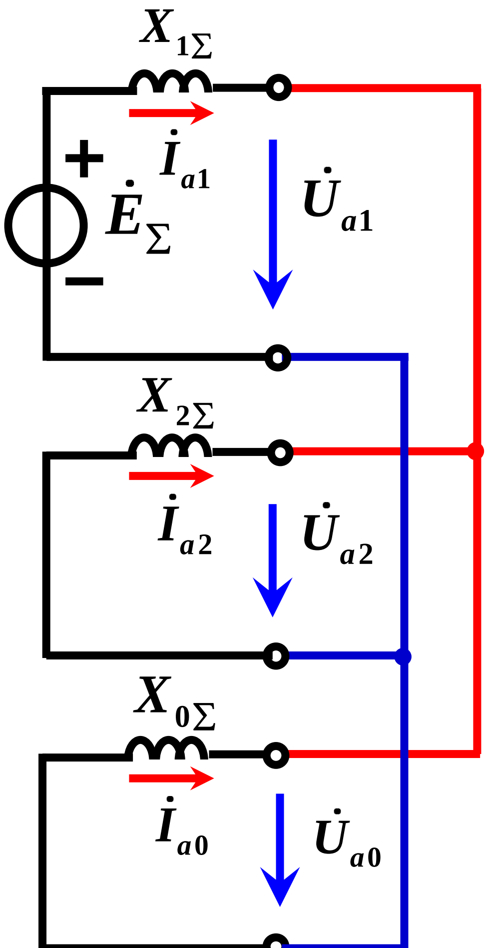
$$\dot{U}_b = 0,\quad \dot{U}_c = 0,\quad \dot{I}_a = 0$$

$$\begin{cases} \dot{U}_b = a^2\dot{U}_{a1} + a\dot{U}_{a2} + \dot{U}_{a0} = 0 \\ \dot{U}_c = a\dot{U}_{a1} + a^2\dot{U}_{a2} + \dot{U}_{a0} = 0 \\ \dot{I}_a = \dot{I}_{a1} + \dot{I}_{a2} + \dot{I}_{a0} = 0 \end{cases}$$

$$\left.\begin{aligned} \dot{U}_{a1} = \dot{U}_{a2} = \dot{U}_{a0} \\ \dot{I}_{a1} + \dot{I}_{a2} + \dot{I}_{a0} = 0 \end{aligned}\right\}$$

边界条件

- b、c 相接地短路故障的复合序网



$$\left.\begin{aligned}&\dot{U}_{a1}=\dot{U}_{a2}=\dot{U}_{a0}\\&\dot{I}_{a1}+\dot{I}_{a2}+\dot{I}_{a0}=0\end{aligned}\right\}$$

$$\begin{cases}\dot{I}_{a1}=\dfrac{E_{\Sigma}}{j\left(X_{1\Sigma}+X_{2\Sigma}//X_{0\Sigma}\right)}\\[2ex]\dot{I}_{a2}=-\dfrac{X_{0\Sigma}}{X_{2\Sigma}+X_{0\Sigma}}\dot{I}_{a1}\\[2ex]\dot{I}_{a0}=-\dfrac{X_{2\Sigma}}{X_{2\Sigma}+X_{0\Sigma}}\dot{I}_{a1}\end{cases}$$

- 短路点 a 相电压的各序分量为：

$$\dot{U}_{a1}=\dot{U}_{a2}=\dot{U}_{a0}=j\frac{X_{2\Sigma}X_{0\Sigma}}{X_{2\Sigma}+X_{0\Sigma}}\dot{I}_{a1}$$

-第10.2节- 不对称短路故障复合序网

- 短路点非故障相电压为：

$$\dot{U}_a=\dot{U}_{a1}+\dot{U}_{a2}+\dot{U}_{a0}=j\frac{3X_{2\Sigma}X_{0\Sigma}}{X_{2\Sigma}+X_{0\Sigma}}\dot{I}_{a1}$$

- 短路的短路电流为：

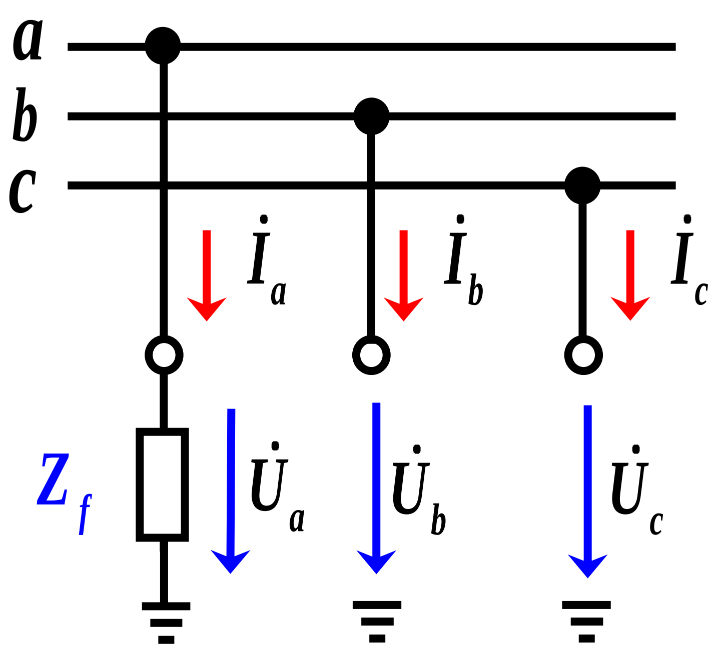
$$\begin{cases}\dot{I}_b=a^2\dot{I}_{a1}+a\dot{I}_{a2}+\dot{I}_{a0}=(a^2-\dfrac{X_{2\Sigma}+aX_{0\Sigma}}{X_{2\Sigma}+X_{0\Sigma}})\dot{I}_{a1}\\[2ex]\dot{I}_c=a\dot{I}_{a1}+a^2\dot{I}_{a2}+\dot{I}_{a0}=(a-\dfrac{X_{2\Sigma}+a^2X_{0\Sigma}}{X_{2\Sigma}+X_{0\Sigma}})\dot{I}_{a1}\end{cases}$$

- 短路电流有效值为：

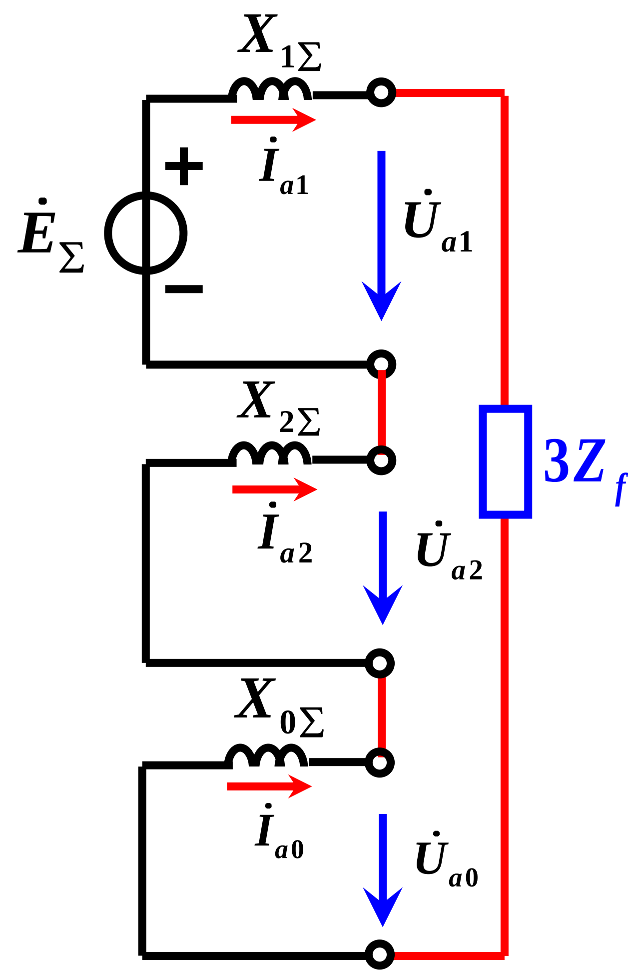
$$I_d^{(1.1)}=I_b=I_c=\sqrt{3}\sqrt{1-\frac{X_{0\Sigma}X_{2\Sigma}}{(X_{0\Sigma}+X_{2\Sigma})^2}}I_{a1}$$

4. 经过渡阻抗 Z_f 短路

- 单相接地短路

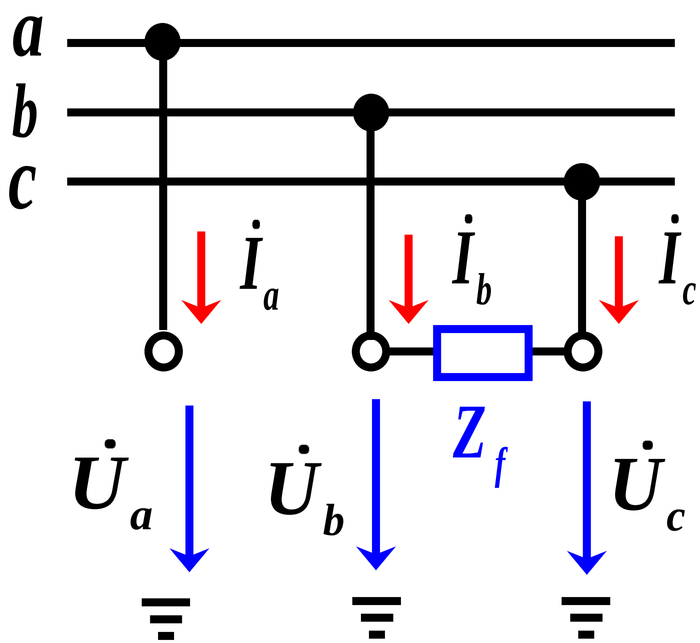


- 复合序网

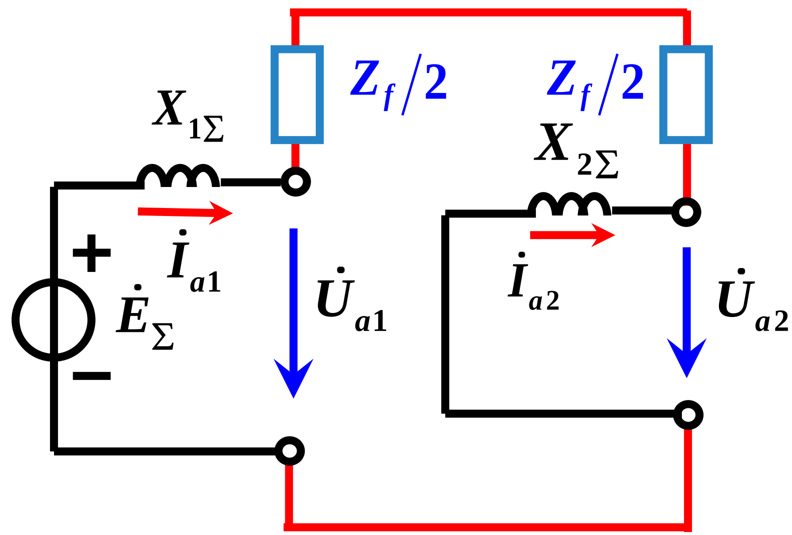


4. 经过渡阻抗 Z_f 短路

- 两相短路



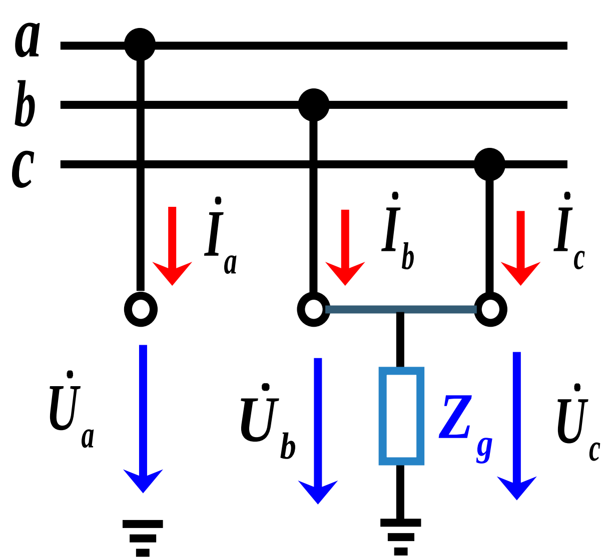
- 复合序网



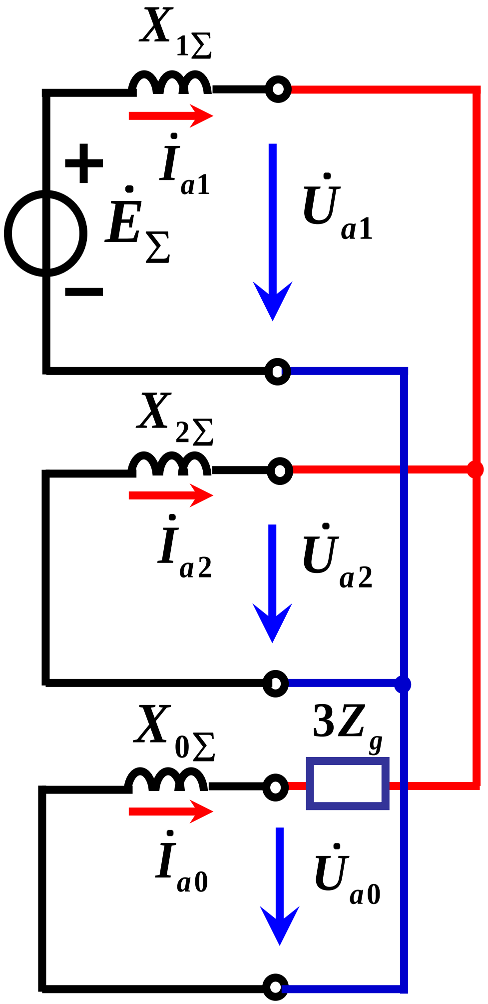
- **两相接地短路**
  - 边界条件 $\dot{U}_b = \dot{U}_c = (\dot{I}_b + \dot{I}_c)Z_g,\ \dot{I}_a = 0$

$$
\begin{cases}
\dot{U}_b = a^2\dot{U}_{a1} + a\dot{U}_{a2} + \dot{U}_{a0} = 3\dot{I}_{a0}Z_g \\
\dot{U}_c = a\dot{U}_{a1} + a^2\dot{U}_{a2} + \dot{U}_{a0} = 3\dot{I}_{a0}Z_g \\
\dot{I}_a = \dot{I}_{a1} + \dot{I}_{a2} + \dot{I}_{a0} = 0
\end{cases}
$$

$$
\begin{cases}
\dot{U}_{a1} = \dot{U}_{a2} \\
\dot{U}_{a0} - \dot{U}_{a1} = 3\dot{I}_{a0}Z_g \\
\dot{I}_{a1} + \dot{I}_{a2} + \dot{I}_{a0} = 0
\end{cases}
$$



- 复合序网



1. 正序电流的计算

- *a* 相接地短路

$$\boxed{\dot{I}_{a1}=\frac{\dot{E}_{\Sigma}}{j(X_{1\Sigma}+X_{2\Sigma}+X_{0\Sigma})} \Rightarrow I_{a1}=\frac{E_{\Sigma}}{X_{1\Sigma}+X_{2\Sigma}+X_{0\Sigma}}}$$

- *b*、*c* 相短路

$$\boxed{\dot{I}_{a1}=\frac{\dot{E}_{\Sigma}}{j(X_{1\Sigma}+X_{2\Sigma})} \Rightarrow I_{a1}=\frac{E_{\Sigma}}{X_{1\Sigma}+X_{2\Sigma}}}$$

- *b*、*c* 相接地短路

$$\boxed{\dot{I}_{a1}=\frac{\dot{E}_{\Sigma}}{j(X_{1\Sigma}+X_{2\Sigma}\parallel X_{0\Sigma})} \Rightarrow I_{a1}=\frac{E_{\Sigma}}{X_{1\Sigma}+X_{2\Sigma}\parallel X_{0\Sigma}}}$$

2. 短路电流与正序电流的关系

- *a* 相接地短路

$$\boxed{I_d^{(1)} = I_a = \left|\dot{I}_{a1} + \dot{I}_{a2} + \dot{I}_{a0}\right| = 3\left|\dot{I}_{a1}\right| = 3I_{a1}}$$

- *b*、*c* 相短路

$$\boxed{I_d^{(2)} = I_b = I_c = \left|a^2\dot{I}_{a1} + a\dot{I}_{a2}\right| = \left|a\dot{I}_{a1} + a^2\dot{I}_{a2}\right| = \sqrt{3}I_{a1}}$$

- *b*、*c* 相接地短路

$$\boxed{I_d^{(1.1)} = I_b = I_c = \sqrt{3}\sqrt{1 - \frac{X_{0\Sigma}X_{2\Sigma}}{(X_{0\Sigma} + X_{2\Sigma})^2}}I_{a1}}$$

3. 正序等效定则

• 不对称短路正序电流的计算通式

$$I_{a1}^{(n)} = \frac{E_{1\Sigma}}{X_{1\Sigma} + X_{\Delta}^{(n)}}$$

$X_{\Delta}^{(n)}$ ——附加电抗;

• 正序等效定则

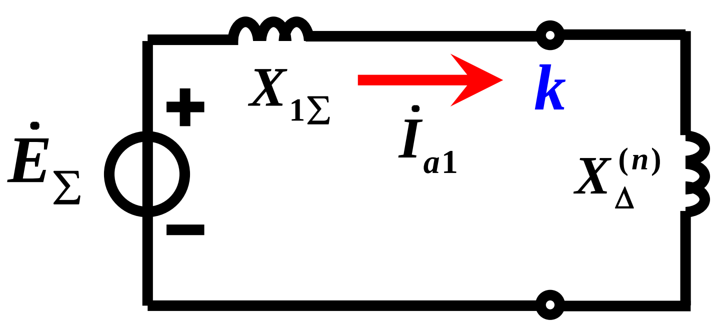
- 在简单不对称短路的情况下，短路点的正序分量电流，与在短路点每一相中接入附加电抗 $X_{\Delta}^{(n)}$ 后发生三相短路的电流相等。

- 短路电流的绝对值与其正序电流的绝对值成正比，即:

$$I_{d}^{(n)} = m^{(n)} I_{a1}^{(n)}$$

金属性短路	$X_{\Delta}^{(n)}$	$m^{(n)}$
三相短路	0	1
两相短路	$X_{2\Sigma}$	$\sqrt{3}$
单相接地短路	$X_{2\Sigma}+X_{0\Sigma}$	3
两相接地短路	$X_{2\Sigma}\,//\,X_{0\Sigma}$	$\sqrt{3}\sqrt{1-\dfrac{X_{2\Sigma}X_{0\Sigma}}{X_{2\Sigma}+X_{0\Sigma}}}$

- 注：**非金属性短路**可根据相应的复合序网求得 $X_{\Delta}^{(n)}$ 和 $m^{(n)}$

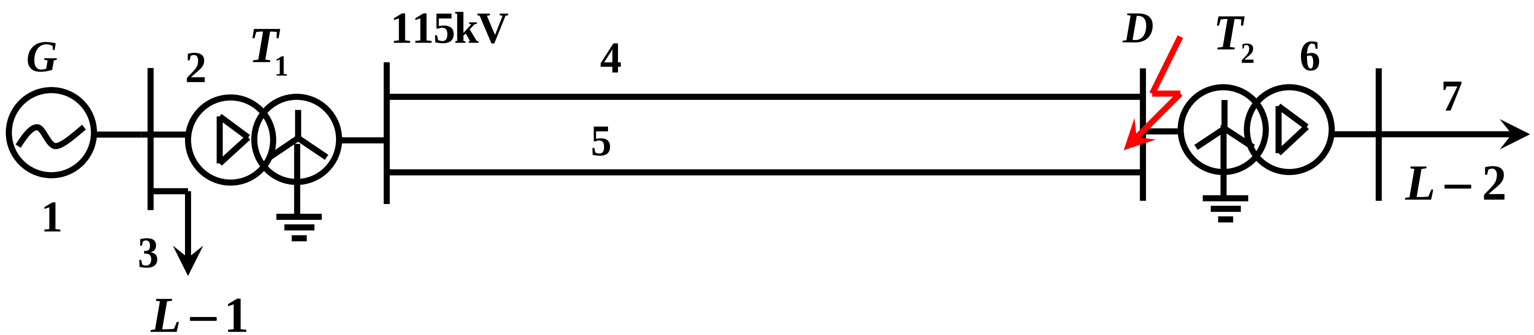


➢4. 不对称短路故障支路短路电流和节点故障电压计算

- 1）计算元件参数，建立各序网，计算各序网络对短路点的等值电抗 $X_{1\Sigma}$、$X_{2\Sigma}$ 及 $X_{0\Sigma}$；
- 2) 根据短路类型，组成复合序网，计算短路点正序电流；
- 3）短路点正序电流一经算出，即可利用各序电压、电流之间的关系计算短路点的各序电流和电压；
- 4）将各相的正、负、零序电压或电流相量相加，即得短路点各相故障电压或各相短路电流；
- 5）依据正序、负序和零序网络求出电网各支路短路电流和节点电压序分量；
- 6）同一支路或节点电流或电压各序分量叠加，即为该支路或节点的相电流或电压。

-第10.3节- 故障点短路电流电压计算

例： 图示变压器$T2$高压母线发生b相单相接地短路，计算短路后短路点的各相电压、电流。



发电机G： $120\text{MVA}, 10.5\text{kV}, x_d'' = x_2 = 0.14$

变压器T_1、T_2： $60\text{MVA}, U_k\% = 10.5$

双回架空线： $105\text{km}, x_1 = 0.4\Omega/\text{km}$， $x_0 = 3x_1$

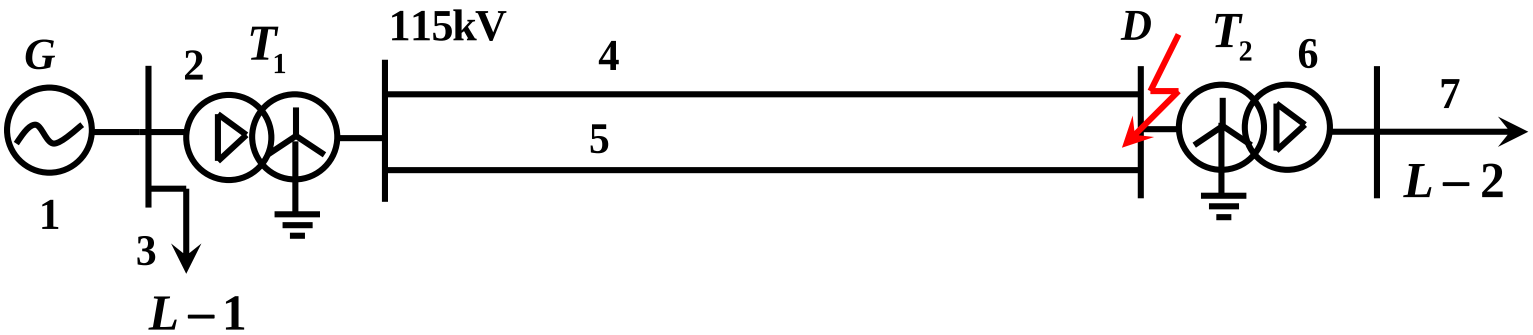
负荷： $L-1: 60\text{MVA}$， $L-2: 40\text{MVA}$， $x_1 = 1.2$， $x_2 = 0.35$

正常运行时D点电压： $\dot{U}_{D(0)} = 109\angle 0^\circ \text{kV}$

变压器T_1为$Y_0/\triangle$-11接线。

解： 1) 参数计算

取S_B=120MVA，$U_B=U_{av}$



-第10.3节- 故障点短路电流电压计算

2) 构建各序网络

- 正序网络

发电机： $X_1=0.14\times120/120=0.14$

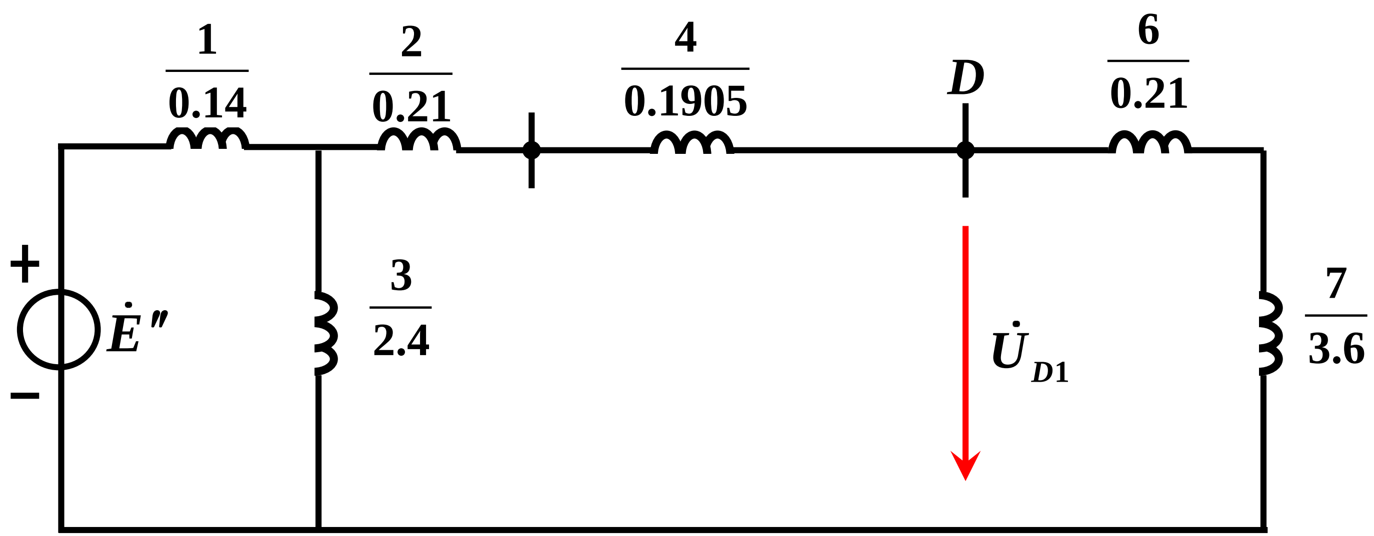
变压器T1： $X_2=0.105\times120/60=0.21$

负荷L-1： $X_3=1.2\times120/60=2.4$

线路： $X_{4\text{-}5}=0.4/2\times105\times120/115^2=0.1905$

变压器T2： $X_6=0.105\times120/60=0.21$

负荷L-2： $X_5=1.2\times120/40=3.6$



- 负序网络

发电机： X_1=0.14×120/120＝0.14

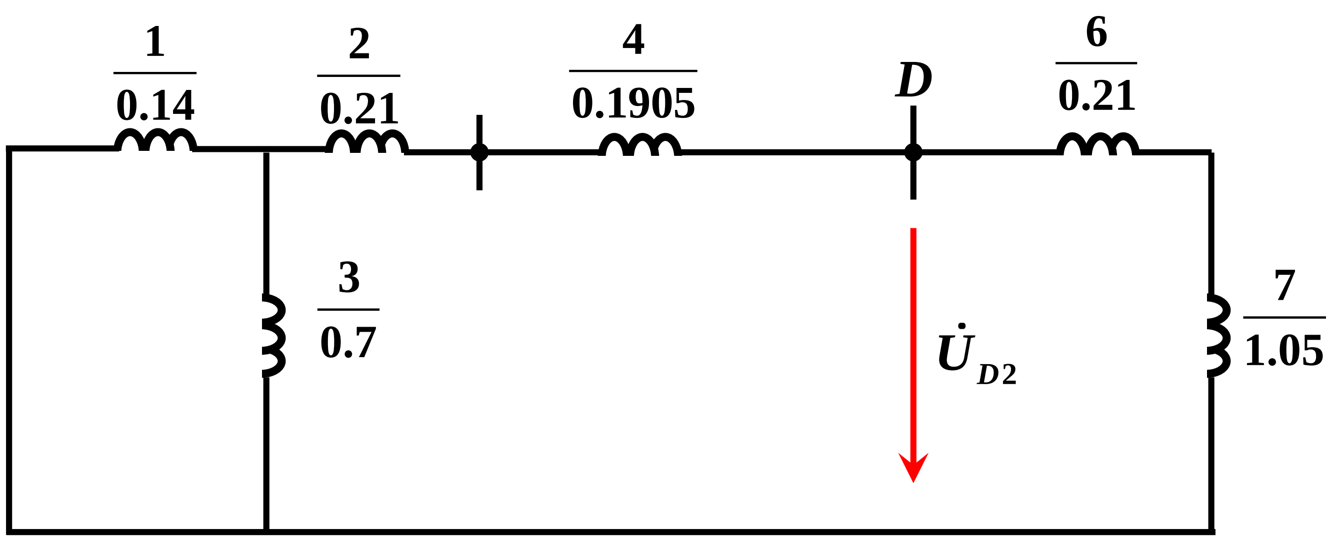
变压器T1： X_2=0.105×120/60＝0.21

负荷L-1： X_3=0.35×120/60＝0.7

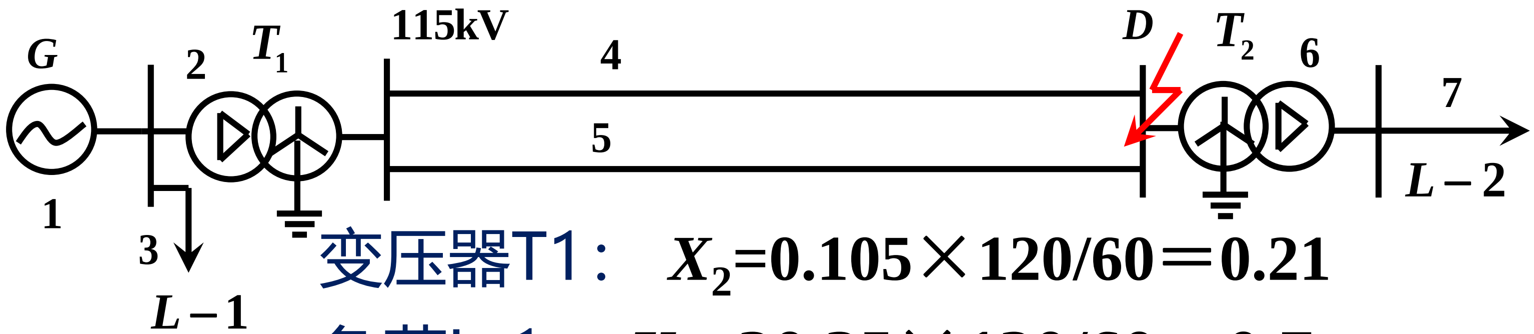
线路： $X_{4\text{-}5}$=0.4/2×105×120/115^2＝0.1905

变压器T2： X_6=0.105×120/60＝0.21

负荷L-2： X_5=0.35×120/40＝1.05



- 零序网络

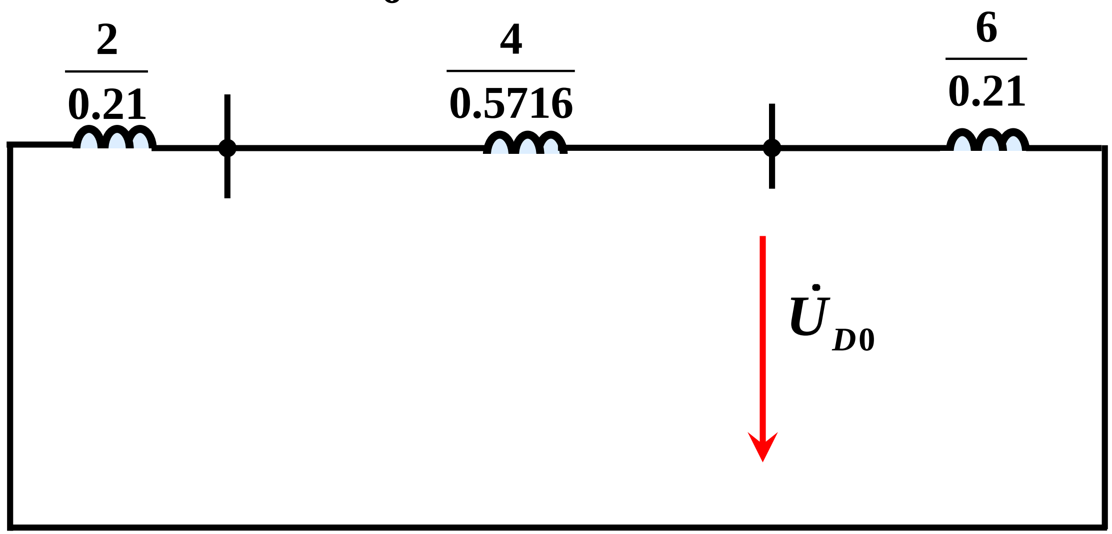


变压器T1： X_2=0.105×120/60＝0.21

负荷L-1： X_3=30.35×120/60＝0.7

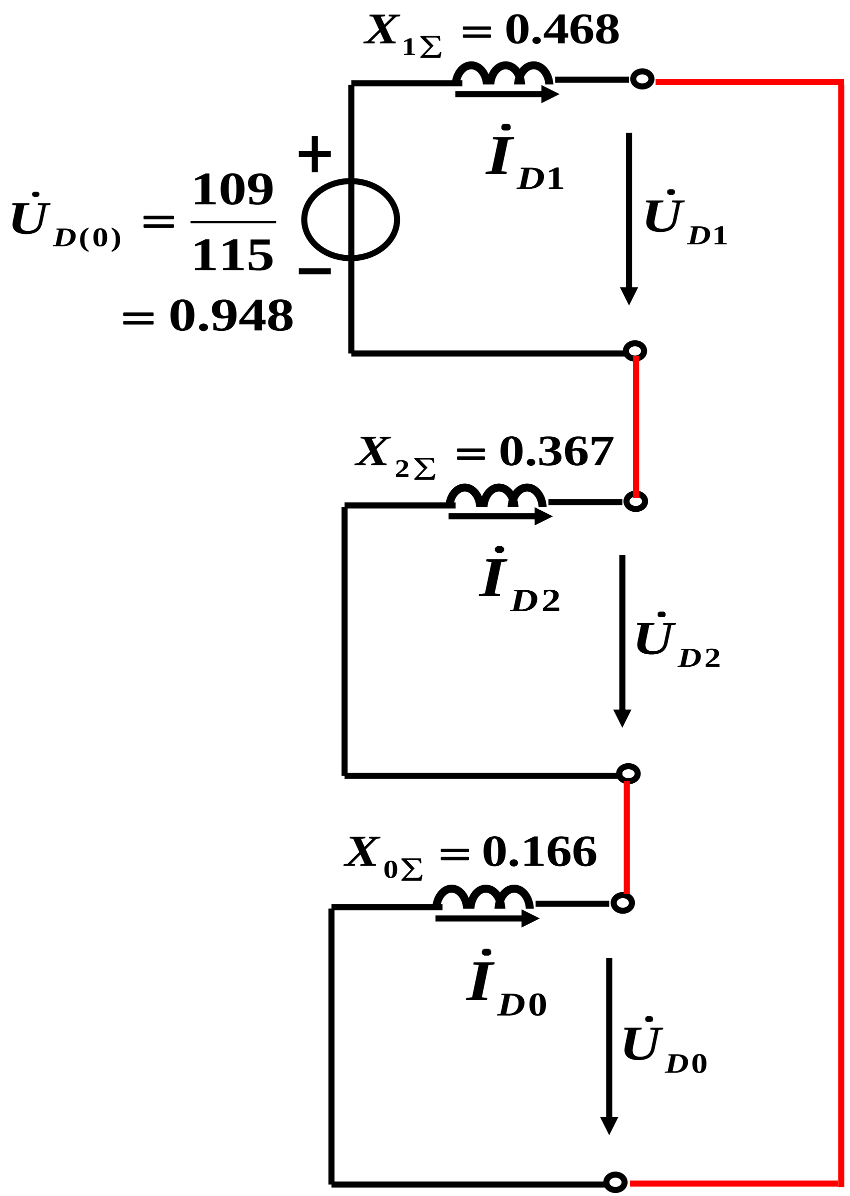
线路： $X_{4\text{-}5}$=3×0.4/2×105×120/115^2＝0.5716

变压器T2： X_6=0.105×120/60＝0.21



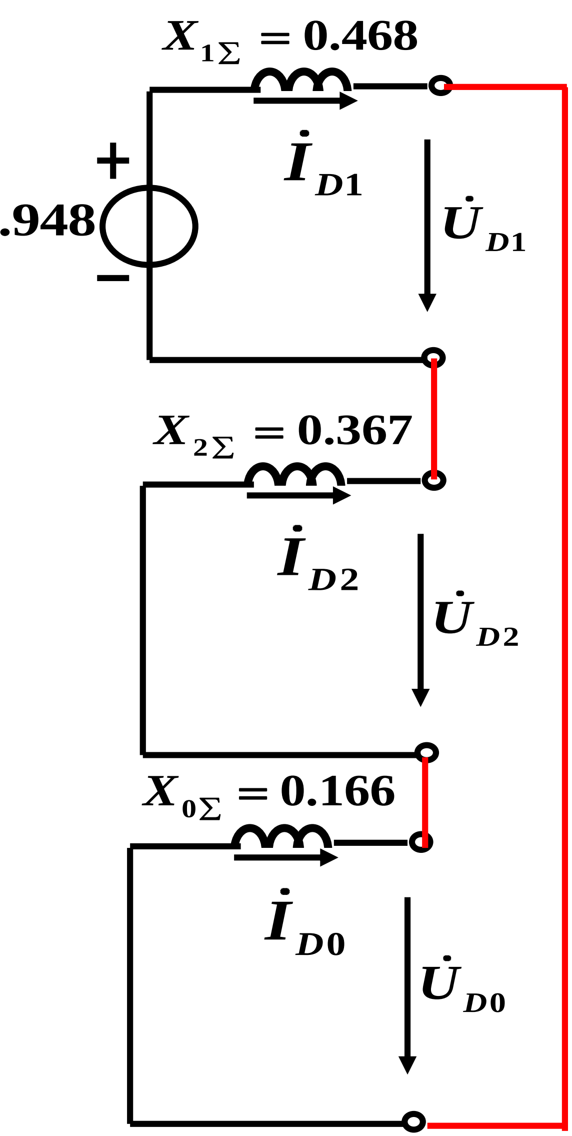
- 序网的合成

复合序网



$X_{1\Sigma}=0.468$
$\dot{I}_{D1}$
$\dot{U}_{D1}$
$\dot{U}_{D(0)}=\frac{109}{115}=0.948$
+
−
$X_{2\Sigma}=0.367$
$\dot{I}_{D2}$
$\dot{U}_{D2}$
$X_{0\Sigma}=0.166$
$\dot{I}_{D0}$
$\dot{U}_{D0}$

3) 根据复合序网计算短路点各序电流、电压



$$\dot{I}_{D1}=-j\frac{\dot{U}_{D(0)}}{X_{1\Sigma}+X_{2\Sigma}+X_{0\Sigma}}$$

$$=-j\frac{0.948}{0.468+0.367+0.166}=-j0.947$$

$$\dot{U}_{D1}=j(X_{2\Sigma}+X_{0\Sigma})\dot{I}_{D1}$$

$$=j(0.367+0.166)(-j0.947)$$

$$=0.505$$

$$\dot{U}_{D2}=-jX_{2\Sigma}\dot{I}_{D1}$$

$$=-j0.367\times(-j0.947)=-0.348$$

$$\boxed{\begin{aligned}\dot{U}_{D0}&=-jX_{0\Sigma}\dot{I}_{D1}\\&=-j0.166\times(-j0.947)=-0.157\end{aligned}}$$

4) 求短路点各相电流、电压

$$\dot{I}_b = \dot{I}_{D0} + \dot{I}_{D1} + \dot{I}_{D2} = -j2.841$$

$$\dot{I}_c = \dot{I}_{D0} + a^2\dot{I}_{D1} + a\dot{I}_{D2} = 0$$

$$\dot{I}_a = \dot{I}_{D0} + a\dot{I}_{D1} + a^2\dot{I}_{D2} = 0$$

$$\dot{U}_b = \dot{U}_{D0} + \dot{U}_{D1} + \dot{U}_{D2} = 0$$

$$\dot{U}_c = \dot{U}_{D0} + a^2\dot{U}_{D1} + a\dot{U}_{D2}$$

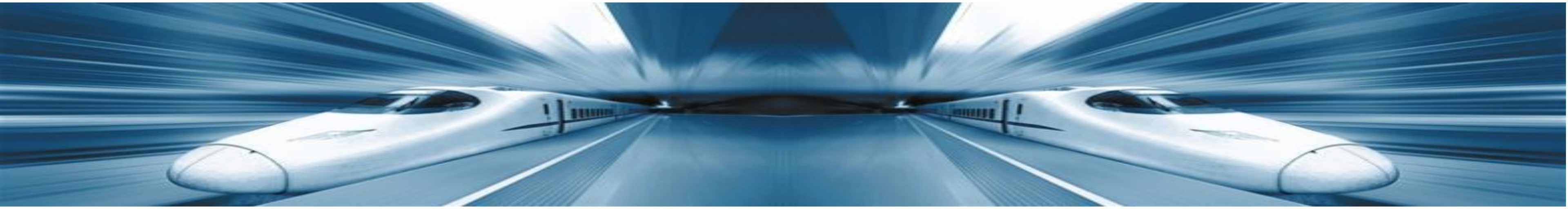
$$= -0.157 + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)\times 0.505 + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)\times -0.348$$

$$= -0.2355 - j0.7387 = 0.775\angle 252.32^\circ$$

$$\dot{U}_a = \dot{U}_{D0} + a\dot{U}_{D1} + a^2\dot{U}_{D2}$$

$$= -0.157 + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)\times 0.505 + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)\times -0.348$$

$$= -0.2355 + j0.7387 = 0.775\angle 107.68^\circ$$



End
谢谢