# 第七章 电力系统各元件的序阻抗和等值电路

7-1 对称分量法在不对称短路计算中的应用

7-2 同步发电机的负序和零序电抗

7-3 变压器的零序等值电路及其参数

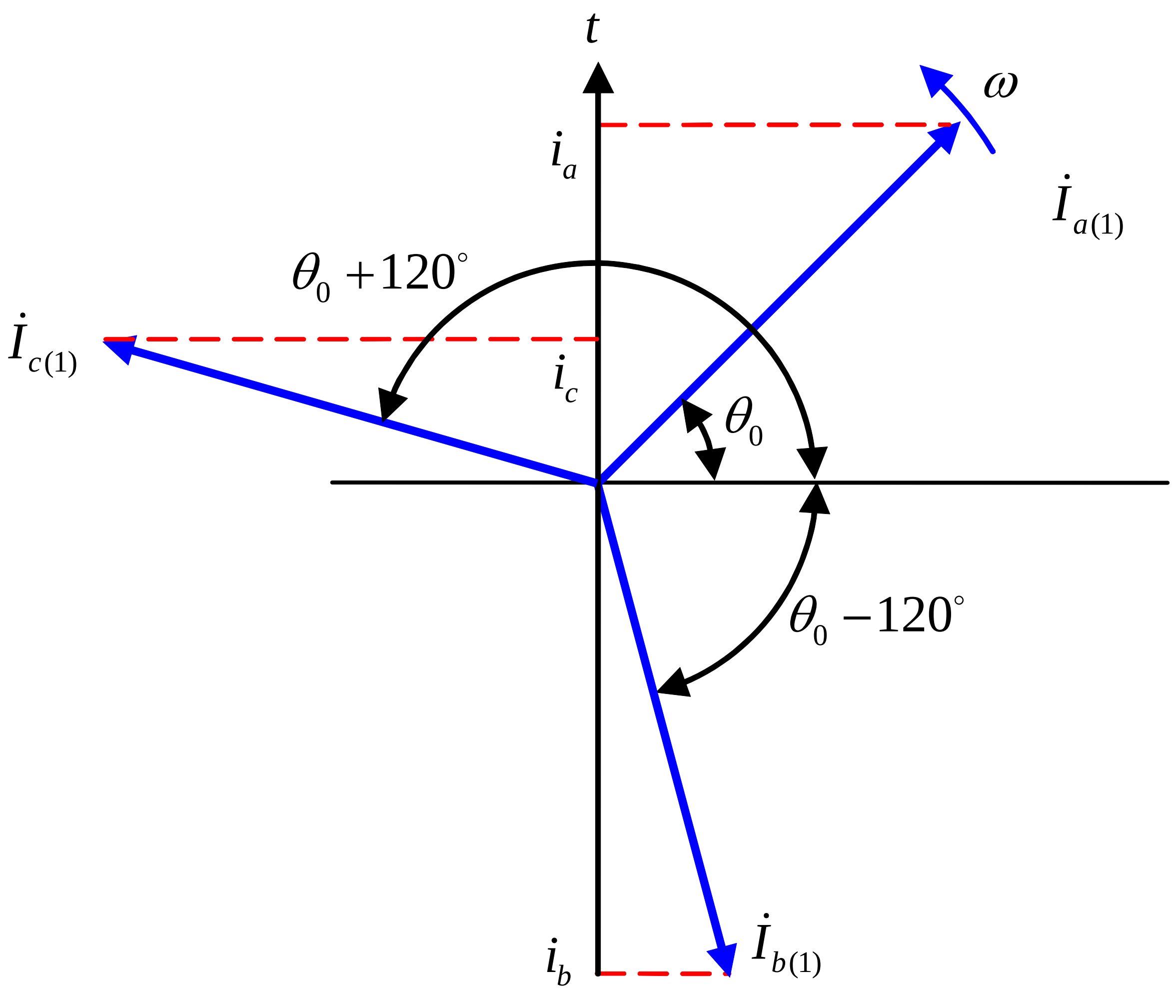
7-4 架空输电线路的零序阻抗及其等值电路

7-6 综合负荷的序阻抗

7-7 电力系统各序网络的制定

# 7-1 对称分量法在不对称短路计算中的应用

## 1. 不对称三相量的分解——对称分量




$$i_a=I_m\sin(\omega t+\theta_0)$$
$$i_b=I_m\sin(\omega t+\theta_0-120^\circ)$$
$$i_c=I_m\sin(\omega t+\theta_0+120^\circ)$$

# 7-1 对称分量法在不对称短路计算中的应用

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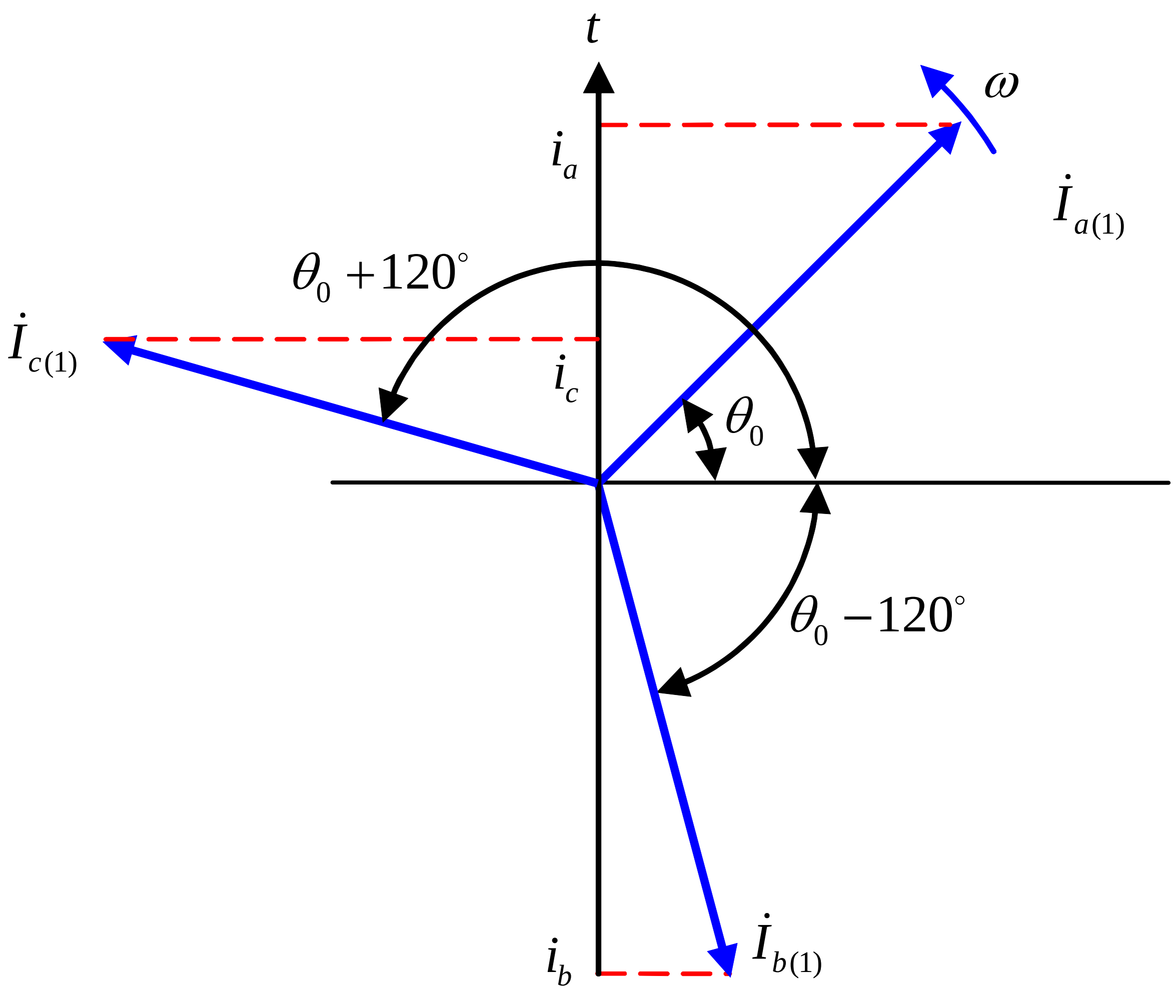


$$i_a=I_m\sin(\omega t+\theta_0)$$
$$i_b=I_m\sin(\omega t+\theta_0-120^\circ)$$
$$i_c=I_m\sin(\omega t+\theta_0+120^\circ)$$

正序分量：

$$\dot{I}_{b(1)}=\alpha^2\dot{I}_{a(1)}=e^{-j120^\circ}\dot{I}_{a(1)}$$
$$\dot{I}_{c(1)}=\alpha\dot{I}_{a(1)}=e^{j120^\circ}\dot{I}_{a(1)}$$

$$\alpha=e^{j120^\circ},\ 1+\alpha+\alpha^2=0$$

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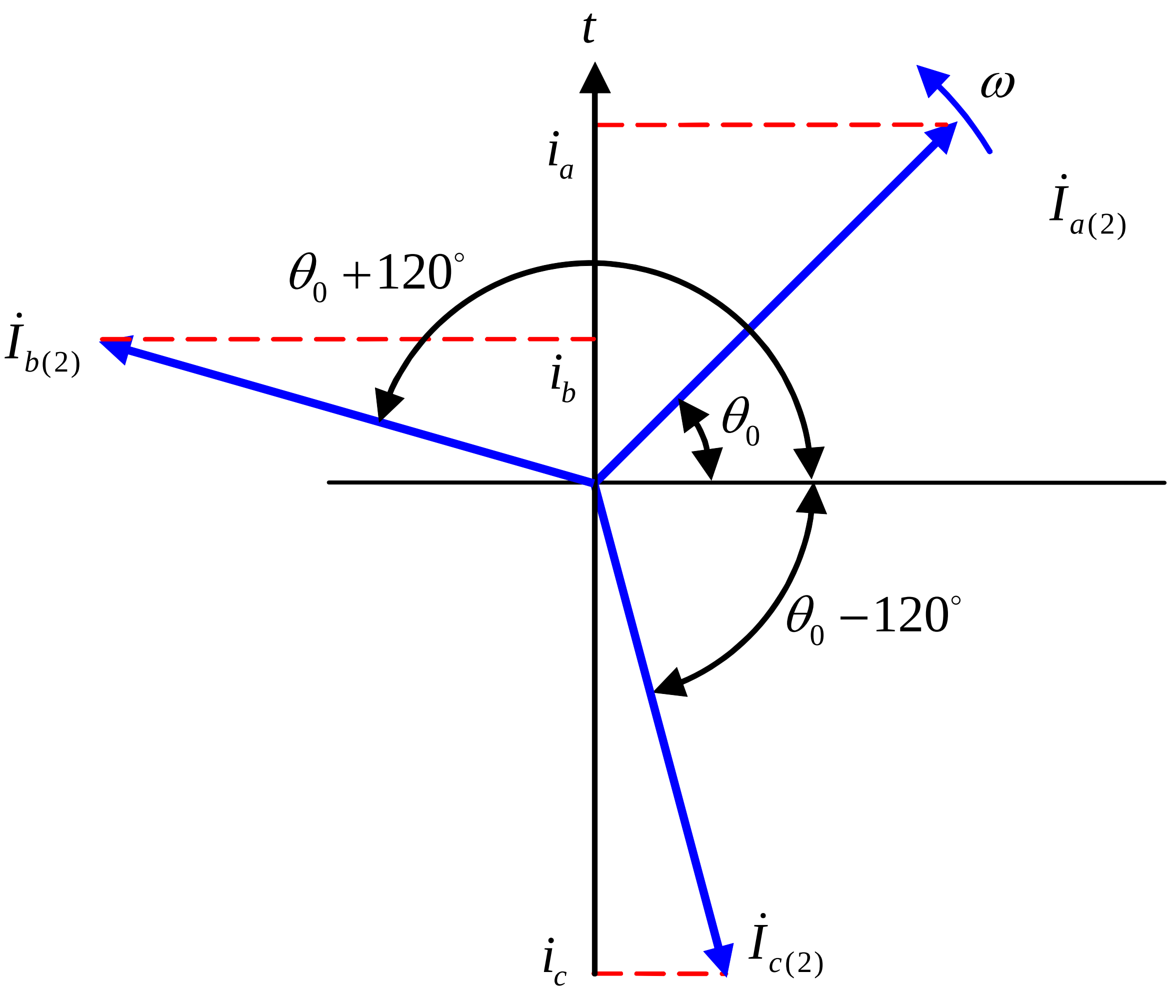


$$i_a = I_m \sin(\omega t + \theta_0)$$

$$i_b = I_m \sin(\omega t + \theta_0 + 120^\circ)$$

$$i_c = I_m \sin(\omega t + \theta_0 - 120^\circ)$$

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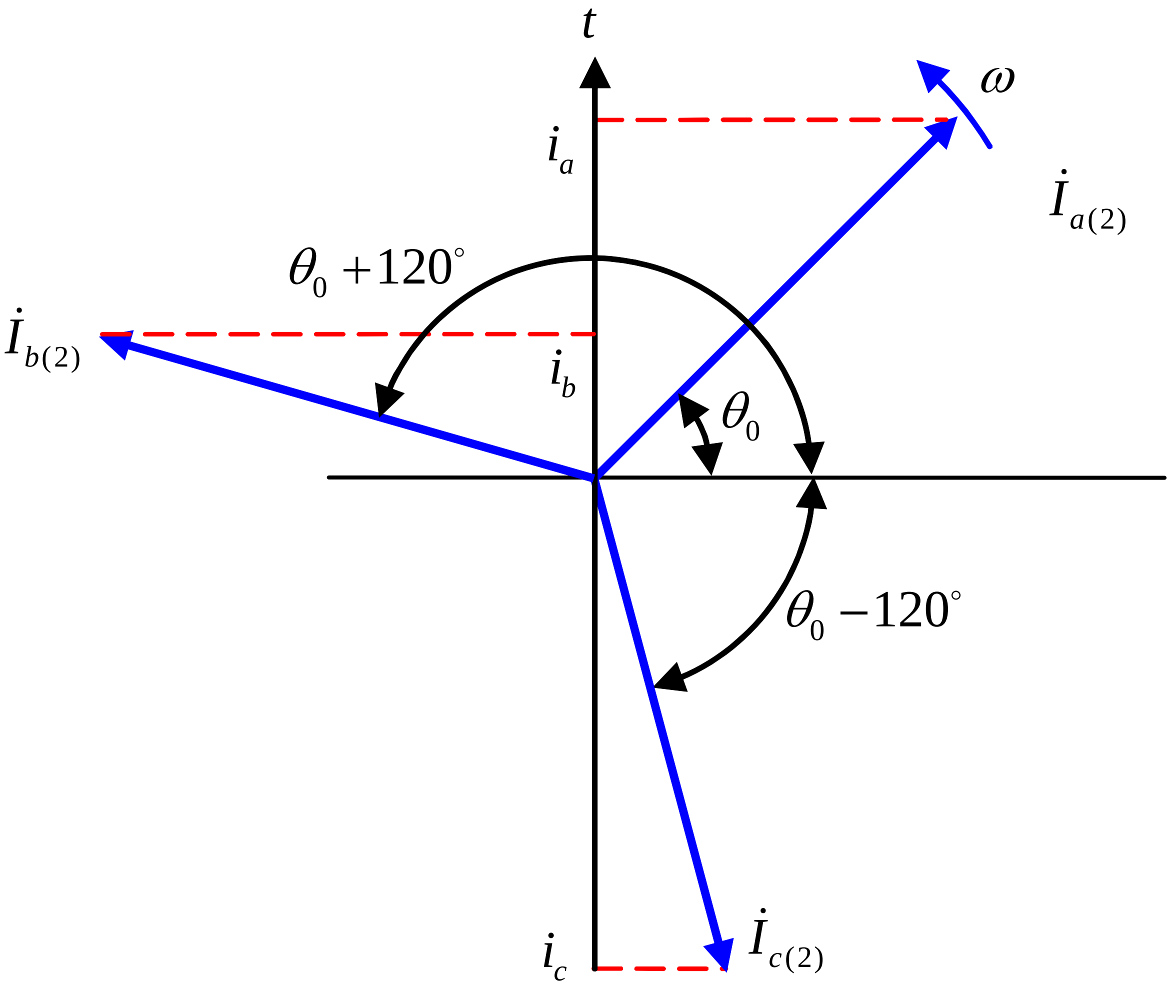


$$i_a=I_m\sin(\omega t+\theta_0)$$

$$i_b=I_m\sin(\omega t+\theta_0+120^\circ)$$

$$i_c=I_m\sin(\omega t+\theta_0-120^\circ)$$

负序分量：

$$\dot{I}_{b(2)}=\alpha\dot{I}_{a(2)}=e^{j120^\circ}\dot{I}_{a(2)}$$

$$\dot{I}_{c(2)}=\alpha^2\dot{I}_{a(2)}=e^{-j120^\circ}\dot{I}_{a(2)}$$

$$\alpha=e^{j120^\circ},\ 1+\alpha+\alpha^2=0$$

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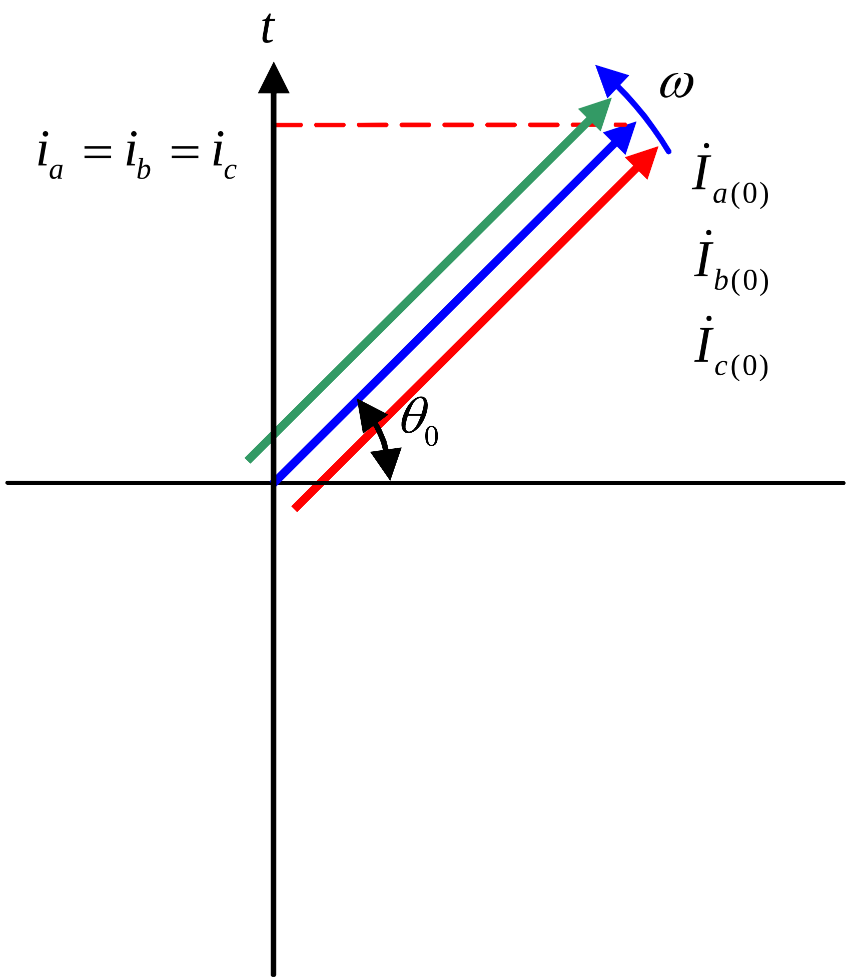


$$i_a = I_m \sin(\omega t + \theta_0)$$
$$i_b = I_m \sin(\omega t + \theta_0)$$
$$i_c = I_m \sin(\omega t + \theta_0)$$

零序分量:

$$\dot{I}_{a(0)} = \dot{I}_{b(0)} = \dot{I}_{c(0)}$$

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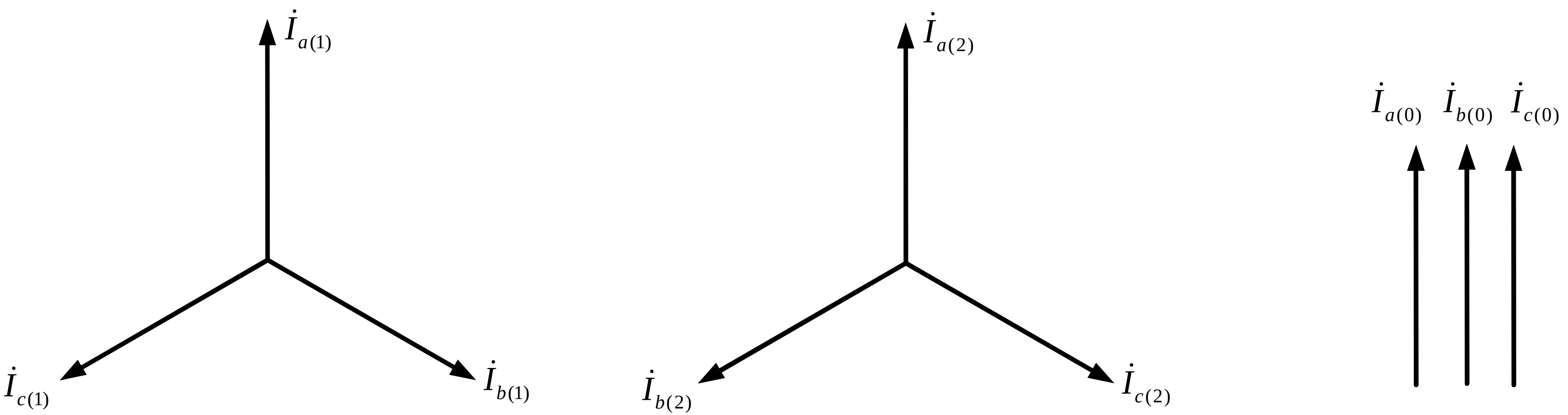
## 1. 不对称三相量的分解——对称分量




正序分量：

$$\dot{I}_{b(1)} = \alpha^2 \dot{I}_{a(1)} = e^{-j120^\circ} \dot{I}_{a(1)}$$

$$\dot{I}_{c(1)} = \alpha \dot{I}_{a(1)} = e^{j120^\circ} \dot{I}_{a(1)}$$

负序分量：

$$\dot{I}_{b(2)} = \alpha \dot{I}_{a(2)} = e^{j120^\circ} \dot{I}_{a(2)}$$

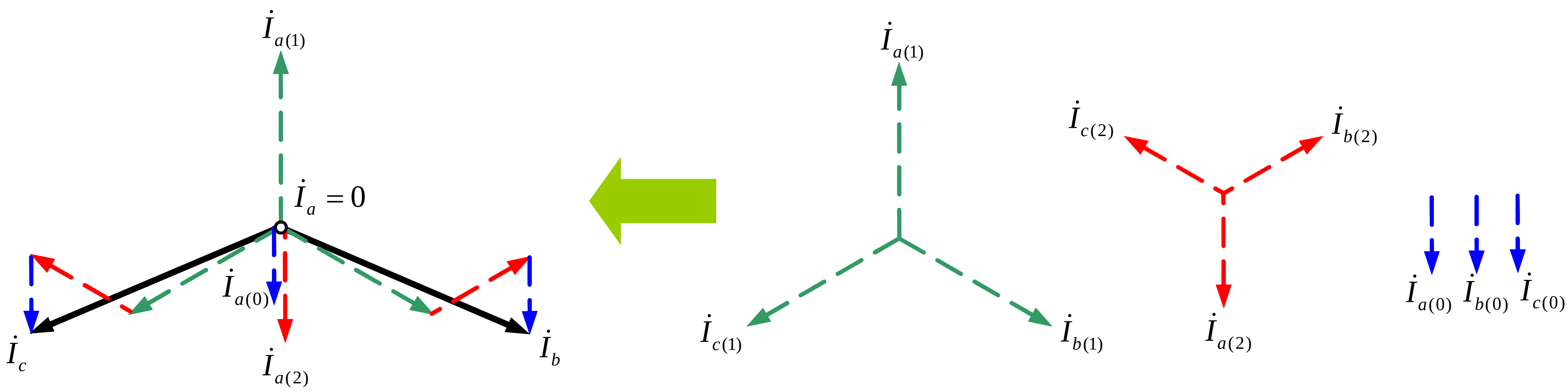
$$\dot{I}_{c(2)} = \alpha^2 \dot{I}_{a(2)} = e^{-j120^\circ} \dot{I}_{a(2)}$$

零序分量：

$$\dot{I}_{a(0)} = \dot{I}_{b(0)} = \dot{I}_{c(0)}$$

# 7-1 对称分量法在不对称短路计算中的应用

## 1. 不对称三相量的分解——对称分量分解




$$\dot{I}_a=\dot{I}_{a(1)}+\dot{I}_{a(2)}+\dot{I}_{a(0)}$$
$$\dot{I}_b=\dot{I}_{b(1)}+\dot{I}_{b(2)}+\dot{I}_{b(0)}$$
$$\dot{I}_c=\dot{I}_{c(1)}+\dot{I}_{c(2)}+\dot{I}_{c(0)}$$

以a相为基准相

$$\dot{I}_a=\dot{I}_{a(1)}+\dot{I}_{a(2)}+\dot{I}_{a(0)}$$
$$\dot{I}_b=\alpha^2\dot{I}_{a(1)}+\alpha\dot{I}_{a(2)}+\dot{I}_{a(0)}$$
$$\dot{I}_c=\alpha\dot{I}_{a(1)}+\alpha^2\dot{I}_{a(2)}+\dot{I}_{a(0)}$$

# 7-1 对称分量法在不对称短路计算中的应用

## 1. 不对称三相量的分解——对称分量分解

$$\boxed{\begin{aligned}\dot I_a &= \dot I_{a(1)} + \dot I_{a(2)} + \dot I_{a(0)} \\ \dot I_b &= \alpha^2 \dot I_{a(1)} + \alpha \dot I_{a(2)} + \dot I_{a(0)} \\ \dot I_c &= \alpha \dot I_{a(1)} + \alpha^2 \dot I_{a(2)} + \dot I_{a(0)}\end{aligned}}$$

# 7-1 对称分量法在不对称短路计算中的应用

## 1. 不对称三相量的分解——对称分量分解

$$\dot{I}_a = \dot{I}_{a(1)} + \dot{I}_{a(2)} + \dot{I}_{a(0)}$$
$$\dot{I}_b = \alpha^2 \dot{I}_{a(1)} + \alpha \dot{I}_{a(2)} + \dot{I}_{a(0)}$$
$$\dot{I}_c = \alpha \dot{I}_{a(1)} + \alpha^2 \dot{I}_{a(2)} + \dot{I}_{a(0)}$$

$$\Rightarrow$$

$$\begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix}$$

# 7-1 对称分量法在不对称短路计算中的应用

## 1. 不对称三相量的分解——对称分量分解

$$\dot{I}_a = \dot{I}_{a(1)} + \dot{I}_{a(2)} + \dot{I}_{a(0)}$$
$$\dot{I}_b = \alpha^2 \dot{I}_{a(1)} + \alpha \dot{I}_{a(2)} + \dot{I}_{a(0)}$$
$$\dot{I}_c = \alpha \dot{I}_{a(1)} + \alpha^2 \dot{I}_{a(2)} + \dot{I}_{a(0)}$$

$$\begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix}$$

$$\dot{\mathbf{I}}_{abc} = \mathbf{S}^{-1} \dot{\mathbf{I}}_{120}$$

# 7-1 对称分量法在不对称短路计算中的应用

## 1. 不对称三相量的分解——对称分量分解

$$\dot{I}_a = \dot{I}_{a(1)} + \dot{I}_{a(2)} + \dot{I}_{a(0)}$$
$$\dot{I}_b = \alpha^2 \dot{I}_{a(1)} + \alpha \dot{I}_{a(2)} + \dot{I}_{a(0)}$$
$$\dot{I}_c = \alpha \dot{I}_{a(1)} + \alpha^2 \dot{I}_{a(2)} + \dot{I}_{a(0)}$$

$$\begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix}$$

$$\dot{\mathbf{I}}_{abc} = \mathbf{S}^{-1} \dot{\mathbf{I}}_{120}$$

$$\dot{\mathbf{I}}_{120} = \mathbf{S} \dot{\mathbf{I}}_{abc}$$

$$\begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix}$$

# 7-1 对称分量法在不对称短路计算中的应用

## 1. 不对称三相量的分解——对称分量分解

$$\begin{aligned}\dot{I}_a &= \dot{I}_{a(1)} + \dot{I}_{a(2)} + \dot{I}_{a(0)}\\ \dot{I}_b &= \alpha^2\dot{I}_{a(1)} + \alpha\dot{I}_{a(2)} + \dot{I}_{a(0)}\\ \dot{I}_c &= \alpha\dot{I}_{a(1)} + \alpha^2\dot{I}_{a(2)} + \dot{I}_{a(0)}\end{aligned}$$

$$\begin{bmatrix}\dot{I}_a\\ \dot{I}_b\\ \dot{I}_c\end{bmatrix} = \begin{bmatrix}1 & 1 & 1\\ \alpha^2 & \alpha & 1\\ \alpha & \alpha^2 & 1\end{bmatrix}\begin{bmatrix}\dot{I}_{a(1)}\\ \dot{I}_{a(2)}\\ \dot{I}_{a(0)}\end{bmatrix}$$

$$\dot{\mathbf{I}}_{abc} = \mathbf{S}^{-1}\dot{\mathbf{I}}_{120}$$

$$\dot{\mathbf{I}}_{120} = \mathbf{S}\dot{\mathbf{I}}_{abc}$$

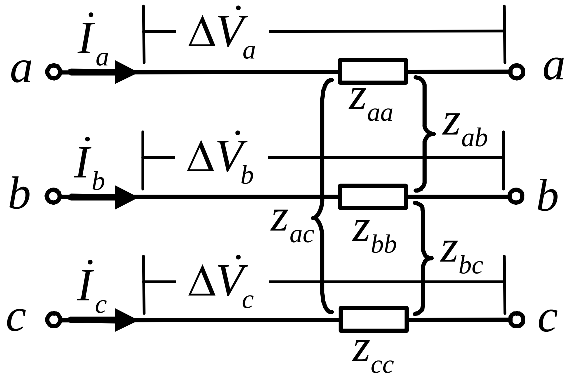
$$\begin{bmatrix}\dot{I}_{a(1)}\\ \dot{I}_{a(2)}\\ \dot{I}_{a(0)}\end{bmatrix} = \frac{1}{3}\begin{bmatrix}1 & \alpha & \alpha^2\\ 1 & \alpha^2 & \alpha\\ 1 & 1 & 1\end{bmatrix}\begin{bmatrix}\dot{I}_a\\ \dot{I}_b\\ \dot{I}_c\end{bmatrix}$$

$$\dot{\mathbf{I}}_{abc} \xleftrightarrow{\text{唯一变换}} \dot{\mathbf{I}}_{120}$$

# 7-1 对称分量法在不对称短路计算中的应用

## 2. 序阻抗的概念——三相对称电路

$$\begin{bmatrix} \Delta\dot{V}_a \\ \Delta\dot{V}_b \\ \Delta\dot{V}_c \end{bmatrix} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ca} \\ z_{ab} & z_{bb} & z_{bc} \\ z_{ca} & z_{bc} & z_{cc} \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix}$$



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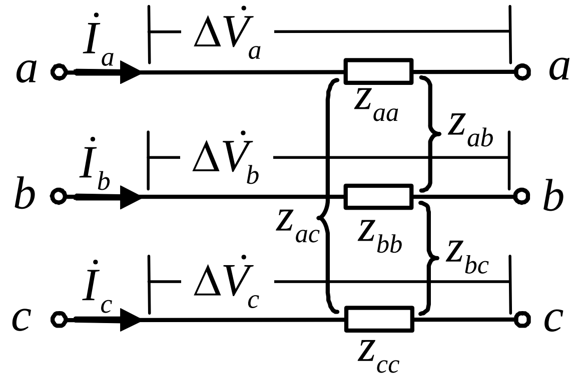
$$\begin{bmatrix} \Delta\dot{V}_a \\ \Delta\dot{V}_b \\ \Delta\dot{V}_c \end{bmatrix} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ca} \\ z_{ab} & z_{bb} & z_{bc} \\ z_{ca} & z_{bc} & z_{cc} \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix}$$




$$\Delta\dot{\mathbf{V}}_{abc} = \mathbf{Z}\dot{\mathbf{I}}_{abc}$$

$$\Delta\dot{\mathbf{V}}_{120} = \mathbf{S}\Delta\dot{\mathbf{V}}_{abc} = \mathbf{SZS}^{-1}\mathbf{S}\dot{\mathbf{I}}_{abc} = \mathbf{Z}_{SC}\dot{\mathbf{I}}_{120}$$

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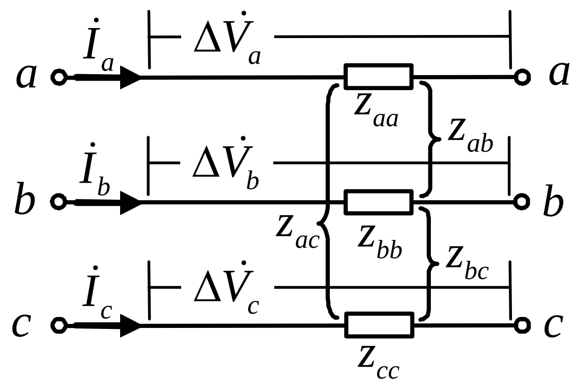
## 2. 序阻抗的概念——三相对称电路

$$\begin{bmatrix} \Delta\dot{V}_a \\ \Delta\dot{V}_b \\ \Delta\dot{V}_c \end{bmatrix} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ca} \\ z_{ab} & z_{bb} & z_{bc} \\ z_{ca} & z_{bc} & z_{cc} \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix}$$




$$\Delta\dot{\mathbf{V}}_{abc} = \mathbf{Z}\dot{\mathbf{I}}_{abc}$$

$$\Delta\dot{\mathbf{V}}_{120} = \mathbf{S}\Delta\dot{\mathbf{V}}_{abc} = \mathbf{SZS}^{-1}\mathbf{S}\dot{\mathbf{I}}_{abc} = \mathbf{Z}_{SC}\dot{\mathbf{I}}_{120}$$

$$\begin{bmatrix} \Delta\dot{V}_{a(1)} \\ \Delta\dot{V}_{a(2)} \\ \Delta\dot{V}_{a(0)} \end{bmatrix} = \begin{bmatrix} z_s - z_m & 0 & 0 \\ 0 & z_s - z_m & 0 \\ 0 & 0 & z_s + 2z_m \end{bmatrix} \begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix}$$

三相对称电路

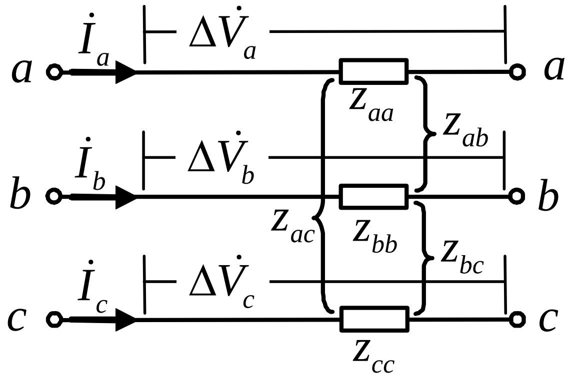
$$z_{aa} = z_{bb} = z_{cc} = z_s$$

$$z_{ab} = z_{bc} = z_{ca} = z_m$$

# 7-1 对称分量法在不对称短路计算中的应用

## 2. 序阻抗的概念——定义

$$\begin{bmatrix} \Delta\dot{V}_{a(1)} \\ \Delta\dot{V}_{a(2)} \\ \Delta\dot{V}_{a(0)} \end{bmatrix} = \begin{bmatrix} z_s - z_m & 0 & 0 \\ 0 & z_s - z_m & 0 \\ 0 & 0 & z_s + 2z_m \end{bmatrix} \begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix}$$



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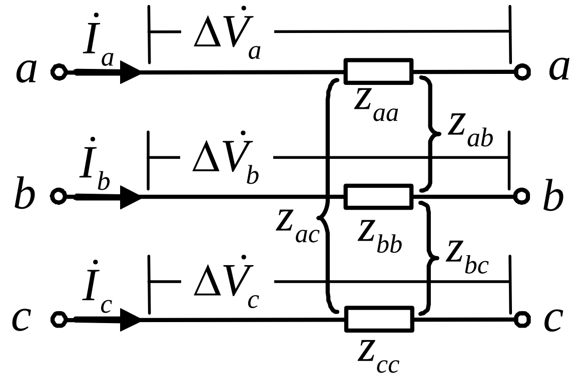


$$\Delta\dot{V}_{a(1)} = (z_s - z_m)\dot{I}_{a(1)}$$
$$\Delta\dot{V}_{b(1)} = (z_s - z_m)\dot{I}_{b(1)}$$
$$\Delta\dot{V}_{c(1)} = (z_s - z_m)\dot{I}_{c(1)}$$

$$\Delta\dot{V}_{a(2)} = (z_s - z_m)\dot{I}_{a(2)}$$
$$\Delta\dot{V}_{b(2)} = (z_s - z_m)\dot{I}_{b(2)}$$
$$\Delta\dot{V}_{c(2)} = (z_s - z_m)\dot{I}_{c(2)}$$

$$\Delta\dot{V}_{a(0)} = (z_s + 2z_m)\dot{I}_{a(0)}$$
$$\Delta\dot{V}_{b(0)} = (z_s + 2z_m)\dot{I}_{b(0)}$$
$$\Delta\dot{V}_{c(0)} = (z_s + 2z_m)\dot{I}_{c(0)}$$

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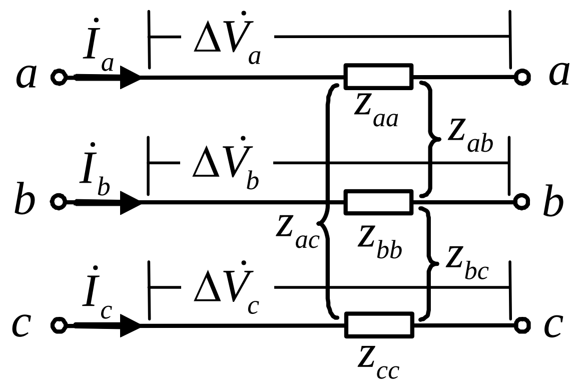
## 2. 序阻抗的概念——定义

$$\begin{bmatrix} \Delta\dot{V}_{a(1)} \\ \Delta\dot{V}_{a(2)} \\ \Delta\dot{V}_{a(0)} \end{bmatrix} = \begin{bmatrix} z_s - z_m & 0 & 0 \\ 0 & z_s - z_m & 0 \\ 0 & 0 & z_s + 2z_m \end{bmatrix} \begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix}$$



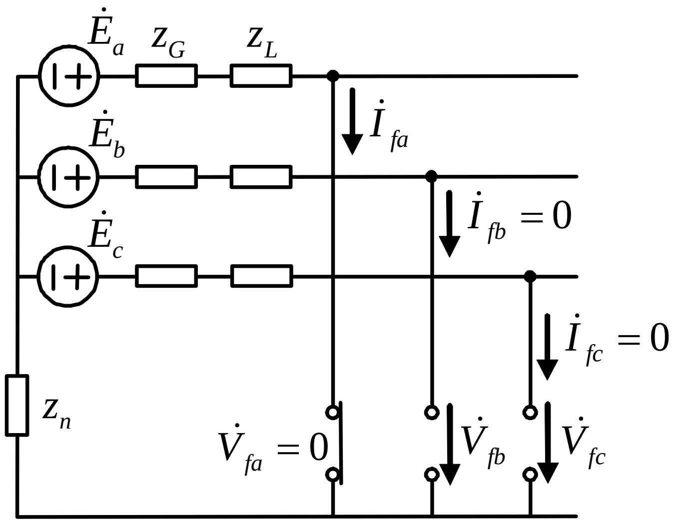

$$\Delta\dot{V}_{a(1)} = (z_s - z_m)\dot{I}_{a(1)}$$
$$\Delta\dot{V}_{b(1)} = (z_s - z_m)\dot{I}_{b(1)}$$
$$\Delta\dot{V}_{c(1)} = (z_s - z_m)\dot{I}_{c(1)}$$

$$\Delta\dot{V}_{a(2)} = (z_s - z_m)\dot{I}_{a(2)}$$
$$\Delta\dot{V}_{b(2)} = (z_s - z_m)\dot{I}_{b(2)}$$
$$\Delta\dot{V}_{c(2)} = (z_s - z_m)\dot{I}_{c(2)}$$

$$\Delta\dot{V}_{a(0)} = (z_s + 2z_m)\dot{I}_{a(0)}$$
$$\Delta\dot{V}_{b(0)} = (z_s + 2z_m)\dot{I}_{b(0)}$$
$$\Delta\dot{V}_{c(0)} = (z_s + 2z_m)\dot{I}_{c(0)}$$

序阻抗定义：$z_{(1)} = \Delta\dot{V}_{a(1)} / \dot{I}_{a(1)}$，$z_{(2)} = \Delta\dot{V}_{a(2)} / \dot{I}_{a(2)}$，$z_{(0)} = \Delta\dot{V}_{a(0)} / \dot{I}_{a(0)}$

## 3. 对称分量法在不对称短路计算中的应用



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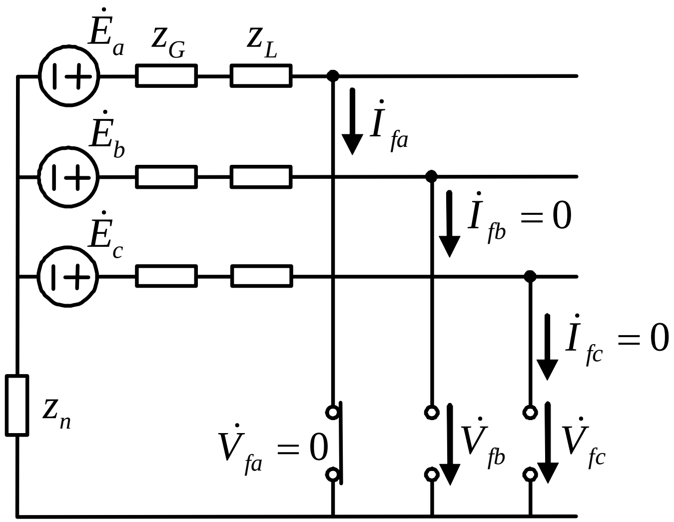


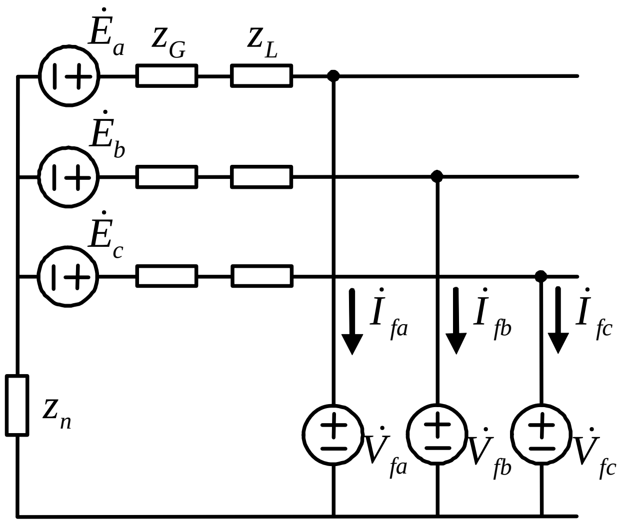

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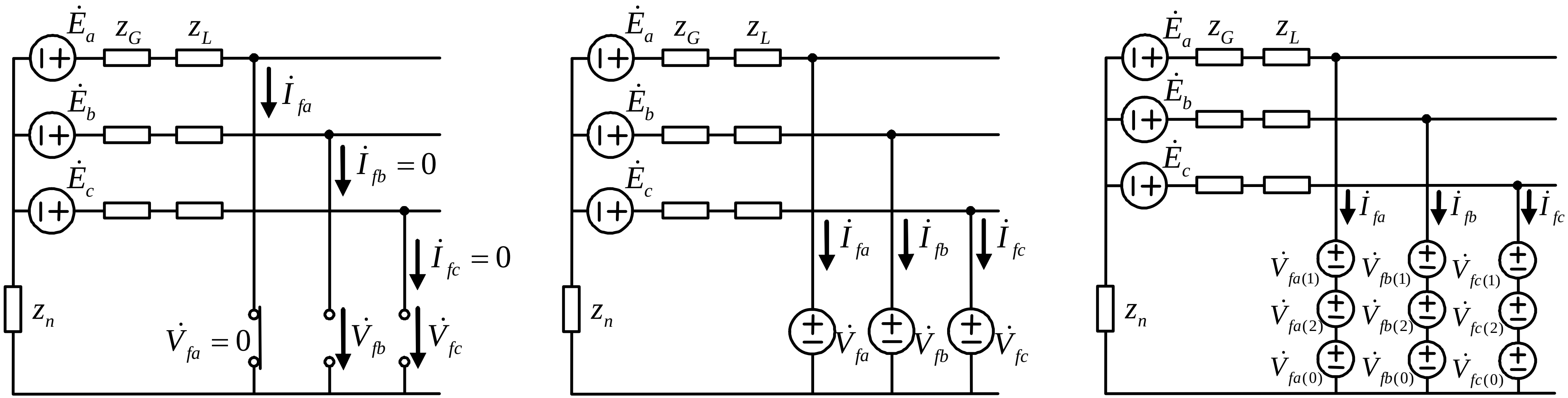
## 3. 对称分量法在不对称短路计算中的应用



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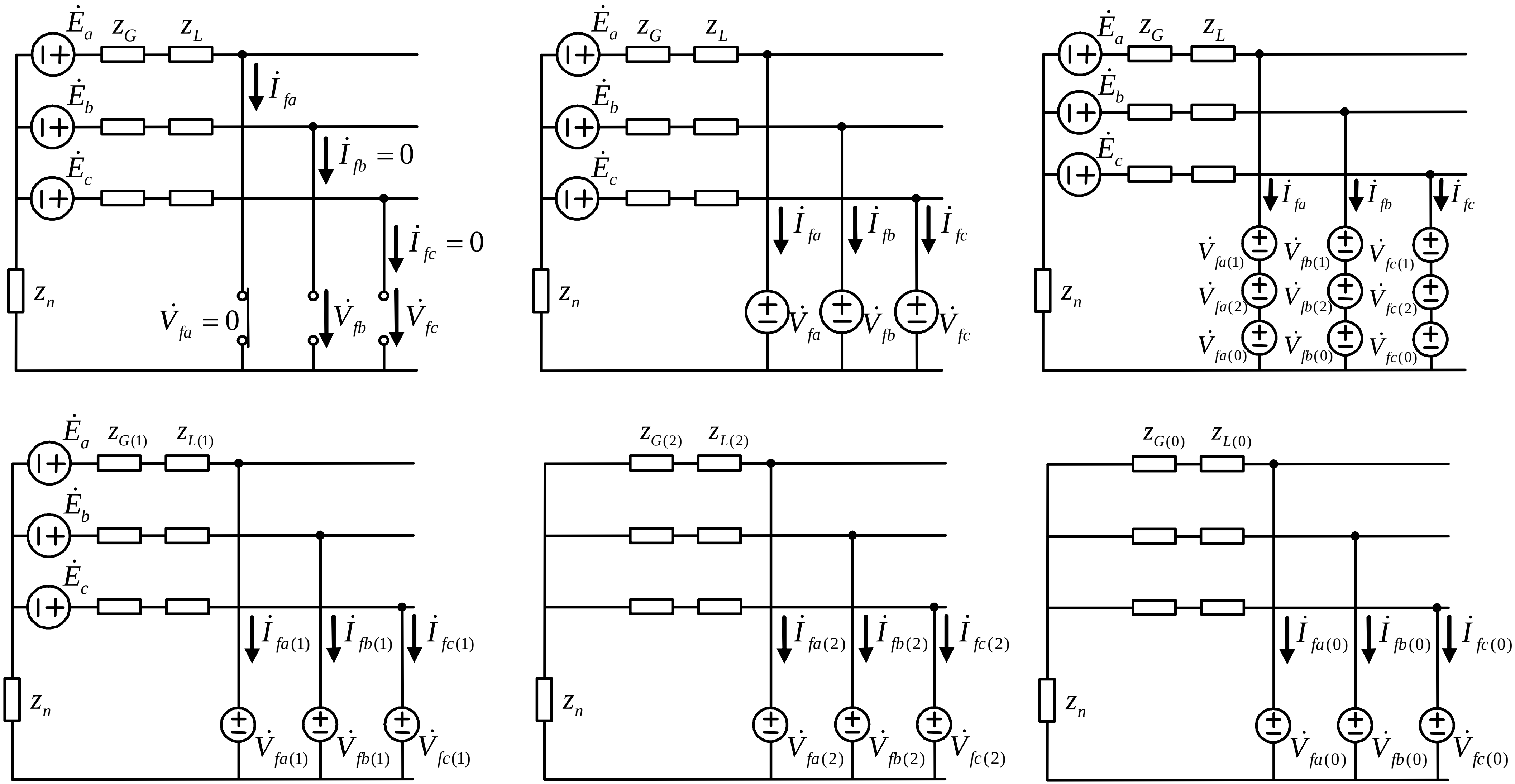

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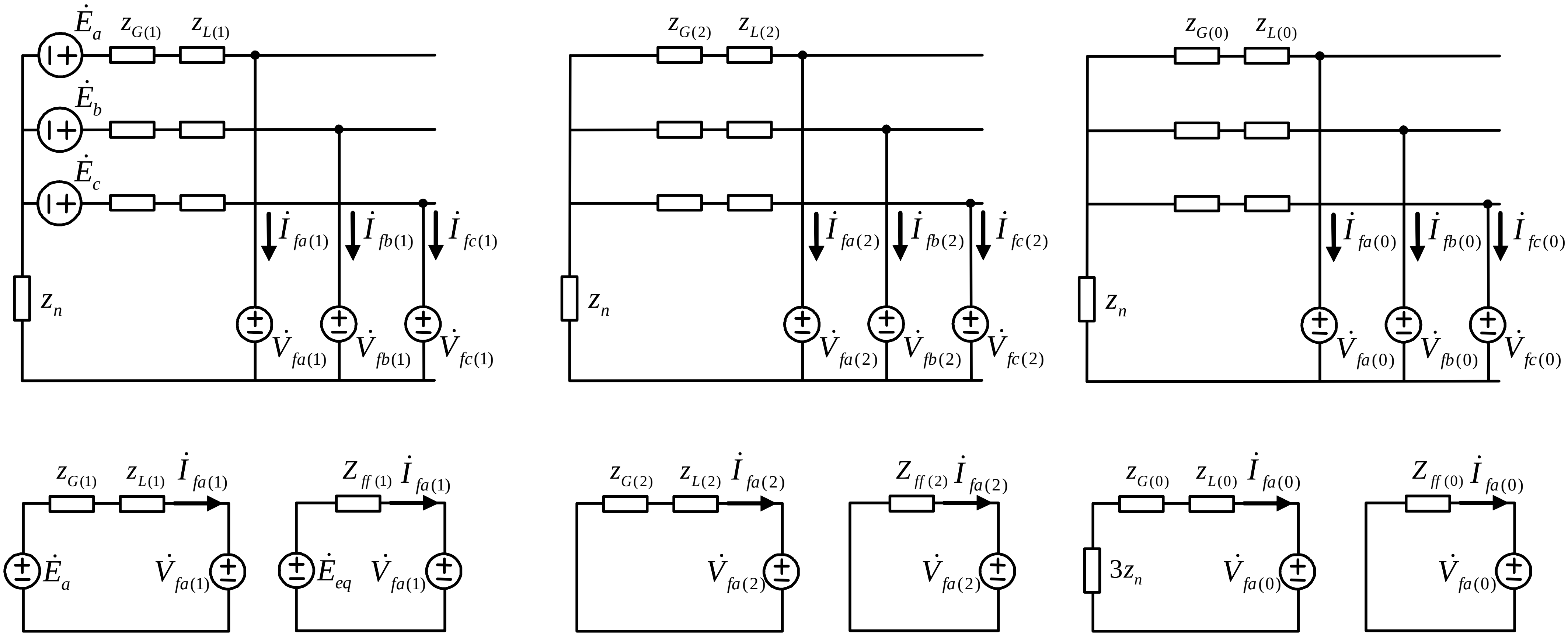
## 3. 对称分量法在不对称短路计算中的应用




$$\boxed{\dot{V}_{fa(1)} = \dot{E}_{eq} - Z_{ff(1)}\dot{I}_{fa(1)}}$$

$$\boxed{\dot{V}_{fa(2)} = -Z_{ff(2)}\dot{I}_{fa(2)}}$$

$$\boxed{\dot{V}_{fa(0)} = -Z_{ff(0)}\dot{I}_{fa(0)}}$$

# 7-1 对称分量法在不对称短路计算中的应用

## 3. 对称分量法在不对称短路计算中的应用

基本方法：用一组不对称电势源代替故障口的结构不对称

然后对称分量分解

基本前提：

三相对称——各序分量独立；

线性网络——叠加原理；

## 3. 对称分量法在不对称短路计算中的应用

基本方法：用一组不对称电势源代替故障口的结构不对称

然后对称分量分解

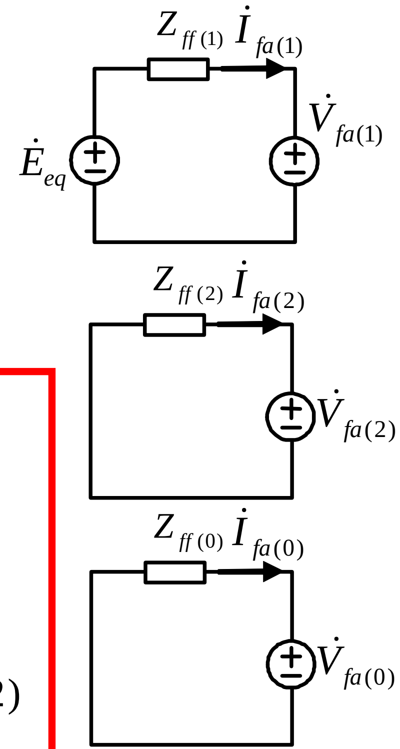
基本前提：

三相对称——各序分量独立；

线性网络——叠加原理；

序网方程

$$\dot{V}_{fa(1)} = \dot{E}_{eq} - Z_{ff(1)}\dot{I}_{fa(1)}$$
$$\dot{V}_{fa(2)} = -Z_{ff(2)}\dot{I}_{fa(2)}$$
$$\dot{V}_{fa(0)} = -Z_{ff(0)}\dot{I}_{fa(0)}$$



## 3. 对称分量法在不对称短路计算中的应用

基本方法：用一组不对称电势源代替故障口的结构不对称

然后对称分量分解

基本前提：

三相对称——各序分量独立；

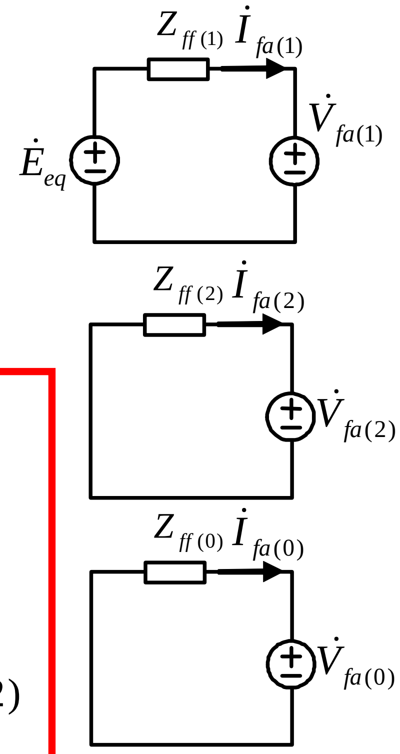
线性网络——叠加原理；

序网方程

$$\dot{V}_{fa(1)} = \dot{E}_{eq} - Z_{ff(1)}\dot{I}_{fa(1)}$$

$$\dot{V}_{fa(2)} = -Z_{ff(2)}\dot{I}_{fa(2)}$$

$$\dot{V}_{fa(0)} = -Z_{ff(0)}\dot{I}_{fa(0)}$$




+

故障口边界条件 → Solution

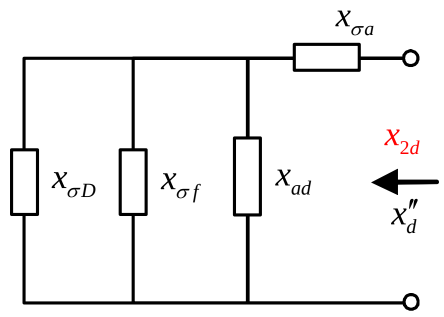
# 7-2 同步电机的负序和零序电抗

## 1. 确定发电机负序电抗的等值电路和计算公式

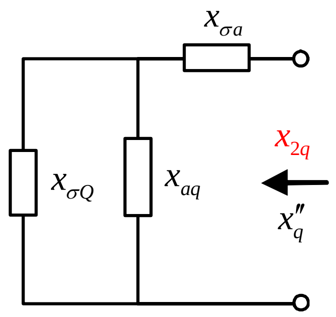
$$f^{(1)}: x_{(2)}^{(1)} = \sqrt{\left(x_d'' + \frac{x_{(0)}}{2}\right)\left(x_q'' + \frac{x_{(0)}}{2}\right)} - \frac{x_{(0)}}{2}$$

$$f^{(2)}: x_{(2)}^{(2)} = \sqrt{x_d'' x_q''}$$

$$f^{(1,1)}: x_{(2)}^{(1,1)} = \frac{x_d'' x_q'' + \sqrt{x_d'' x_q'' (2x_{(0)} + x_d'')(2x_{(0)} + x_q'')}}{2x_{(0)} + x_d'' + x_q''}$$




$$\boxed{x_{(2)} = \frac{1}{2}(x_d'' + x_q'')}$$




$$\boxed{x_{(2)} = \sqrt{x_d' x_q}}$$

# 7-2 同步电机的负序和零序电抗

## 1. 确定发电机负序电抗的等值电路和计算公式

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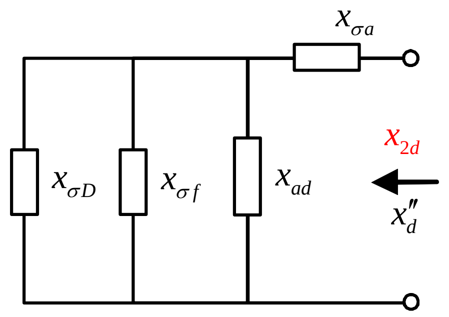
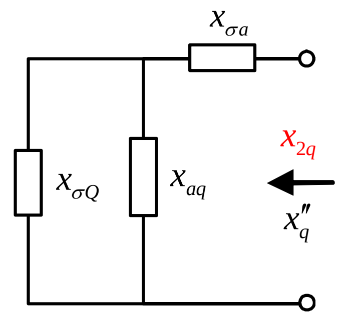



$$\boxed{x_{(2)} = \frac{1}{2}(x_d'' + x_q'')}$$




$$\boxed{x_{(2)} = \sqrt{x_d' x_q}}$$

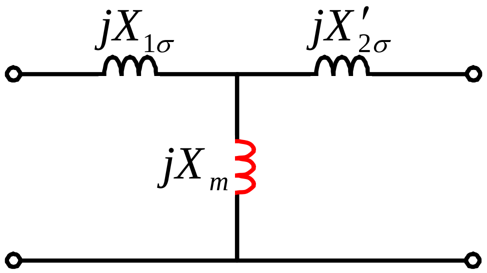
## 表7-2 同步电机负序和零序电抗的典型值

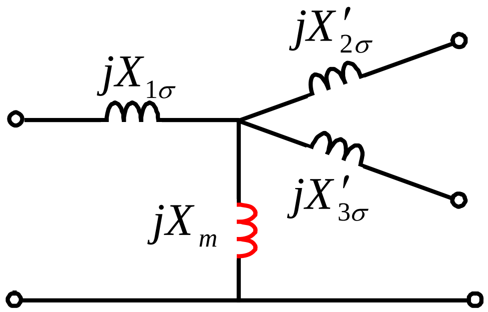
| 电机类型 | $x_{(2)}$ | $x_{(0)}$ | 电机类型 | $x_{(2)}$ | $x_{(0)}$ |
|---|---|---|---|---|---|
| 汽轮发电机 | 0.16 | 0.06 | 无阻尼绕组水轮发电机 | 0.45 | 0.07 |
| 有阻尼绕组水轮发电机 | 0.25 | 0.07 | 同步调相机、大型同步电动机 | 0.24 | 0.08 |

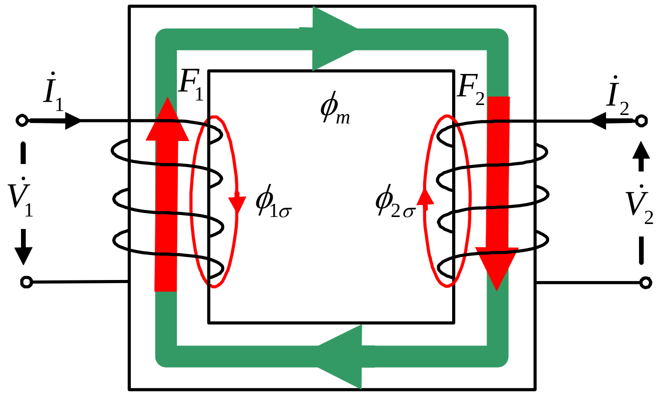
# 7-3 变压器的零序等值电路及其参数

## 1. 普通变压器的零序等值电路——结论1

(1) **电路结构相同**——变压器的一相等值电路反应了原副方的电磁耦合关系，对各序电流这种耦合关系相同；



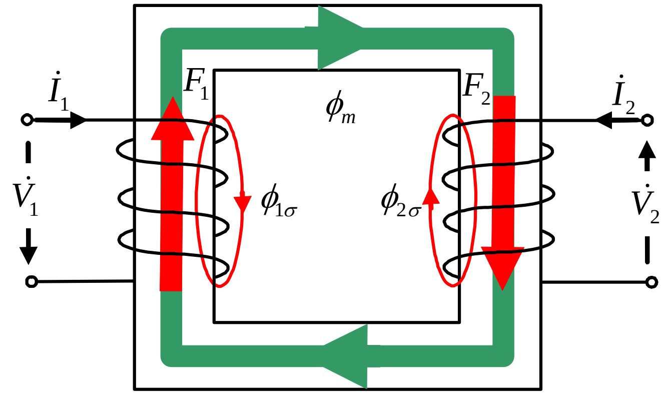



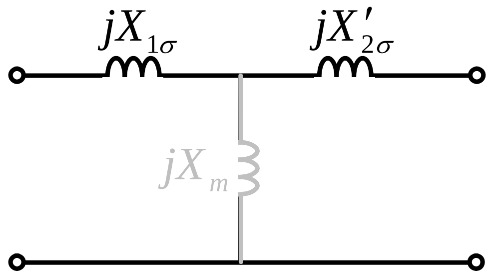



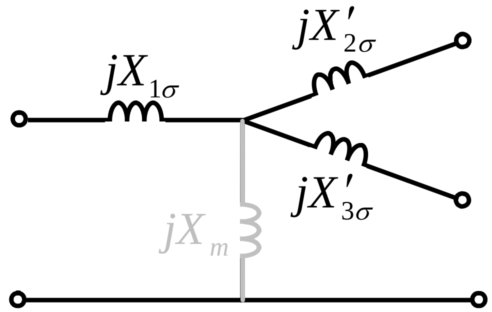
# 7-3 变压器的零序等值电路及其参数

## 1. 普通变压器的零序等值电路——结论2

(2)各序漏电抗相等——等值电路中采用漏电抗压降表示漏磁通感生的电势，漏电抗数值取决于对应的漏磁通路径的磁导率，绕组通过各序电流，其漏磁通路径相同，并且磁导率为常数$X_{\sigma(1)}= X_{\sigma(2)} =X_{\sigma(0)}$;；



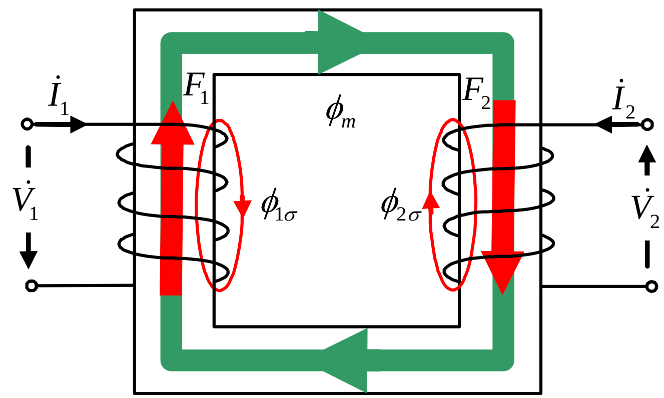



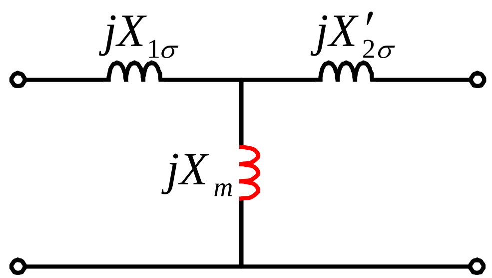



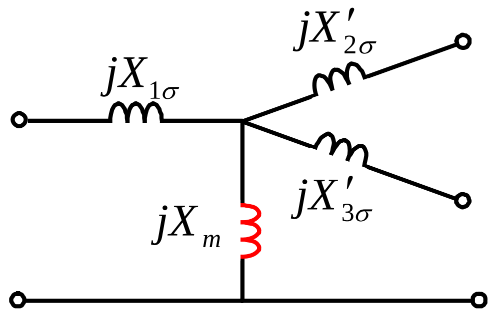
# 7-3 变压器的零序等值电路及其参数

## 1. 普通变压器的零序等值电路——结论3

(3) 激磁电抗——变压器主磁通感生的电势用激磁电抗压降表示，激磁电抗数值取决于主磁通路径的磁导率；



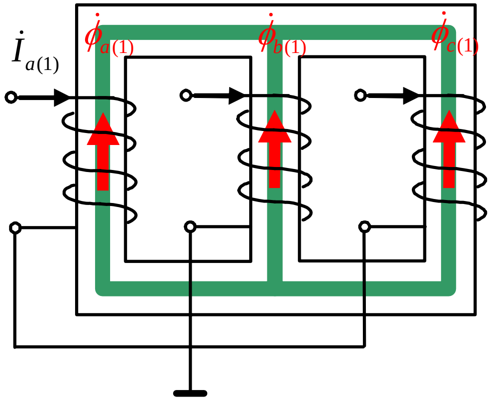



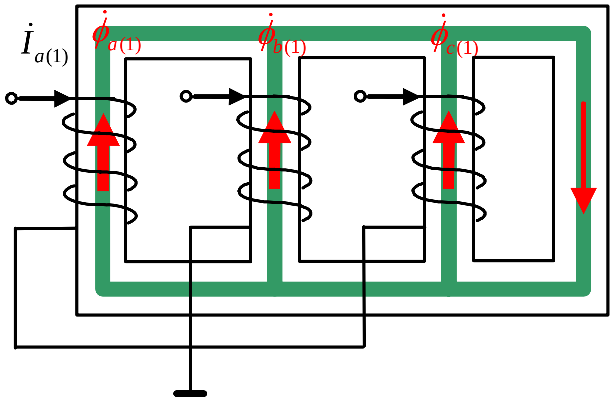



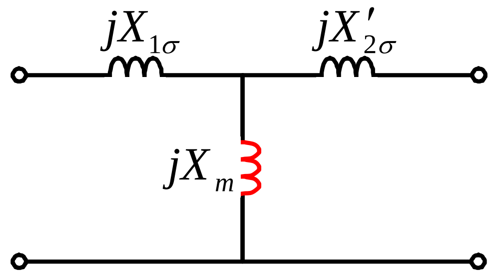
# 7-3 变压器的零序等值电路及其参数

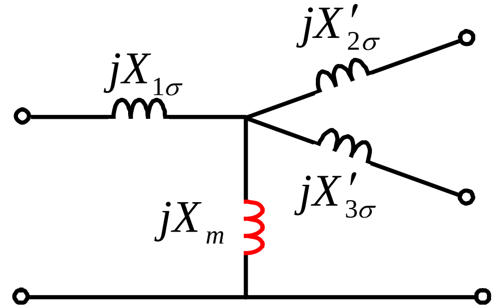
## 1. 普通变压器的零序等值电路——结论4

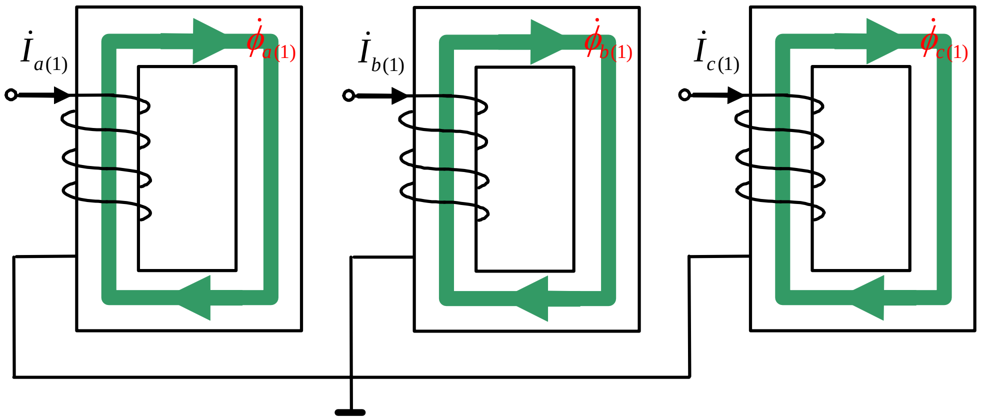
(4) 绕组通过正序或者负序电流，主磁通路径都是铁芯， $X_{m(1)}=X_{m(2)}$，并且磁导率远大于漏磁通路径，因此 $X_{m(1)}$ 远大于 $X_{\sigma(1)}$;



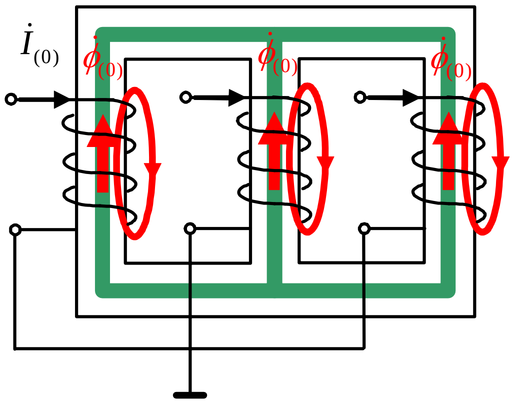



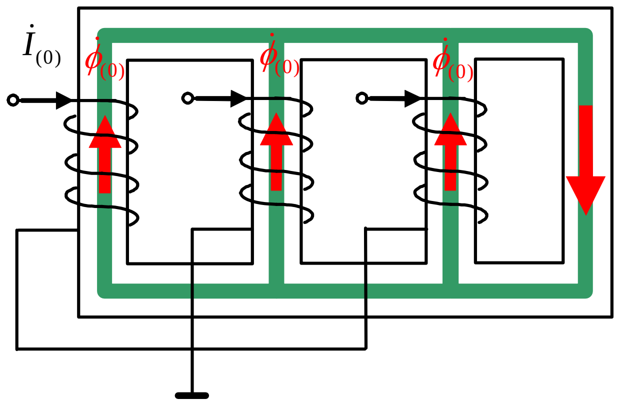

$$\boxed{\dot{\phi}_{a(1)}+\dot{\phi}_{b(1)}+\dot{\phi}_{c(1)}=0}$$

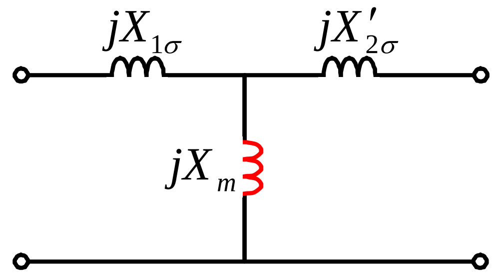
# 7-3 变压器的零序等值电路及其参数

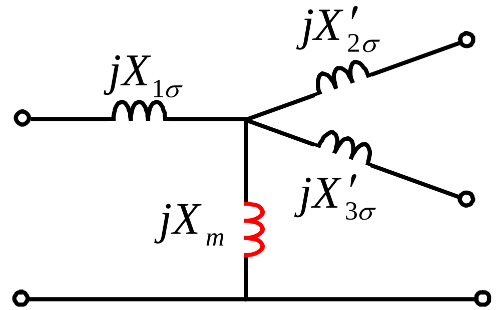
## 1. 普通变压器的零序等值电路——结论5

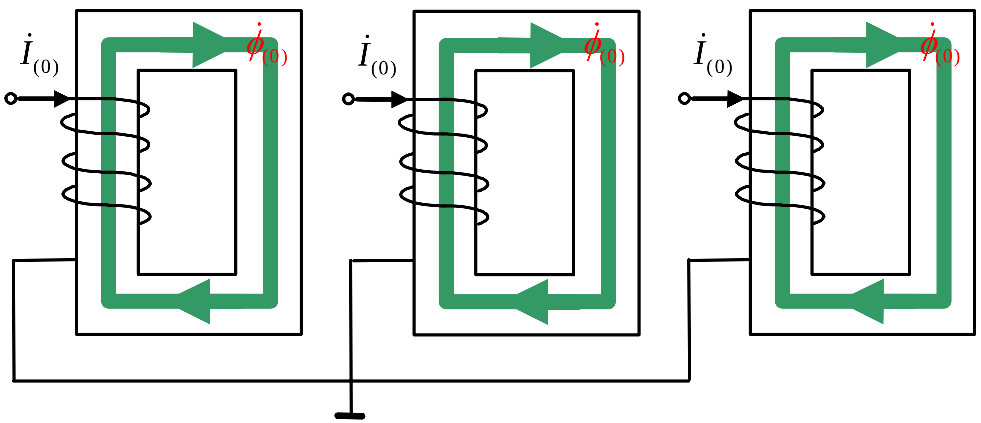
(5) 绕组通过零序电流，三相三柱式变压器零序主磁通路径只能沿铁芯和空气构成回路，磁导率与漏磁通路径相当，因此$X_{m(0)} < X_{m(1)}$;其他铁芯结构，$X_{m(0)} = X_{m(1)}$ ;



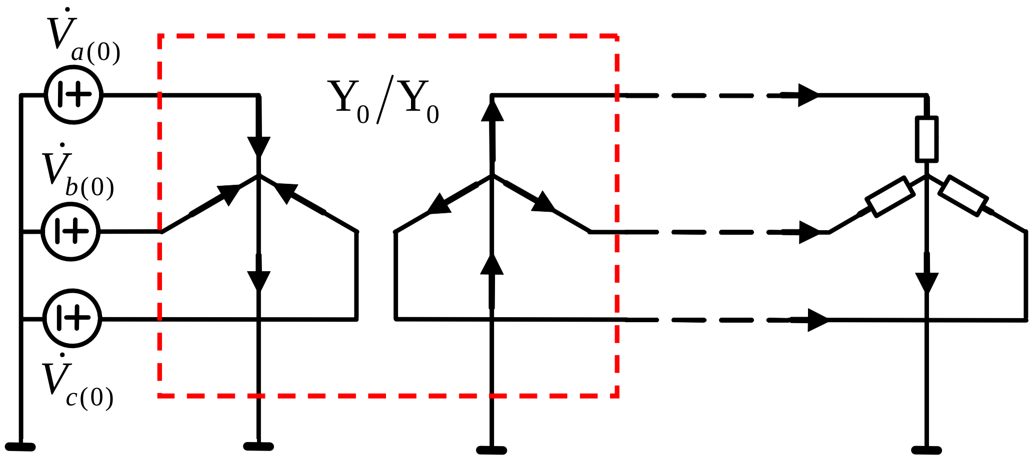



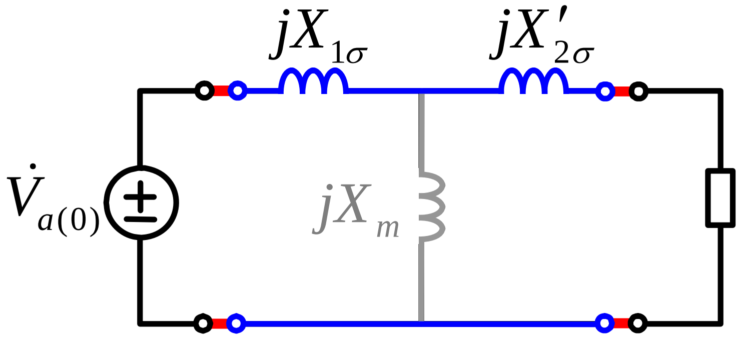



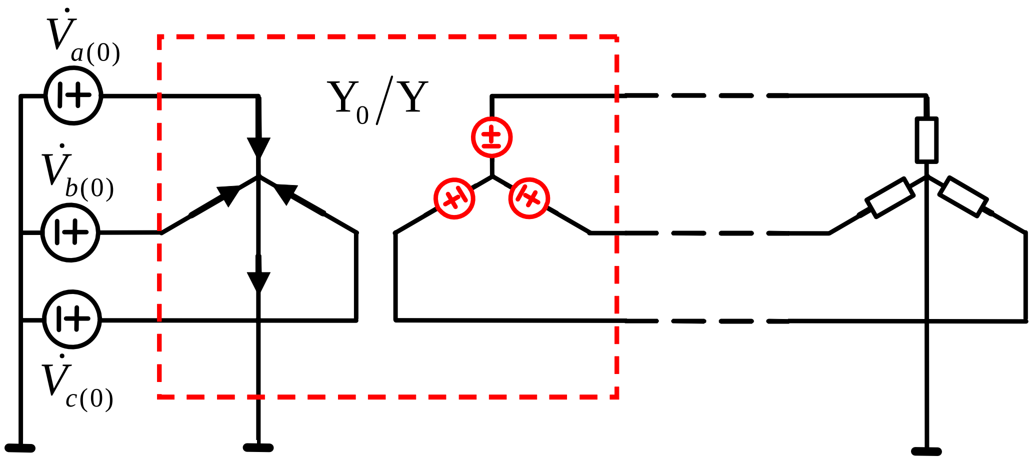

$$\boxed{\dot\phi_{a(0)} = \dot\phi_{b(0)} = \dot\phi_{c(0)}}$$

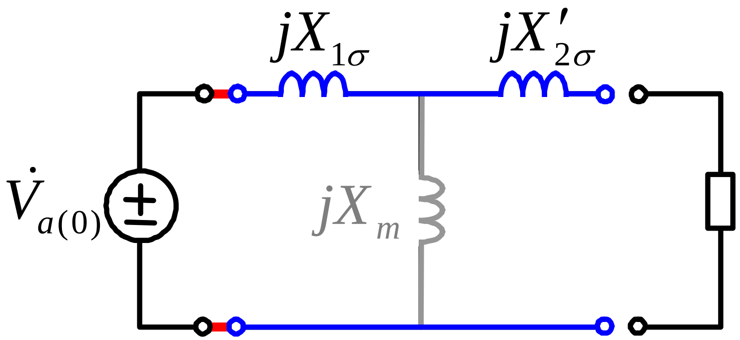
# 7-3 变压器的零序等值电路及其参数

## 2. 变压器的零序等值电路与外电路的联接



# 7-3 变压器的零序等值电路及其参数

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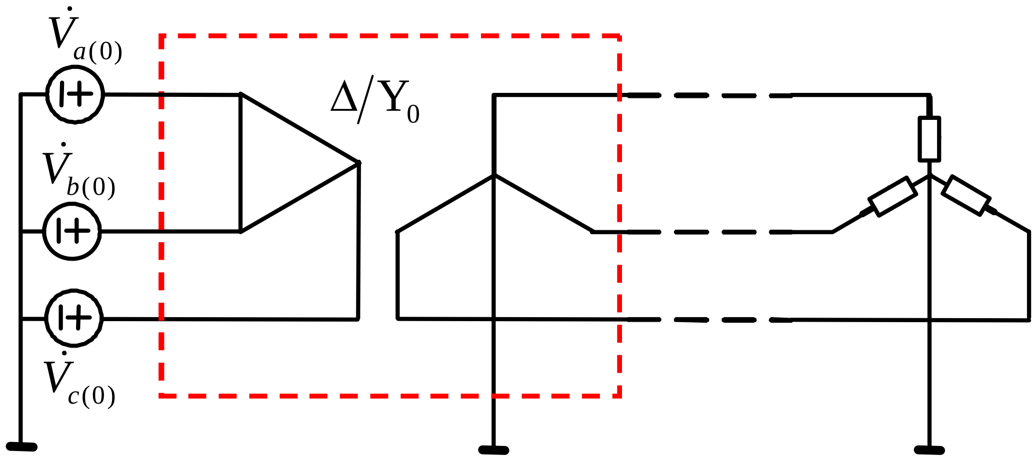
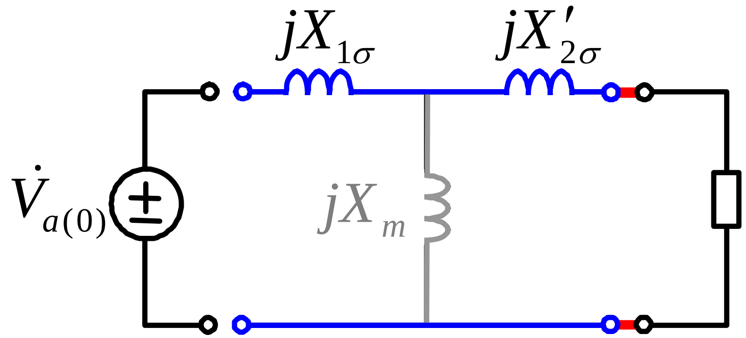
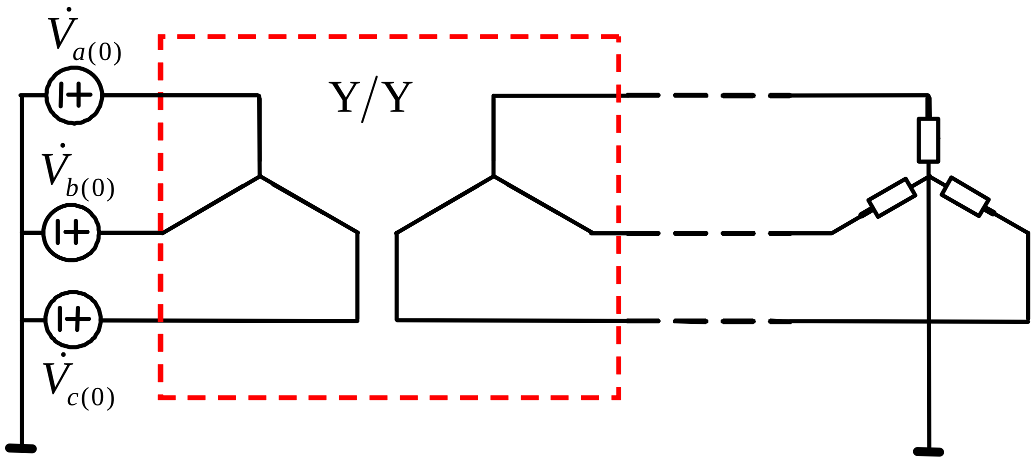
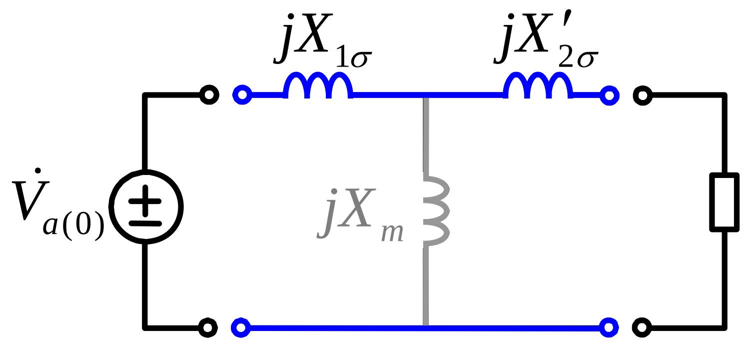
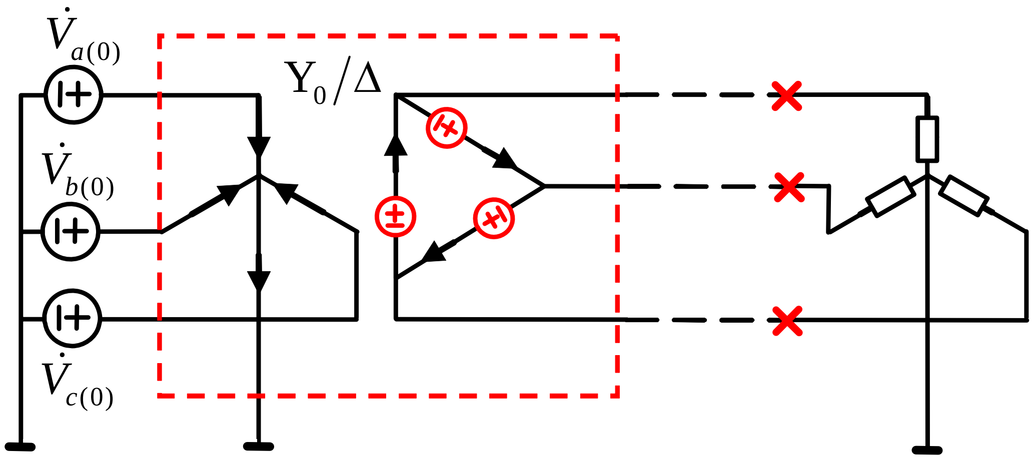


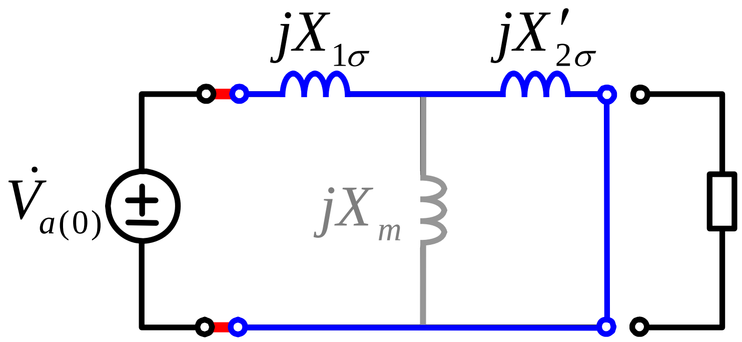



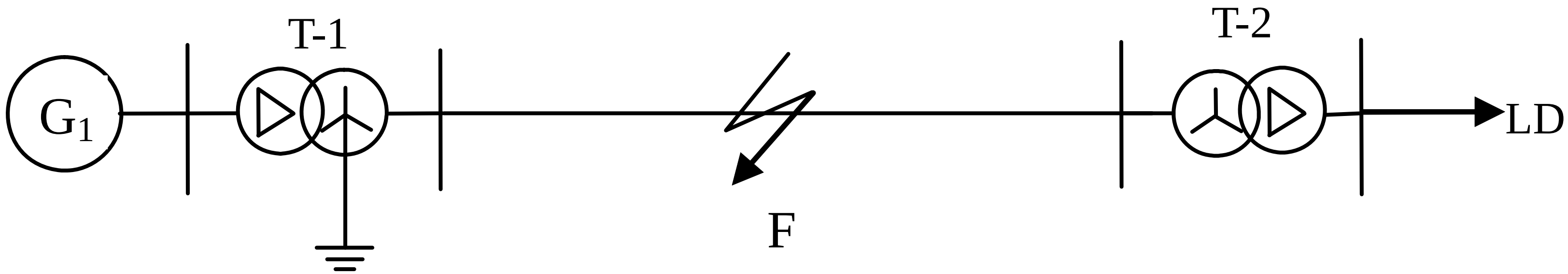



## 2. 变压器的零序等值电路与外电路的联接

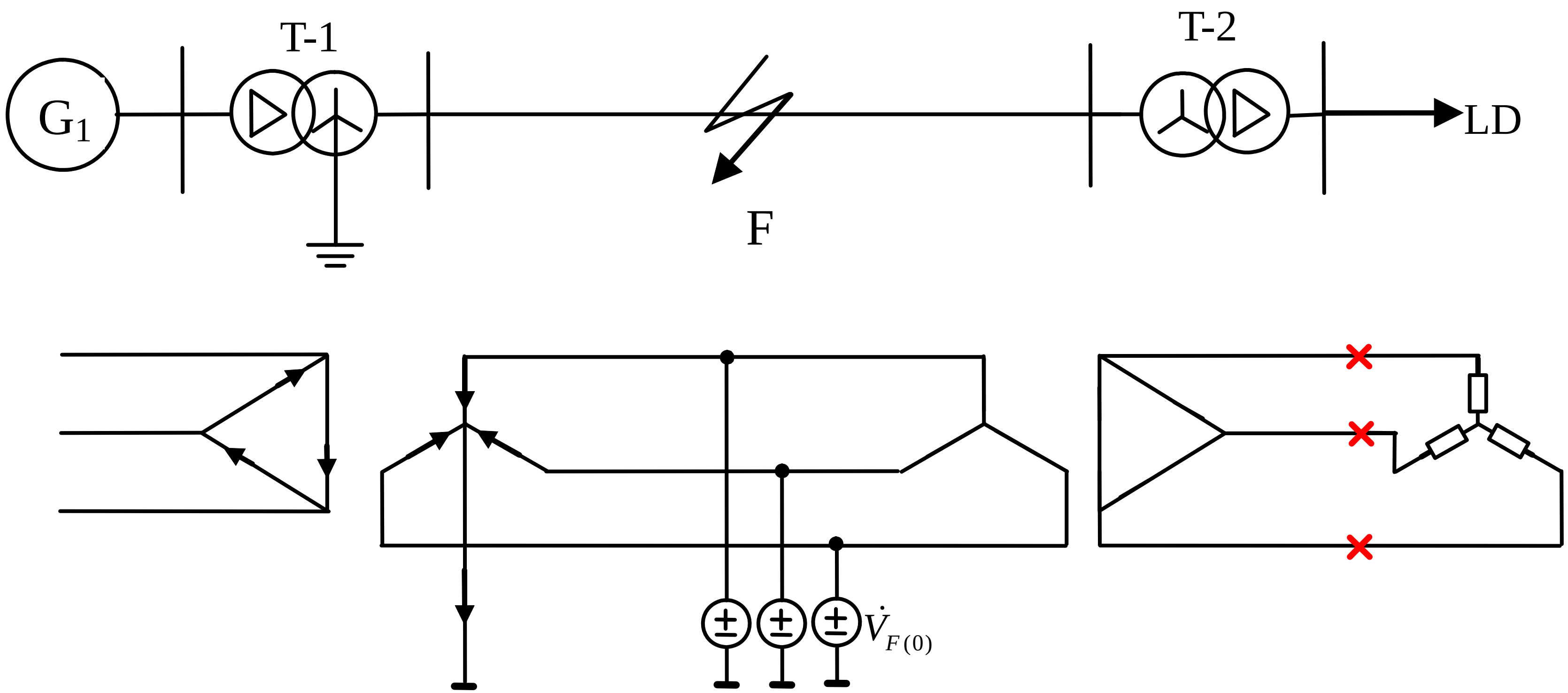


# 2. 变压器的零序等值电路与外电路的联接——举例



# 2. 变压器的零序等值电路与外电路的联接——举例



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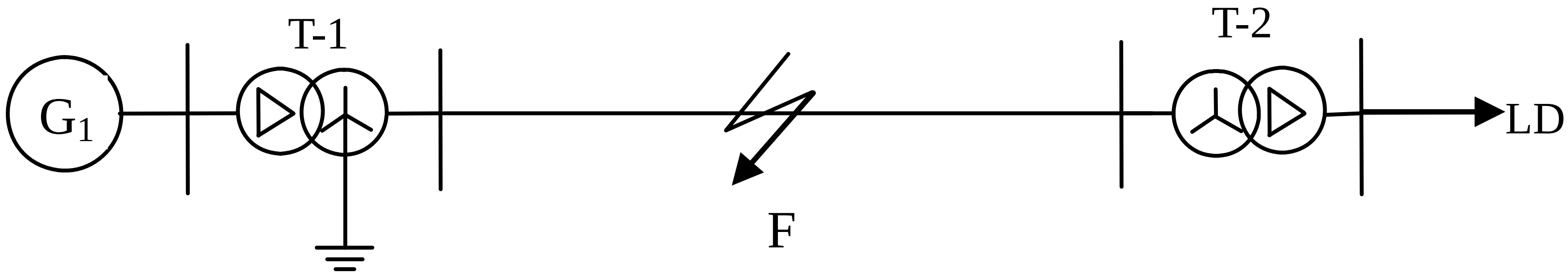


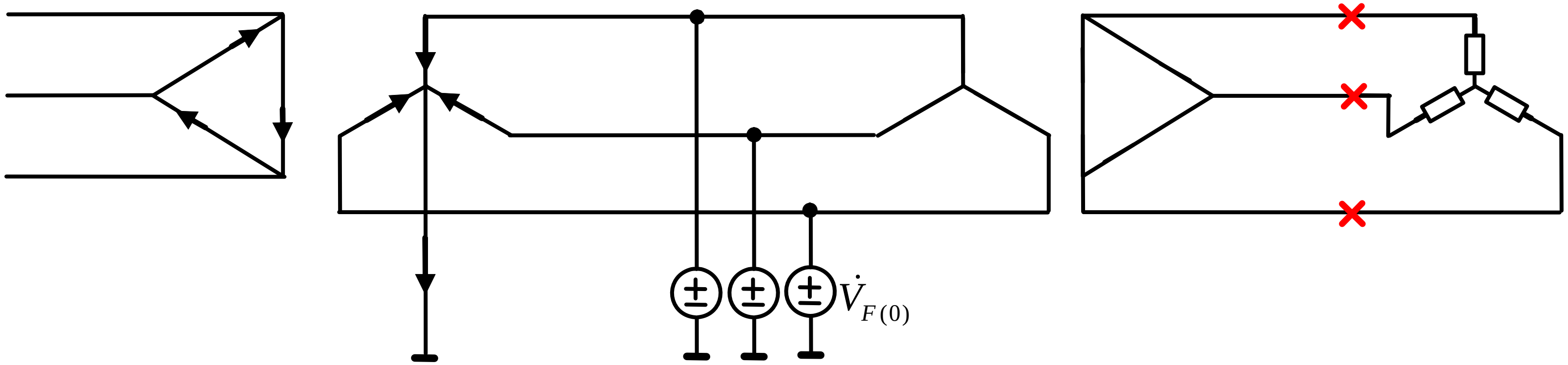


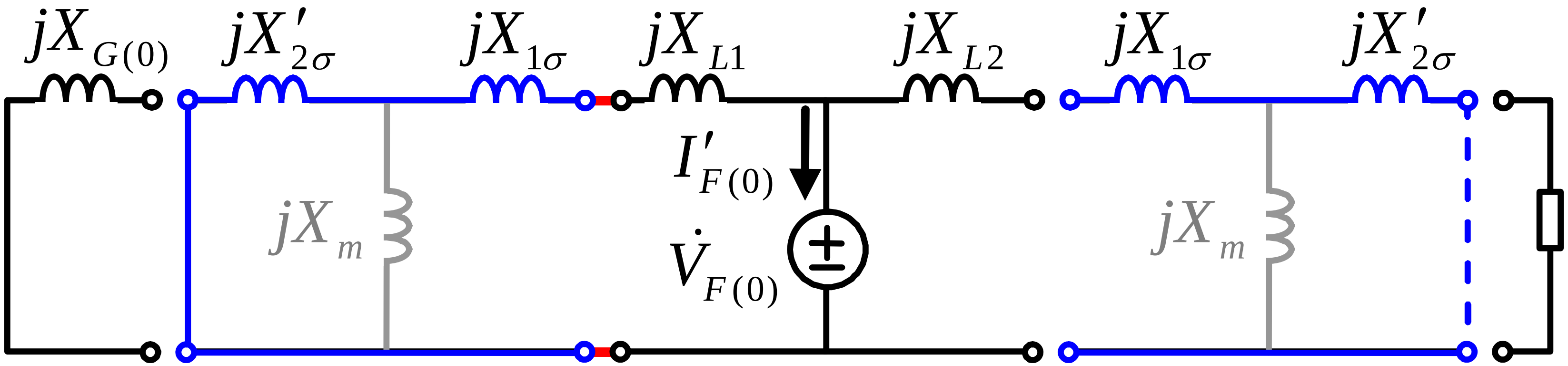

# 2. 变压器的零序等值电路与外电路的联接——举例

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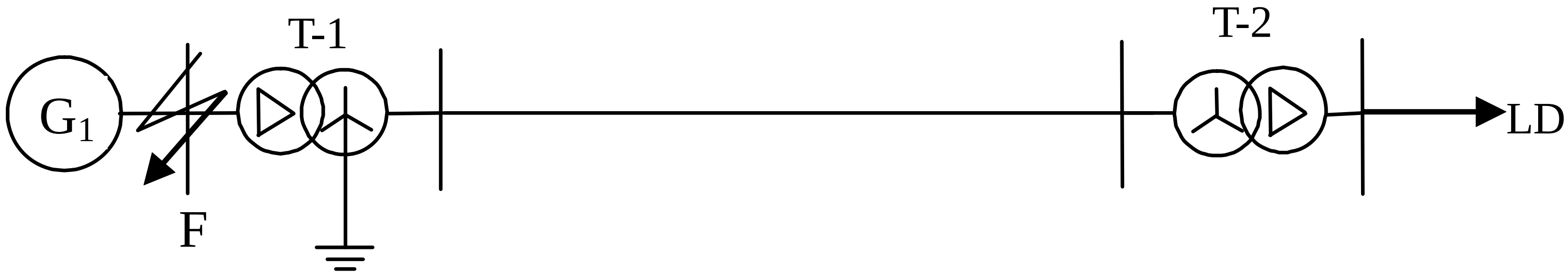


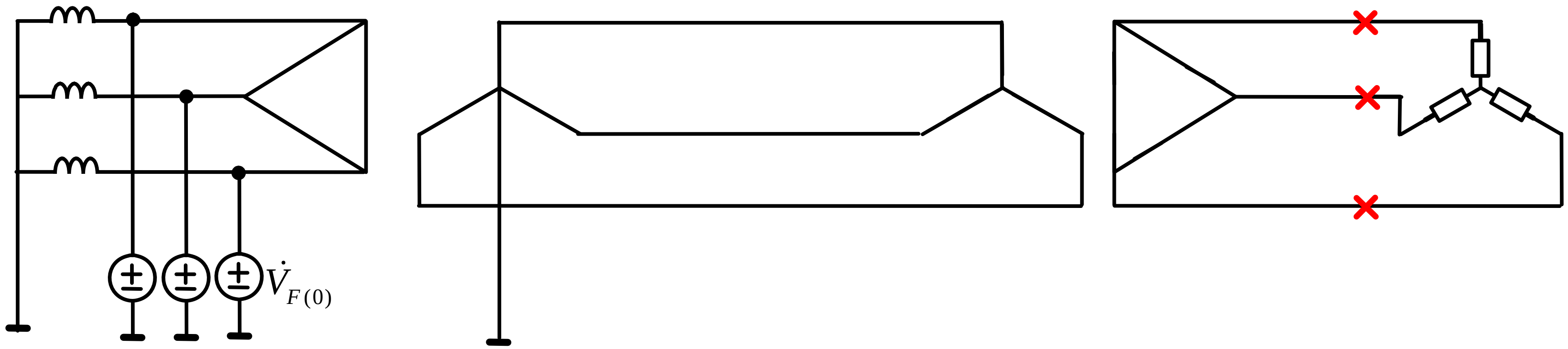

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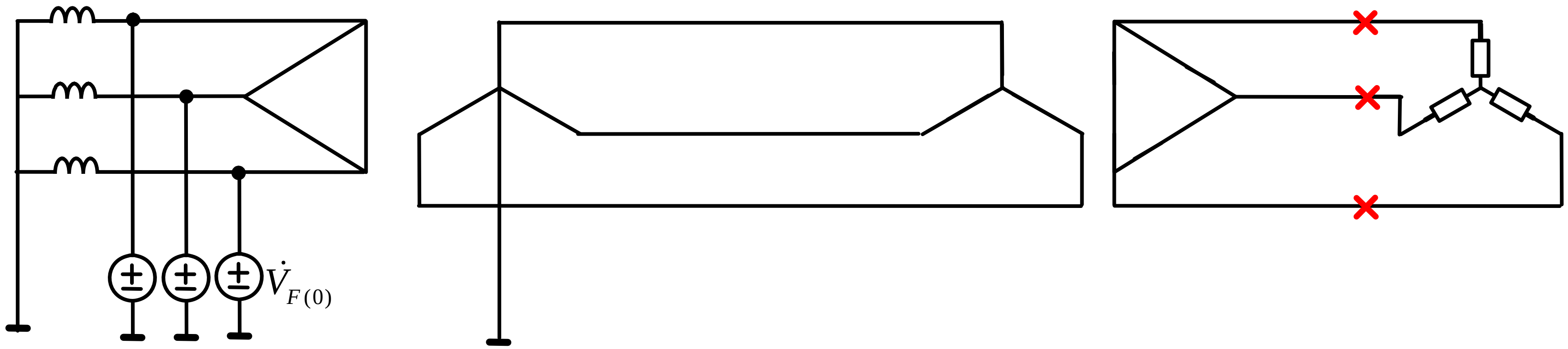
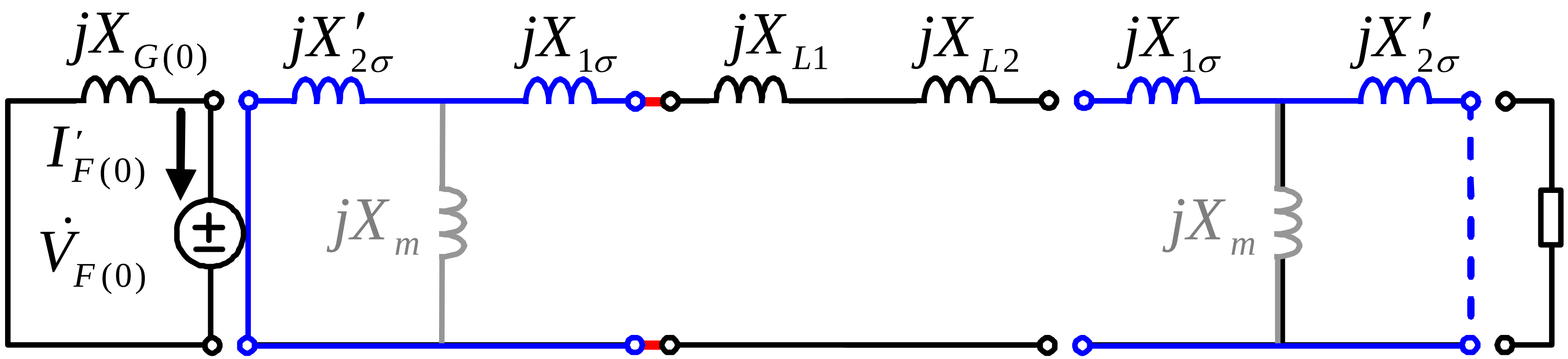
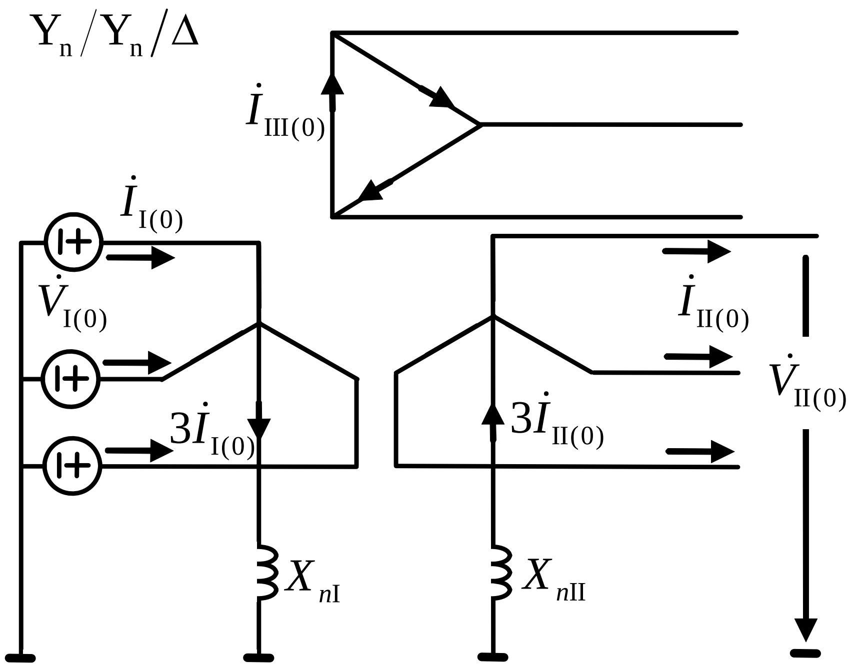


# 7-3 变压器的零序等值电路及其参数

## 3.中性点有接地阻抗的变压器零序等值电路



# 7-3 变压器的零序等值电路及其参数

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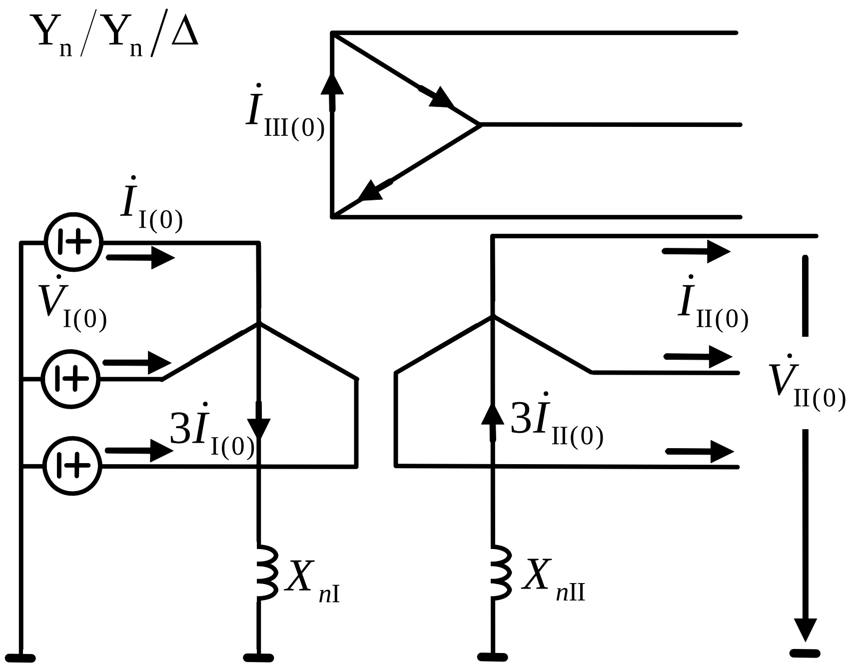
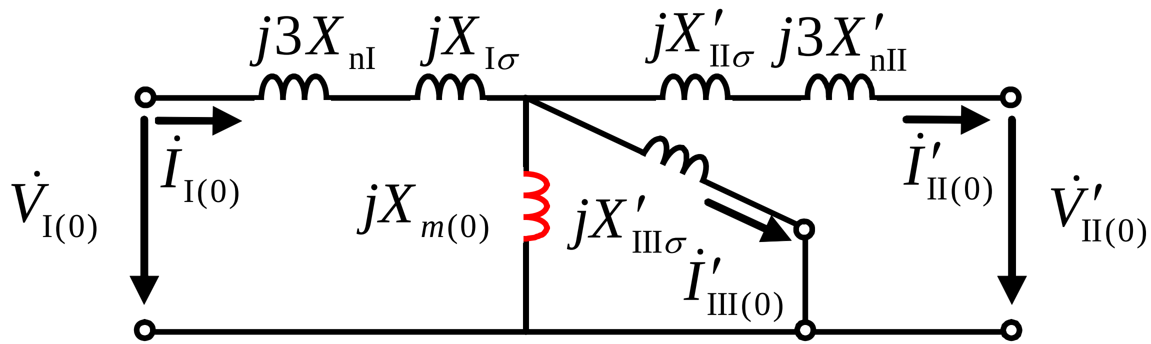
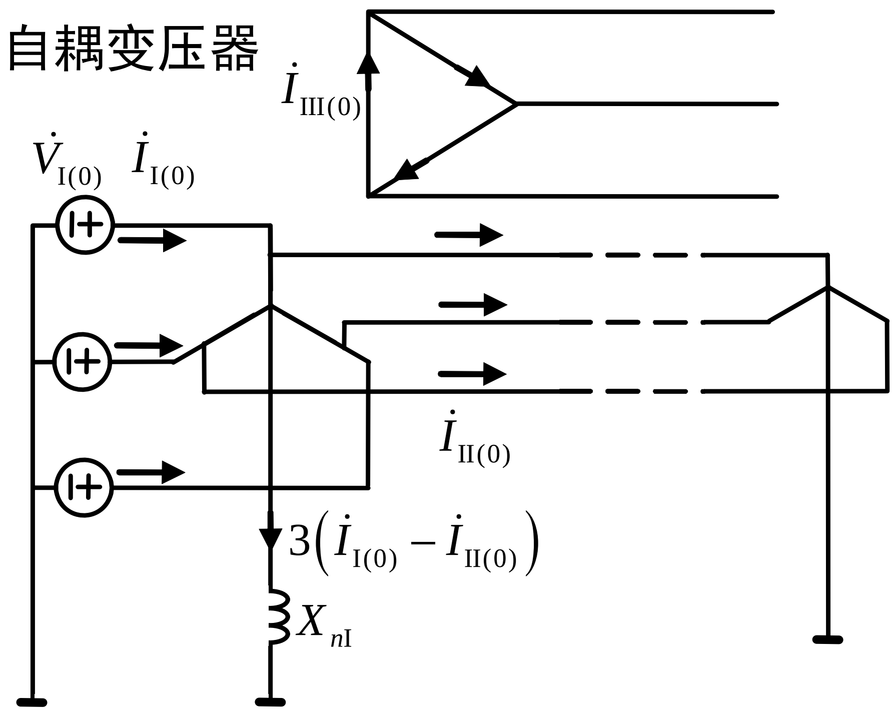


# 7-3 变压器的零序等值电路及其参数

## 4.自耦变压器的零序等值电路及其参数*




自耦变压器的特点：

(1) 原副方之间有直接的电气联系；

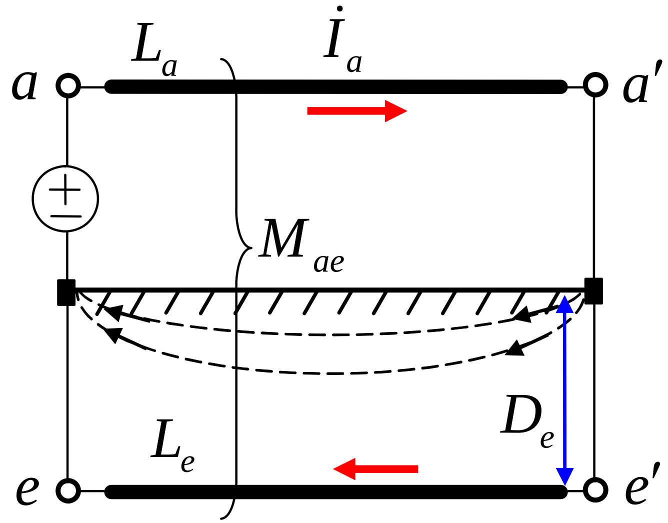
(2) 中性点入地电流取决于原副方零序电流

(3) 中性点接地阻抗对各侧绕组零序参数均有影响；

# 7-4 架空输电线的零序阻抗及其等值电路

## 1. 单导线——大地回路的自阻抗

自阻抗:单导线以大地为回路时对应于单位长度导线的回路阻抗



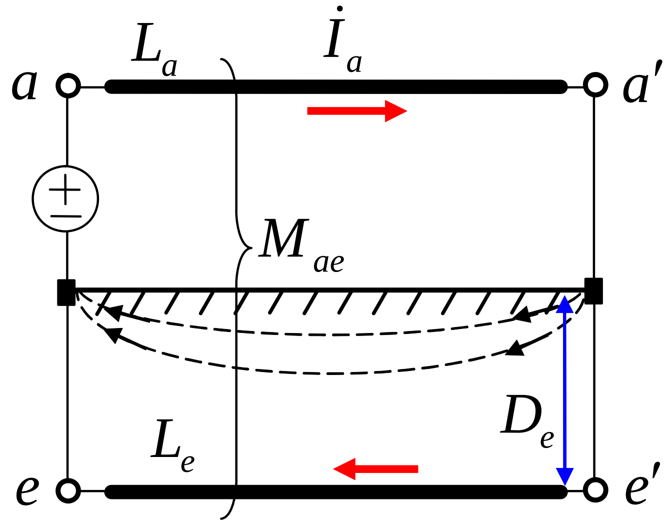
# 7-4 架空输电线的零序阻抗及其等值电路

## 1. 单导线—大地回路的自阻抗

自阻抗:单导线以大地为回路时对应于单位长度导线的回路阻抗

$$\{L\}_{\mathrm{H/m}} = \frac{\mu_0}{2\pi}\left[\ln\frac{2l}{D_S} - 1\right]$$

$$\{M\}_{\mathrm{H/m}} = \frac{\mu_0}{2\pi}\left[\ln\frac{2l}{D} - 1\right]$$



# 7-4 架空输电线的零序阻抗及其等值电路

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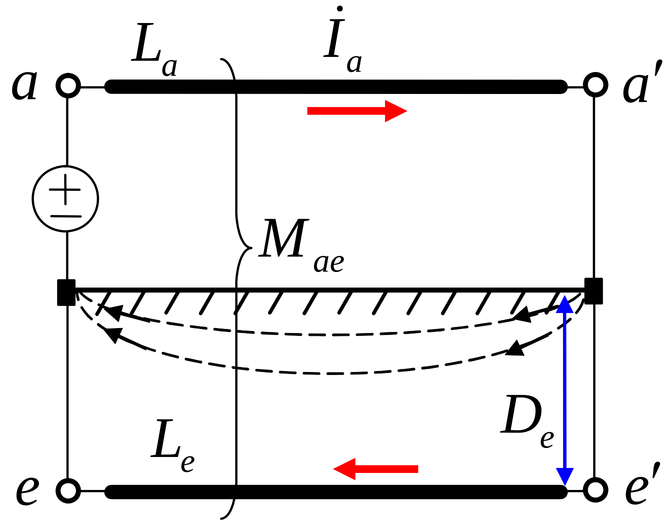



$$\{L\}_{\mathrm{H/m}} = \frac{\mu_0}{2\pi}\left[\ln\frac{2l}{D_S} - 1\right]$$

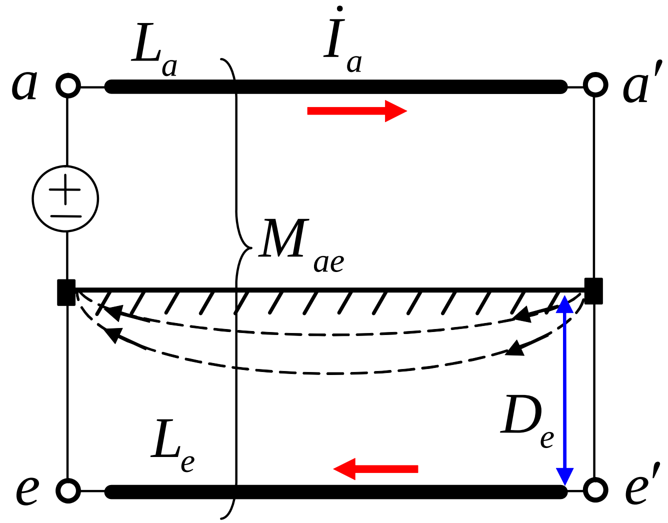
$$\{M\}_{\mathrm{H/m}} = \frac{\mu_0}{2\pi}\left[\ln\frac{2l}{D} - 1\right]$$

$$\{L_S\}_{\mathrm{H/m}} = L_a + L_e - 2M_{ae} = 2\times10^{-7}\ln\frac{D_e}{D_S}$$

# 7-4 架空输电线的零序阻抗及其等值电路

## 1. 单导线——大地回路的自阻抗

自阻抗:单导线以大地为回路时对应于单位长度导线的回路阻抗




$$\{L\}_{\mathrm{H/m}} = \frac{\mu_0}{2\pi}\left[\ln\frac{2l}{D_S} - 1\right]$$

$$\{M\}_{\mathrm{H/m}} = \frac{\mu_0}{2\pi}\left[\ln\frac{2l}{D} - 1\right]$$

$$\{L_S\}_{\mathrm{H/m}} = L_a + L_e - 2M_{ae} = 2\times10^{-7}\ln\frac{D_e}{D_S}$$

$$\{z_S\}_{\Omega/\mathrm{km}} = r_a + r_e + j\omega L_S = r_a + r_e + j0.1445\lg\frac{D_e}{D_S}$$

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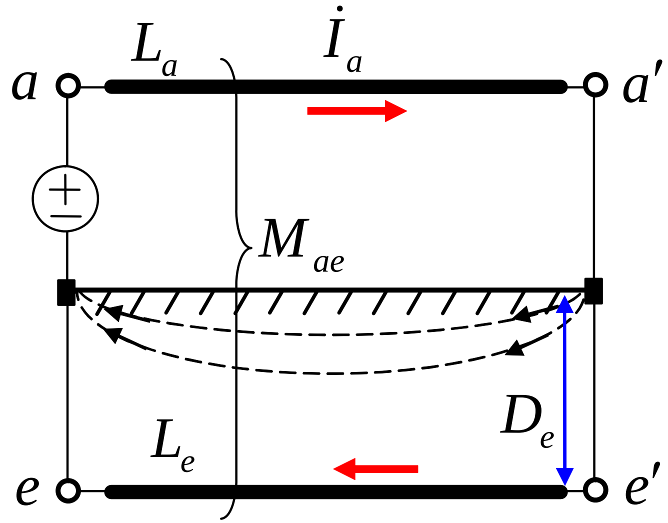
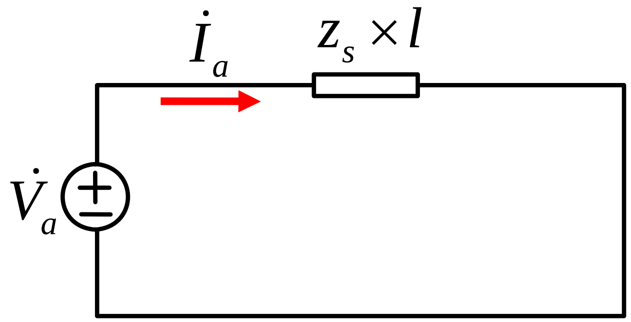
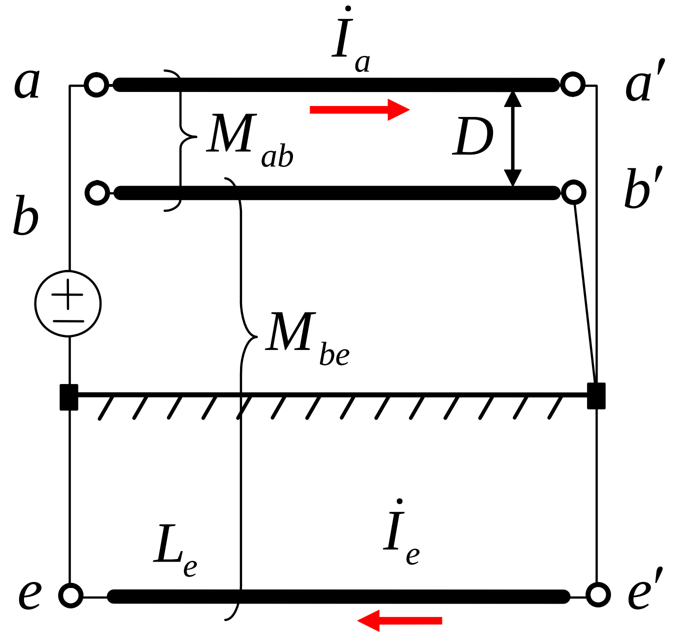


# 7-4 架空输电线的零序阻抗及其等值电路

## 2. 两平行单导线——大地回路间的互阻抗

互阻抗:一个回路通过单位电流时，在另一个回路单位长度上产生的压降



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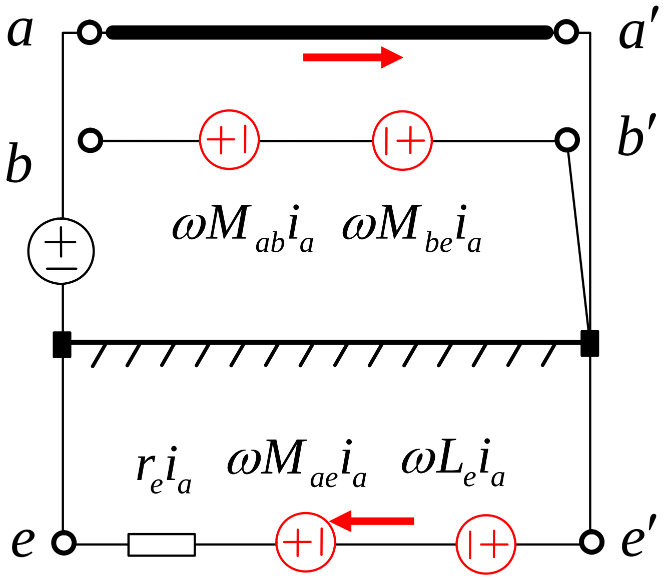


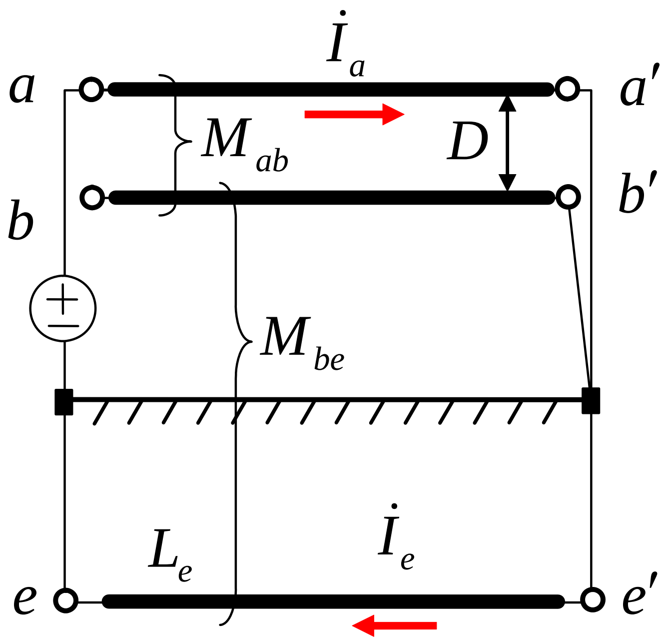


$$\psi_{bb'} = \left(M_{ab} - M_{be}\right) i_a$$

$$\psi_{ee'} = \left(M_{ae} - L_e\right) i_a$$

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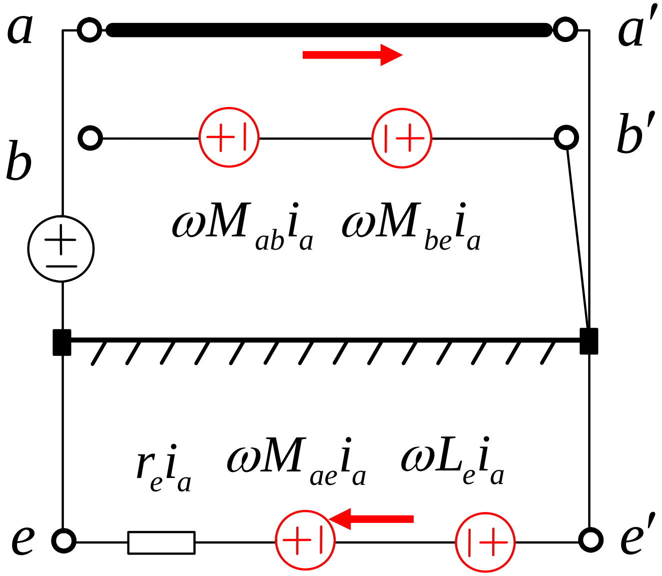


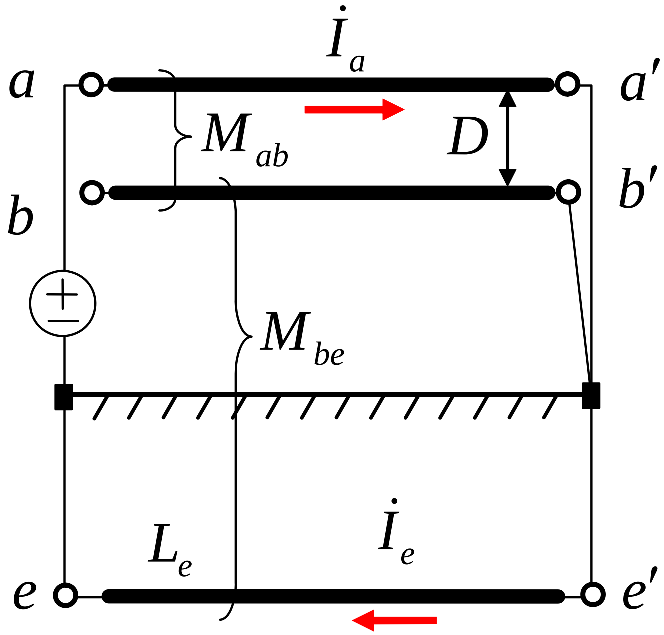


$$\psi_{bb'} = \left(M_{ab} - M_{be}\right) i_a$$

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$$\left\{\Delta \dot{E}\right\}_{\Omega/\mathrm{km}} = j\omega\left[M_{ab} - M_{be} + L_e - M_{ae}\right]\dot{I}_a$$

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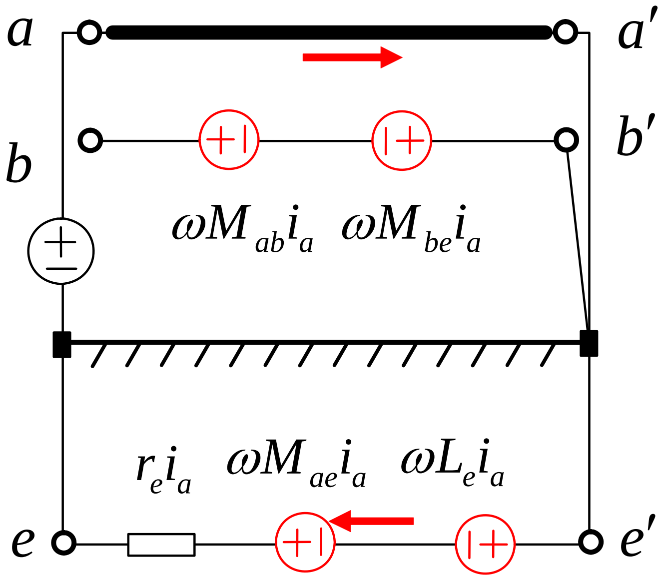


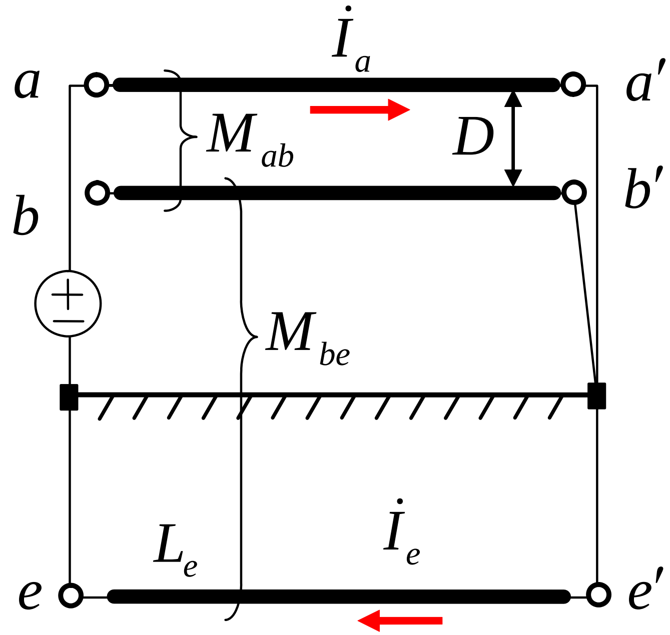


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$$\left\{z_m\right\}_{\Omega/\mathrm{km}} = r_e + j\omega\left(M_{ab} - M_{be} - M_{ae} + L_e\right) = r_e + j0.1445\lg\frac{D_e}{D}$$

# 7-4 架空输电线的零序阻抗及其等值电路

## 3. 三相输电线路的零序阻抗

$$\dot{V}_a = z_s \dot{I}_a + z_m \dot{I}_b + z_m \dot{I}_c$$

$$\dot{V}_{a(1)} = \left(z_s - z_m\right) \dot{I}_{a(1)}$$

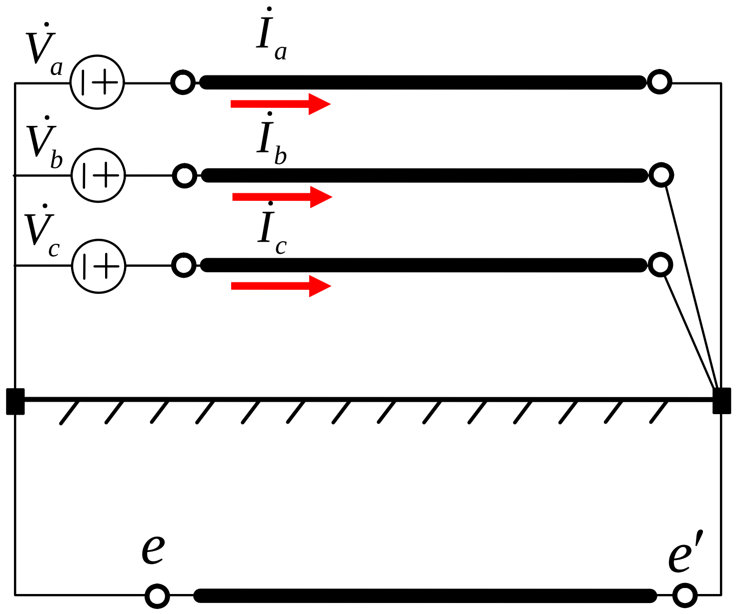
$$\dot{V}_{a(2)} = \left(z_s - z_m\right) \dot{I}_{a(2)}$$

$$\dot{V}_{a(0)} = \left(z_s + 2z_m\right) \dot{I}_{a(0)}$$

$$z_{(1)} = z_s - z_m$$

$$z_{(2)} = z_s - z_m$$

$$z_{(0)} = z_s + 2z_m$$



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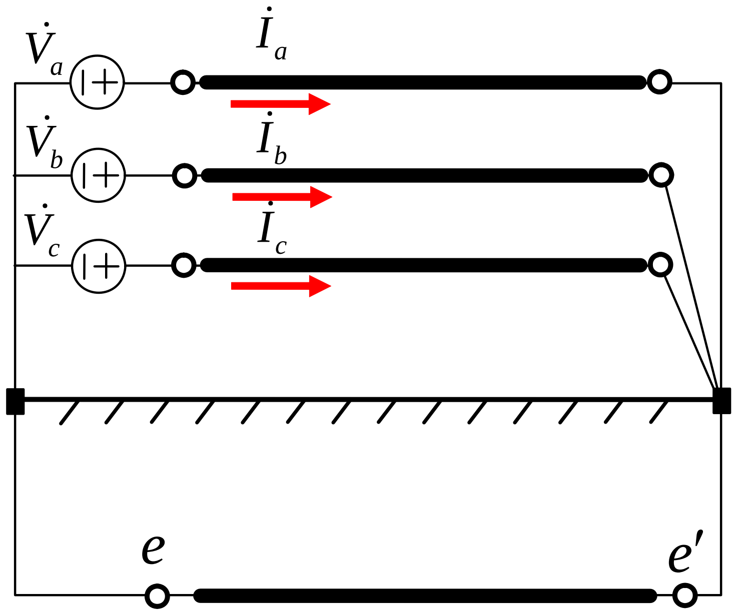


$$\dot{V}_{a(1)} = \left(z_s - z_m\right) \dot{I}_{a(1)}$$
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$$z_{(1)} = z_s - z_m$$
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$$\left\{L_S\right\}_{\mathrm{H/m}} = L_a + L_e - 2M_{ae}$$

$$\left\{z_S\right\}_{\Omega/\mathrm{km}} = r_a + r_e + j\omega L_S$$

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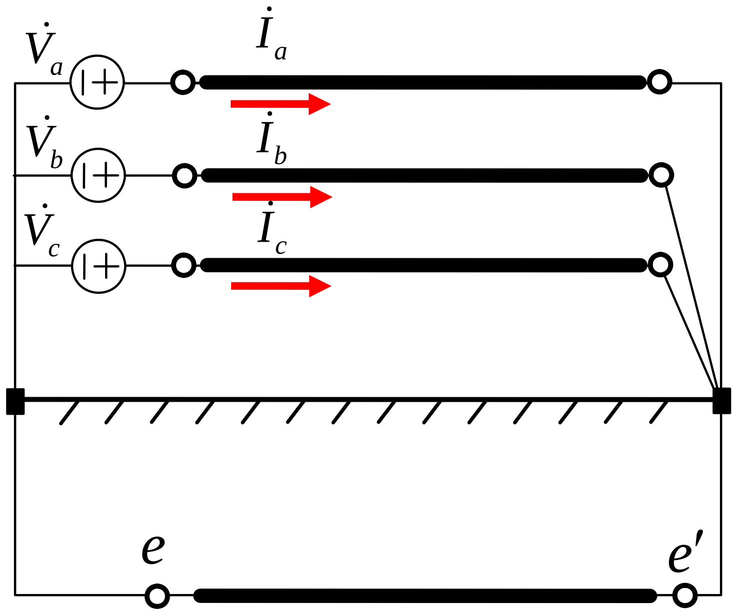


$$\dot{V}_{a(1)} = (z_s - z_m)\dot{I}_{a(1)}$$
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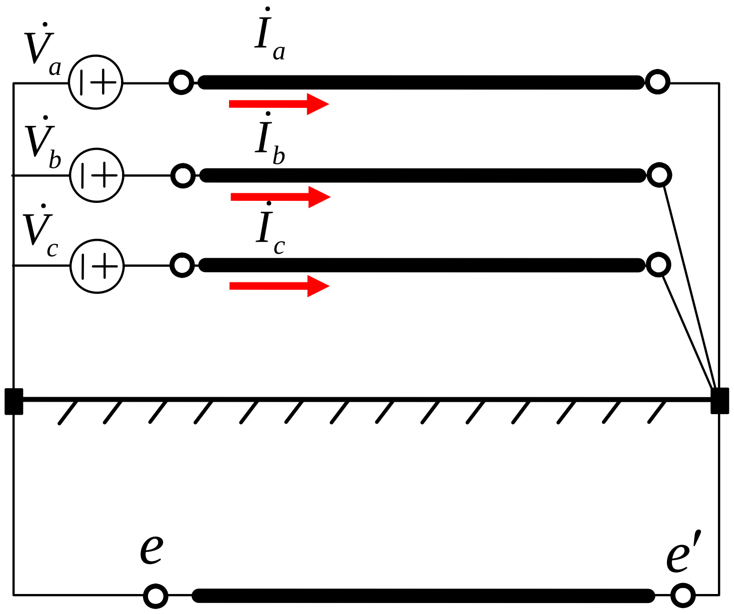


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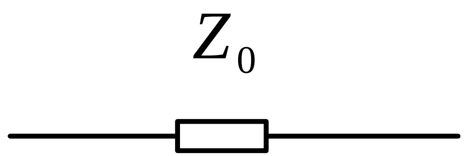



$$\{z_{(0)}\}_{\Omega/\text{km}} = r_a + 3r_e + j0.4335\lg\frac{D_e}{D_{ST}}$$

$$\{z_S\}_{\Omega/\text{km}} = r_a + r_e + j\omega L_S$$

$$\{z_m\}_{\Omega/\text{km}} = r_e + j\omega(M_{ab} - M_{be} - M_{ae} + L_e)$$

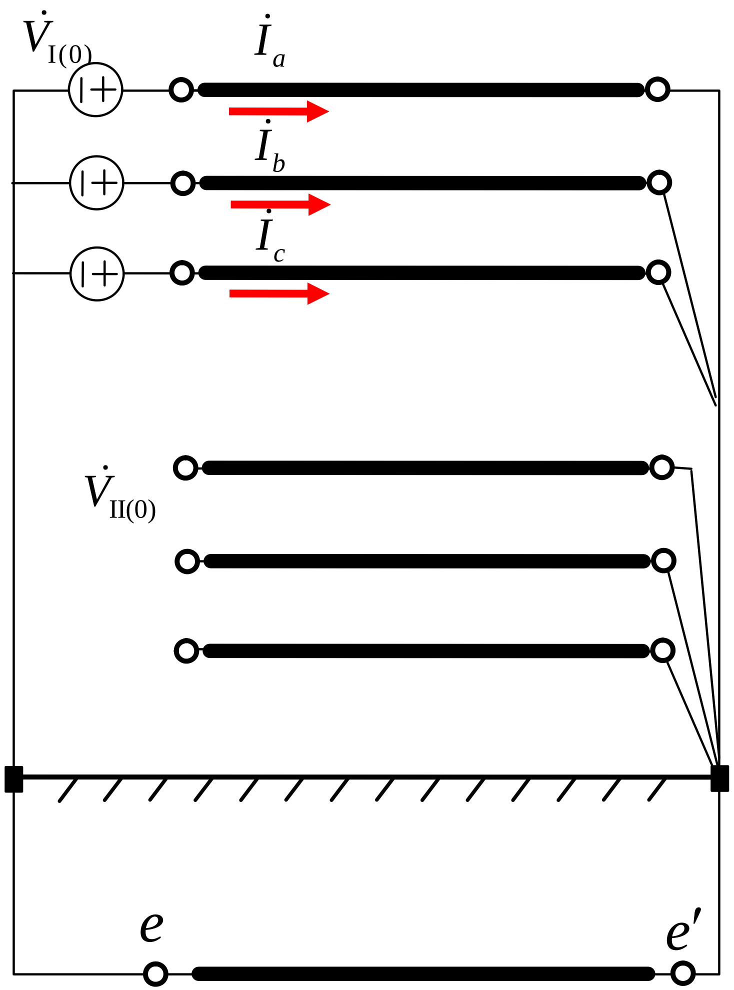
# 7-4 架空输电线的零序阻抗及其等值电路

## 4. 平行架设双回输电线路的零序阻抗及等值电路

### (1) 线路零序参数

$$\left\{z_{\mathrm{I}(0)}\right\}_{\Omega/\mathrm{km}}=r_a+3r_e+j0.4335\lg\frac{D_e}{D_{ST}}$$

互阻抗的求法$Z_{\text{I-II}(0)}$：I 回输电线路三相通过单位零序电流$\dot{I}_{\mathrm{I}(0)}$，在 II 回每相产生的电压降落在数值上即为$Z_{\text{I-II}(0)}$



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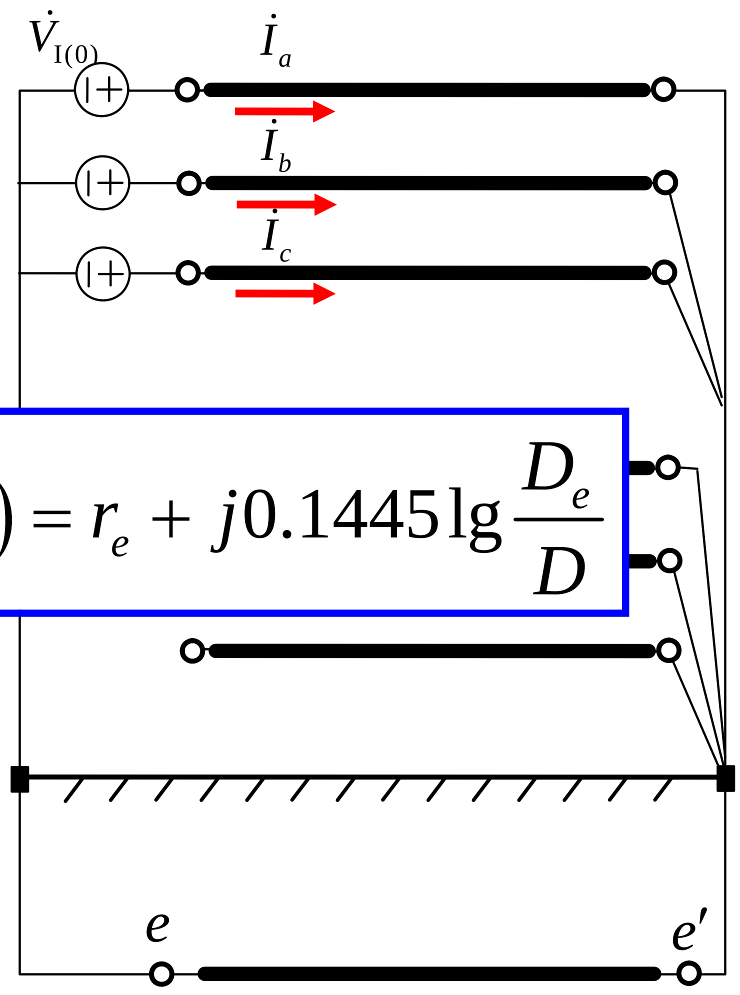

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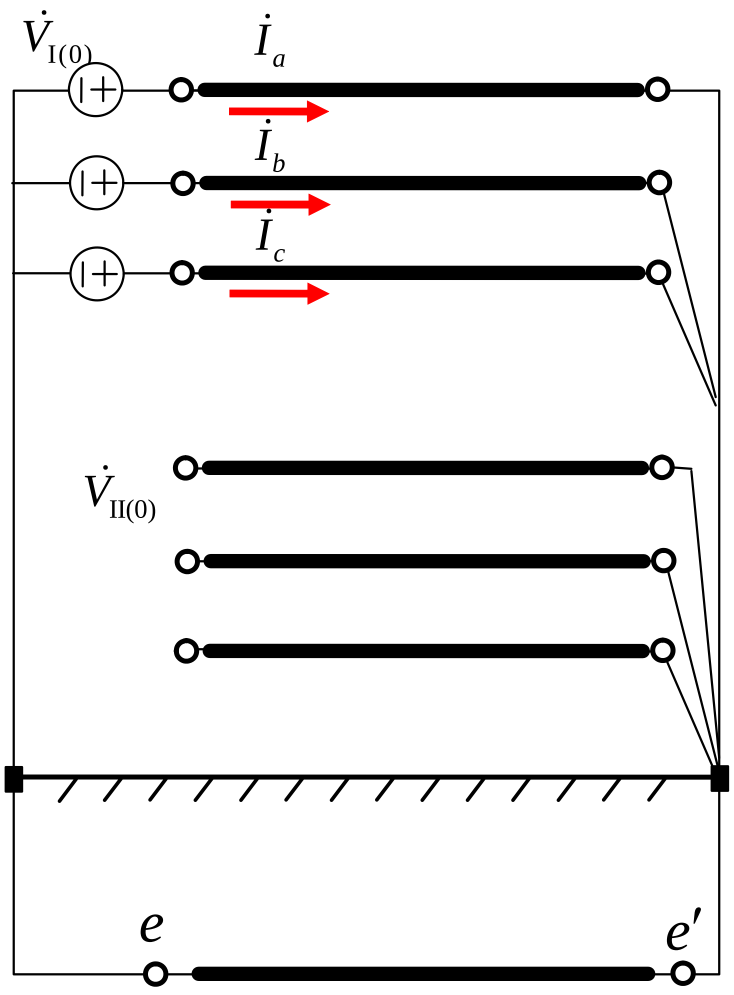
$$\left\{z_{\mathrm{I\text{-}II}(0)}\right\}_{\Omega/\mathrm{km}} = 3\left[r_e + j0.1445\lg\frac{D_e}{D_{\mathrm{I\text{-}II}}}\right]$$

互阻抗的求法$Z_{\mathrm{I\text{-}II}(0)}$：I 回输电线路三相通过单位零序电流$\dot{I}_{\mathrm{I}(0)}$，在 II 回每相产生的电压降落在数值上即为$Z_{\mathrm{I\text{-}II}(0)}$



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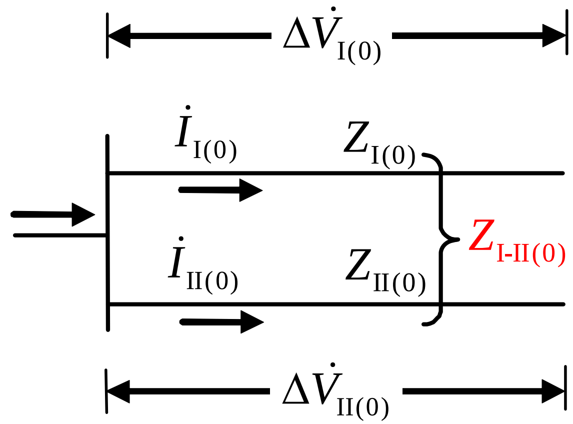
(2) 平行架设双回输电线路的零序等值电路(首端相连)



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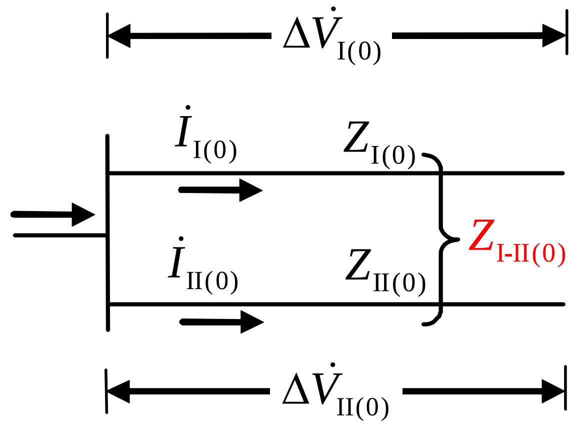


$$\boxed{\begin{aligned}\dot{V}_{\mathrm{I}(0)} &= Z_{\mathrm{I}(0)}\dot{I}_{\mathrm{I}(0)} + Z_{\text{I-II}(0)}\dot{I}_{\mathrm{II}(0)}\\ \dot{V}_{\mathrm{II}(0)} &= Z_{\text{I-II}(0)}\dot{I}_{\mathrm{I}(0)} + Z_{\mathrm{II}(0)}\dot{I}_{\mathrm{II}(0)}\end{aligned}}$$

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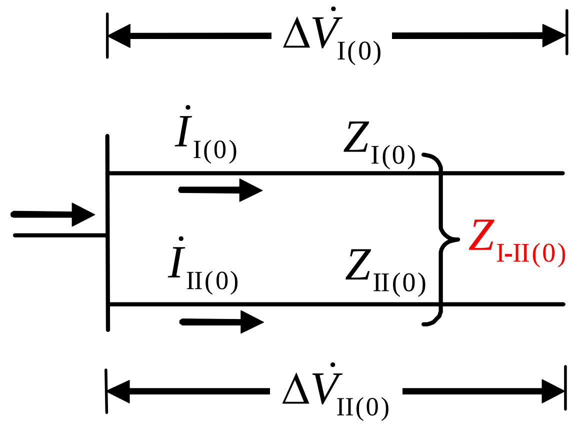


$$\boxed{\begin{aligned}\dot{V}_{\mathrm{I}(0)} &= Z_{\mathrm{I}(0)}\dot{I}_{\mathrm{I}(0)} + Z_{\mathrm{I\text{-}II}(0)}\dot{I}_{\mathrm{II}(0)} \\ \dot{V}_{\mathrm{II}(0)} &= Z_{\mathrm{I\text{-}II}(0)}\dot{I}_{\mathrm{I}(0)} + Z_{\mathrm{II}(0)}\dot{I}_{\mathrm{II}(0)}\end{aligned}}$$

$$\boxed{\begin{aligned}\dot{V}_{\mathrm{I}(0)} &= Z_{\mathrm{I\text{-}II}(0)}\left(\dot{I}_{\mathrm{I}(0)} + \dot{I}_{\mathrm{II}(0)}\right) + \left(Z_{\mathrm{I}(0)} - Z_{\mathrm{I\text{-}II}(0)}\right)\dot{I}_{\mathrm{I}(0)} \\ \dot{V}_{\mathrm{II}(0)} &= Z_{\mathrm{I\text{-}II}(0)}\left(\dot{I}_{\mathrm{I}(0)} + \dot{I}_{\mathrm{II}(0)}\right) + \left(Z_{\mathrm{II}(0)} - Z_{\mathrm{I\text{-}II}(0)}\right)\dot{I}_{\mathrm{II}(0)}\end{aligned}}$$

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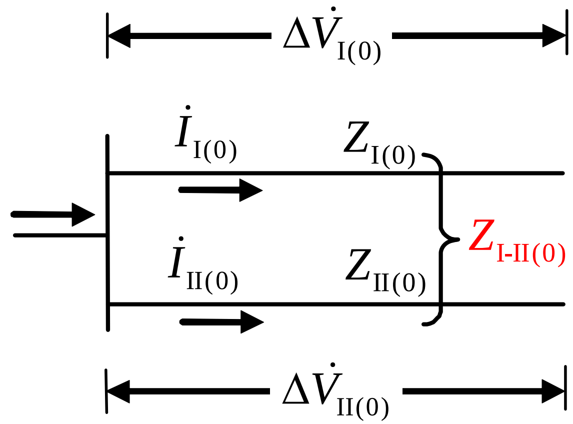
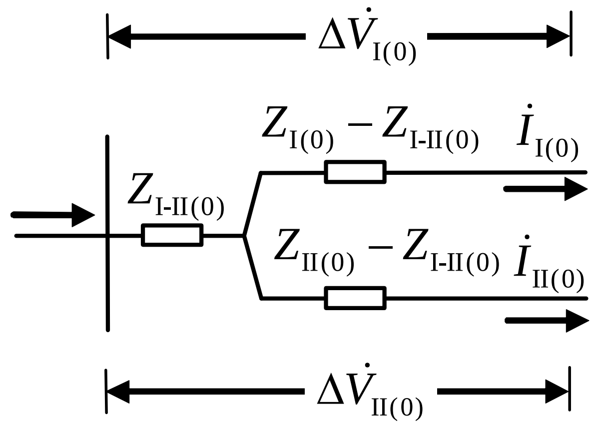



$$\boxed{\begin{aligned}\dot{V}_{\mathrm{I}(0)} &= Z_{\mathrm{I}(0)}\dot{I}_{\mathrm{I}(0)} + Z_{\mathrm{I\text{-}II}(0)}\dot{I}_{\mathrm{II}(0)}\\ \dot{V}_{\mathrm{II}(0)} &= Z_{\mathrm{I\text{-}II}(0)}\dot{I}_{\mathrm{I}(0)} + Z_{\mathrm{II}(0)}\dot{I}_{\mathrm{II}(0)}\end{aligned}}$$




$$\boxed{\begin{aligned}\dot{V}_{\mathrm{I}(0)} &= Z_{\mathrm{I\text{-}II}(0)}\left(\dot{I}_{\mathrm{I}(0)} + \dot{I}_{\mathrm{II}(0)}\right) + \left(Z_{\mathrm{I}(0)} - Z_{\mathrm{I\text{-}II}(0)}\right)\dot{I}_{\mathrm{I}(0)}\\ \dot{V}_{\mathrm{II}(0)} &= Z_{\mathrm{I\text{-}II}(0)}\left(\dot{I}_{\mathrm{I}(0)} + \dot{I}_{\mathrm{II}(0)}\right) + \left(Z_{\mathrm{II}(0)} - Z_{\mathrm{I\text{-}II}(0)}\right)\dot{I}_{\mathrm{II}(0)}\end{aligned}}$$

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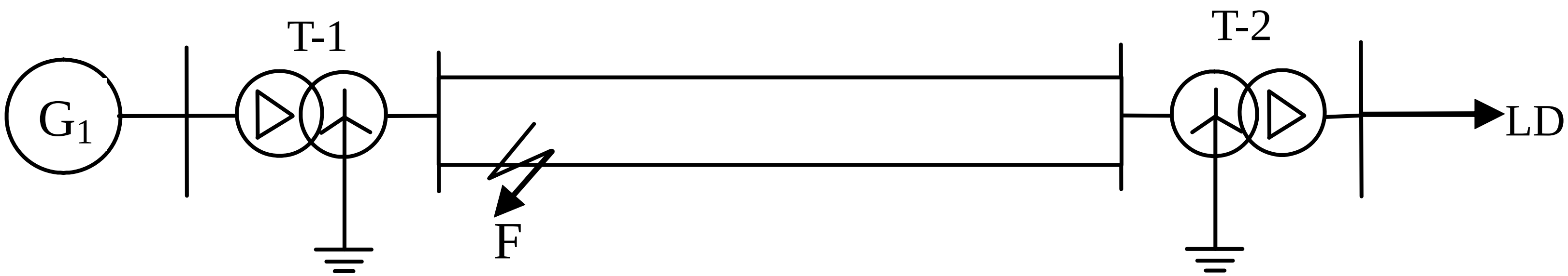
## (2) 平行架设双回输电线路的零序等值电路——应用举例



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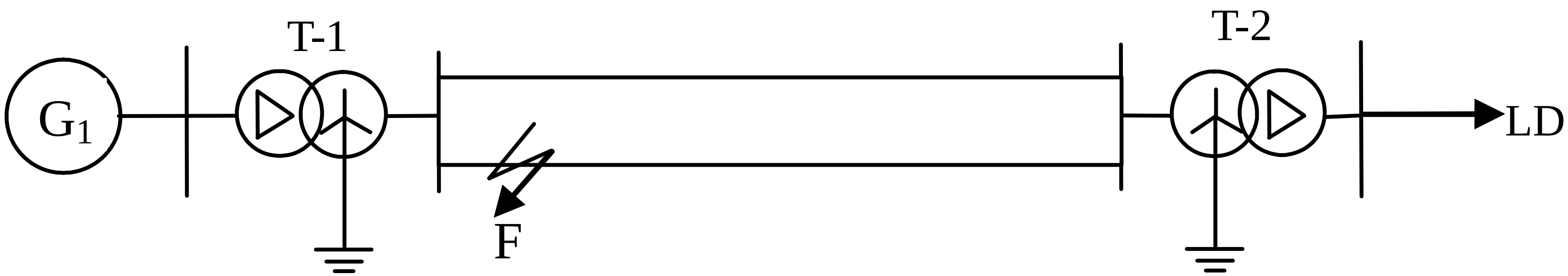


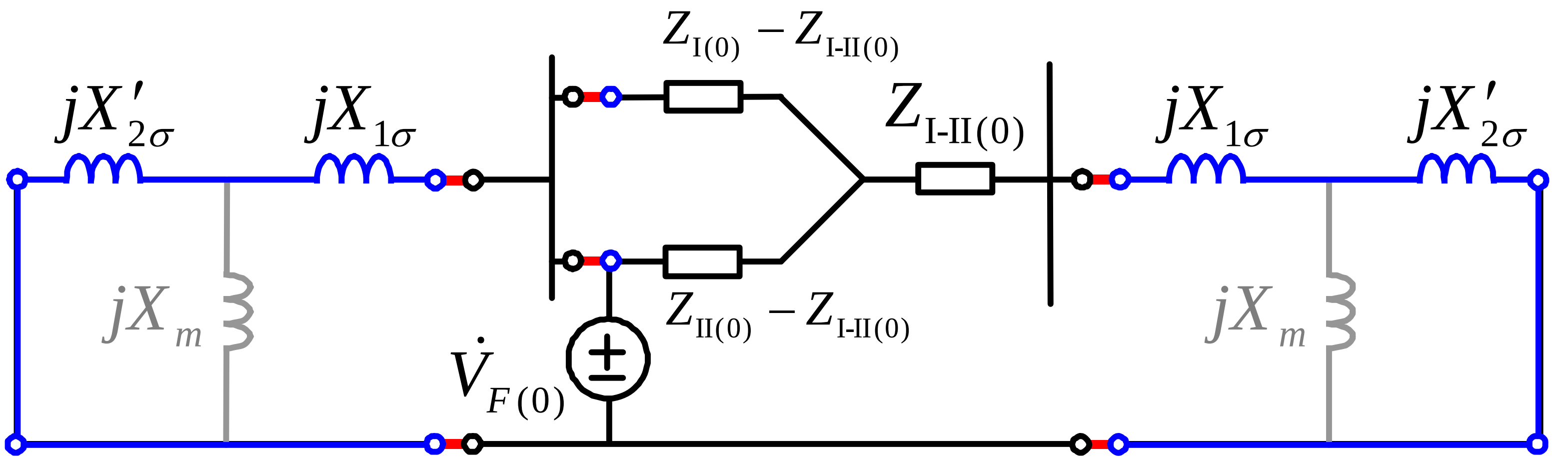

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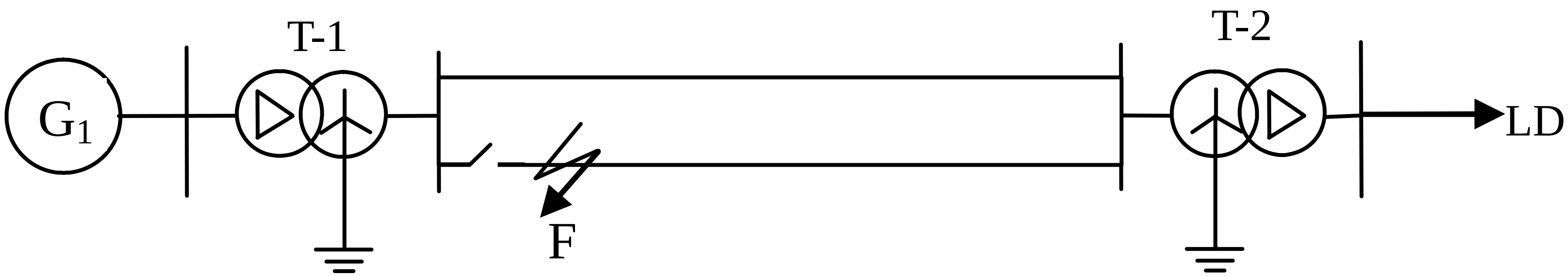

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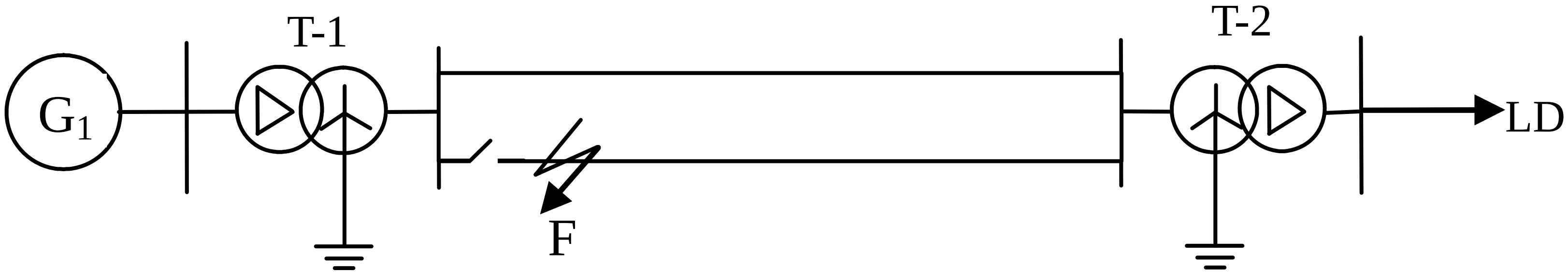


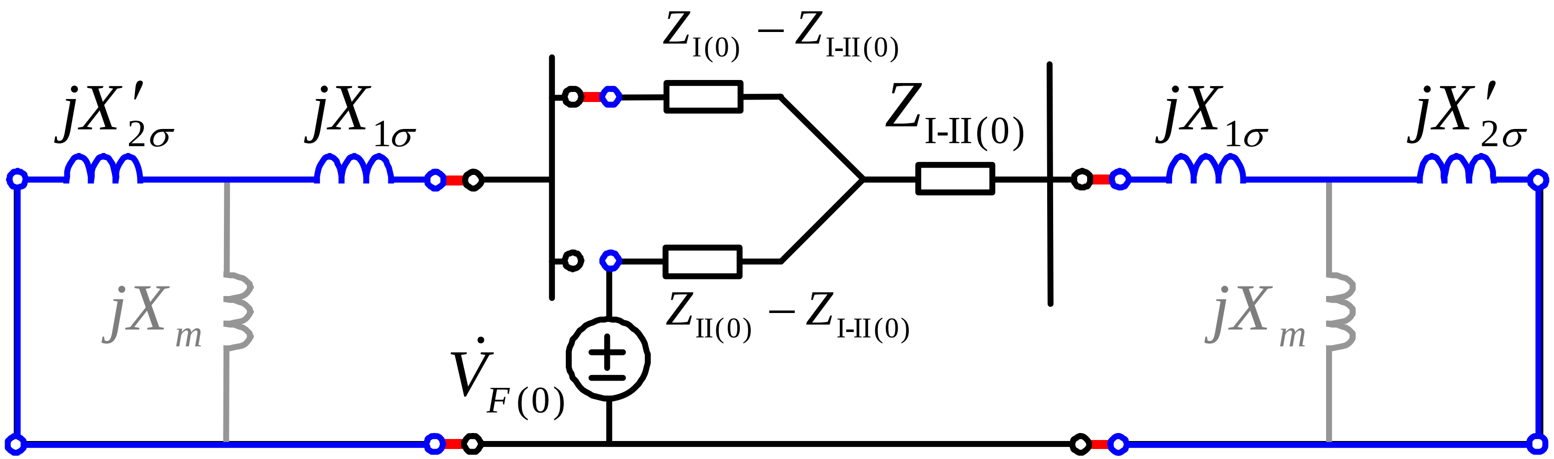

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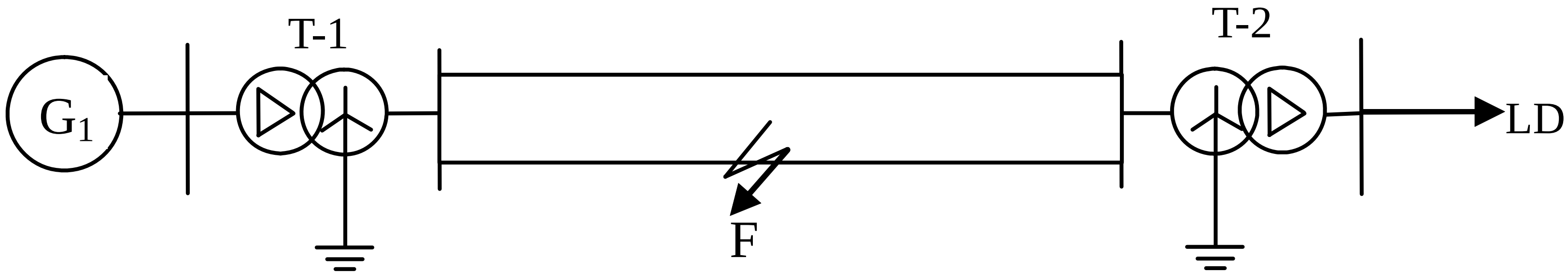

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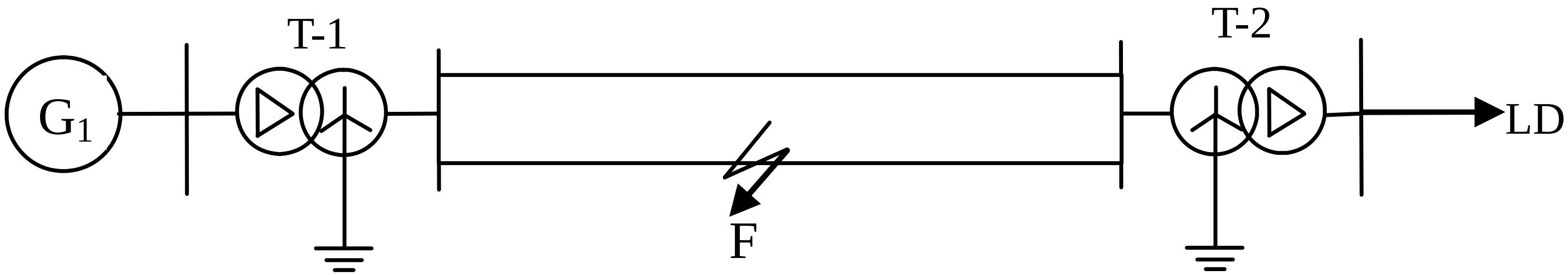
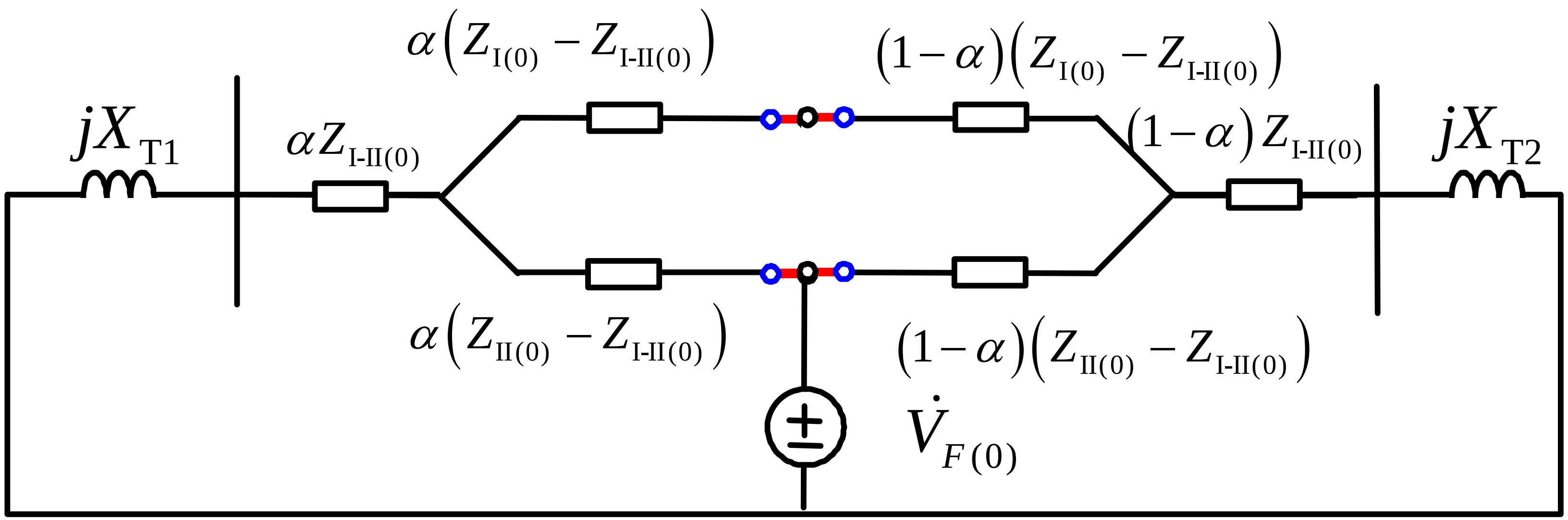
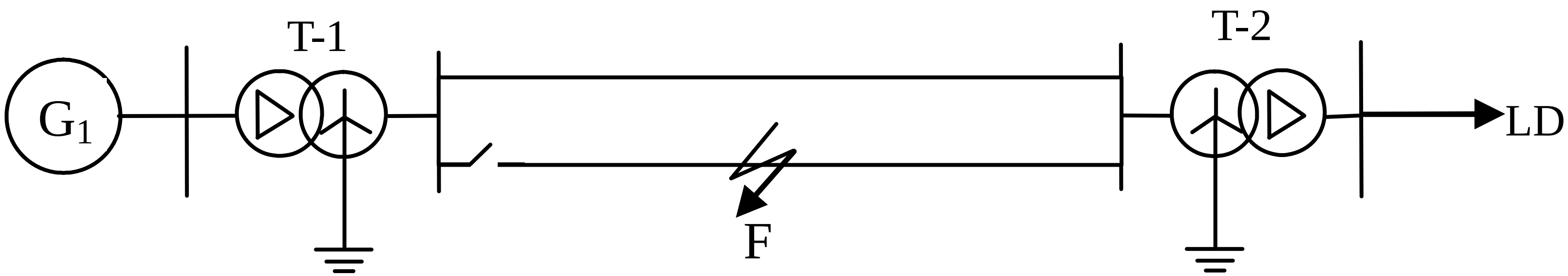


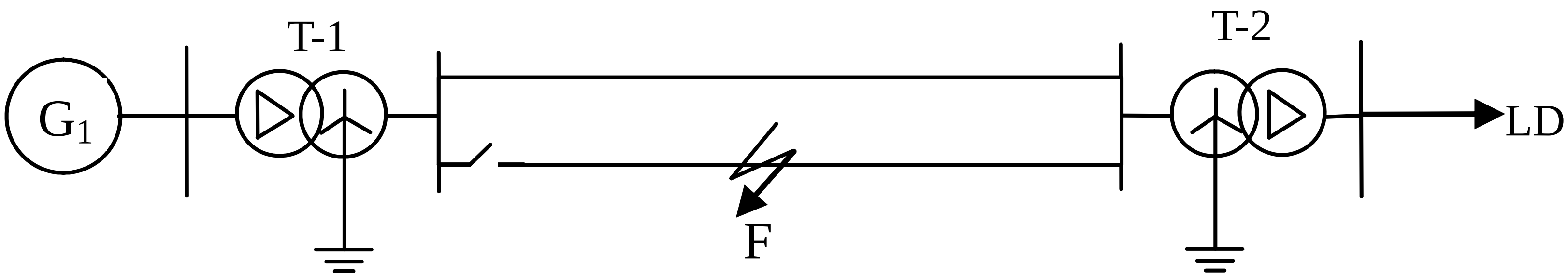
# 4. 平行架设双回输电线路的零序阻抗及等值电路

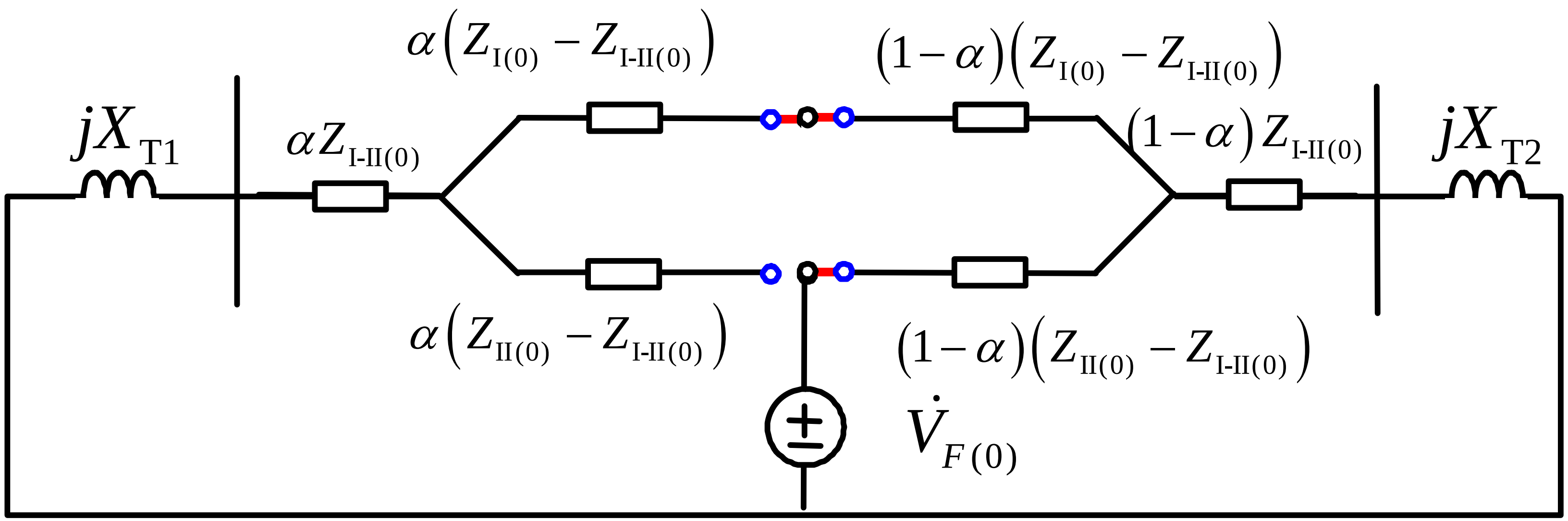
## (2) 平行架设双回输电线路的零序等值电路——应用举例



# 4. 平行架设双回输电线路的零序阻抗及等值电路

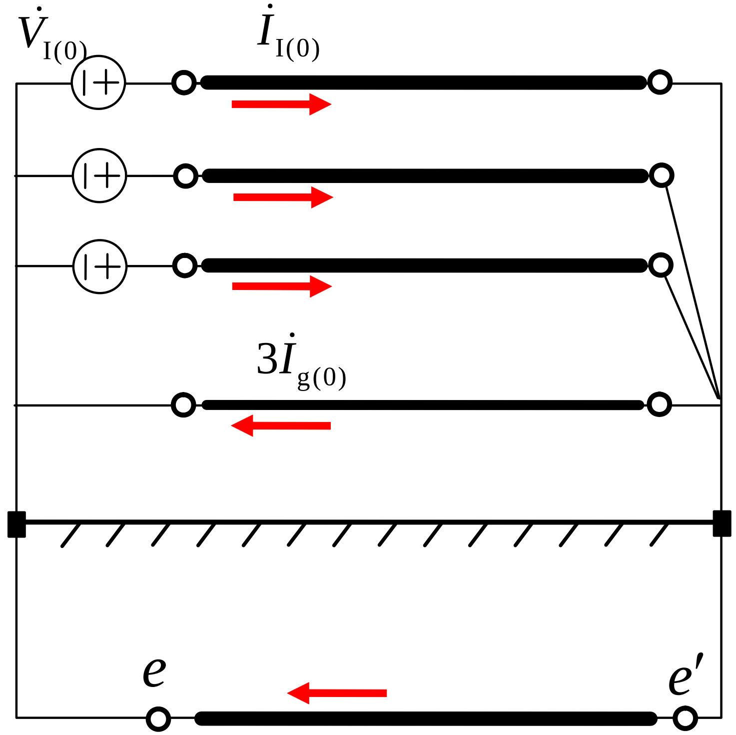
## (2) 平行架设双回输电线路的零序等值电路——应用举例



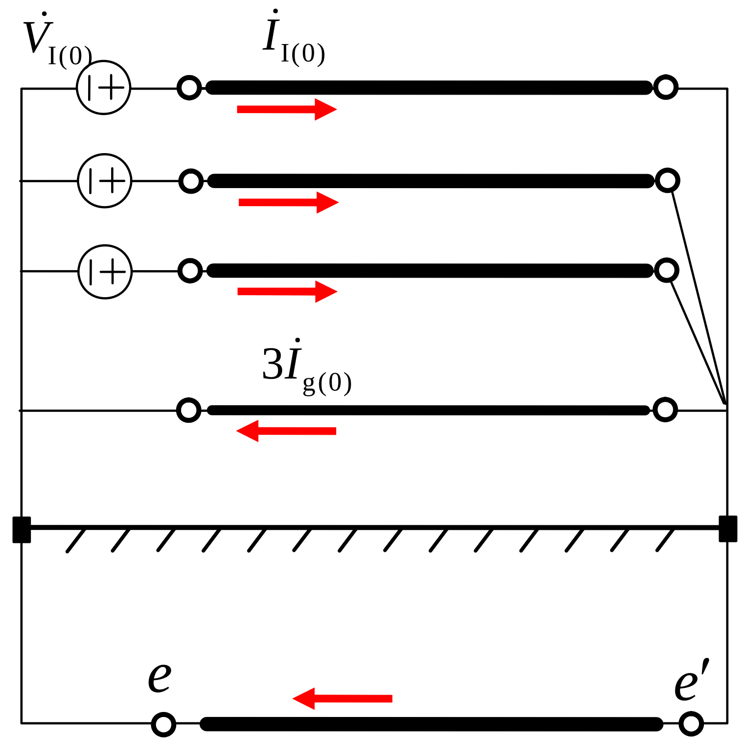
# 4. 平行架设双回输电线路的零序阻抗及等值电路

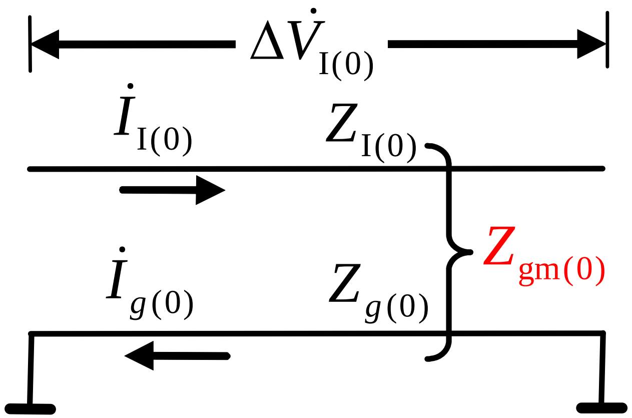
## (3) 有架空地线的单回输电线路的零序等值电路



# 4. 平行架设双回输电线路的零序阻抗及等值电路

## (3) 有架空地线的单回输电线路的零序等值电路



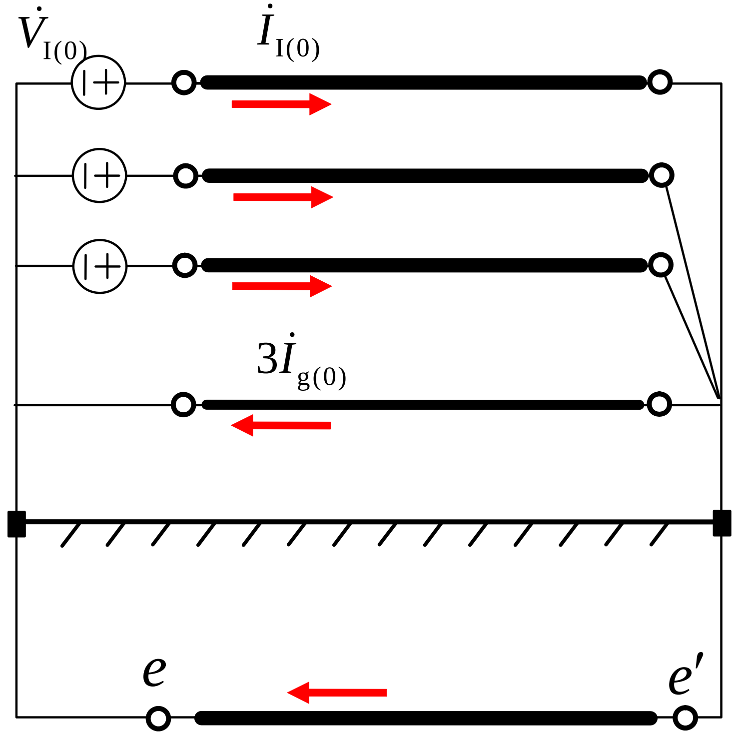



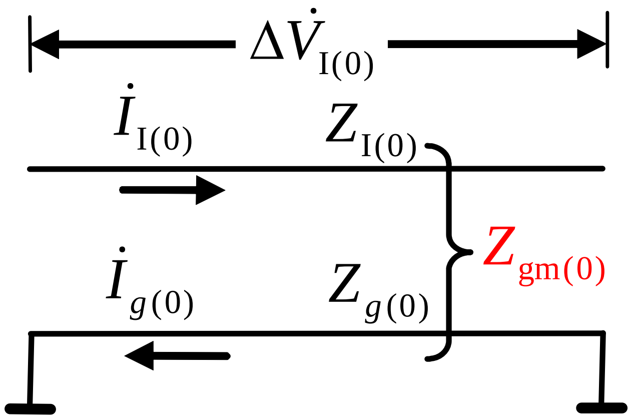
# 4. 平行架设双回输电线路的零序阻抗及等值电路

## (3) 有架空地线的单回输电线路的零序等值电路

$$\Delta \dot{V}_{\mathrm{I}(0)} = Z_{\mathrm{I}(0)}\dot{I}_{\mathrm{I}(0)} - Z_{\mathrm{gm}(0)}\dot{I}_{\mathrm{g}(0)}$$

$$0 = Z_{\mathrm{g}(0)}\dot{I}_{\mathrm{g}(0)} - Z_{\mathrm{gm}(0)}\dot{I}_{\mathrm{I}(0)}$$



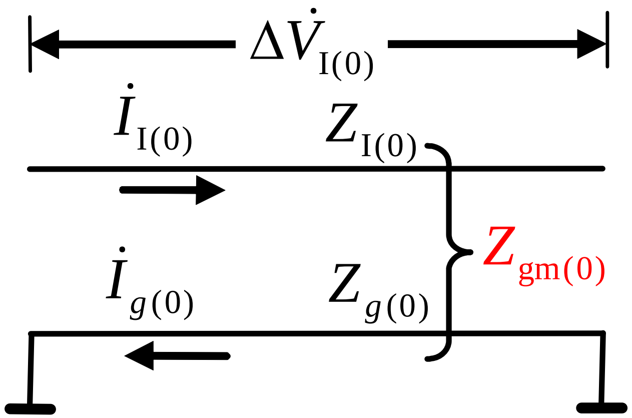
# 4. 平行架设双回输电线路的零序阻抗及等值电路

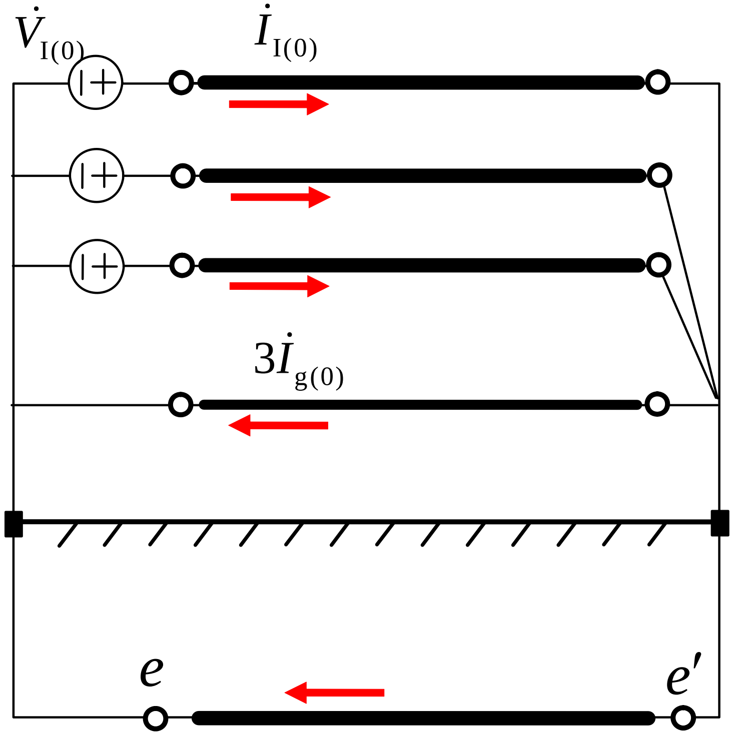
## (3) 有架空地线的单回输电线路的零序等值电路

$$\Delta\dot{V}_{\mathrm{I}(0)}=Z_{\mathrm{I}(0)}\dot{I}_{\mathrm{I}(0)}-Z_{\mathrm{gm}(0)}\dot{I}_{\mathrm{g}(0)}$$

$$0=Z_{\mathrm{g}(0)}\dot{I}_{\mathrm{g}(0)}-Z_{\mathrm{gm}(0)}\dot{I}_{\mathrm{I}(0)}$$

$$\dot{V}_{\mathrm{I}(0)}=\left(Z_{\mathrm{I}(0)}-\frac{Z_{\mathrm{gm}(0)}^{2}}{Z_{\mathrm{g}(0)}}\right)\dot{I}_{\mathrm{I}(0)}$$



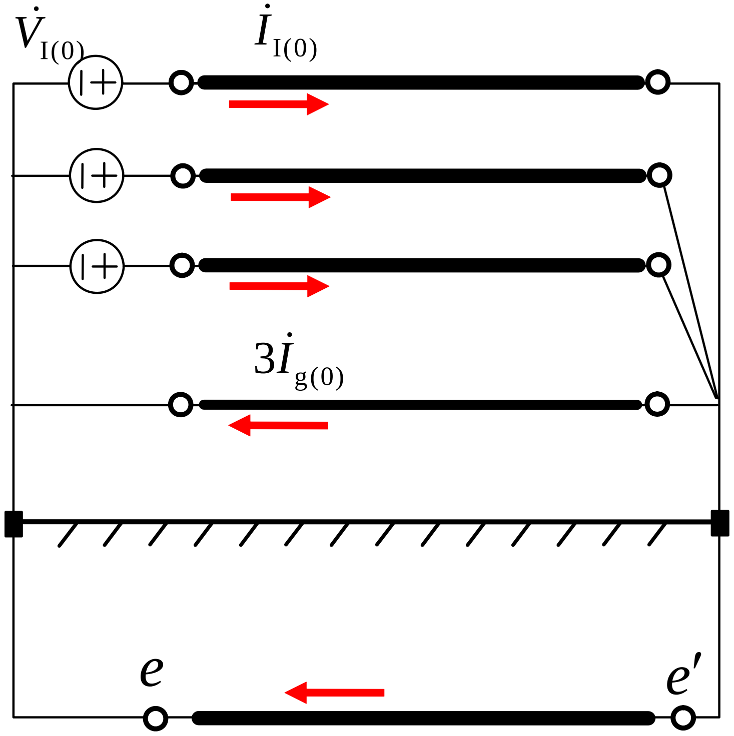



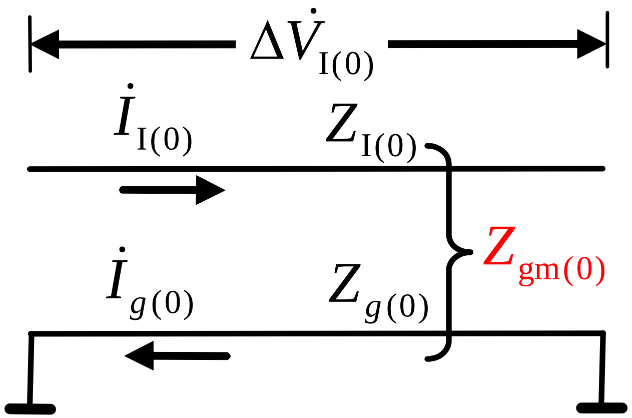
# 4. 平行架设双回输电线路的零序阻抗及等值电路

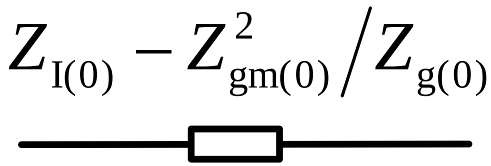
## (3) 有架空地线的单回输电线路的零序等值电路

$$\boxed{\begin{aligned}\Delta\dot{V}_{\mathrm{I}(0)} &= Z_{\mathrm{I}(0)}\dot{I}_{\mathrm{I}(0)} - Z_{\mathrm{gm}(0)}\dot{I}_{\mathrm{g}(0)} \\ 0 &= Z_{\mathrm{g}(0)}\dot{I}_{\mathrm{g}(0)} - Z_{\mathrm{gm}(0)}\dot{I}_{\mathrm{I}(0)}\end{aligned}}$$

$$\boxed{\dot{V}_{\mathrm{I}(0)} = \left(Z_{\mathrm{I}(0)} - \frac{Z_{\mathrm{gm}(0)}^{2}}{Z_{\mathrm{g}(0)}}\right)\dot{I}_{\mathrm{I}(0)}}$$

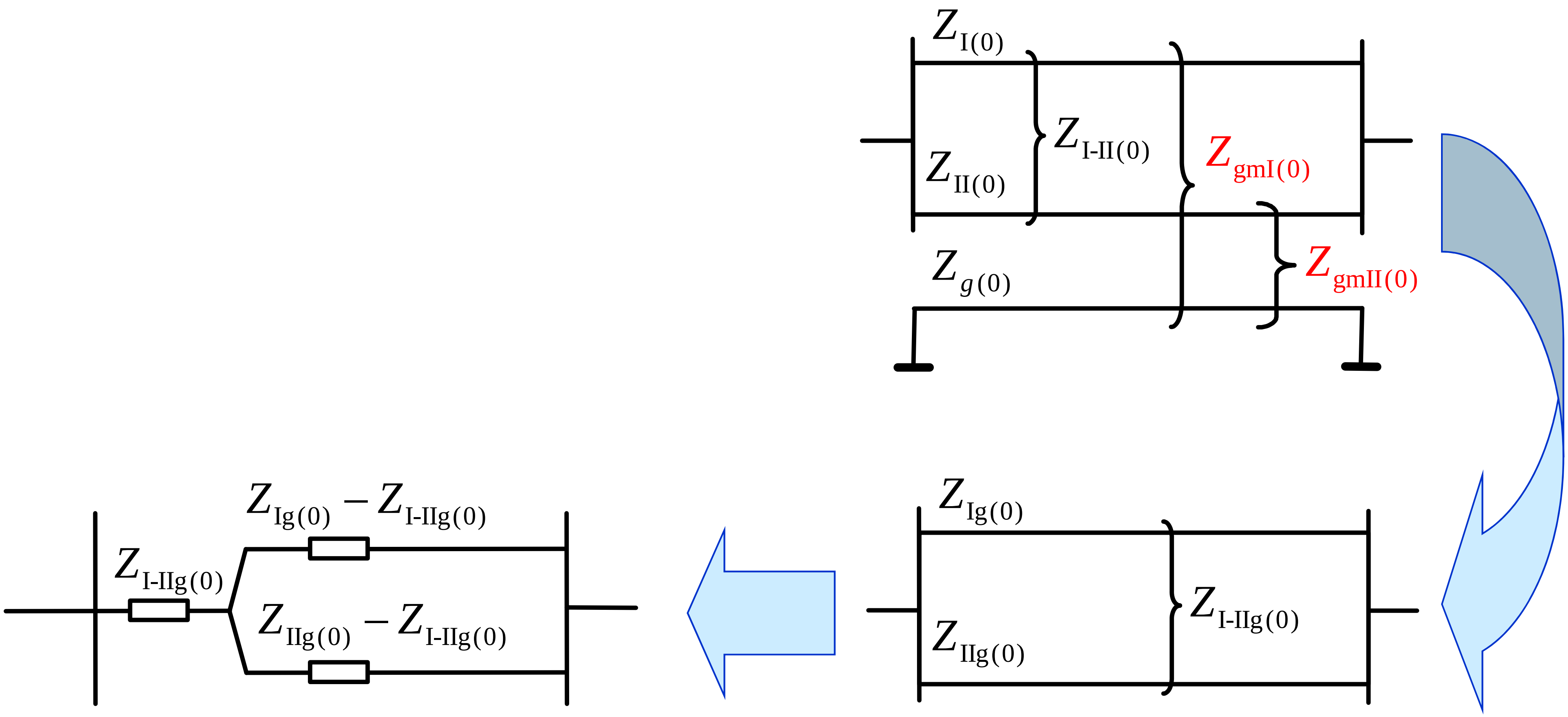


# 4. 平行架设双回输电线路的零序阻抗及等值电路

## (3) 有架空地线的双回输电线路的零序等值电路



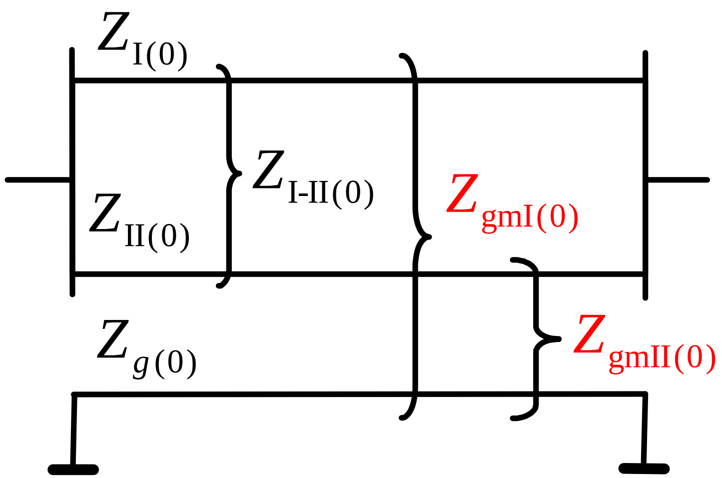
# 4. 平行架设双回输电线路的零序阻抗及等值电路

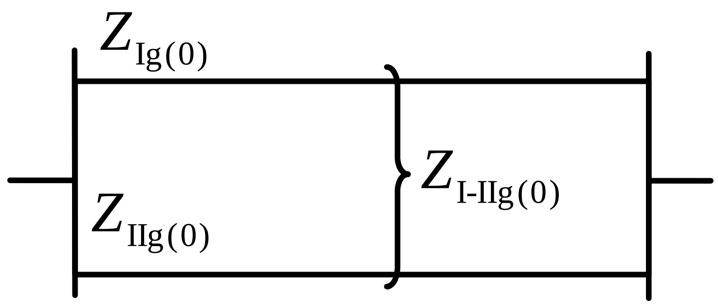
## (3) 有架空地线的双回输电线路的零序等值电路

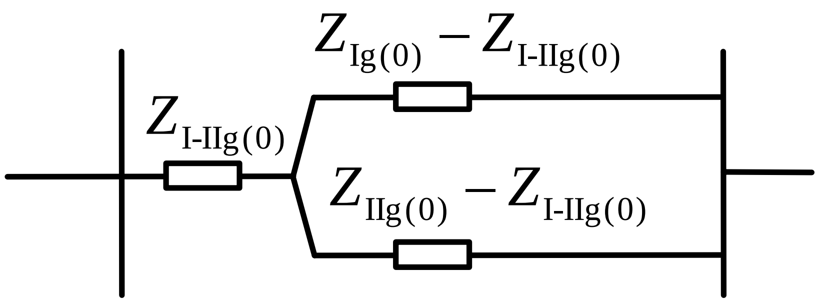
$$Z_{\mathrm{Ig}(0)} = Z_{\mathrm{I}(0)} - Z_{\mathrm{gmI}(0)}^{2} / Z_{\mathrm{g}(0)}$$

$$Z_{\mathrm{IIg}(0)} = Z_{\mathrm{II}(0)} - Z_{\mathrm{gmII}(0)}^{2} / Z_{\mathrm{g}(0)}$$

$$Z_{\mathrm{I\text{-}IIg}(0)} = Z_{\mathrm{I\text{-}II}(0)} - \left(Z_{\mathrm{gmI}(0)} \times Z_{\mathrm{gmII}(0)}\right) / Z_{\mathrm{g}(0)}$$



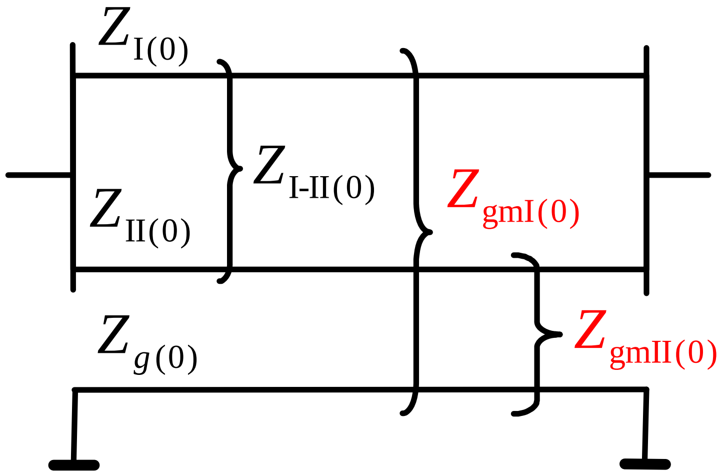



# 4. 平行架设双回输电线路的零序阻抗及等值电路

## (3) 有架空地线的双回输电线路的零序等值电路

$$
\begin{aligned}
\Delta \dot{V}_{\mathrm{I}(0)} &= Z_{\mathrm{I}(0)} \dot{I}_{\mathrm{I}(0)} + Z_{\text{I-II}(0)} \dot{I}_{\mathrm{II}(0)} - Z_{\mathrm{gmI}(0)} \dot{I}_{\mathrm{g}(0)} \\
\Delta \dot{V}_{\mathrm{II}(0)} &= Z_{\mathrm{II}(0)} \dot{I}_{\mathrm{II}(0)} + Z_{\text{I-II}(0)} \dot{I}_{\mathrm{I}(0)} - Z_{\mathrm{gmII}(0)} \dot{I}_{\mathrm{g}(0)} \\
0 &= Z_{\mathrm{g}(0)} \dot{I}_{\mathrm{g}(0)} - Z_{\mathrm{gmI}(0)} \dot{I}_{\mathrm{I}(0)} - Z_{\mathrm{gmII}(0)} \dot{I}_{\mathrm{II}(0)}
\end{aligned}
$$

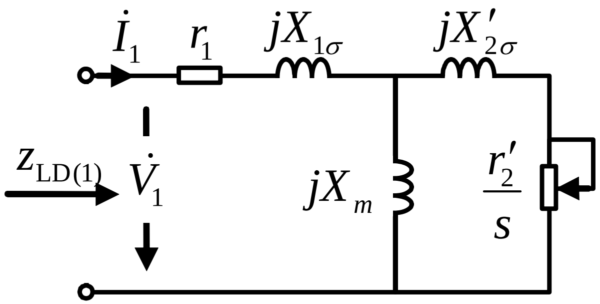
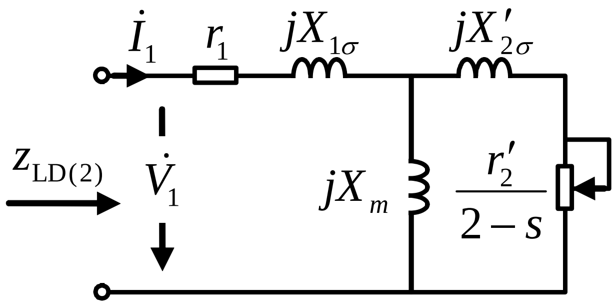
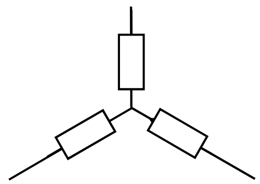



$$
\begin{aligned}
Z_{\mathrm{gmI}(0)} \dot{I}_{\mathrm{g}(0)} &= \left( Z_{\mathrm{gmI}(0)}^{2} / Z_{\mathrm{g}(0)} \right) \dot{I}_{\mathrm{I}(0)} + \left( Z_{\mathrm{gmI}(0)} Z_{\mathrm{gmII}(0)} / Z_{\mathrm{g}(0)} \right) \dot{I}_{\mathrm{II}(0)} \\
Z_{\mathrm{gmII}(0)} \dot{I}_{\mathrm{g}(0)} &= \left( Z_{\mathrm{gmI}(0)} Z_{\mathrm{gmII}(0)} / Z_{\mathrm{g}(0)} \right) \dot{I}_{\mathrm{I}(0)} + \left( Z_{\mathrm{gmII}(0)}^{2} / Z_{\mathrm{g}(0)} \right) \dot{I}_{\mathrm{II}(0)}
\end{aligned}
$$

$$
\begin{aligned}
\Delta \dot{V}_{\mathrm{I}(0)} &= Z_{\mathrm{Ig}(0)} \dot{I}_{\mathrm{I}(0)} + Z_{\text{I-IIg}(0)} \dot{I}_{\mathrm{II}(0)} \\
\Delta \dot{V}_{\mathrm{II}(0)} &= Z_{\mathrm{IIg}(0)} \dot{I}_{\mathrm{II}(0)} + Z_{\text{I-IIg}(0)} \dot{I}_{\mathrm{I}(0)}
\end{aligned}
$$

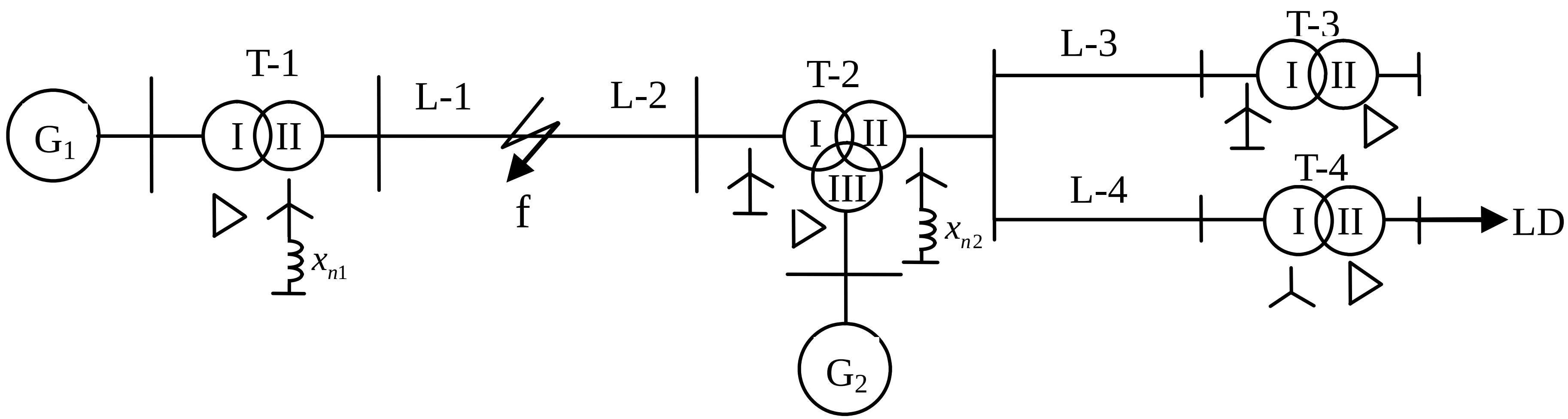
$$
\begin{aligned}
Z_{\mathrm{Ig}(0)} &= Z_{\mathrm{I}(0)} - Z_{\mathrm{gmI}(0)}^{2} / Z_{\mathrm{g}(0)} \\
Z_{\mathrm{IIg}(0)} &= Z_{\mathrm{II}(0)} - Z_{\mathrm{gmII}(0)}^{2} / Z_{\mathrm{g}(0)} \\
Z_{\text{I-IIg}(0)} &= Z_{\text{I-II}(0)} - \left( Z_{\mathrm{gmI}(0)} \times Z_{\mathrm{gmI}(0)} \right) / Z_{\mathrm{g}(0)}
\end{aligned}
$$

# 7-6 综合负荷的序阻抗

| 正序阻抗 | 负序阻抗 | 零序阻抗 |
|---|---|---|
|  |  |  |
| $z_{\mathrm{LD}(1)}=\frac{V_{\mathrm{LD}}^2}{S_{\mathrm{LD}}}(\cos\varphi+j\sin\varphi)$ | | |
| $z_{\mathrm{LD}(1)}=0.8+j0.6$<br>$z_{\mathrm{LD}(1)}=j1.2$ | $x_{(2)}=j0.35$ | $x_{(0)}=\infty$ |

# 7-7电力系统各序网络的制定

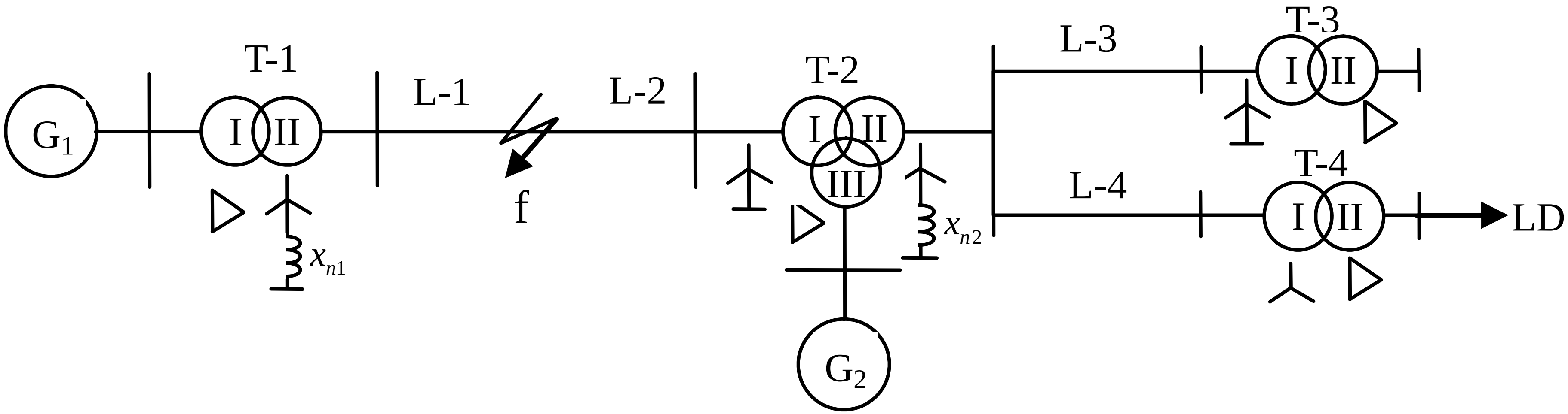
## 算例




- 在故障点分别叠加各序电势，从故障点开始，逐步查明各序电流流通的情况；
- 正序负序看负荷，零序网络看电流。

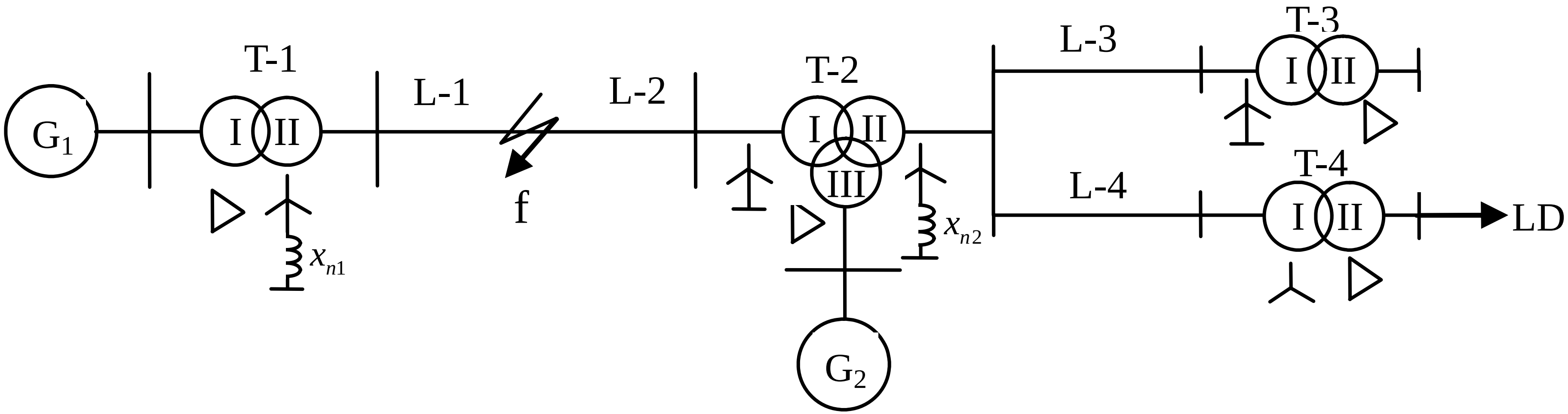
# 7-7电力系统各序网络的制定

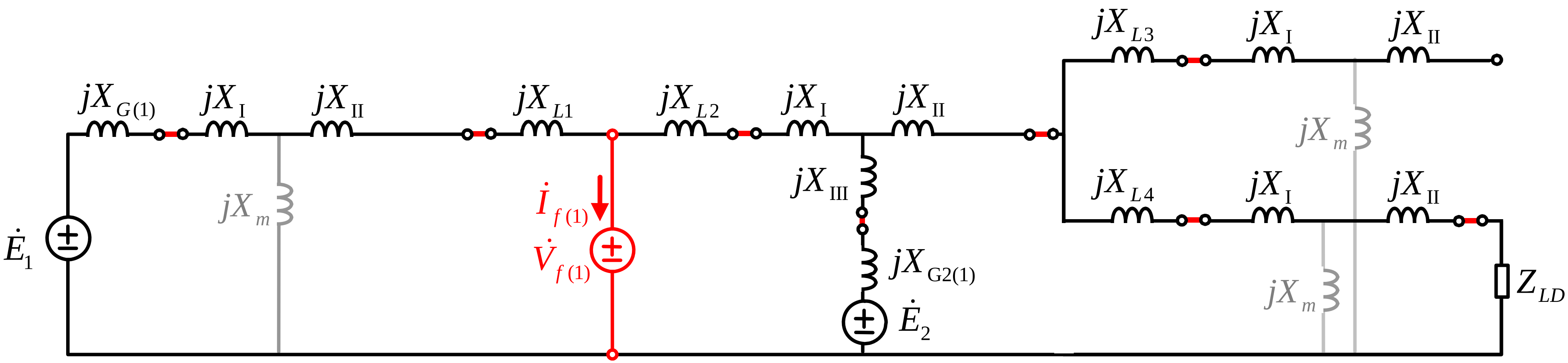
## 算例——正序网络



# 7-7电力系统各序网络的制定

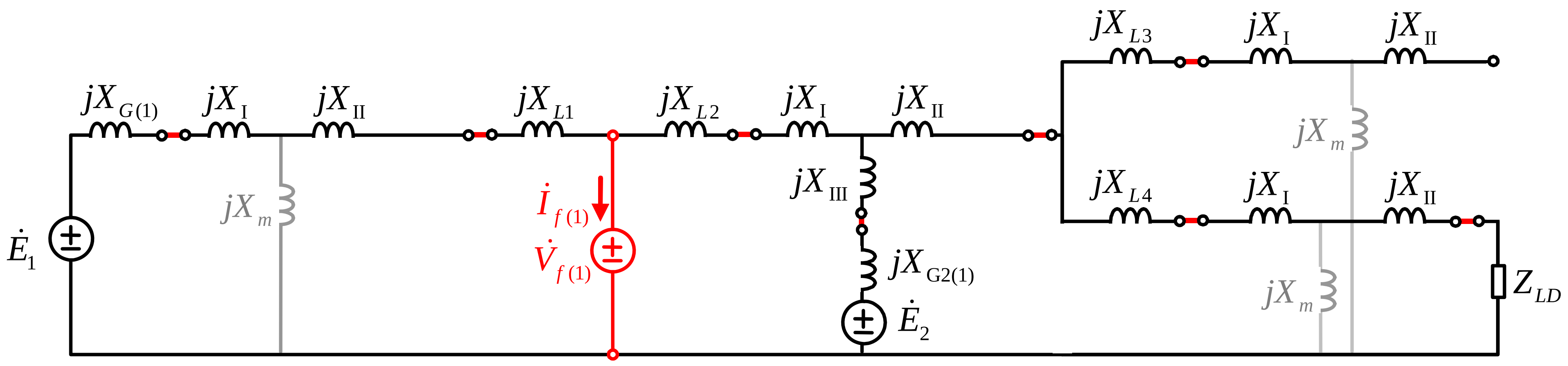
## 算例——正序网络

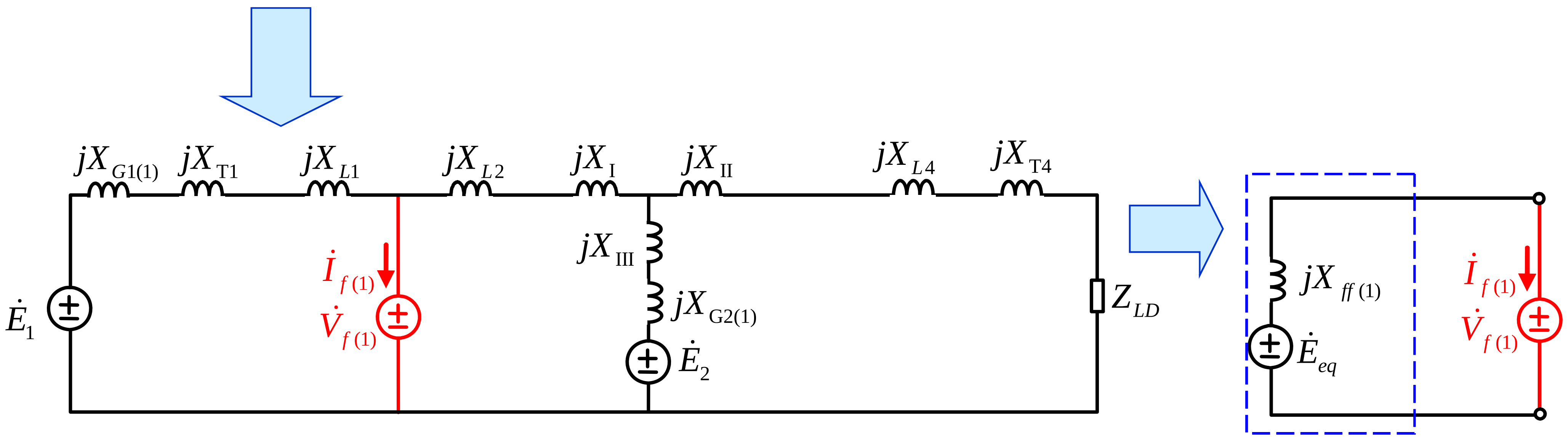


# 7-7 电力系统各序网络的制定

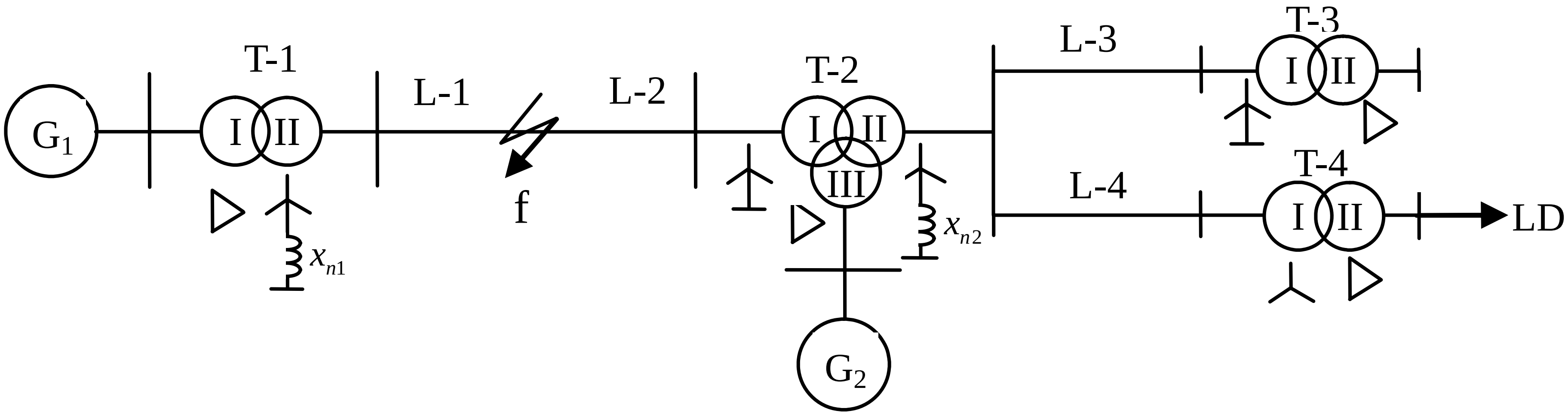
## 算例——正序网络



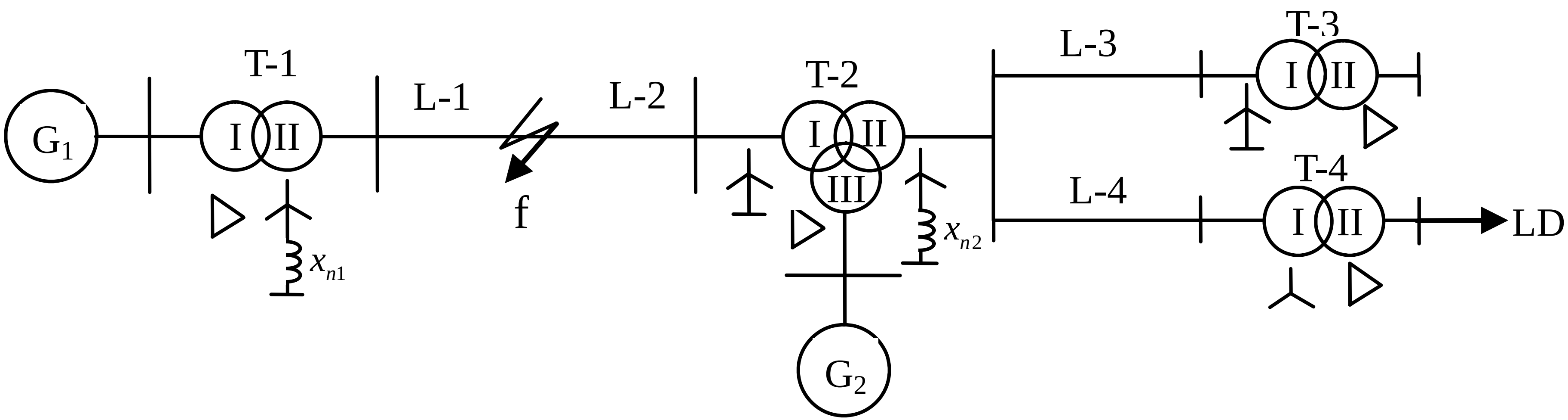
# 7-7电力系统各序网络的制定

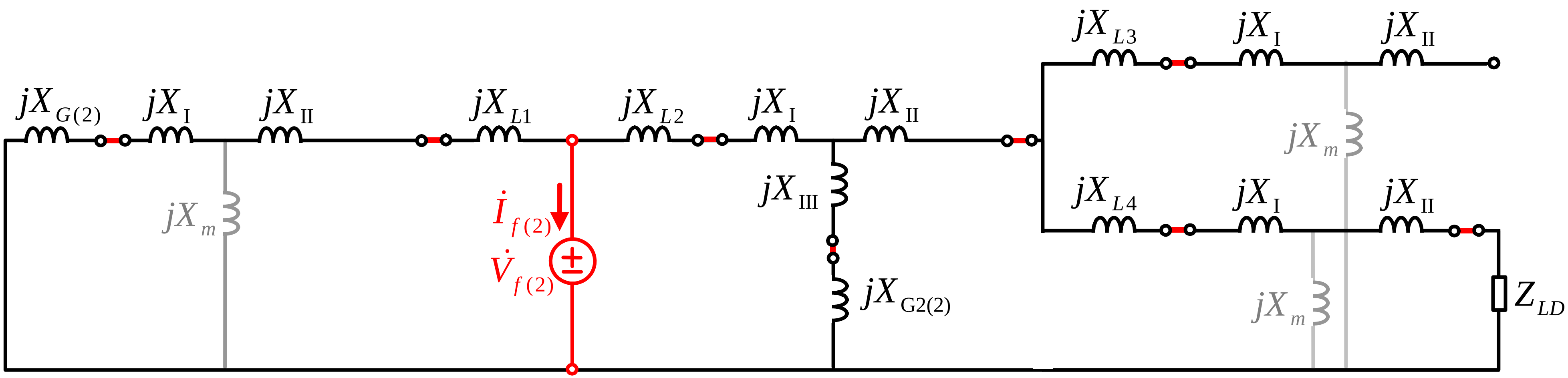
## 算例——负序网络



# 7-7电力系统各序网络的制定

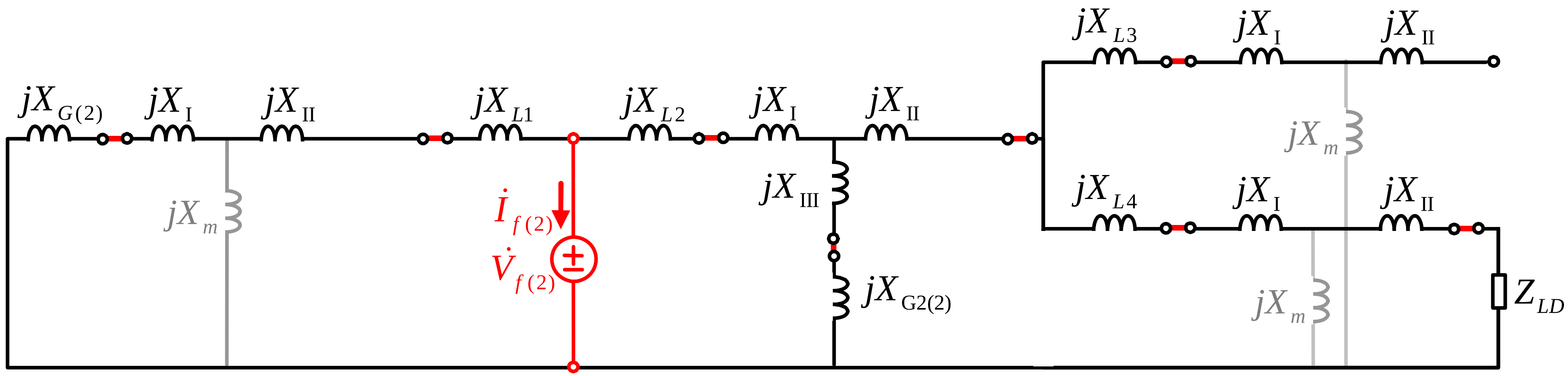
## 算例——负序网络

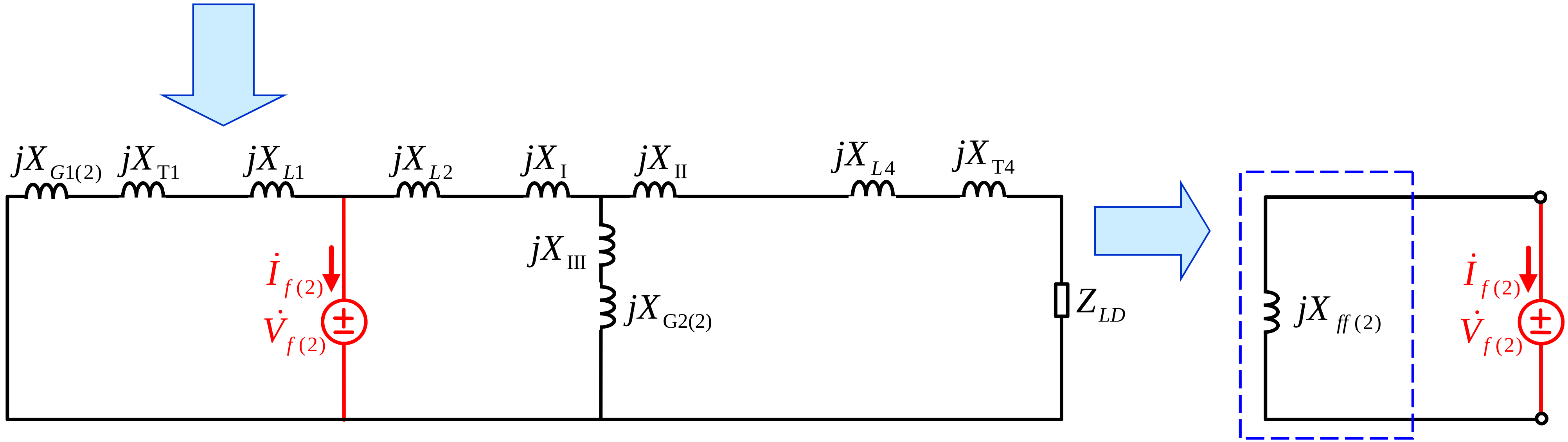


# 7-7 电力系统各序网络的制定

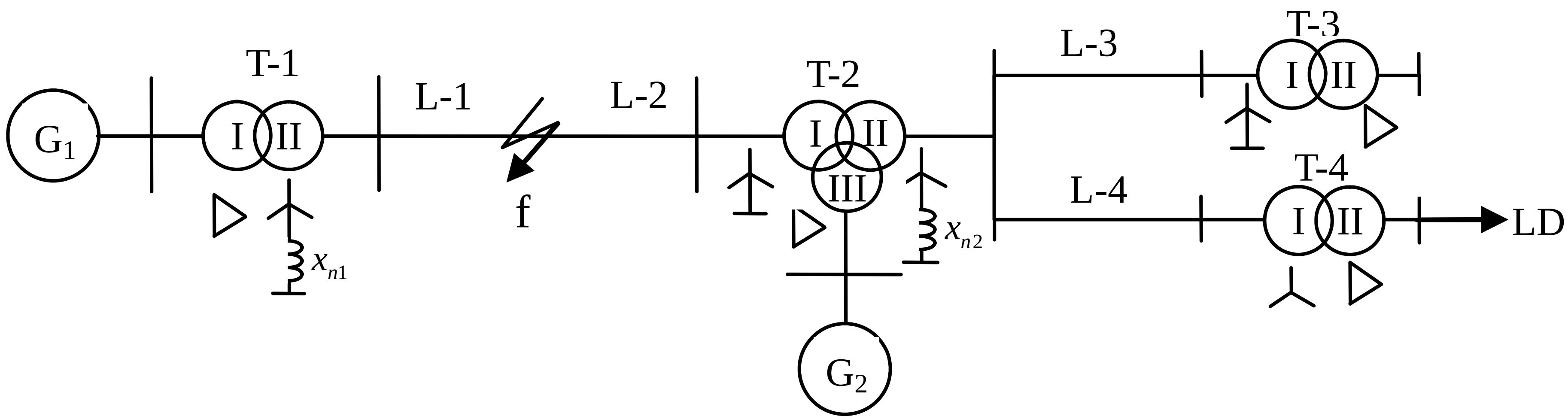
## 算例——负序网络



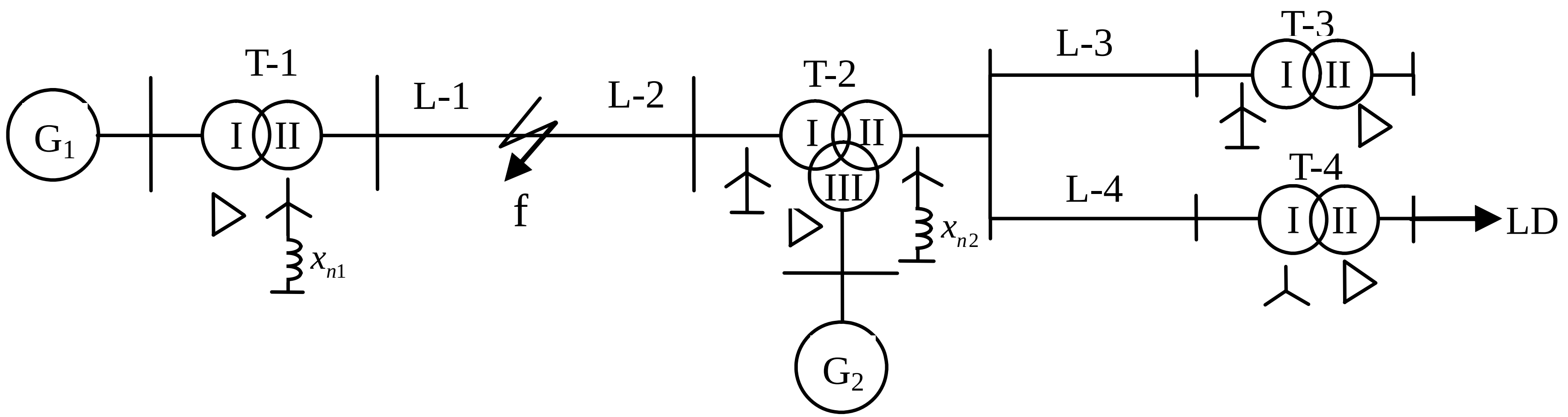
# 7-7 电力系统各序网络的制定

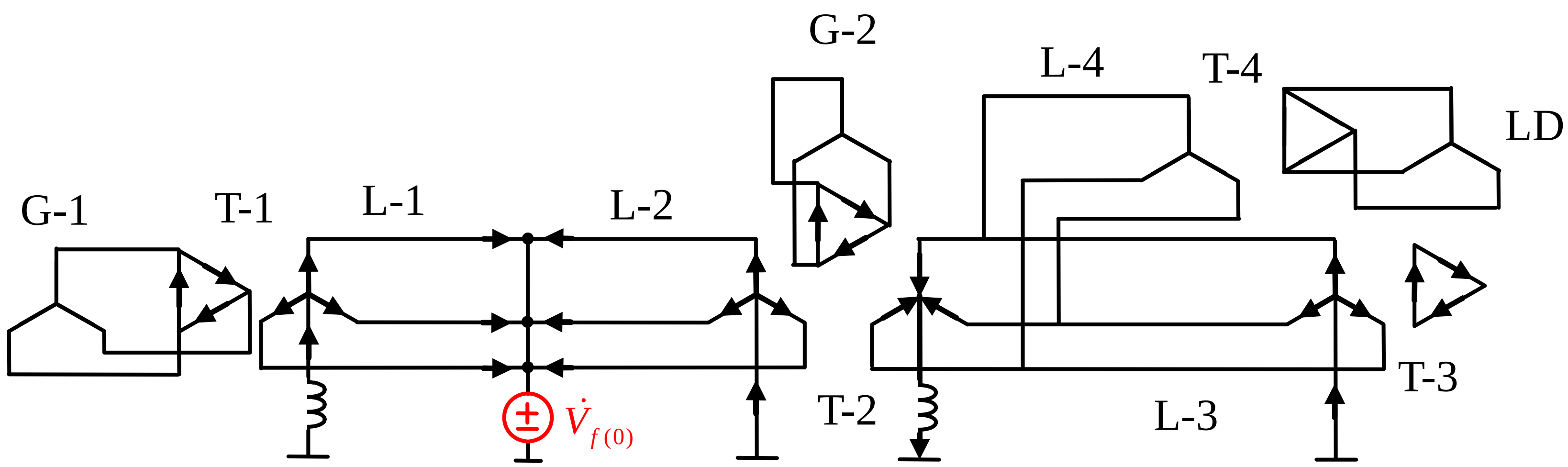
## 算例——零序网络



# 7-7 电力系统各序网络的制定

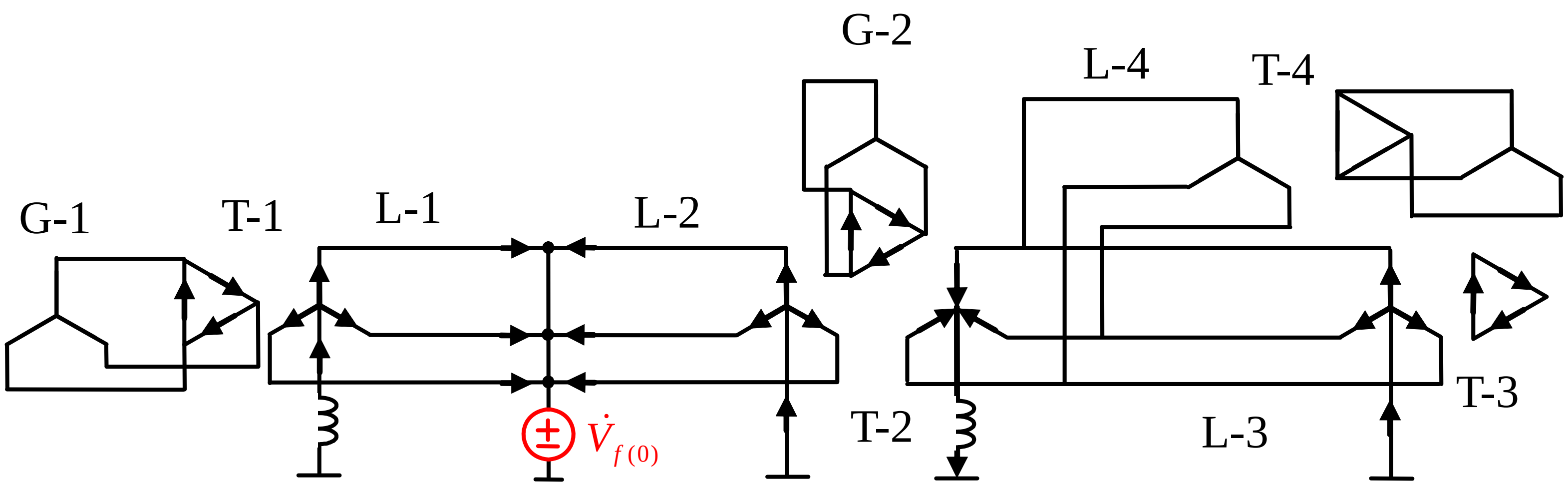
## 算例——零序网络

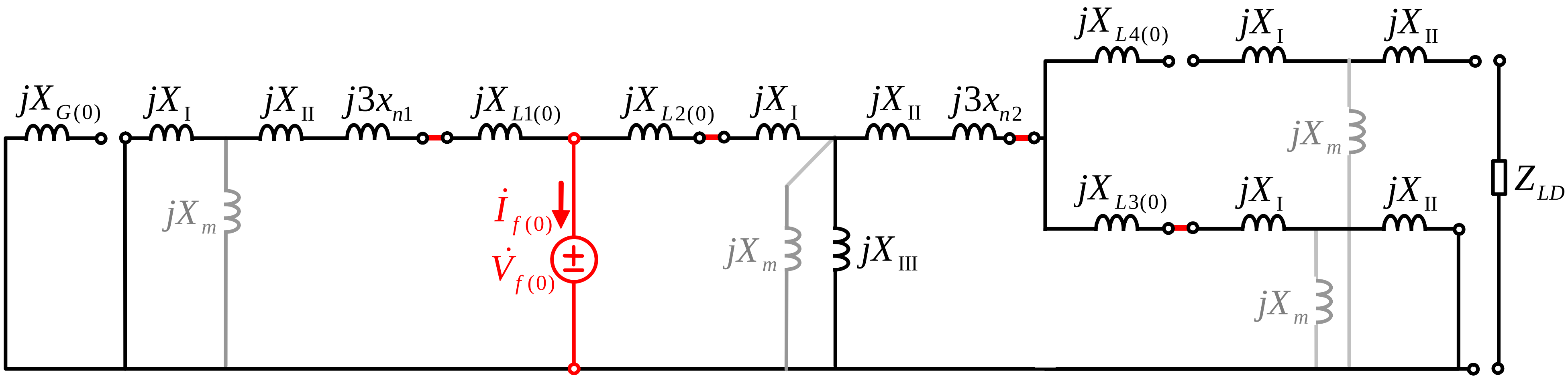


# 7-7电力系统各序网络的制定

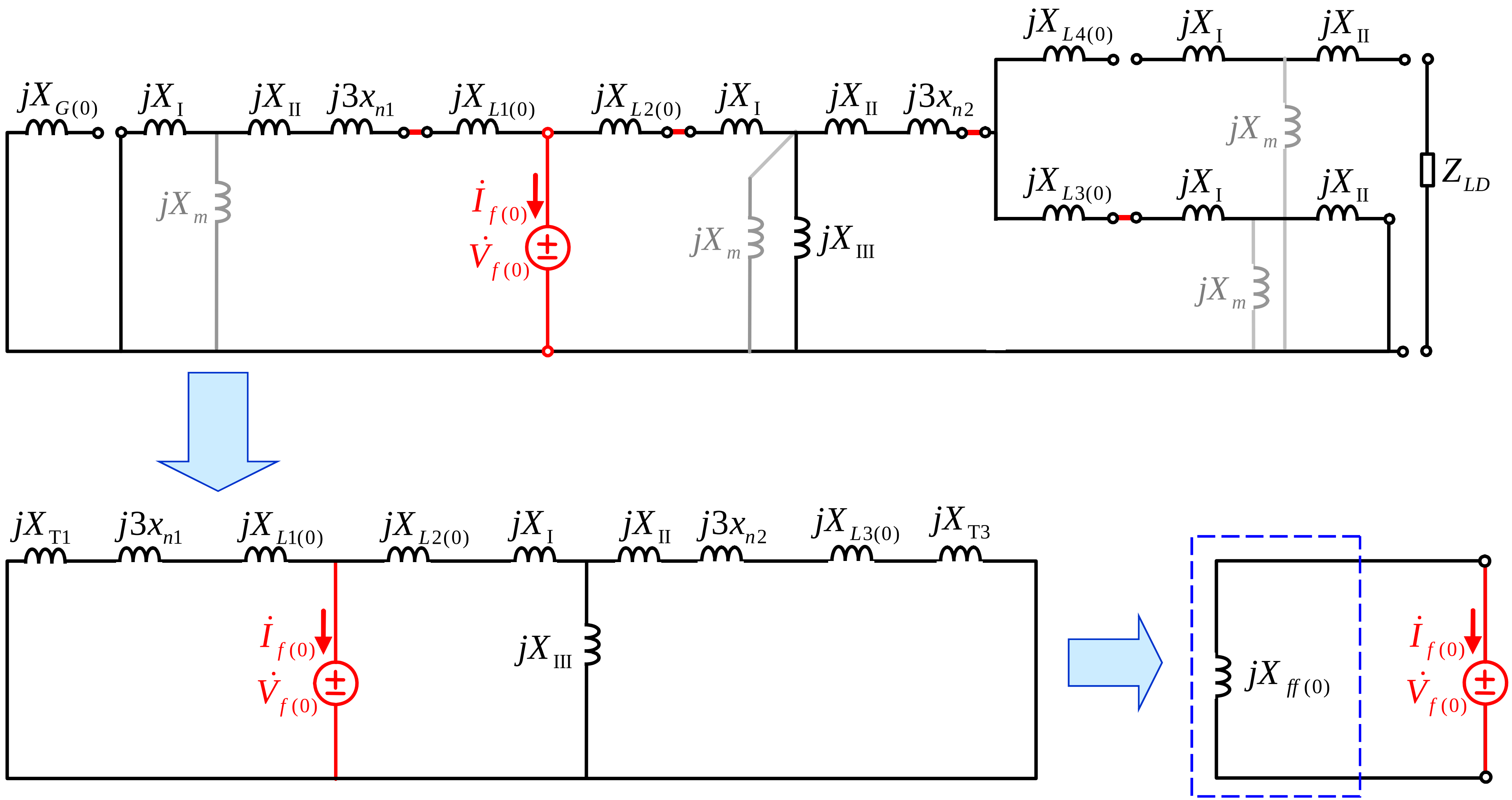
## 算例——零序网络



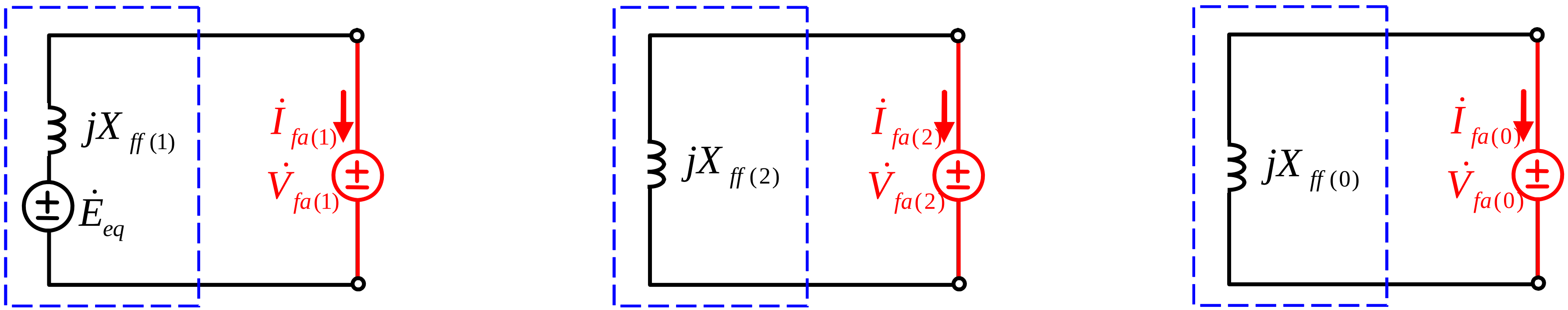
# 7-7电力系统各序网络的制定

## 算例——零序网络



# 7-7电力系统各序网络的制定

## 序网方程




$$\boxed{\dot{V}_{fa(1)} = \dot{E}_{eq} - Z_{ff(1)}\dot{I}_{fa(1)}}$$

$$\boxed{\dot{V}_{fa(2)} = -Z_{ff(2)}\dot{I}_{fa(2)}}$$

$$\boxed{\dot{V}_{fa(0)} = -Z_{ff(0)}\dot{I}_{fa(0)}}$$

# 本章小结

- ❖对称分量法分析不对称故障的原理和方法；
- ❖变压器的零序等值电路和参数；
- ❖输电线路零序等值电路及参数；
- ❖制定序网的原则和方法；

**Ex 7-3, 7-5, 7-7**

**End of Chapter 7**