華中科技大學

Huazhong University of Science and Technology

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《电力系统分析》（I）

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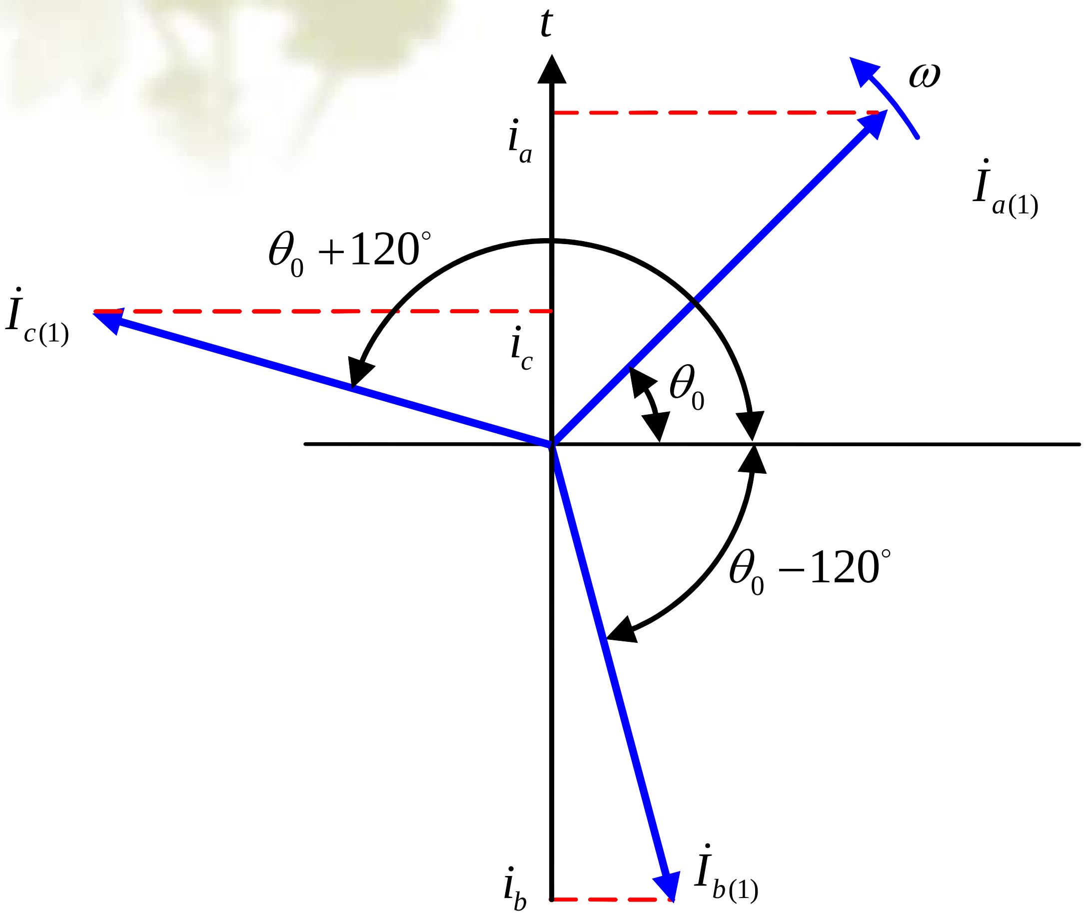
第七章 电力系统各元件的序阻抗和等值电路

7-1 对称分量法在不对称短路计算中的应用

1. 不对称三相量的分解——对称分量



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

正序分量：

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

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

7-1 对称分量法在不对称短路计算中的应用

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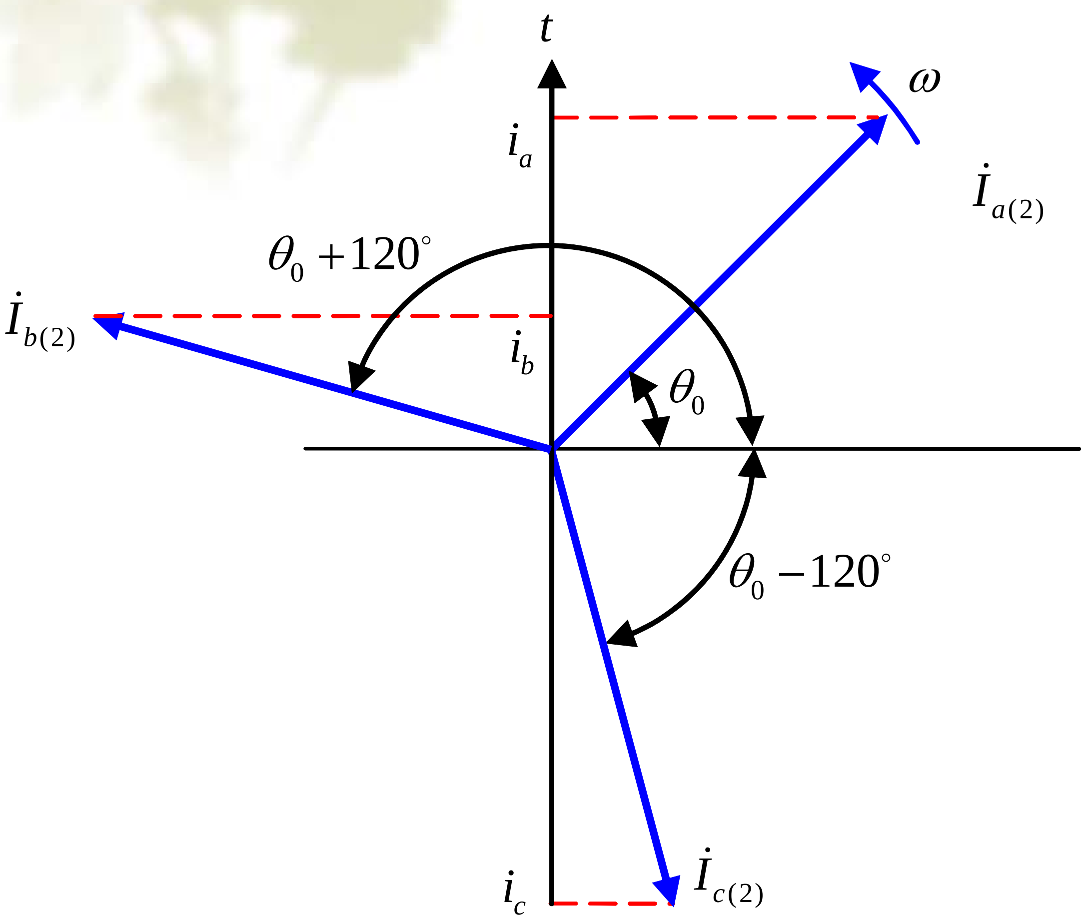

$$i_a = I_m \sin(\omega t + \theta_0)$$
$$i_b = I_m \sin(\omega t + \theta_0 + 120^\circ)$$
$$i_c = I_m \sin(\omega t + \theta_0 - 120^\circ)$$

负序分量：

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

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

7-1 对称分量法在不对称短路计算中的应用

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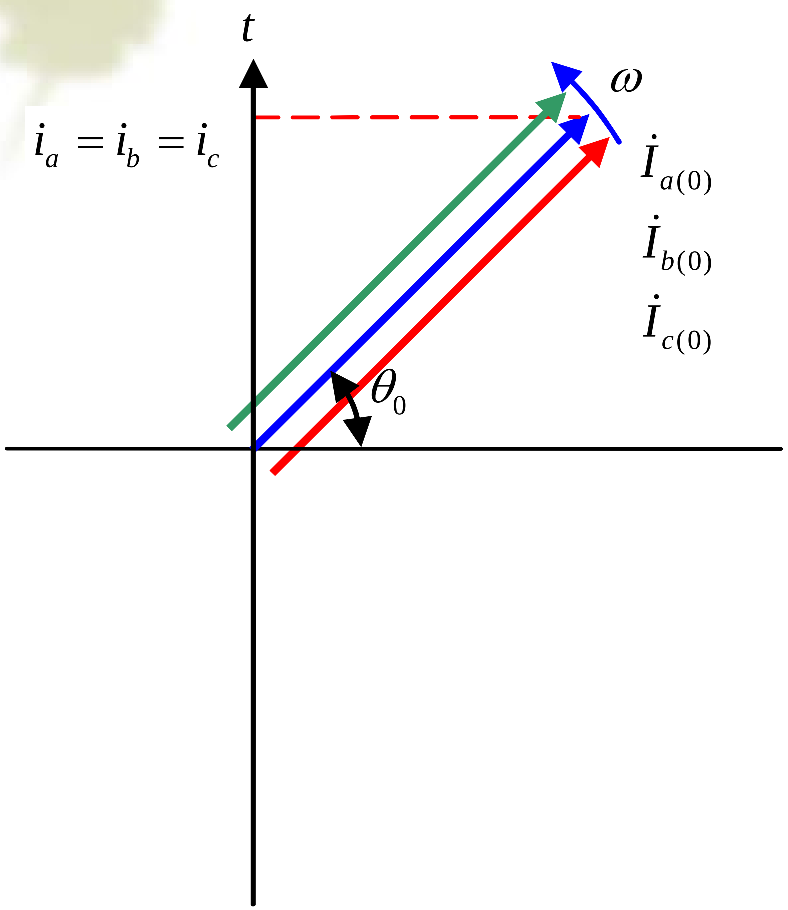


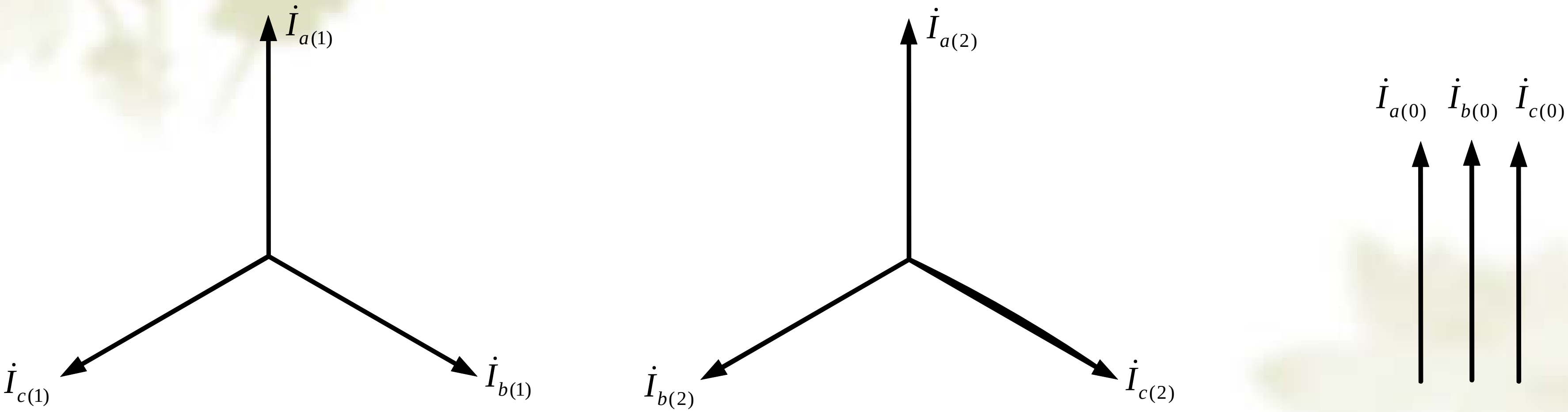
$$i_a = I_m \sin(\omega t + \theta_0)$$
$$i_b = I_m \sin(\omega t + \theta_0)$$
$$i_c = I_m \sin(\omega t + \theta_0)$$

零序分量：

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

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



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：

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

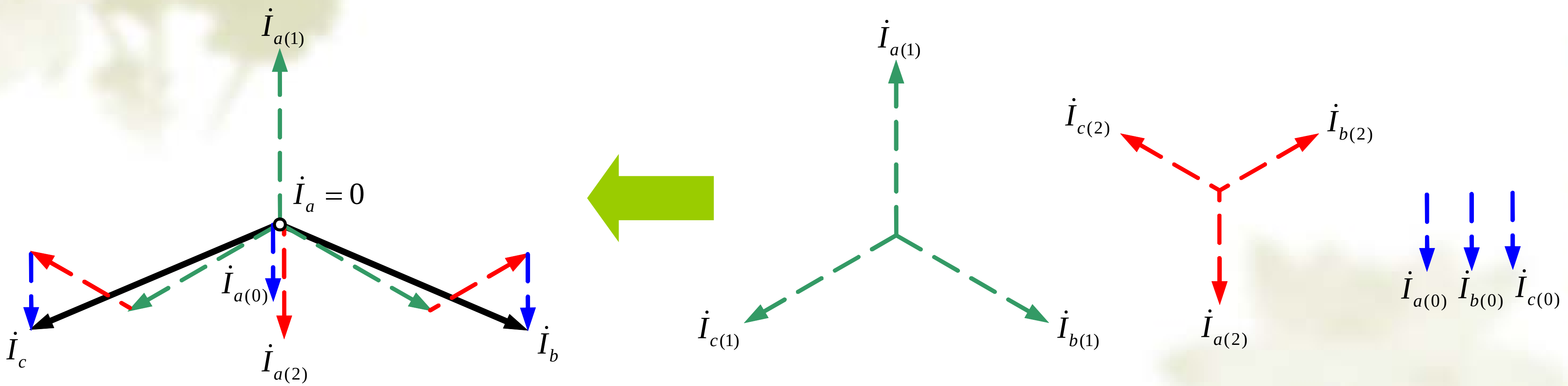
$$\dot{I}_{c(2)}=\alpha^2\dot{I}_{a(2)}=e^{-j120^\circ}\dot{I}_{a(2)}$$

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

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

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

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

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

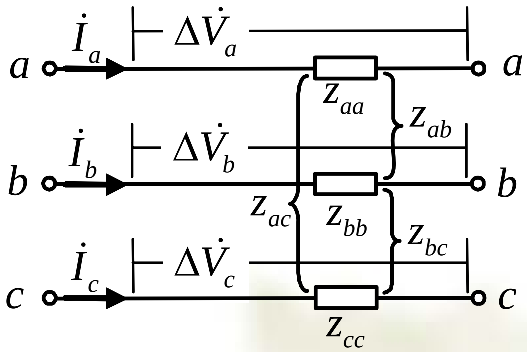
$$\begin{bmatrix} \dot{I}_{a(1)} \\ \dot{I}_{a(2)} \\ \dot{I}_{a(0)} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix}$$

$\dot{\mathbf{I}}_{abc}$ ⟺ 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

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



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

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

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

三相对称电路

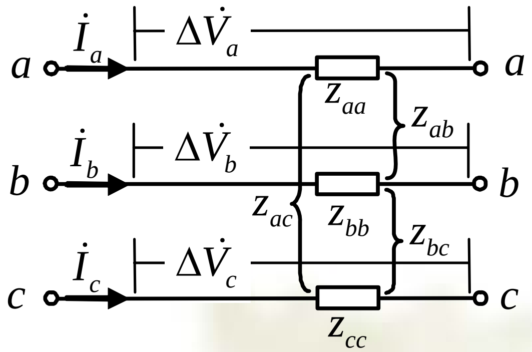
$$z_{aa} = z_{bb} = z_{cc} = z_s$$

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

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

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



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

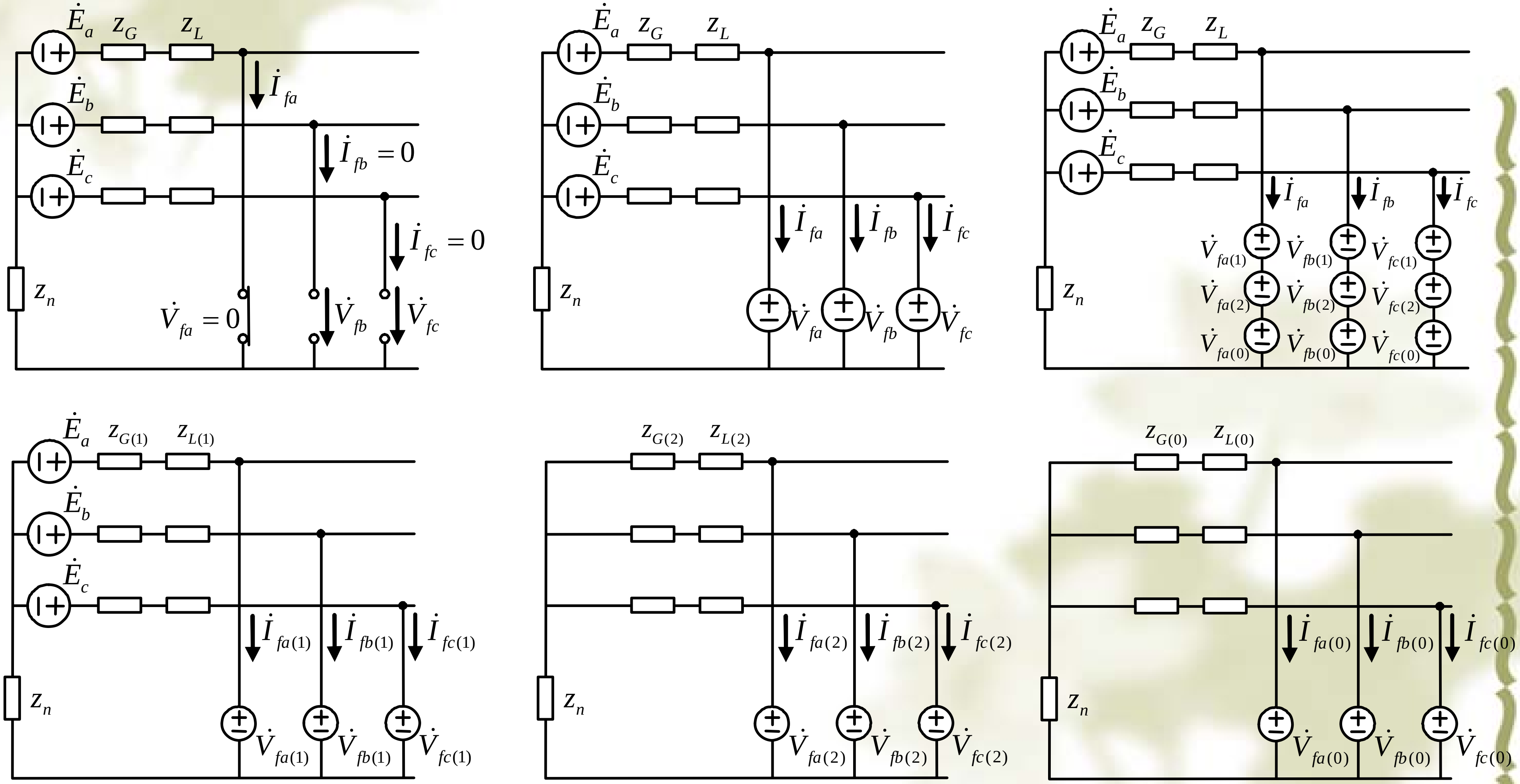
$$\Delta\dot{V}_{a(2)} = (z_s - z_m)\dot{I}_{a(2)}$$
$$\Delta\dot{V}_{b(2)} = (z_s - z_m)\dot{I}_{b(2)}$$
$$\Delta\dot{V}_{c(2)} = (z_s - z_m)\dot{I}_{c(2)}$$

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

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

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



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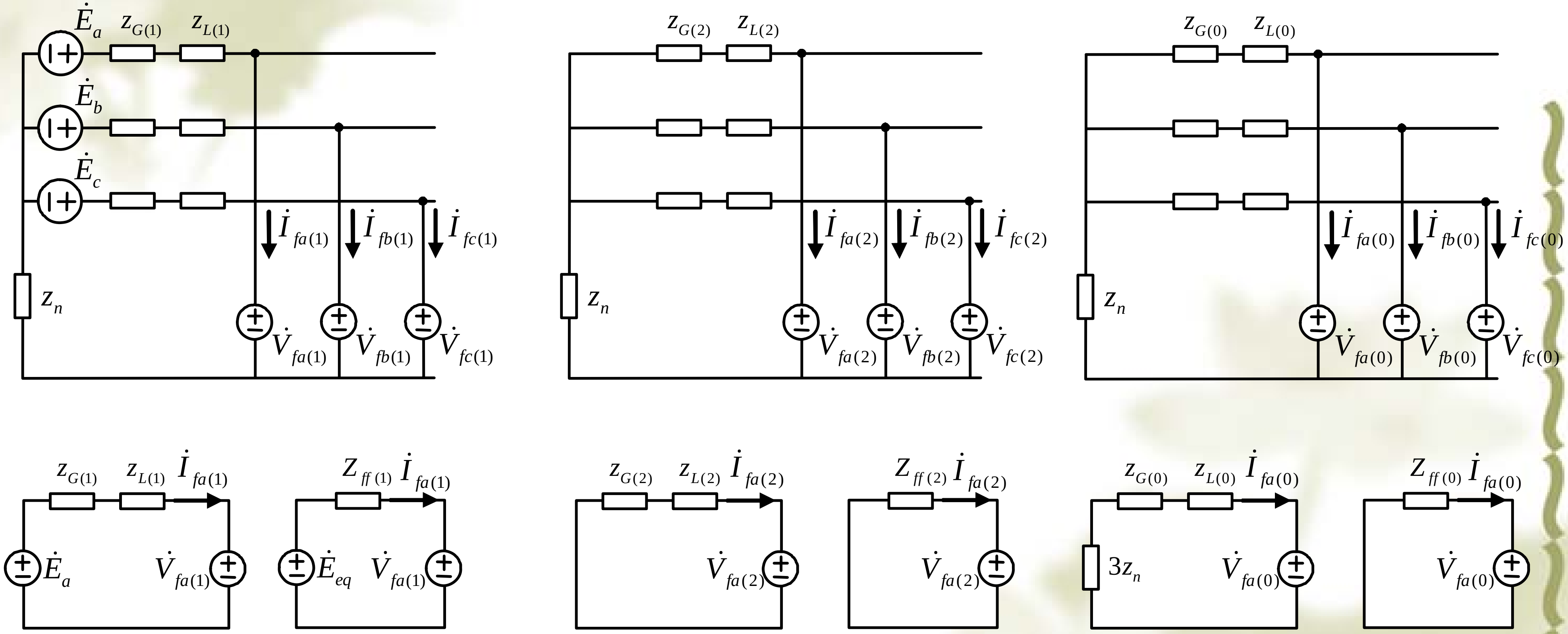


$$\dot{V}_{fa(1)} = \dot{E}_{eq} - Z_{ff(1)}\dot{I}_{fa(1)}$$

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

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

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；

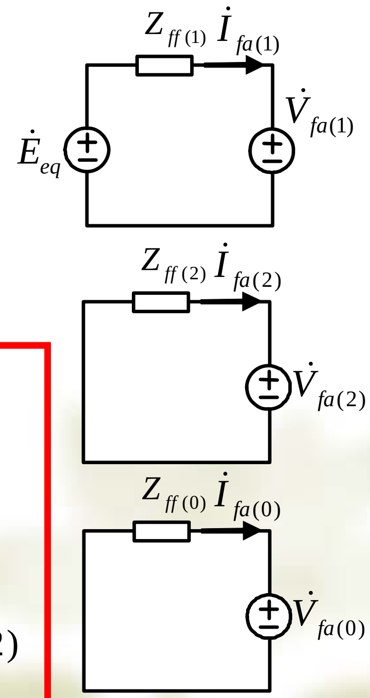
线性网络——叠加原理；

序网方程

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

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

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



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故障口边界条件 → Solution

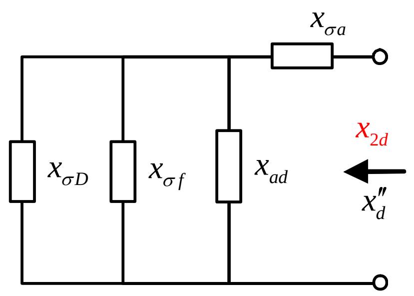
7-2 同步电机的负序和零序电抗

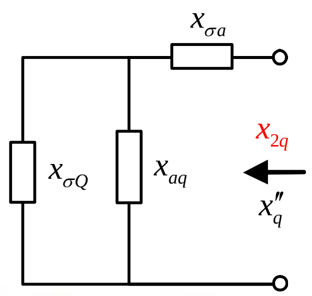
1. 确定发电机负序电抗的等值电路和计算公式

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

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

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





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

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

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

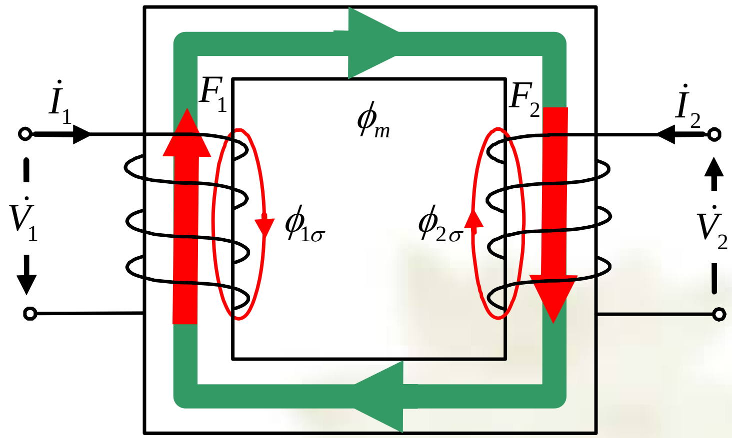
1. 普通变压器的零序等值电路

$$F_1 = w_1 \dot{I}_1, \quad \dot{\phi}_{1\sigma} = F_1 \Lambda_{1\sigma} = w_1 \Lambda_{1\sigma} \dot{I}_1$$

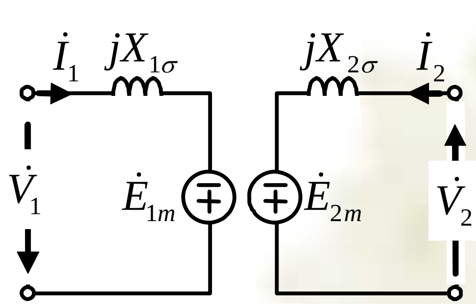
$$\dot{E}_{1\sigma} = -j\omega w_1 \dot{\phi}_{1\sigma} = -j\omega w_1^2 \Lambda_{1\sigma} \dot{I}_1$$

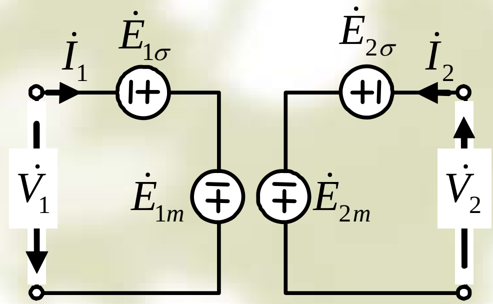
$$-\dot{E}_{1\sigma} = jX_{1\sigma} \dot{I}_1, \quad X_{1\sigma} = \omega w_1^2 \Lambda_{1\sigma}$$

同理有：$-\dot{E}_{2\sigma} = jX_{2\sigma} \dot{I}_2$



$$\dot{V}_1 = -\dot{E}_{1\sigma} - \dot{E}_{1m} = jX_{1\sigma} \dot{I}_1 - \dot{E}_{1m}$$





$$\dot{V}_2 = \dot{E}_{2\sigma} + \dot{E}_{2m}$$

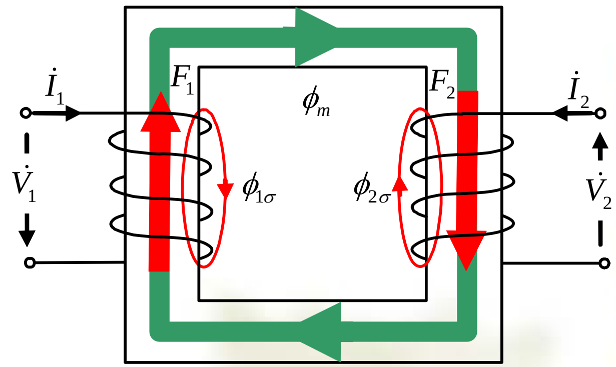
7-3 变压器的零序等值电路及其参数

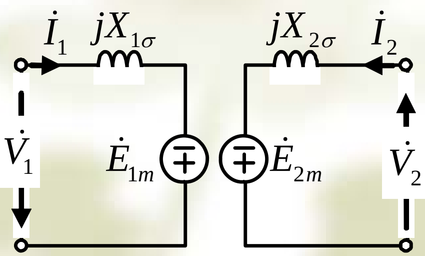
1. 普通变压器的零序等值电路

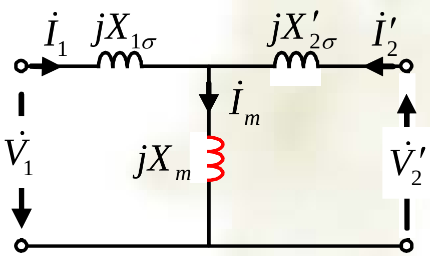
$$\dot{\phi}_m=\left(F_1+F_2\right)\Lambda_m=\left(w_1\dot{I}_1+w_2\dot{I}_2\right)\Lambda_m$$
$$=w_1\left(\dot{I}_1+\dot{I}_2'\right)\Lambda_m=w_1\dot{I}_m\Lambda_m$$

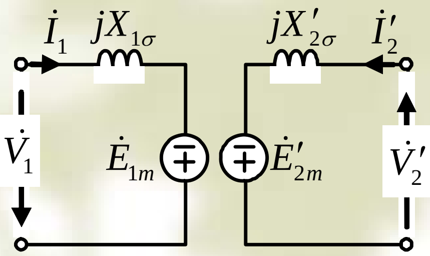
$$\dot{E}_{1m}=-j\omega w_1\dot{\phi}_m=-j\omega w_1^2\Lambda_m\dot{I}_m$$
$$\dot{E}_{2m}=-j\omega w_1\dot{\phi}_m=-j\omega w_2 w_1\Lambda_m\dot{I}_m$$
$$\dot{E}_{2m}'=\left(w_1/w_2\right)\dot{E}_{2m}=-j\omega w_1^2\Lambda_m\dot{I}_m$$

$$-\dot{E}_{1m}=jX_m\dot{I}_m=jX_m\left(\dot{I}_1+\dot{I}_2'\right)$$
$$-\dot{E}_{2m}'=jX_m\dot{I}_m=jX_m\left(\dot{I}_1+\dot{I}_2'\right)$$





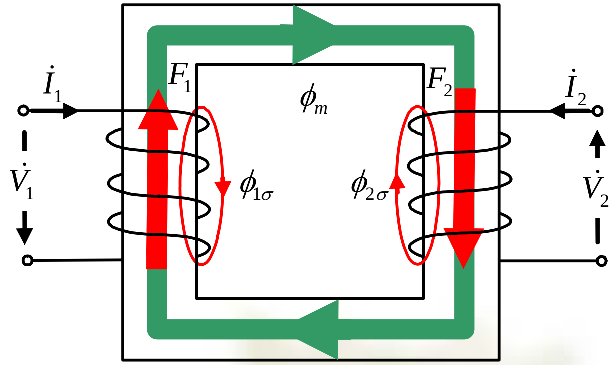


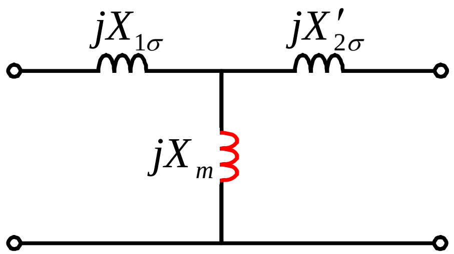


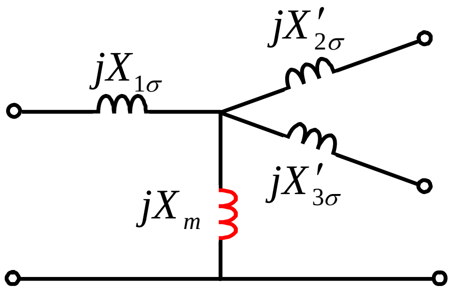
7-3 变压器的零序等值电路及其参数

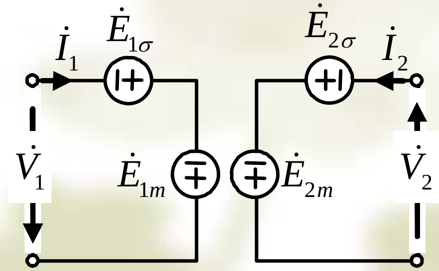
1. 普通变压器的零序等值电路——结论1

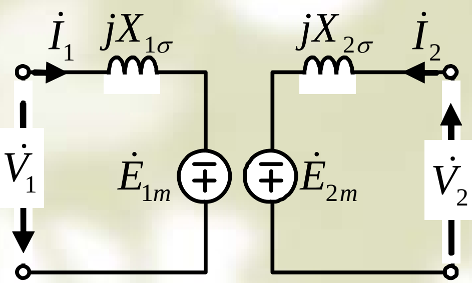
(1) 电路结构相同——变压器的一相等值电路反应了原副方的电磁耦合关系，对各序电流这种耦合关系相同；

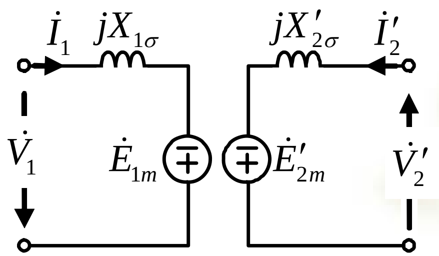


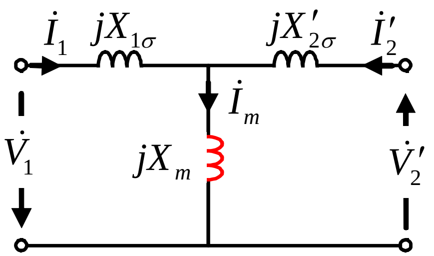








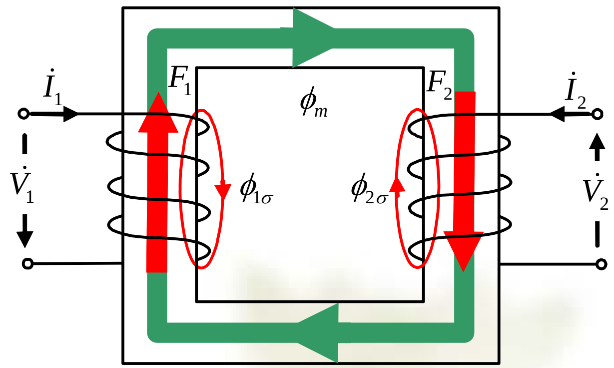


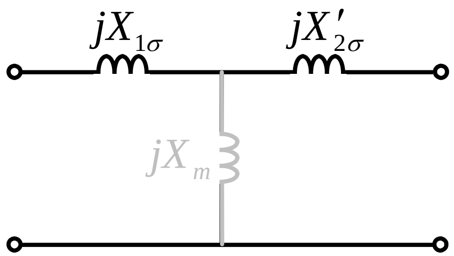


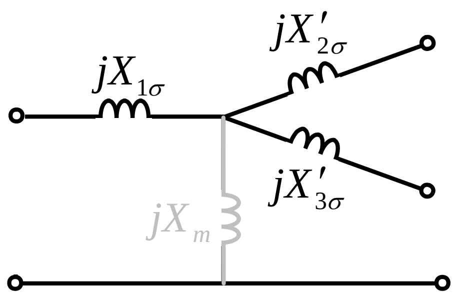
7-3 变压器的零序等值电路及其参数

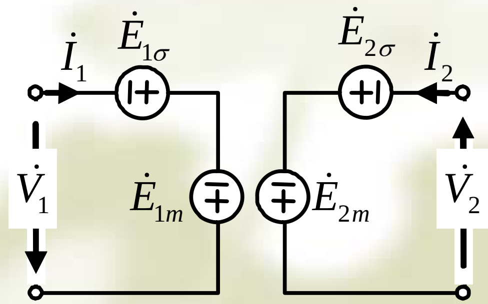
1. 普通变压器的零序等值电路——结论2

(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$X_{\sigma(1)}= X_{\sigma(2)} =X_{\sigma(0)}$;；







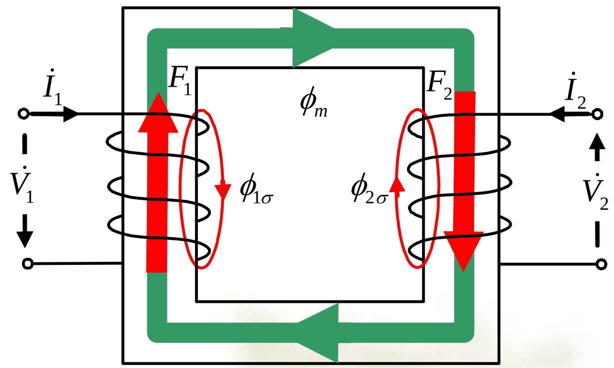


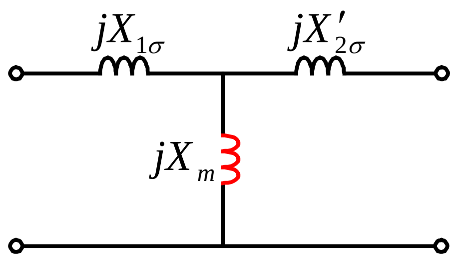
$$-\dot{E}_{1\sigma} = jX_{1\sigma}\dot{I}_1,\ X_{1\sigma} = \omega w_1^2\Lambda_{1\sigma},\quad -\dot{E}_{2\sigma} = jX_{2\sigma}\dot{I}_2,\ X_{2\sigma} = \omega w_2^2\Lambda_{1\sigma},$$

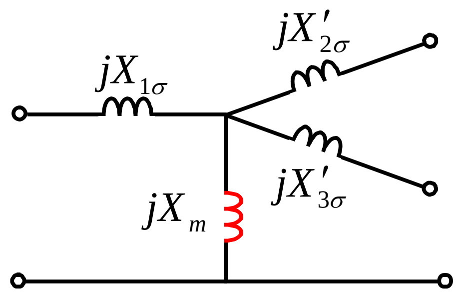
7-3 变压器的零序等值电路及其参数

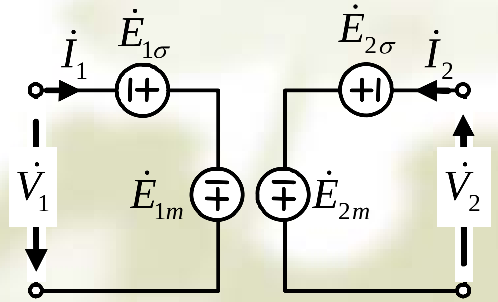
1. 普通变压器的零序等值电路——结论3

(3) 零序激磁电抗与变压器铁芯结构相关——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；







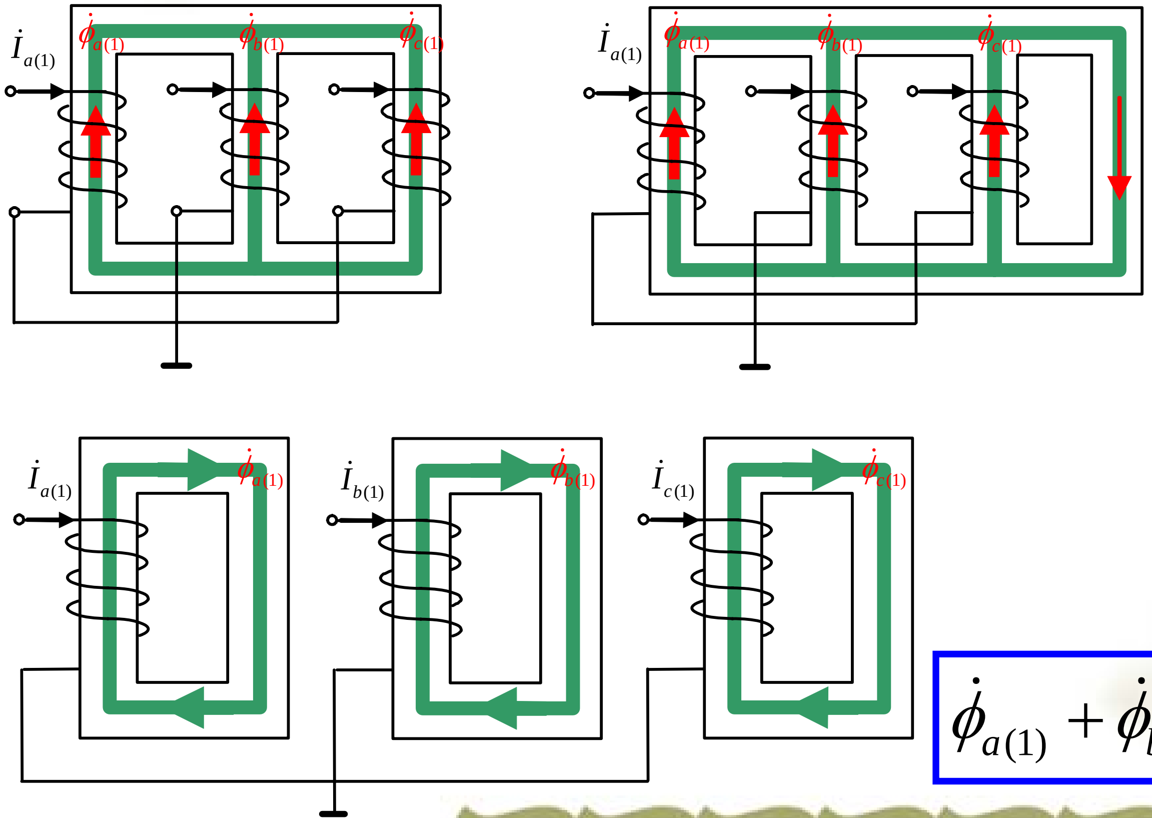


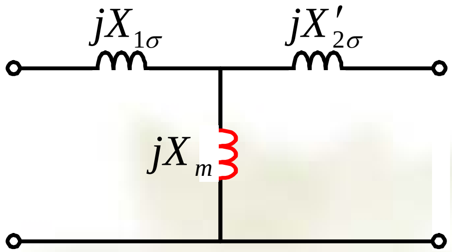
$$-\dot{E}_{1m} = j\omega w_1^2 \Lambda_m \dot{I}_m = jX_m \dot{I}_m, \quad -\dot{E}'_{2m} = j\omega w_1^2 \Lambda_m \dot{I}_m = jX_m \dot{I}_m$$

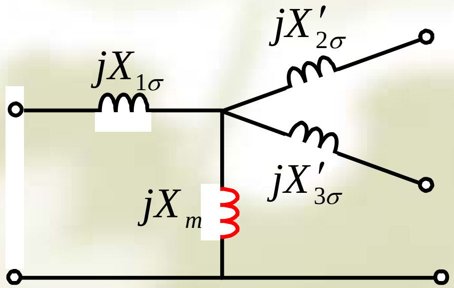
7-3 变压器的零序等值电路及其参数

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$X_{\sigma(1)}$;







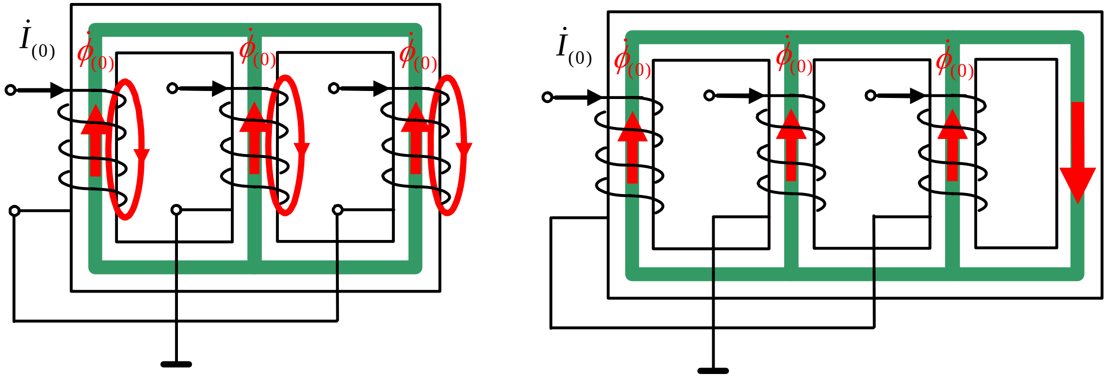
$$\dot{\phi}_{a(1)}+\dot{\phi}_{b(1)}+\dot{\phi}_{c(1)}=0$$

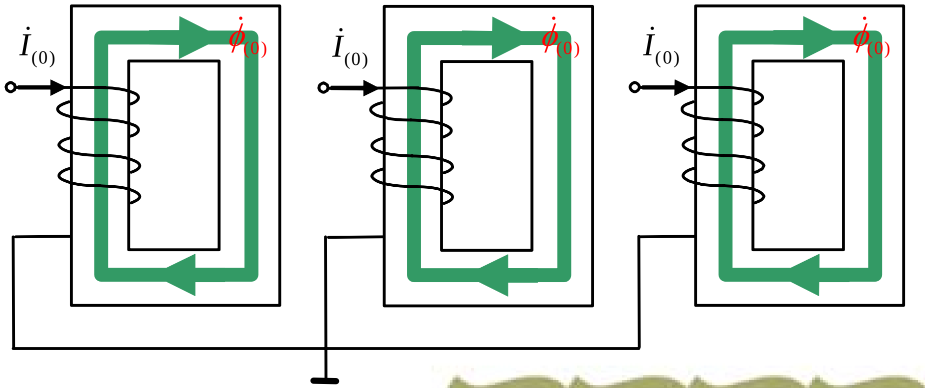
$$X_m=\omega w_1^2\Lambda_m$$

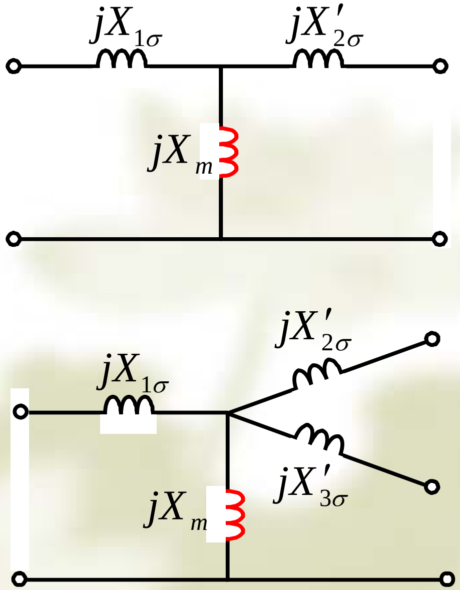
7-3 变压器的零序等值电路及其参数

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，$X_{m(0)} = X_{m(1)}$；





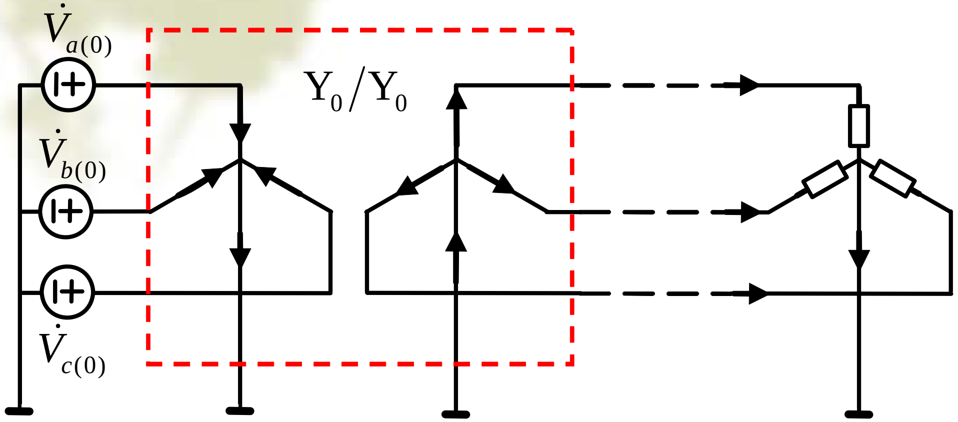


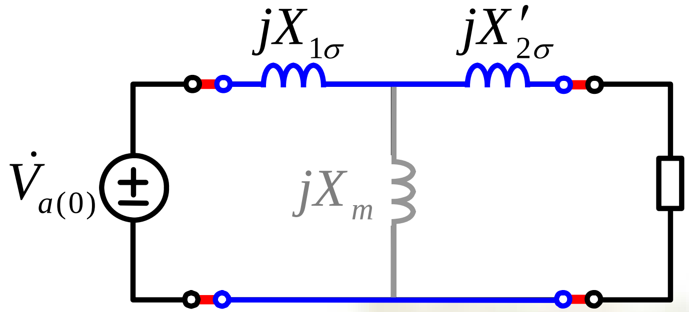
$$\dot{\phi}_{a(0)} = \dot{\phi}_{b(0)} = \dot{\phi}_{c(0)}$$

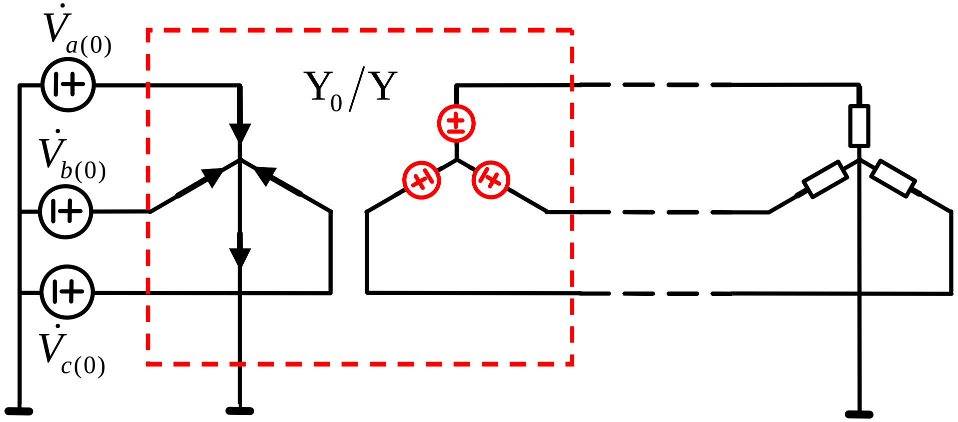
$$X_m = \omega w_1^2 \Lambda_m$$

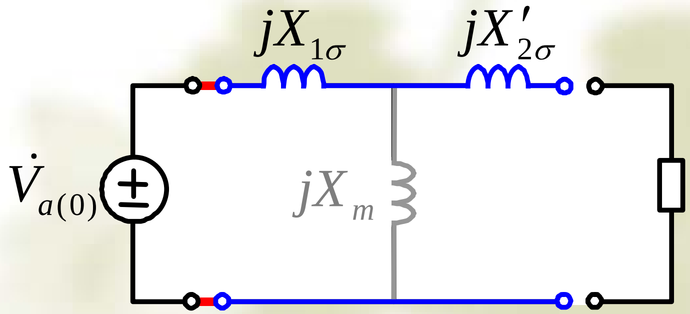
7-3 变压器的零序等值电路及其参数

2. 变压器的零序等值电路与外电路的联接



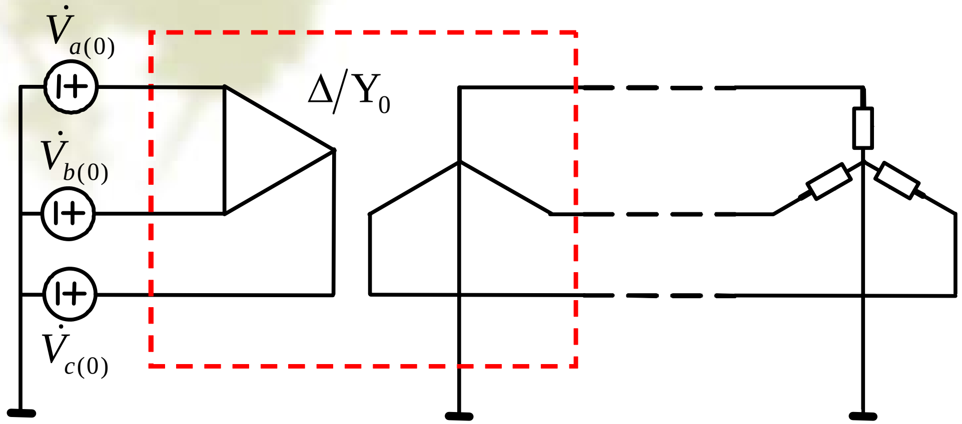


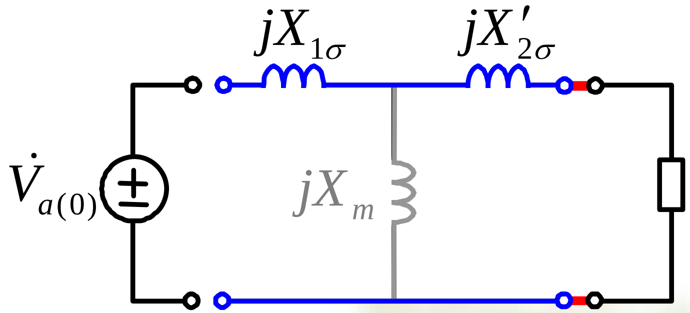


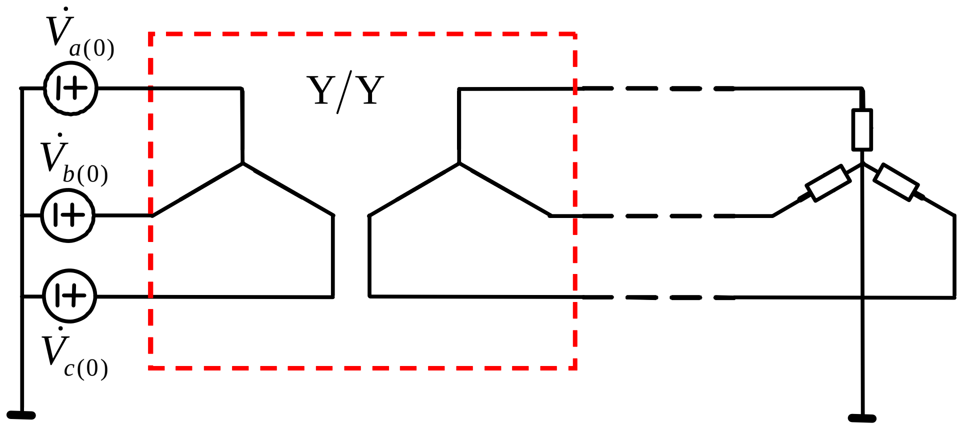


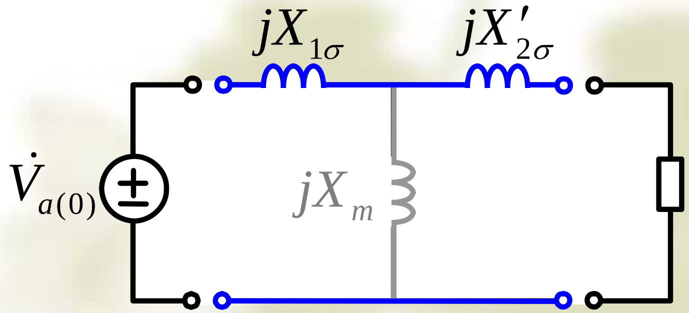
7-3 变压器的零序等值电路及其参数

2. 变压器的零序等值电路与外电路的联接



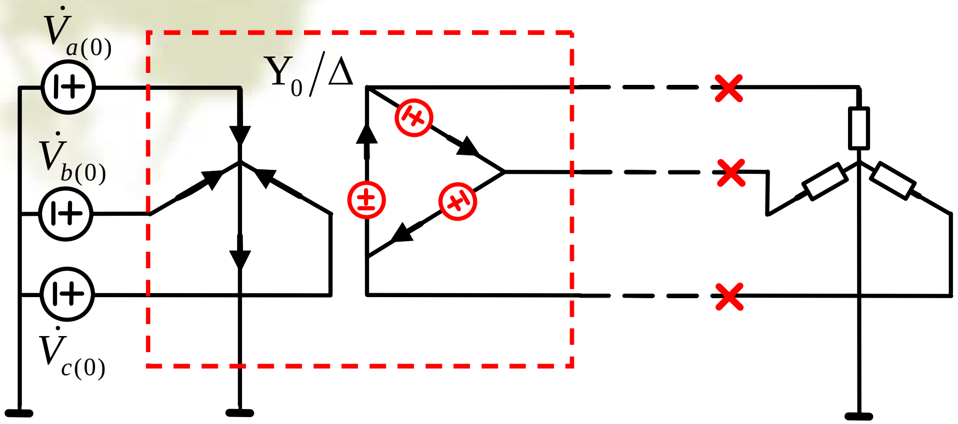


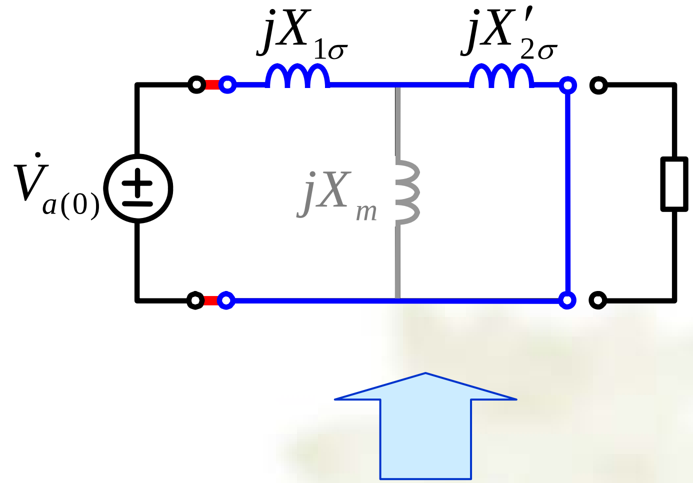


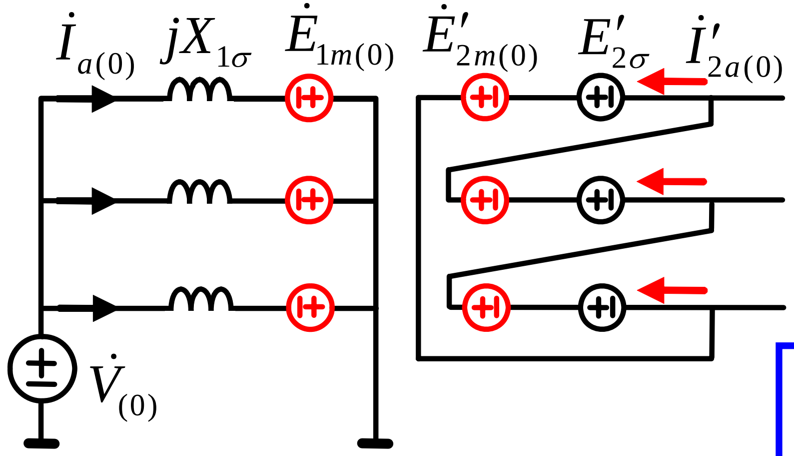


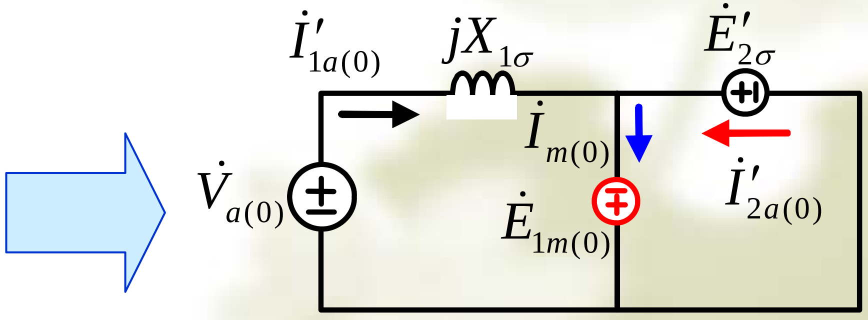
7-3 变压器的零序等值电路及其参数

2. 变压器的零序等值电路与外电路的联接



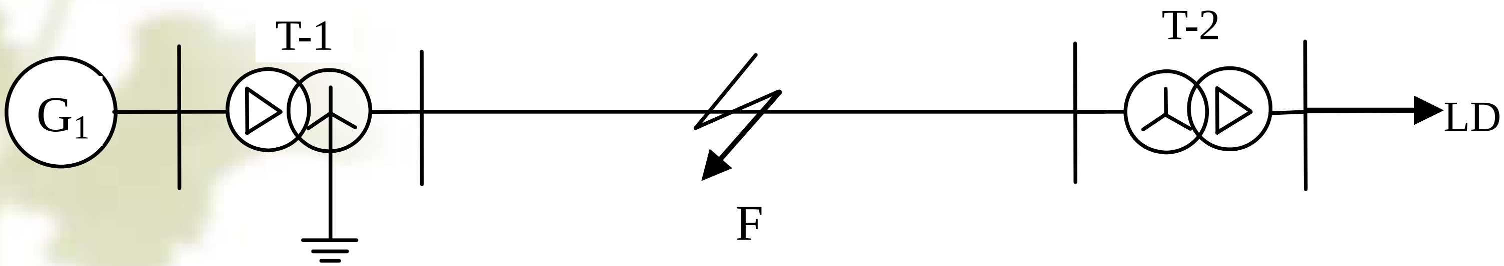


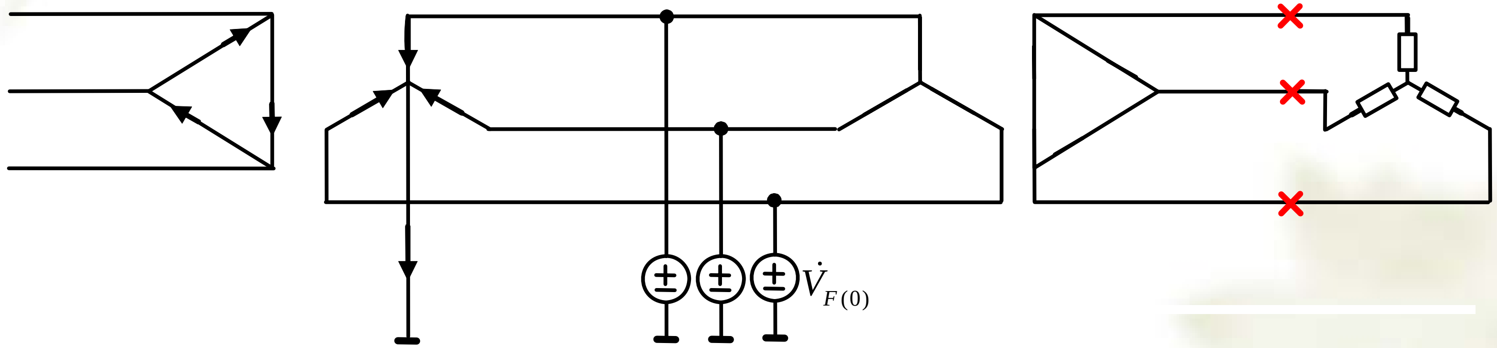


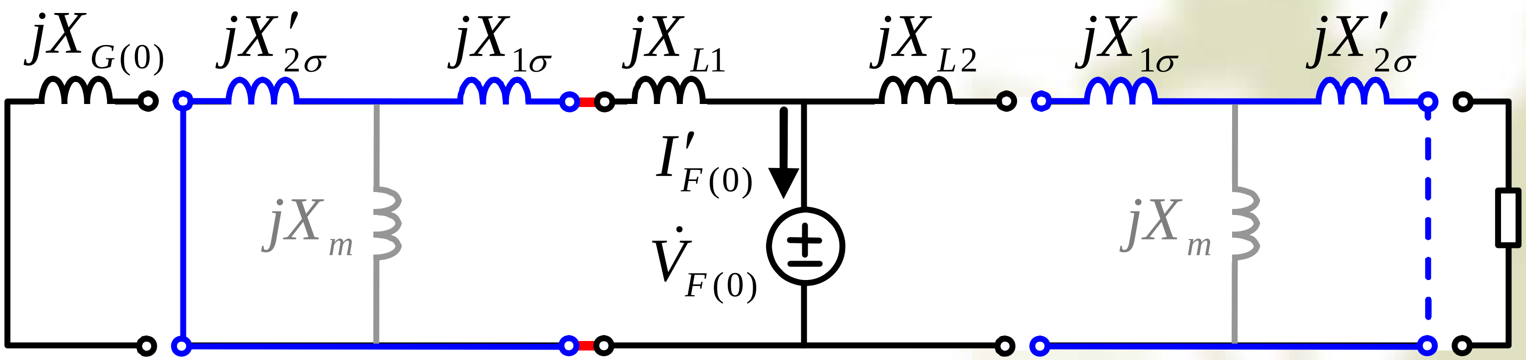


$$-\dot{E}'_{2m(0)} = jX_{m(0)}\dot{I}_{m(0)}, -\dot{E}'_{2\sigma} = jX'_{2\sigma}\dot{I}'_{2a(0)}$$

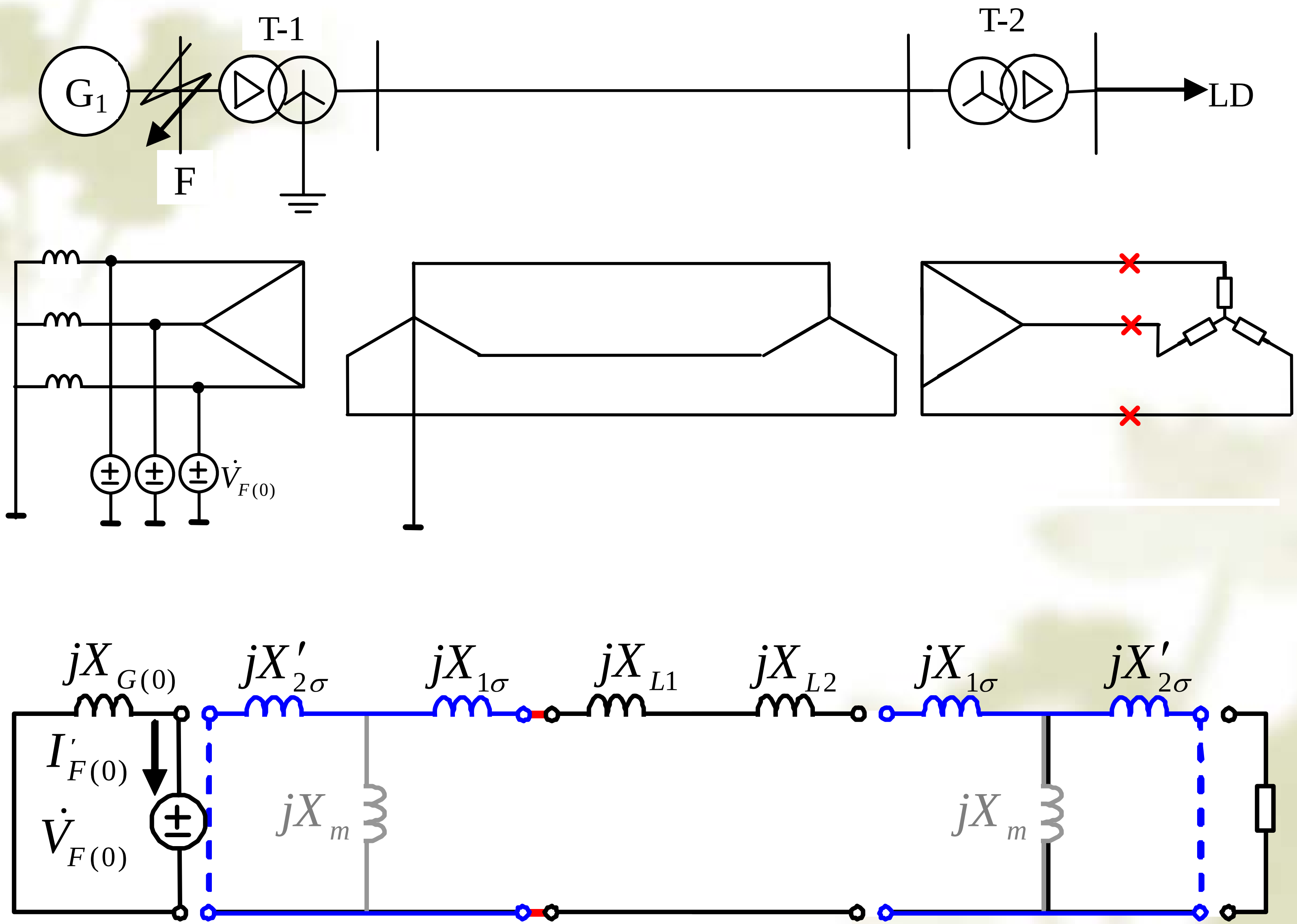
2. 变压器的零序等值电路与外电路的联接——举例





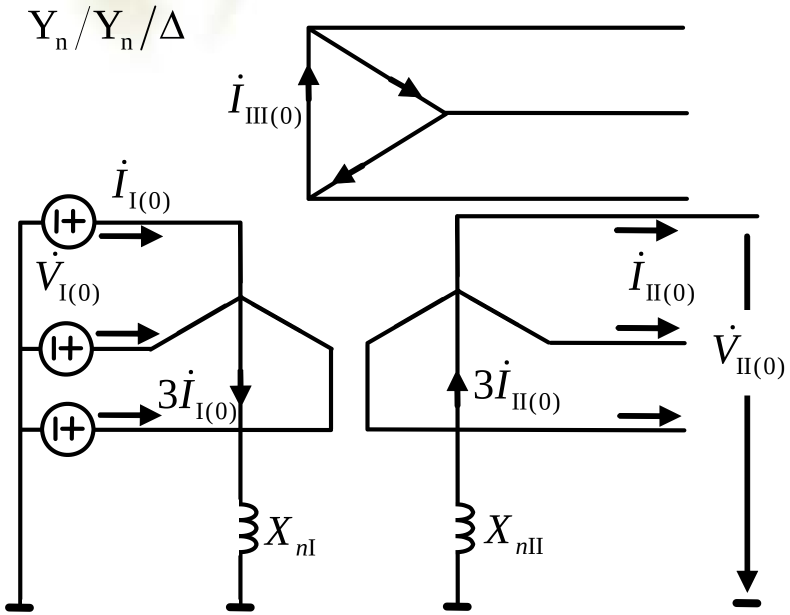


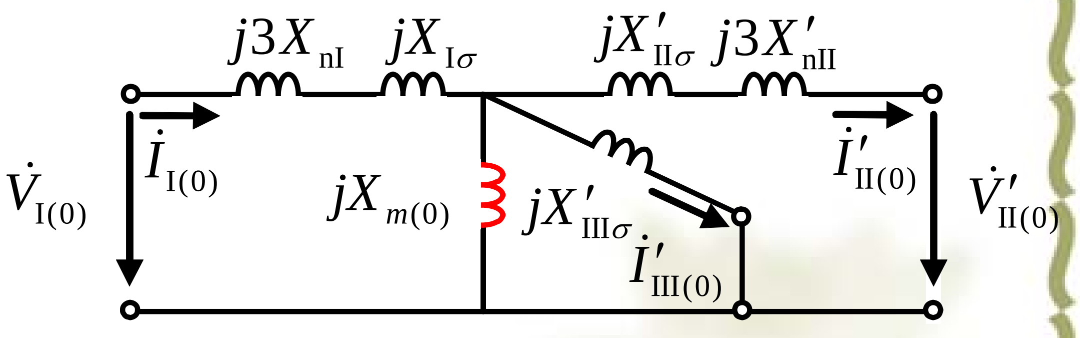
2. 变压器的零序等值电路与外电路的联接——举例

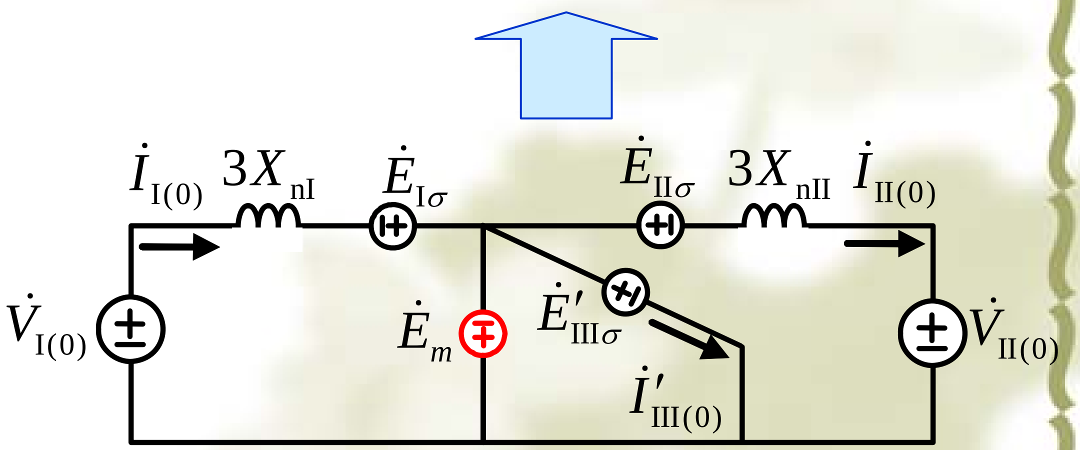


7-3 变压器的零序等值电路及其参数

3.中性点有接地阻抗的变压器零序等值电路

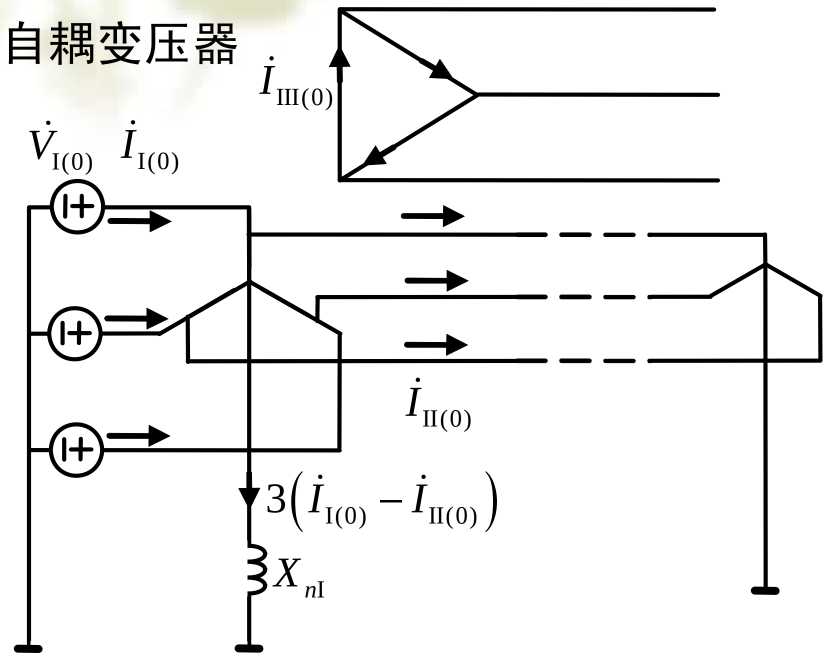






7-3 变压器的零序等值电路及其参数

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

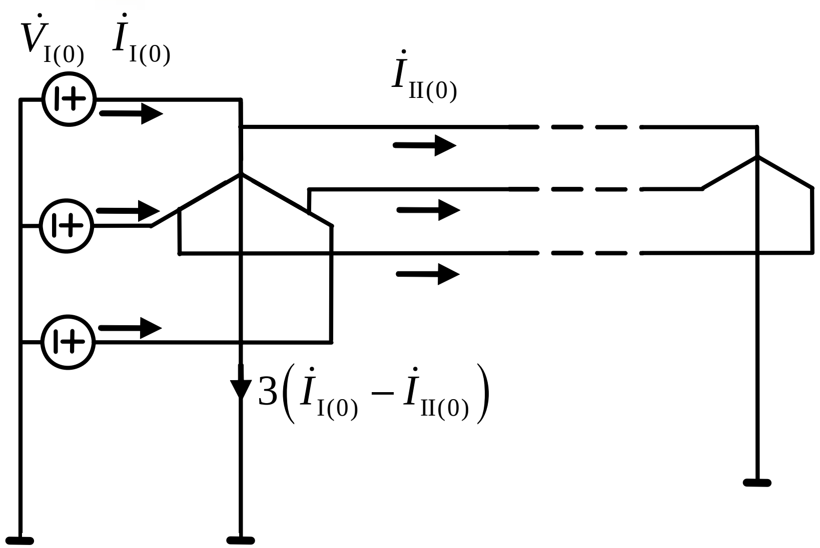
(3) 中性点接地阻抗对各侧绕组零序参数均有影响；

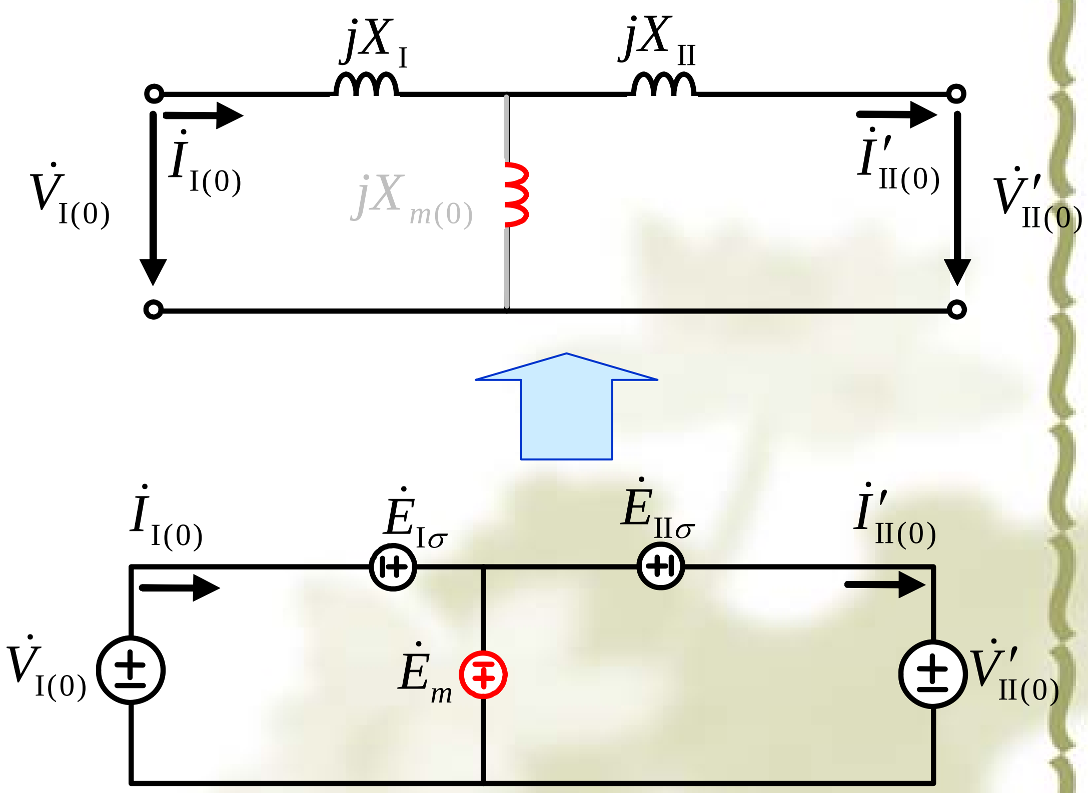
(4) 中性点不接地也可能通过零序电流

4.自耦变压器的零序等值电路及其参数

(1) 中性点直接接地的双绕组自耦变压器

双绕组自耦变压器，中性点直接接地

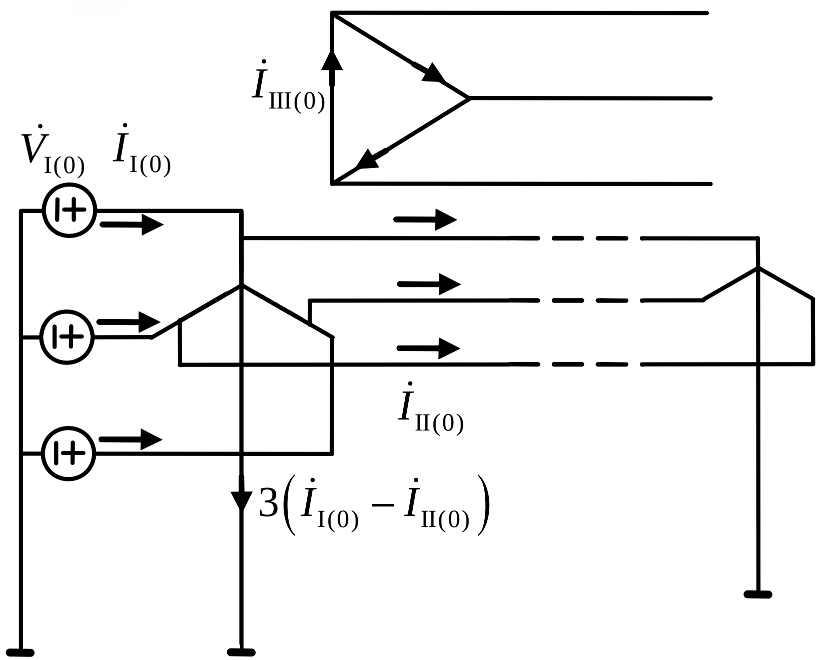


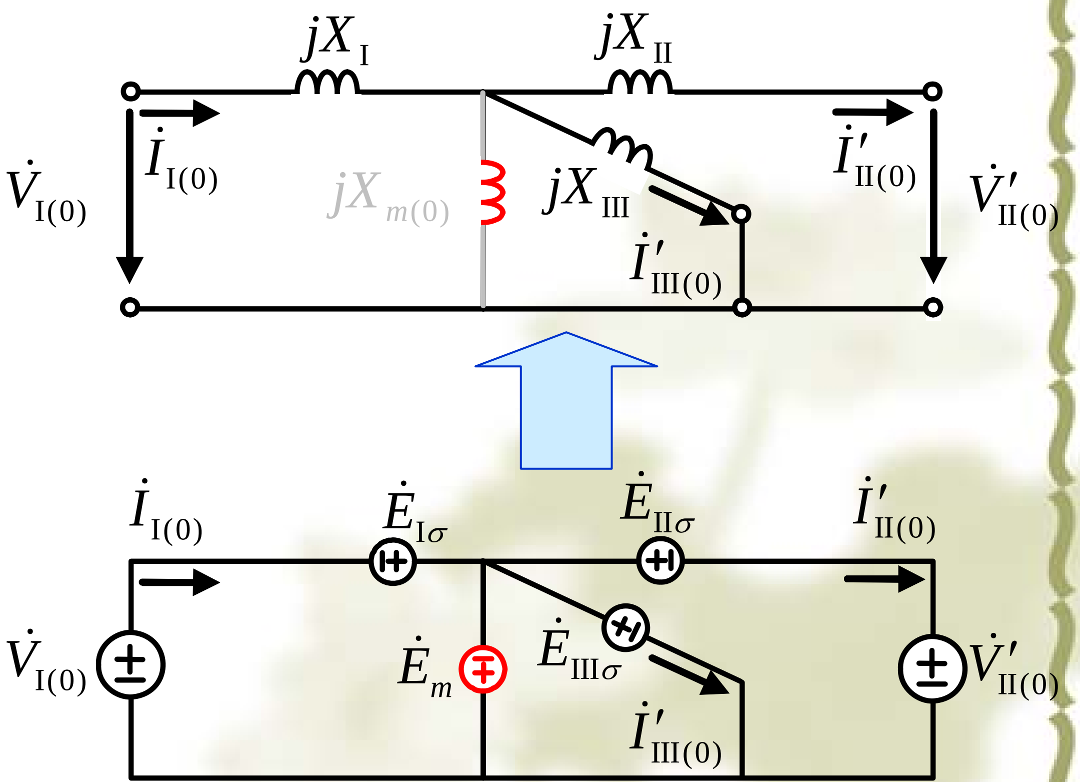


4.自耦变压器的零序等值电路及其参数

(2) 中性点直接接地的三绕组自耦变压器

三绕组自耦变压器，中性点直接接地

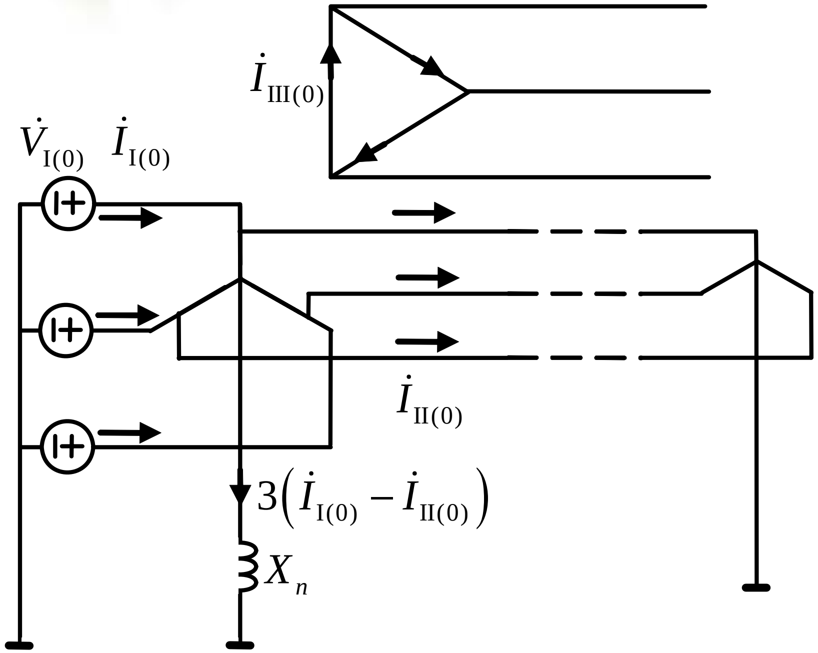


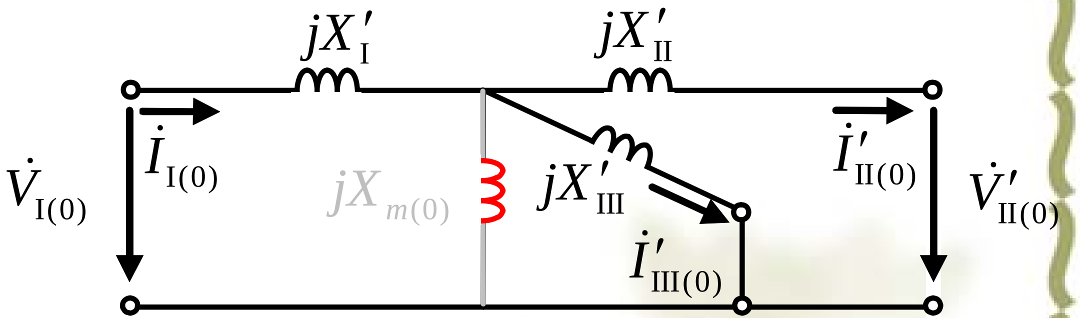


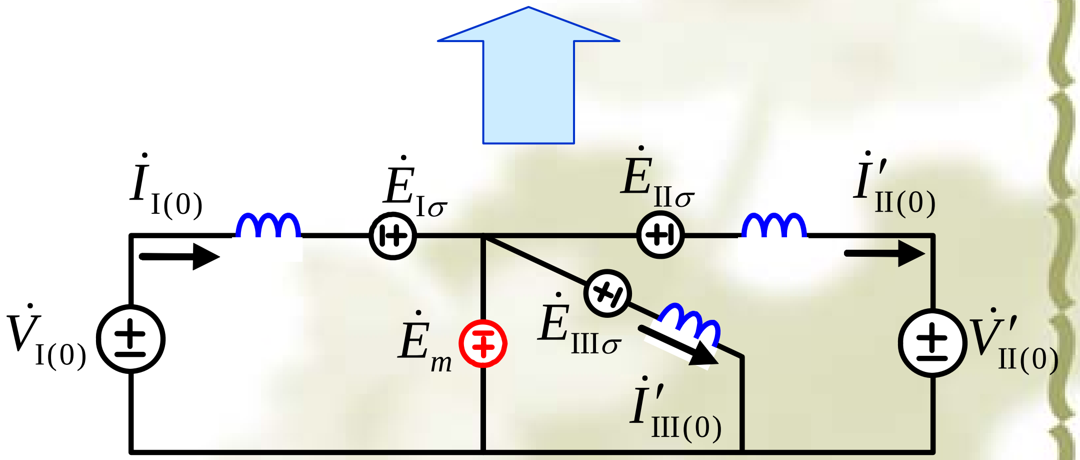
4.自耦变压器的零序等值电路及其参数

(3) 中性点经电抗接地的三绕组自耦变压器

三绕组自耦变压器，中性点经电抗接地



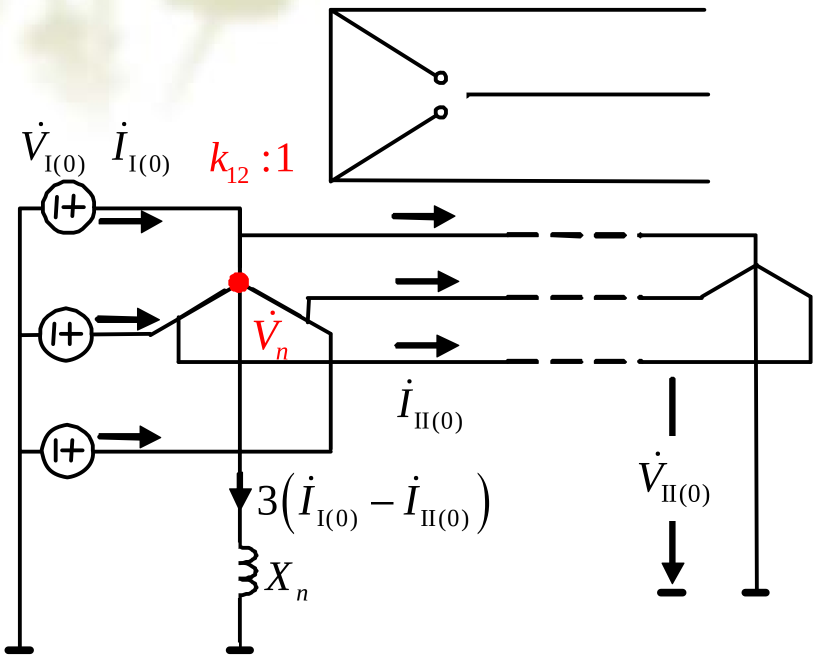


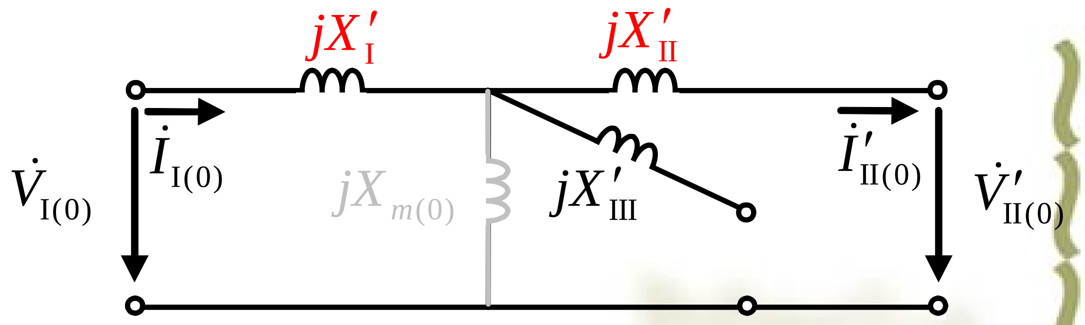


4.自耦变压器的零序等值电路及其参数

(3) 中性点经电抗接地的三绕组自耦变压器

三绕组自耦变压器，三角侧绕组开路





$$\dot V_{I(0)}=\dot V_{In}+\dot V_n,\quad \dot V_{II(0)}=\dot V_{IIn}+\dot V_n$$

$$\dot V_n=3x_n\left(\dot I_{I(0)}-\dot I_{II(0)}\right)=3x_n\left(1-k_{12}\right)\dot I_{I(0)}$$

$$j\left(X'_{I}+X'_{II}\right)=\frac{\dot V_{I(0)}-\dot V'_{II(0)}}{\dot I_{I(0)}}$$

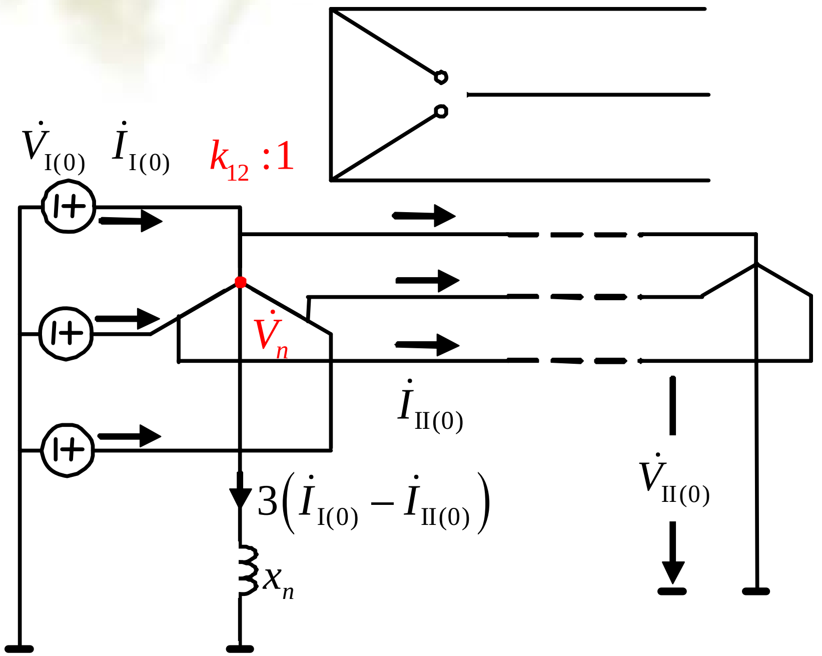
$$=\frac{\left(\dot V_{In}+\dot V_n\right)-k_{12}\left(\dot V_{IIn}+\dot V_n\right)}{\dot I_{I(0)}}$$

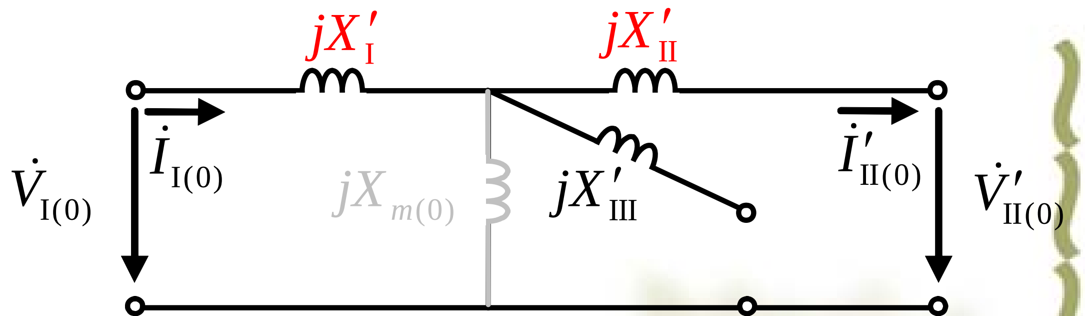
$$=\frac{\dot V_{In}-k_{12}\dot V_{IIn}}{\dot I_{I(0)}}+\frac{\left(1-k_{12}\right)\dot V_n}{\dot I_{I(0)}}$$

4.自耦变压器的零序等值电路及其参数

(3) 中性点经电抗接地的三绕组自耦变压器

三绕组自耦变压器，三角侧绕组开路





$$j(X'_{I}+X'_{II})=jX_{I}+jX_{II}+j3x_n(1-k_{12})^2$$

$$j(X'_{I}+X'_{II})=\frac{\dot{V}_{In}-k_{12}\dot{V}_{IIn}}{\dot{I}_{I(0)}}+\frac{(1-k_{12})\dot{V}_n}{\dot{I}_{I(0)}}$$

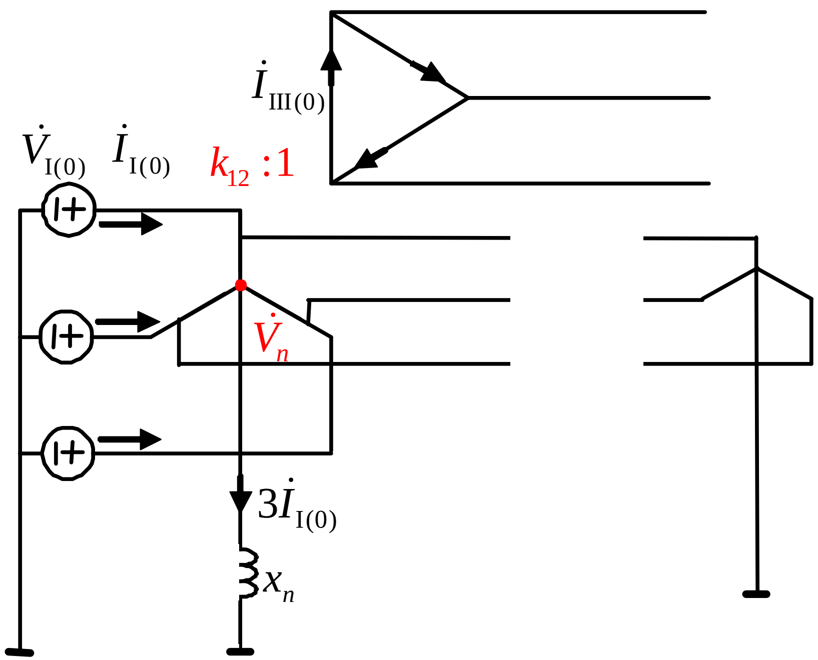
$$\dot{V}_n=3x_n(\dot{I}_{I(0)}-\dot{I}_{II(0)})=3x_n(1-k_{12})\dot{I}_{I(0)}$$

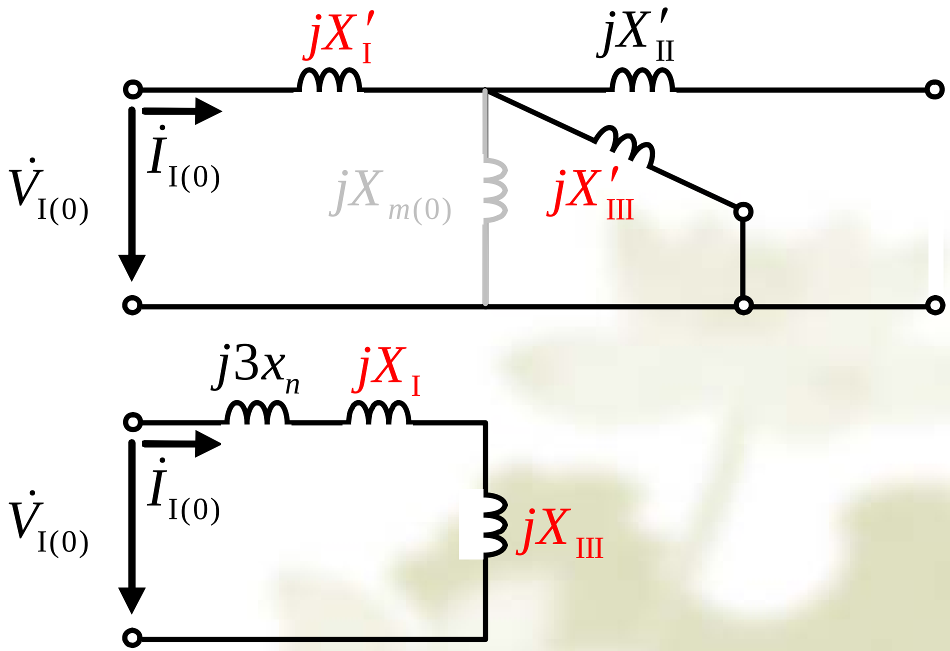
$$j(X_{I}+X_{II})=\frac{\dot{V}_{In}-k_{12}\dot{V}_{IIn}}{\dot{I}_{I(0)}}$$

4.自耦变压器的零序等值电路及其参数

(3) 中性点经电抗接地的三绕组自耦变压器

三绕组自耦变压器，二次侧绕组开路



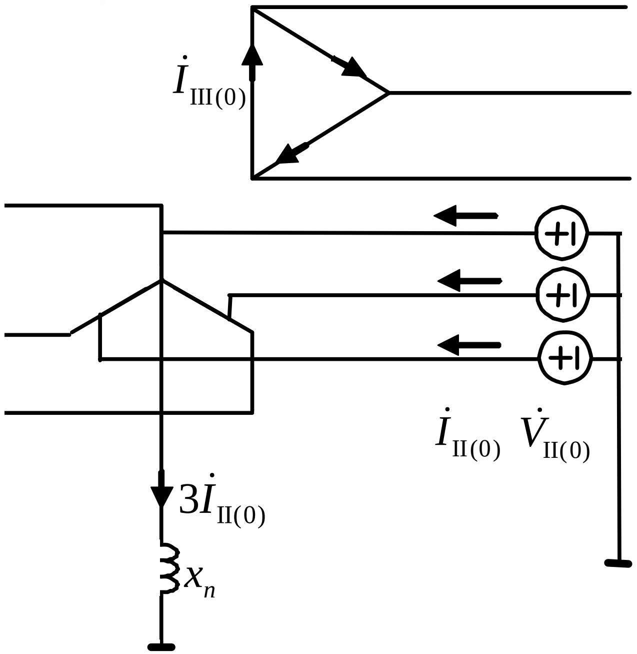


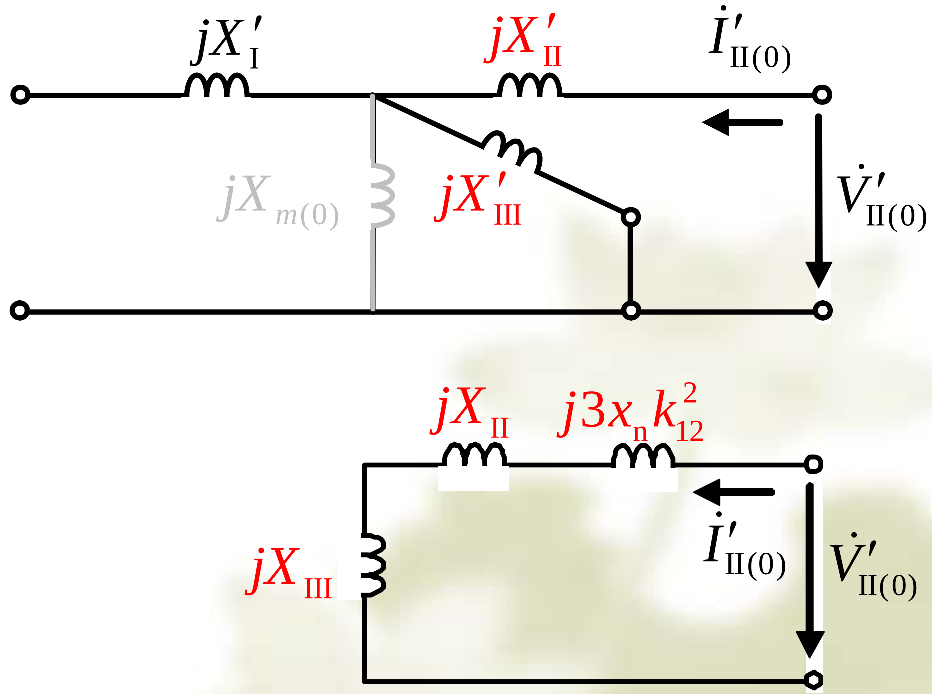
$$j\left(X'_I + X'_{III}\right) = jX_I + jX_{III} + j3x_n$$

4.自耦变压器的零序等值电路及其参数

(3) 中性点经电抗接地的三绕组自耦变压器

三绕组自耦变压器，一次侧绕组开路





$$j\left(X'_{II}+X'_{III}\right)=jX_{II}+jX_{III}+j3x_n k_{12}^2$$

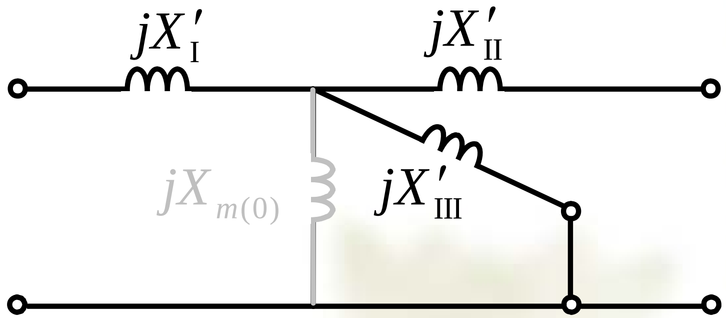
4.自耦变压器的零序等值电路及其参数

(3) 中性点经电抗接地的三线组自耦变压器

$$j\left(X_{\mathrm{I}}'+X_{\mathrm{II}}'\right)=jX_{\mathrm{I}}+jX_{\mathrm{II}}+j3x_n\left(1-k_{12}\right)^2$$

$$j\left(X_{\mathrm{I}}'+X_{\mathrm{III}}'\right)=jX_{\mathrm{I}}+jX_{\mathrm{III}}+j3x_n$$

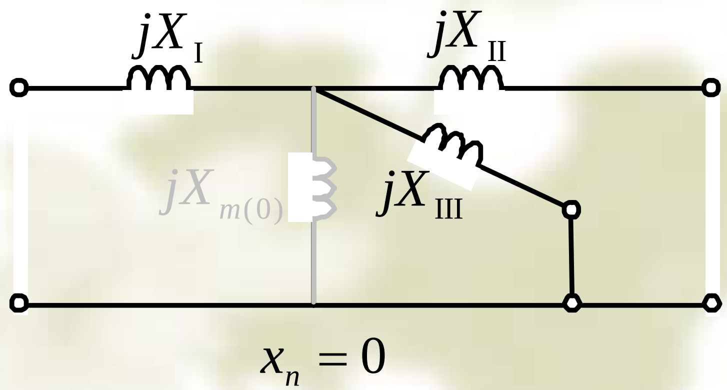
$$j\left(X_{\mathrm{II}}'+X_{\mathrm{III}}'\right)=jX_{\mathrm{II}}+jX_{\mathrm{III}}+j3x_nk_{12}^2$$



$$jX_{\mathrm{I}}'=jX_{\mathrm{I}}+j3x_n\left(1-k_{12}\right)$$

$$jX_{\mathrm{II}}'=jX_{\mathrm{II}}+j3x_nk_{12}\left(1-k_{12}\right)$$

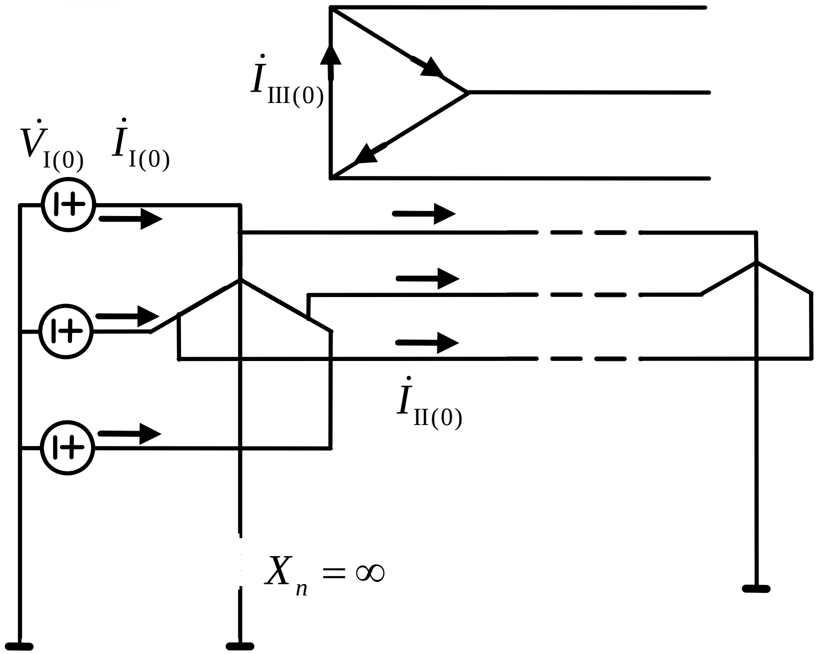
$$jX_{\mathrm{III}}'=jX_{\mathrm{III}}+j3x_nk_{12}$$

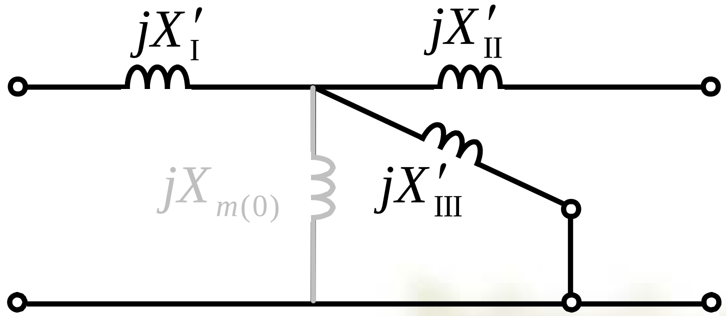


4.自耦变压器的零序等值电路及其参数

(4) 中性点不接地的三绕组自耦变压器

三绕组自耦变压器，中性点不接地





$$jX'_{\mathrm{I}}=jX_{\mathrm{I}}+j3x_n(1-k_{12})$$

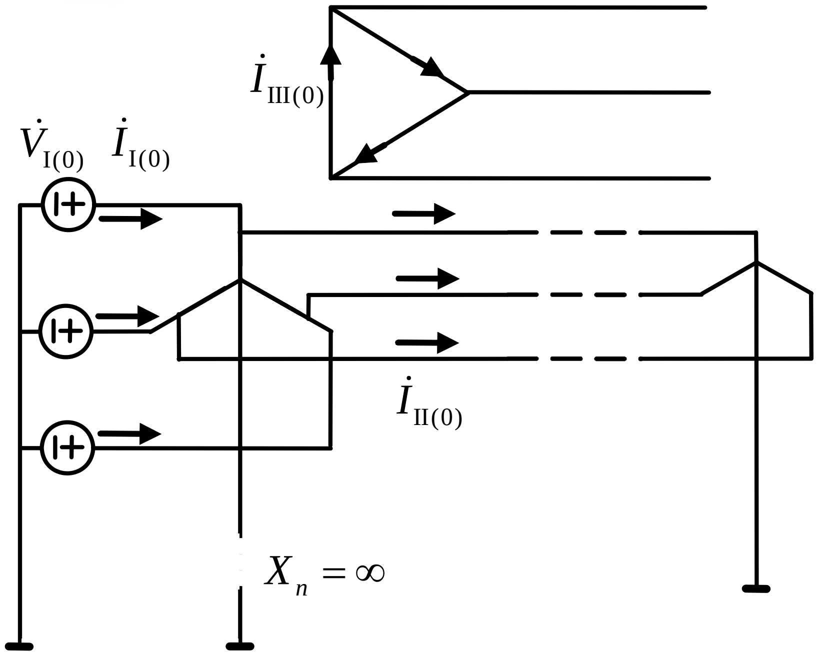
$$jX'_{\mathrm{II}}=jX_{\mathrm{I}}+j3x_nk_{12}(1-k_{12})$$

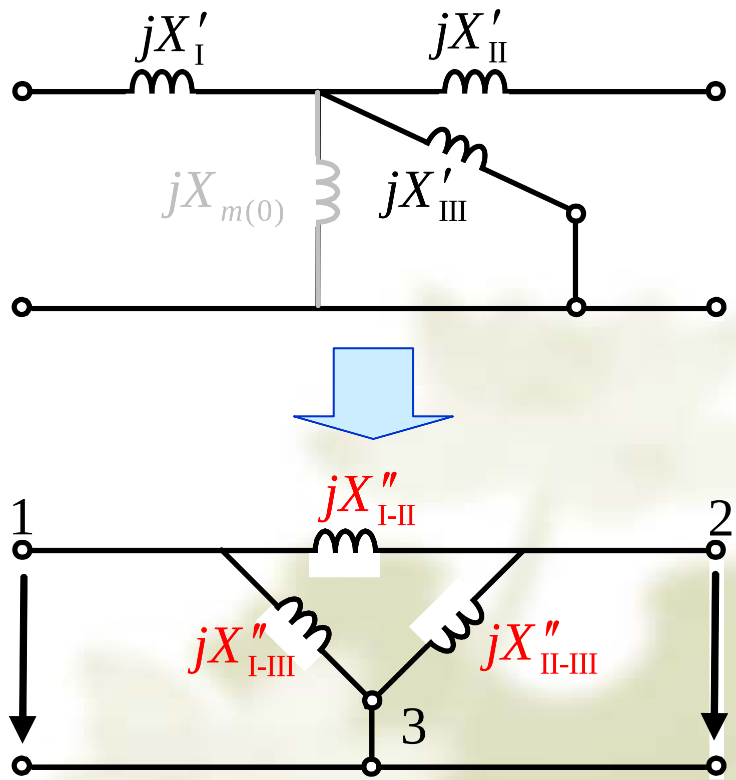
$$jX'_{\mathrm{III}}=jX_{\mathrm{III}}+j3x_nk_{12}$$

4.自耦变压器的零序等值电路及其参数

(4) 中性点不接地的三绕组自耦变压器

三绕组自耦变压器，中性点不接地





$$jX''_{I\text{-}II}+jX''_{I\text{-}III}+jX''_{II\text{-}III}=0$$

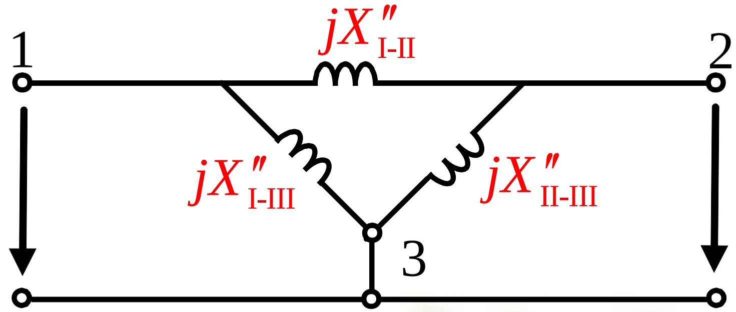
4.自耦变压器的零序等值电路及其参数

(4) 中性点不接地的三绕组自耦变压器

$$jX'_{\mathrm{I}} = jX_{\mathrm{I}} + j3x_n(1-k_{12})$$

$$jX'_{\mathrm{II}} = jX_{\mathrm{I}} + j3x_n k_{12}(1-k_{12})$$

$$jX'_{\mathrm{III}} = jX_{\mathrm{III}} + j3x_n k_{12}$$



$$jX'_{\text{I-II}} = \lim_{x_n\to\infty}\left(jX'_{\mathrm{I}} + jX'_{\mathrm{II}} + \frac{jX'_{\mathrm{I}}\times jX'_{\mathrm{II}}}{jX'_{\mathrm{III}}}\right) = k_{12}X_{\mathrm{I}} + \frac{1}{k_{12}}X_{\mathrm{II}} + \frac{(1-k_{12})^2}{k_{12}}X_{\mathrm{III}}$$

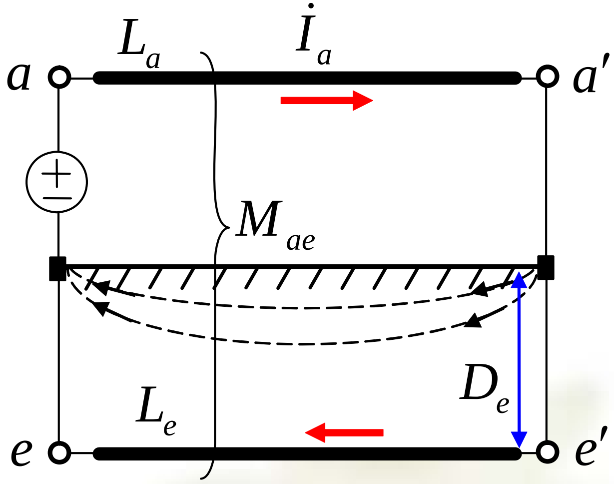
$$jX'_{\text{I-III}} = \lim_{x_n\to\infty}\left(jX'_{\mathrm{I}} + jX'_{\mathrm{III}} + \frac{jX'_{\mathrm{I}}\times jX'_{\mathrm{III}}}{jX'_{\mathrm{II}}}\right) = -\frac{k_{12}}{1-k_{12}}X_{\mathrm{I}} - \frac{1}{k_{12}(1-k_{12})}X_{\mathrm{II}} - \frac{1-k_{12}}{k_{12}}X_{\mathrm{III}}$$

$$jX'_{\text{II-III}} = \lim_{x_n\to\infty}\left(jX'_{\mathrm{II}} + jX'_{\mathrm{III}} + \frac{jX'_{\mathrm{II}}\times jX'_{\mathrm{III}}}{jX'_{\mathrm{I}}}\right) = \frac{k_{12}^2}{1-k_{12}}X_{\mathrm{I}} + \frac{1}{(1-k_{12})}X_{\mathrm{II}} + (1-k_{12})X_{\mathrm{III}}$$

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

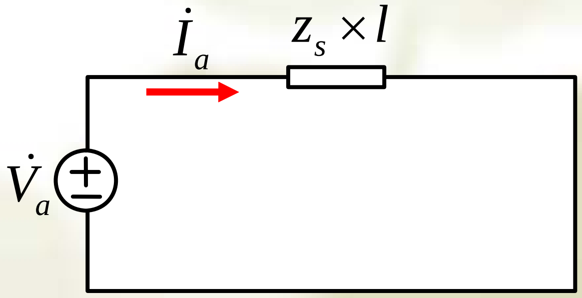
自阻抗:单导线以大地为回路时对应于单位长度导线的回路阻抗



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

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

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

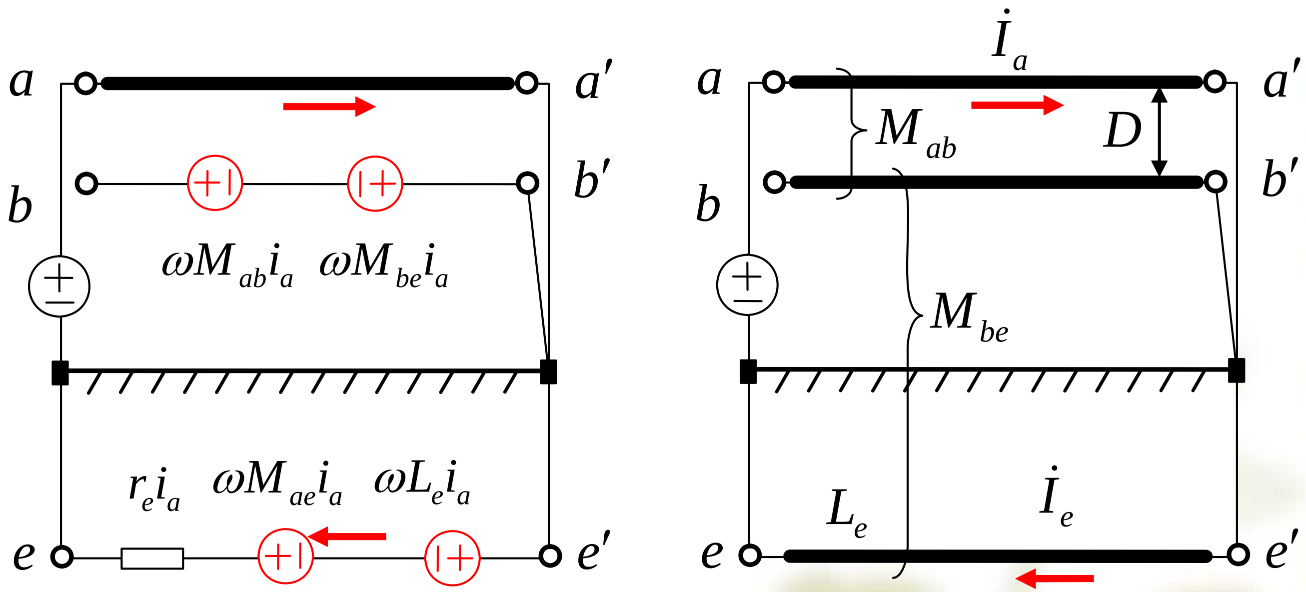


$$\{z_S\}_{\Omega/\mathrm{km}}=r_a+r_e+j\omega L_S=r_a+r_e+j0.1445\lg\frac{D_e}{D_S}$$

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



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

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

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

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

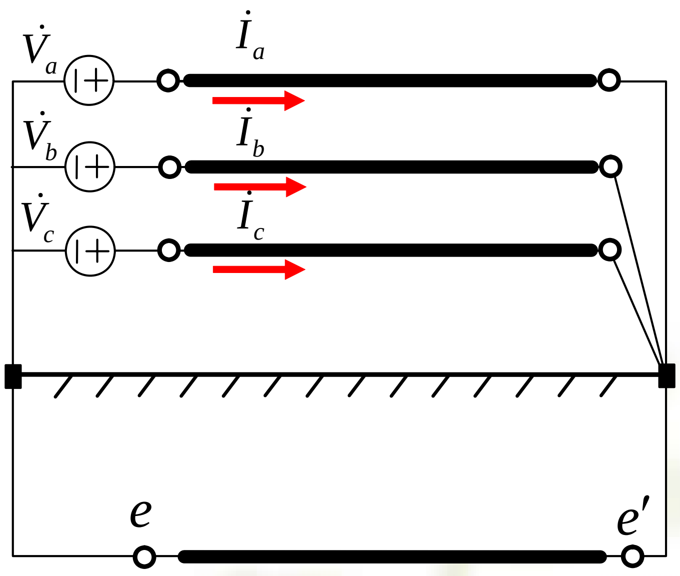
7-4 架空输电线的零序阻抗及其等值电路

3. 三相输电线路的一相等值零序阻抗

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

$$\dot{V}_{a(1)} = (z_s - z_m)\dot{I}_{a(1)}$$
$$\dot{V}_{a(2)} = (z_s - z_m)\dot{I}_{a(2)}$$
$$\dot{V}_{a(0)} = (z_s + 2z_m)\dot{I}_{a(0)}$$

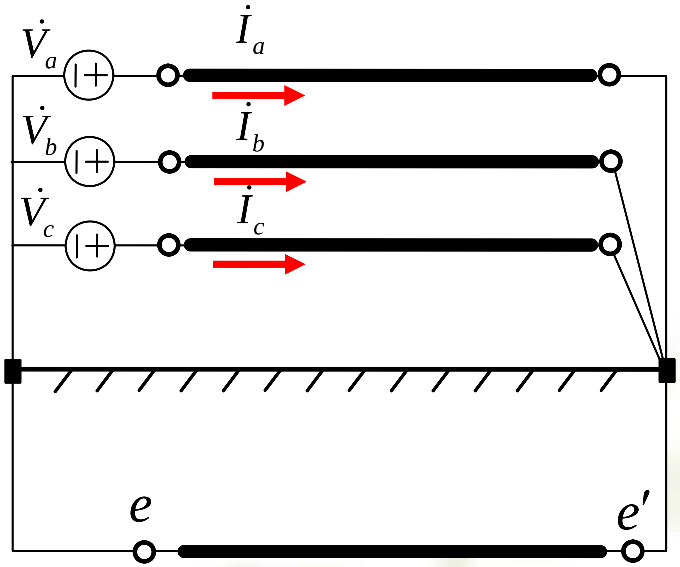
$$z_{(1)} = z_s - z_m$$
$$z_{(2)} = z_s - z_m$$
$$z_{(0)} = z_s + 2z_m$$



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

7-4 架空输电线的零序阻抗及其等值电路

3. 三相输电线路的一相等值零序阻抗



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

$$\dot{V}_{a(1)} = (z_s - z_m)\dot{I}_{a(1)}$$
$$\dot{V}_{a(2)} = (z_s - z_m)\dot{I}_{a(2)}$$
$$\dot{V}_{a(0)} = (z_s + 2z_m)\dot{I}_{a(0)}$$

$$z_{(1)} = z_s - z_m$$
$$z_{(2)} = z_s - z_m$$
$$z_{(0)} = z_s + 2z_m$$

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

$$\{L_S\}_{\text{H/m}} = L_a + L_e - 2M_{ae}$$

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

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

7-4 架空输电线的零序阻抗及其等值电路

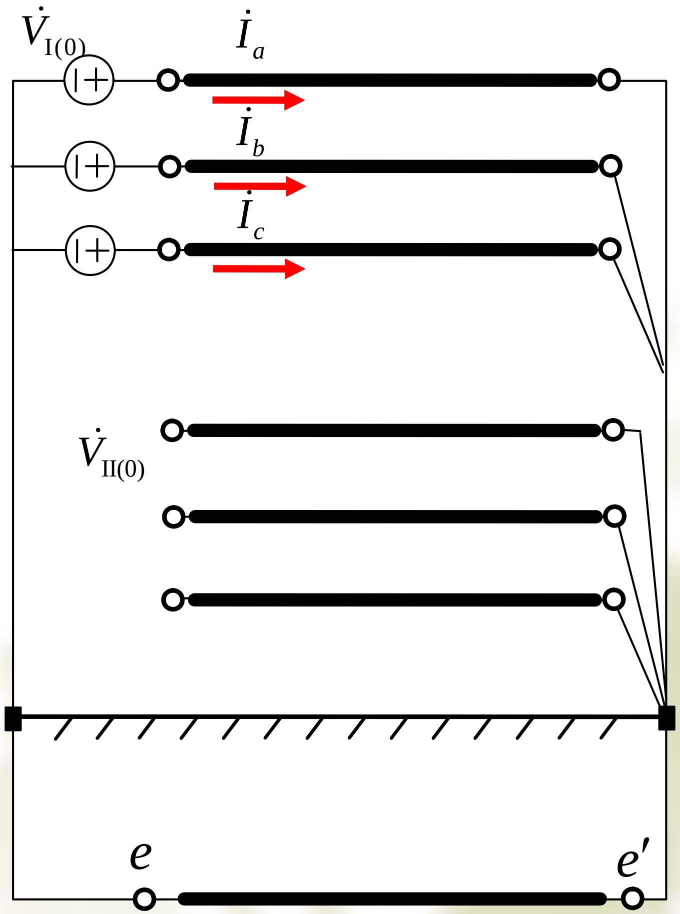
4. 平行架设双回输电线路的零序阻抗及等值电路

(1) 线路零序参数

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

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

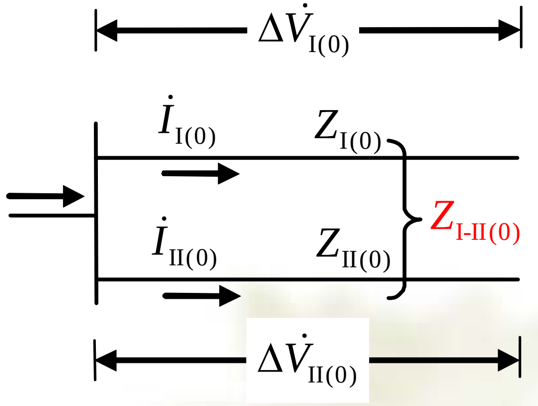
互阻抗的求法$Z_{\text{I-II}(0)}$：I 回输电线路三相通过单位零序电流$\dot{I}_{\mathrm{I}(0)}$，在 II 回每相产生的电压降落在数值上即为$Z_{\text{I-II}(0)}$



7-4 架空输电线的零序阻抗及其等值电路

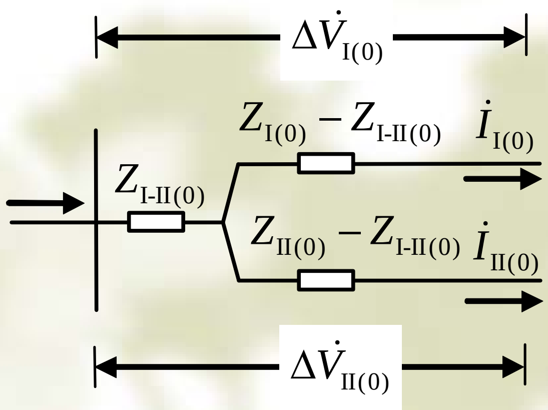
4. 平行架设双回输电线路的零序阻抗及等值电路

(2) 平行架设双回输电线路的零序等值电路(首端相连)



$$\dot{V}_{\text{I}(0)} = Z_{\text{I}(0)}\dot{I}_{\text{I}(0)} + Z_{\text{I-II}(0)}\dot{I}_{\text{II}(0)}$$

$$\dot{V}_{\text{II}(0)} = Z_{\text{I-II}(0)}\dot{I}_{\text{I}(0)} + Z_{\text{II}(0)}\dot{I}_{\text{II}(0)}$$

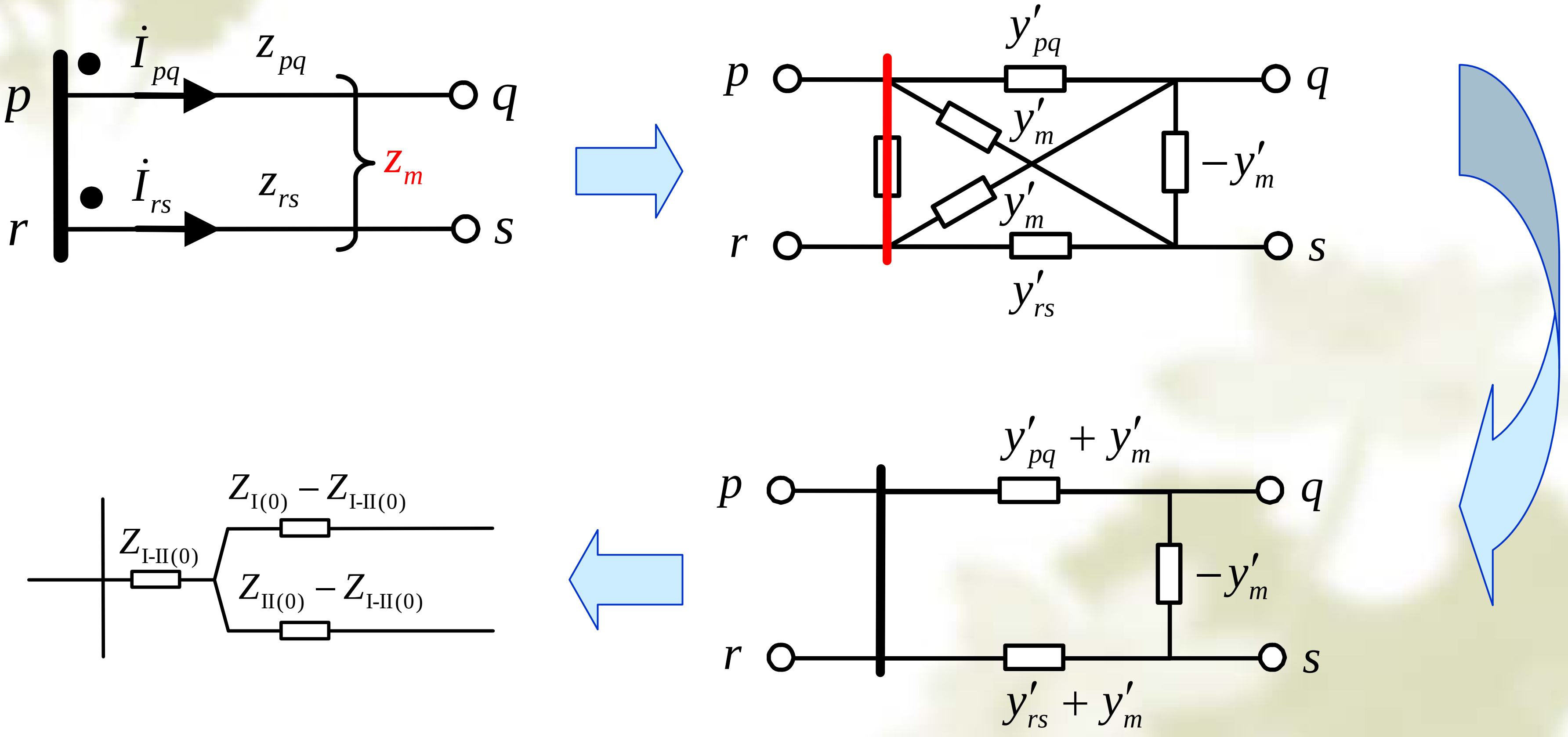


$$\dot{V}_{\text{I}(0)} = Z_{\text{I-II}(0)}\left(\dot{I}_{\text{I}(0)} + \dot{I}_{\text{II}(0)}\right) + \left(Z_{\text{I}(0)} - Z_{\text{I-II}(0)}\right)\dot{I}_{\text{I}(0)}$$

$$\dot{V}_{\text{II}(0)} = Z_{\text{I-II}(0)}\left(\dot{I}_{\text{I}(0)} + \dot{I}_{\text{II}(0)}\right) + \left(Z_{\text{II}(0)} - Z_{\text{I-II}(0)}\right)\dot{I}_{\text{II}(0)}$$

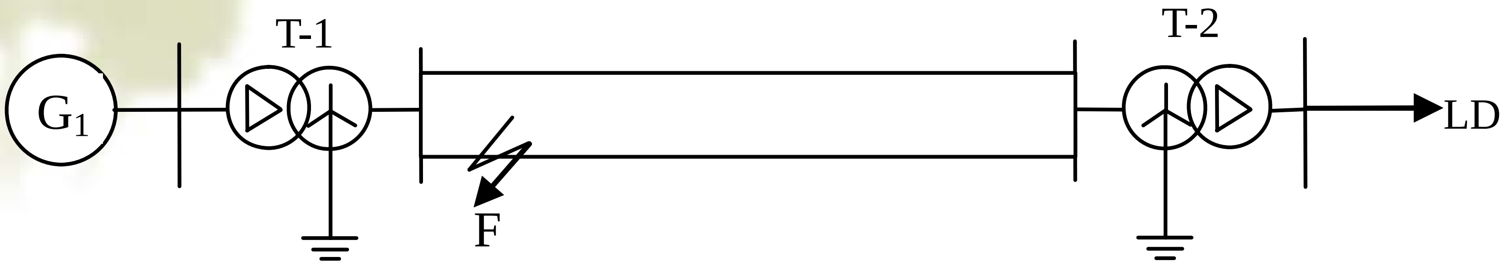
Review：4-1 节点导纳矩阵

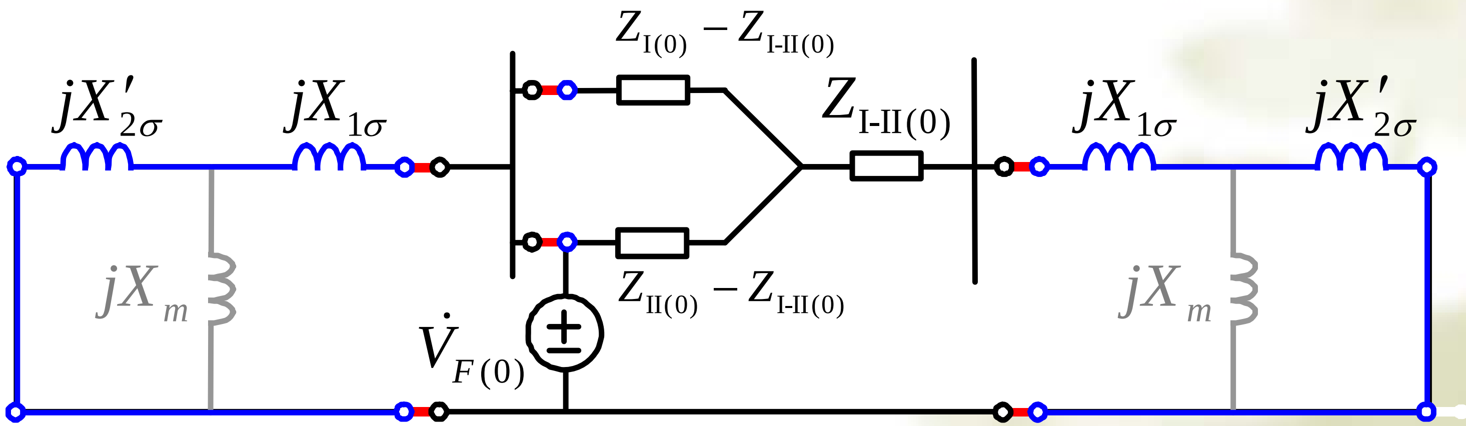
Y阵的修改——一端互联的互感支路



4. 平行架设双回输电线路的零序阻抗及等值电路

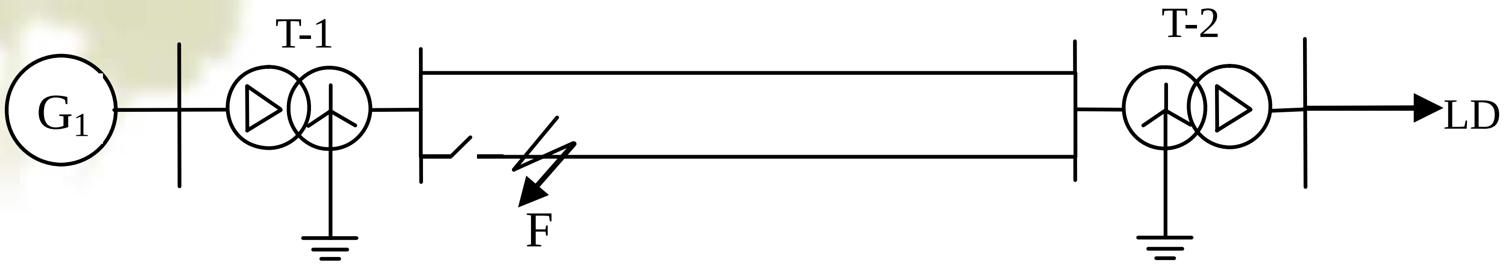
(2) 平行架设双回输电线路的零序等值电路——应用举例

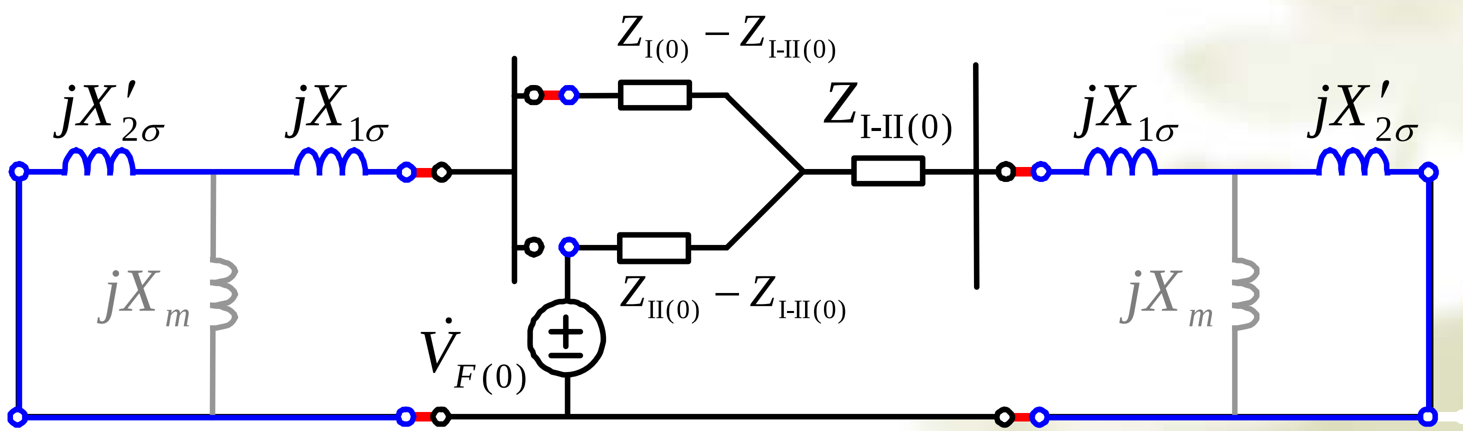




4. 平行架设双回输电线路的零序阻抗及等值电路

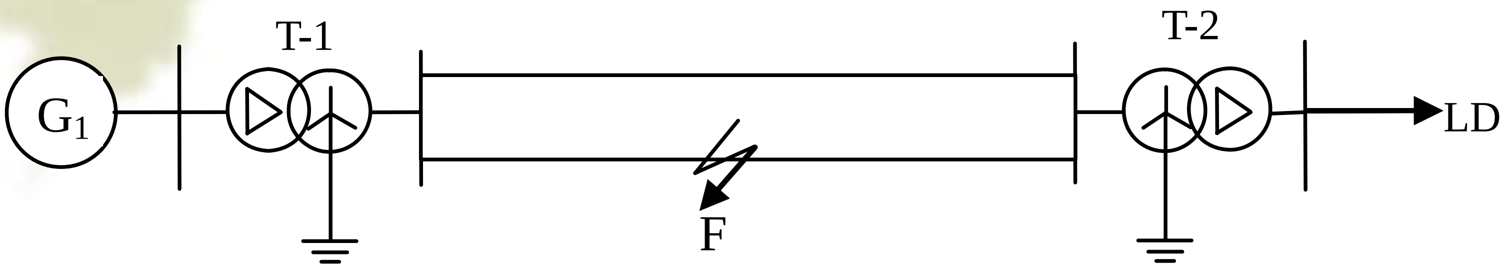
(2) 平行架设双回输电线路的零序等值电路——应用举例

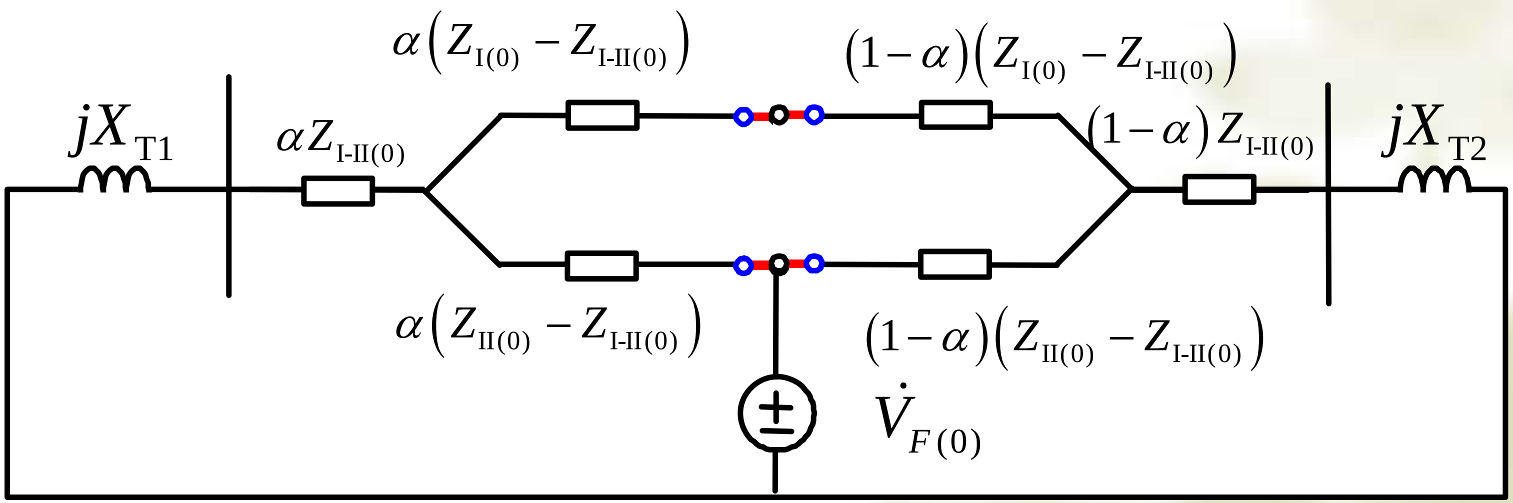




4. 平行架设双回输电线路的零序阻抗及等值电路

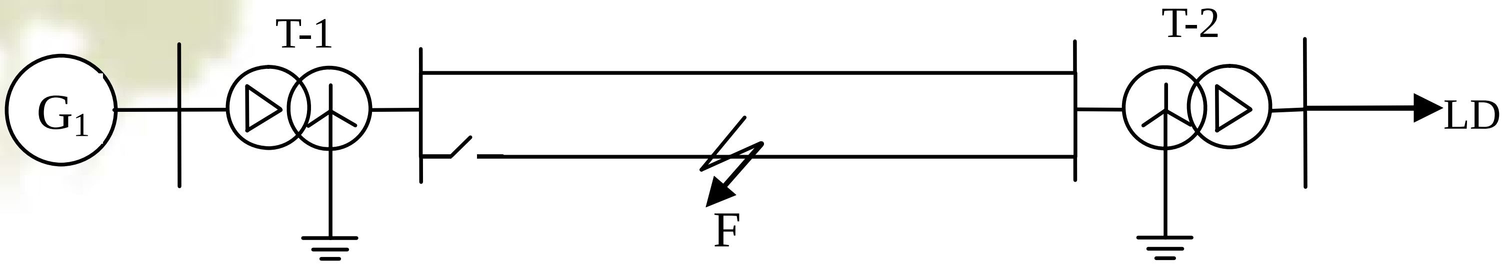
(2) 平行架设双回输电线路的零序等值电路——应用举例

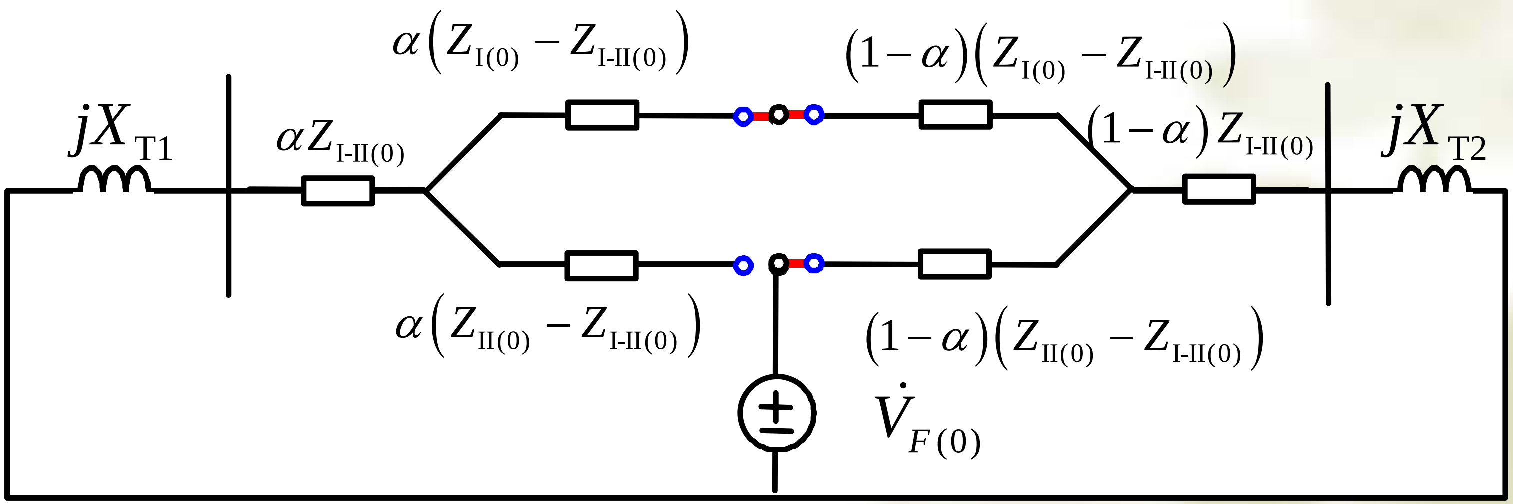




4. 平行架设双回输电线路的零序阻抗及等值电路

(2) 平行架设双回输电线路的零序等值电路——应用举例





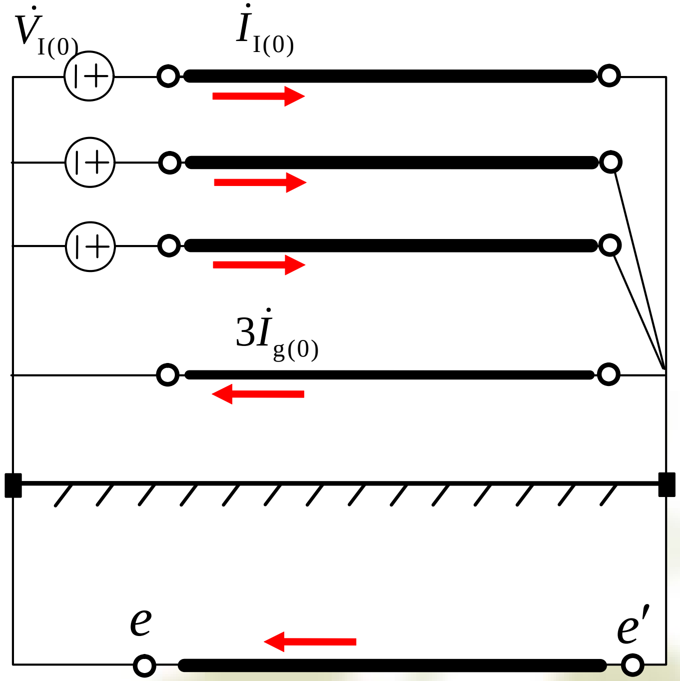
4. 平行架设双回输电线路的零序阻抗及等值电路

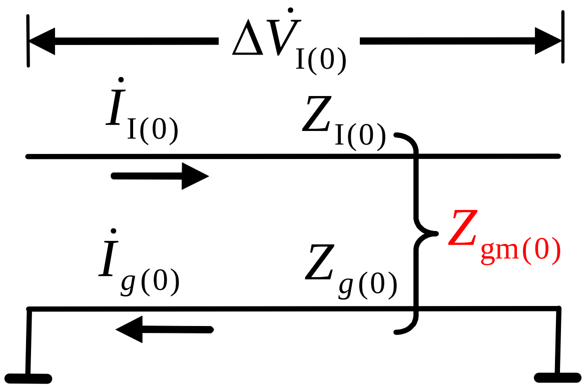
(3) 有架空地线的单回输电线路的零序等值电路

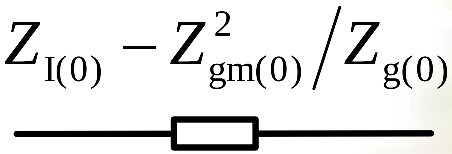
$$\Delta\dot{V}_{\mathrm{I}(0)} = Z_{\mathrm{I}(0)}\dot{I}_{\mathrm{I}(0)} - Z_{\mathrm{gm}(0)}\dot{I}_{\mathrm{g}(0)}$$

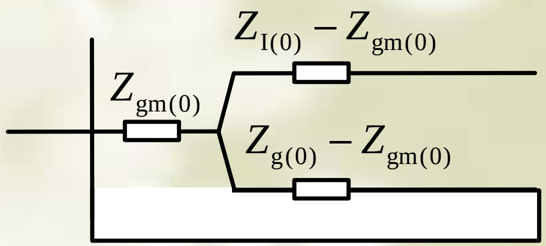
$$0 = Z_{\mathrm{g}(0)}\dot{I}_{\mathrm{g}(0)} - Z_{\mathrm{gm}(0)}\dot{I}_{\mathrm{I}(0)}$$

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



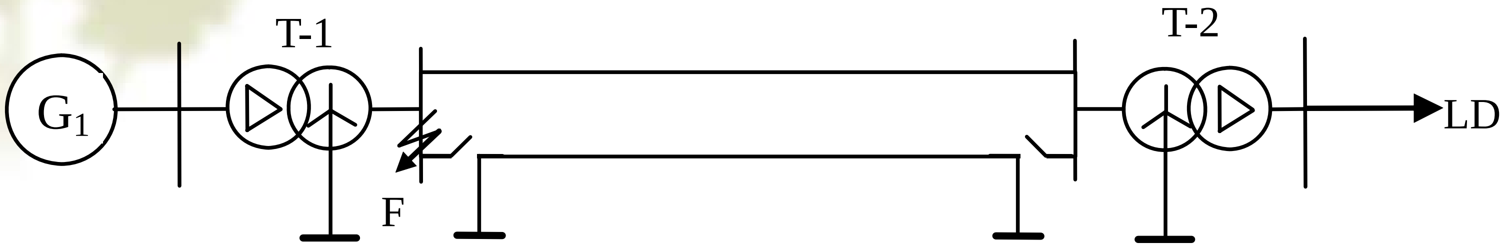


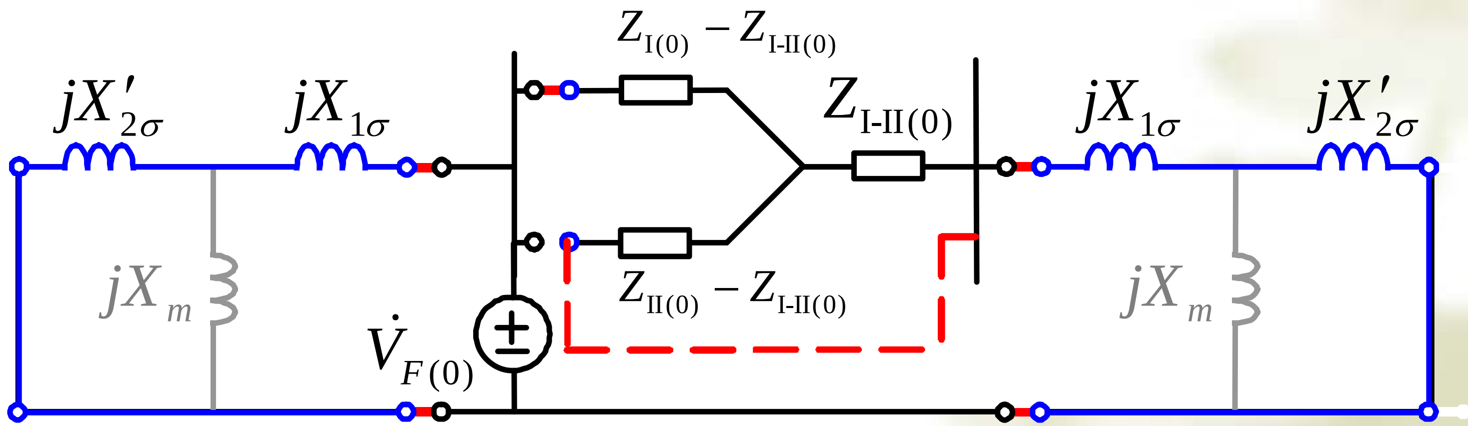




4. 平行架设双回输电线路的零序阻抗及等值电路

(3) 平行架设双回输电线路，一回停电检修 —应用举例





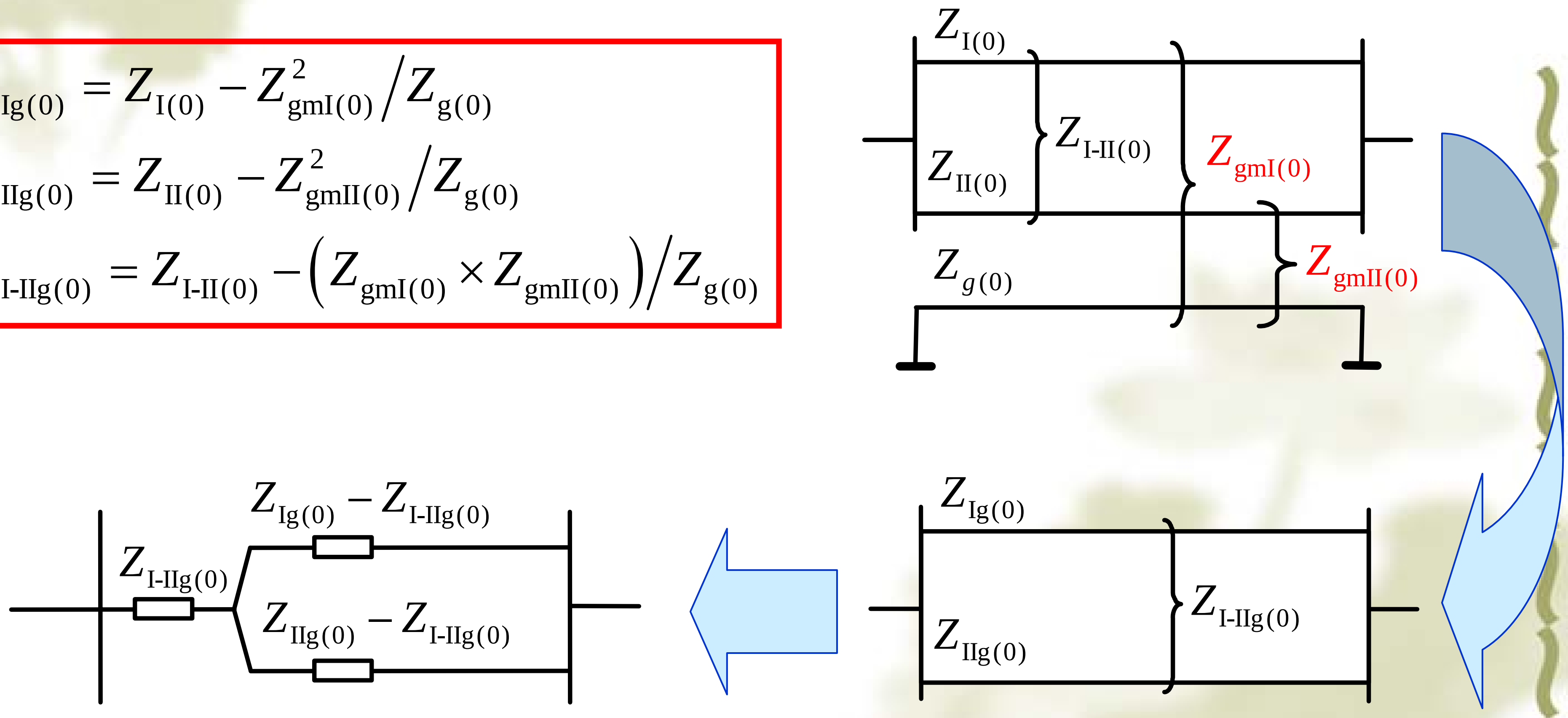
4. 平行架设双回输电线路的零序阻抗及等值电路

(3) 有架空地线的双回输电线路的零序等值电路

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

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

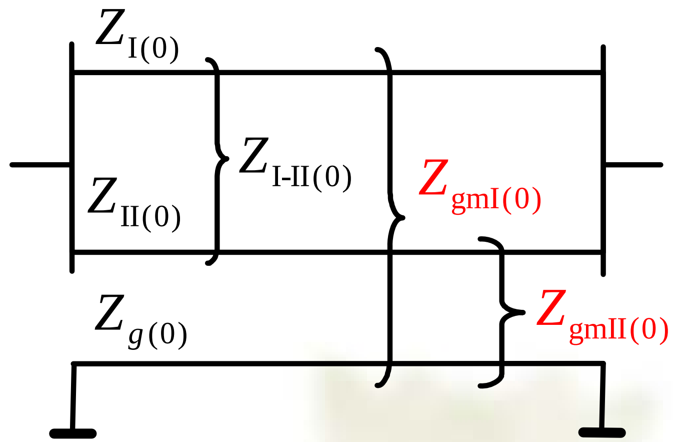
$$Z_{\text{I-IIg}(0)} = Z_{\text{I-II}(0)} - \left(Z_{\text{gmI}(0)} \times Z_{\text{gmII}(0)}\right) \big/ Z_{\text{g}(0)}$$



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

$$\Delta\dot V_{I(0)} = Z_{I(0)}\dot I_{I(0)} + Z_{I\text{-}II(0)}\dot I_{II(0)} - Z_{gmI(0)}\dot I_{g(0)}$$
$$\Delta\dot V_{II(0)} = Z_{II(0)}\dot I_{II(0)} + Z_{I\text{-}II(0)}\dot I_{I(0)} - Z_{gmII(0)}\dot I_{g(0)}$$
$$0 = Z_{g(0)}\dot I_{g(0)} - Z_{gmI(0)}\dot I_{I(0)} - Z_{gmII(0)}\dot I_{II(0)}$$

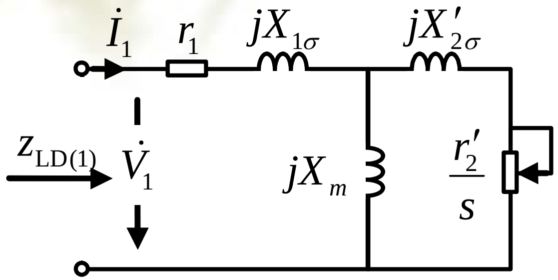
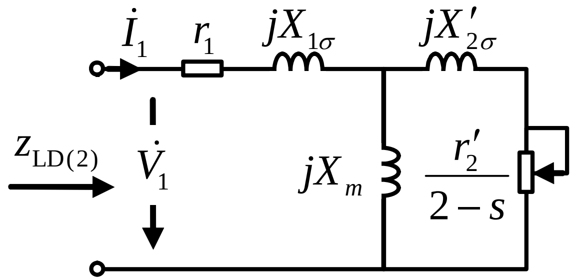
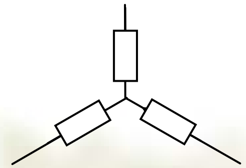


$$Z_{gmI(0)}\dot I_{g(0)} = \left(Z^2_{gmI(0)}/Z_{g(0)}\right)\dot I_{I(0)} + \left(Z_{gmI(0)}Z_{gmII(0)}/Z_{g(0)}\right)\dot I_{II(0)}$$
$$Z_{gmII(0)}\dot I_{g(0)} = \left(Z_{gmI(0)}Z_{gmII(0)}/Z_{g(0)}\right)\dot I_{I(0)} + \left(Z^2_{gmII(0)}/Z_{g(0)}\right)\dot I_{II(0)}$$

$$\Delta\dot V_{I(0)} = Z_{Ig(0)}\dot I_{I(0)} + Z_{I\text{-}IIg(0)}\dot I_{II(0)}$$
$$\Delta\dot V_{II(0)} = Z_{IIg(0)}\dot I_{II(0)} + Z_{I\text{-}IIg(0)}\dot I_{I(0)}$$

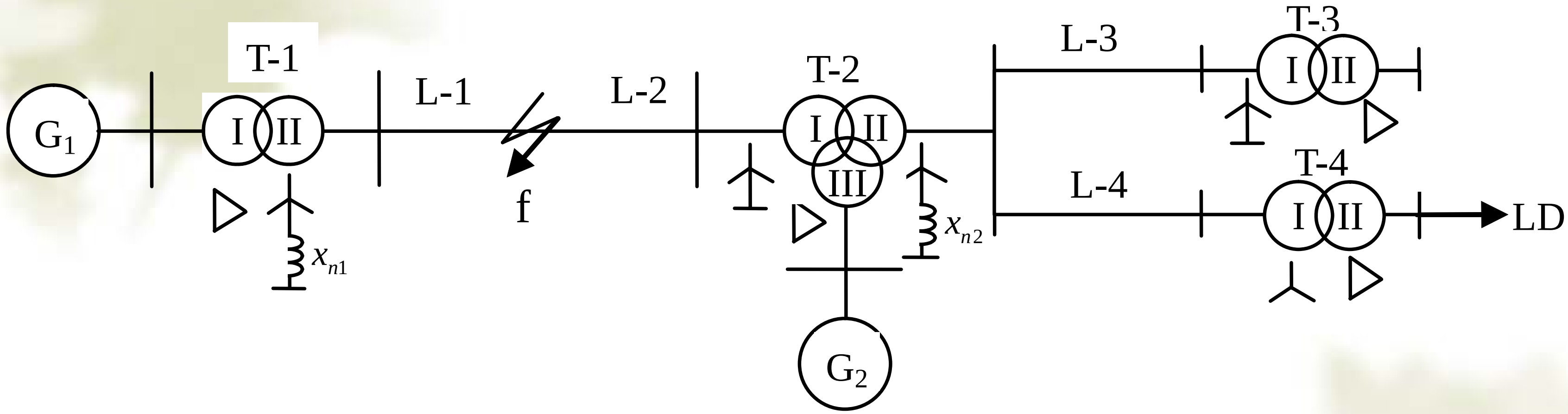
$$Z_{Ig(0)} = Z_{I(0)} - Z^2_{gmI(0)}/Z_{g(0)}$$
$$Z_{IIg(0)} = Z_{II(0)} - Z^2_{gmII(0)}/Z_{g(0)}$$
$$Z_{I\text{-}IIg(0)} = Z_{I\text{-}II(0)} - \left(Z_{gmI(0)}\times Z_{gmII(0)}\right)/Z_{g(0)}$$

7-6 综合负荷的序阻抗

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

7-7电力系统各序网络的制定

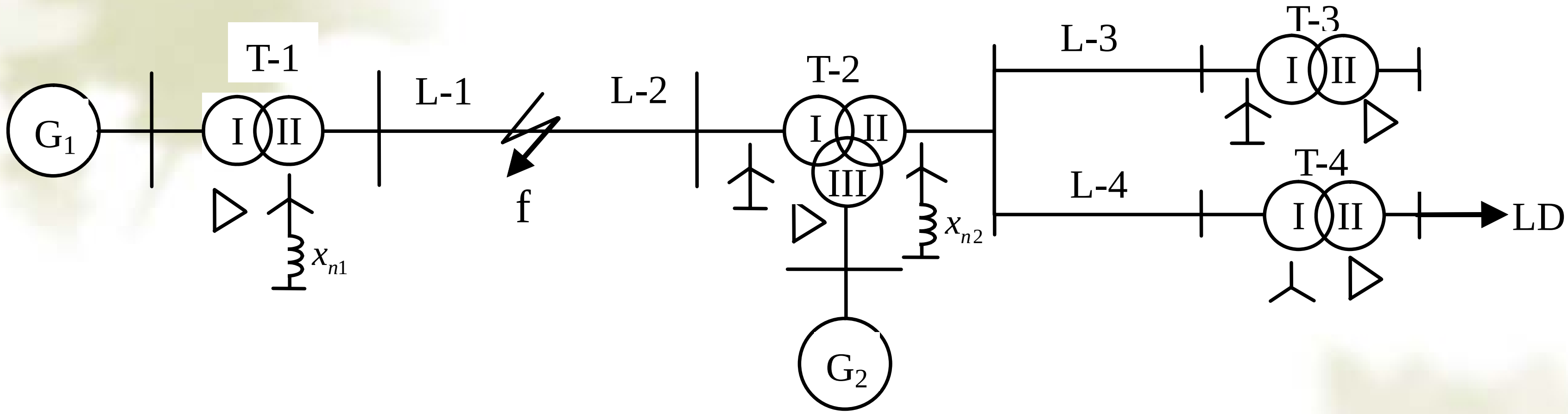
算例

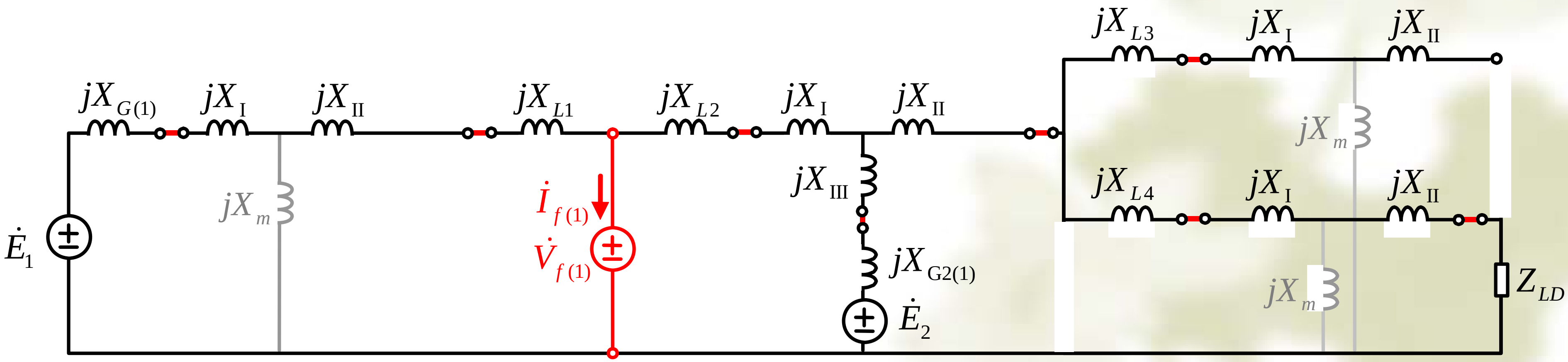


- 在故障点分别叠加各序电势，从故障点开始，逐步查明各序电流流通的情况；
- 某一序电流能流通的元件，必须包括在该序网络中，并用相应的序参数和等值电路表示。

7-7电力系统各序网络的制定

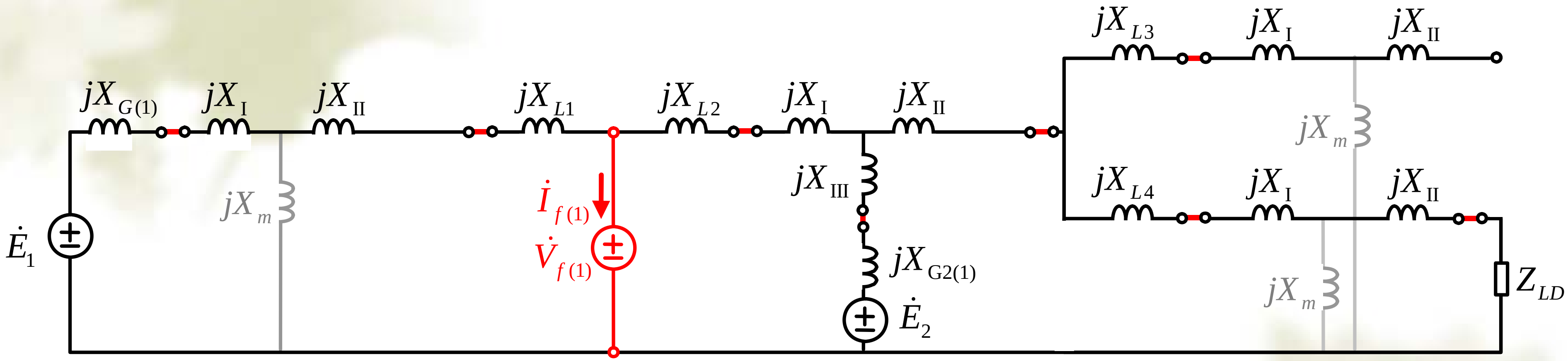
算例——正序网络

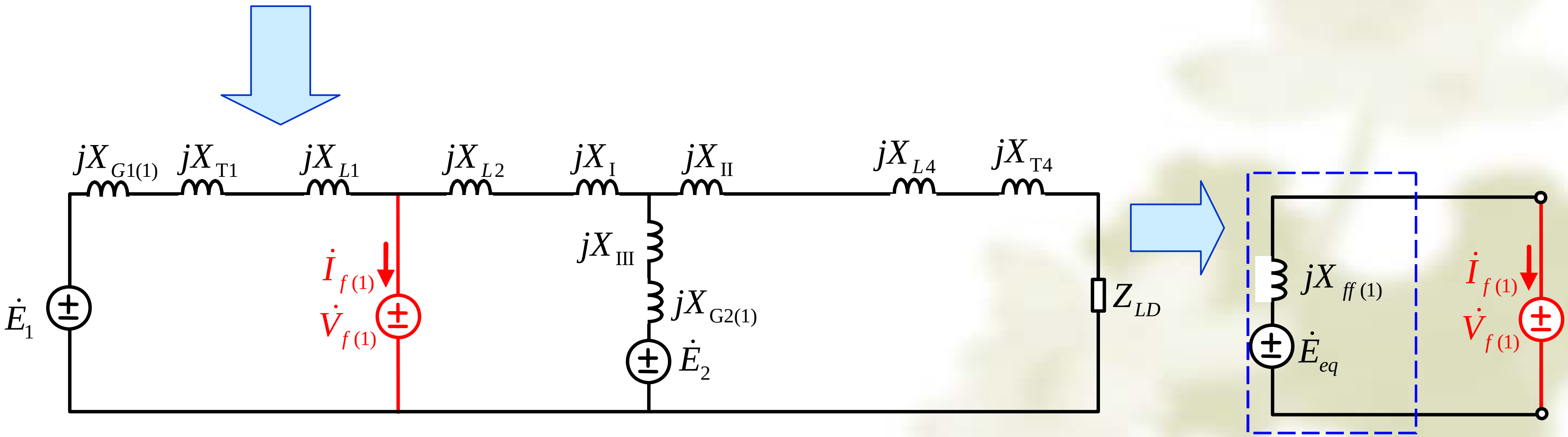




7-7电力系统各序网络的制定

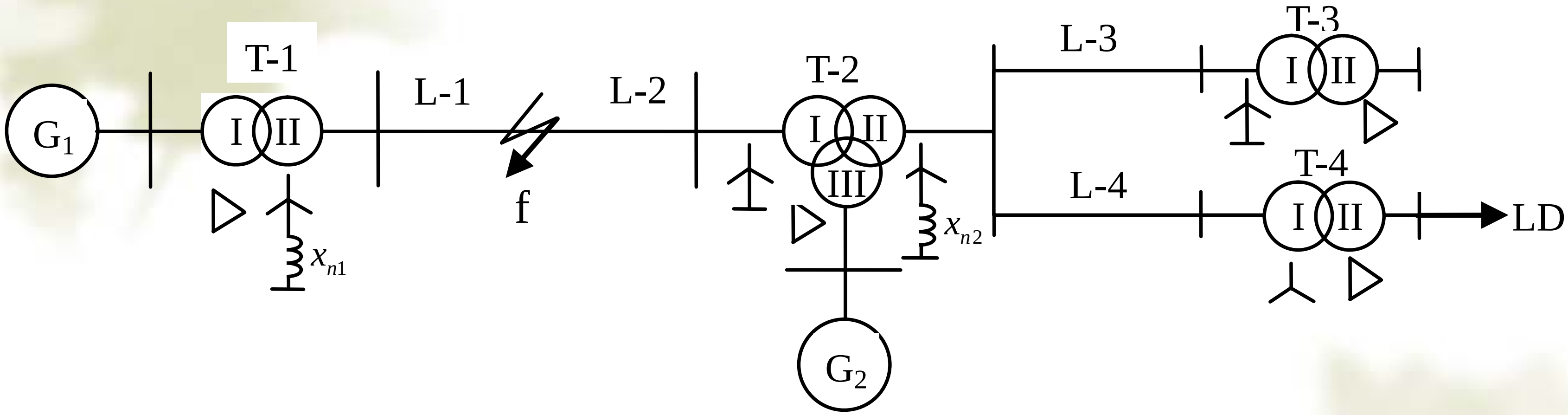
算例——正序网络

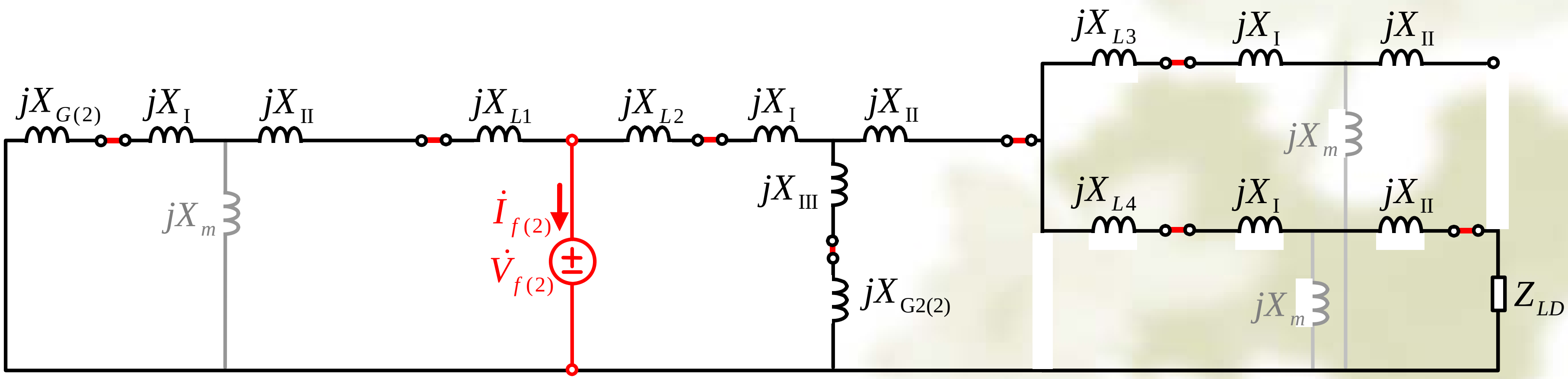




7-7电力系统各序网络的制定

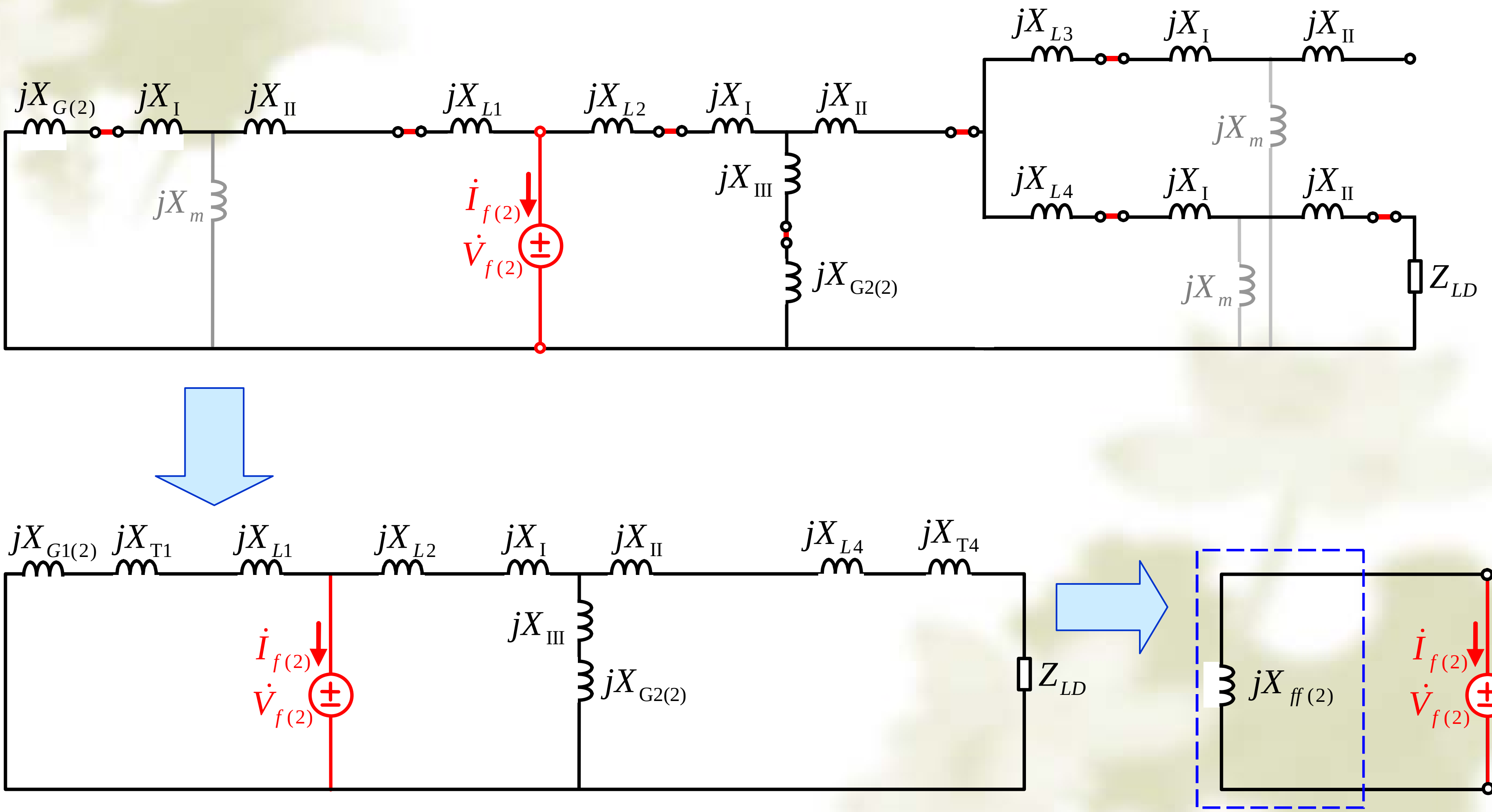
算例——负序网络





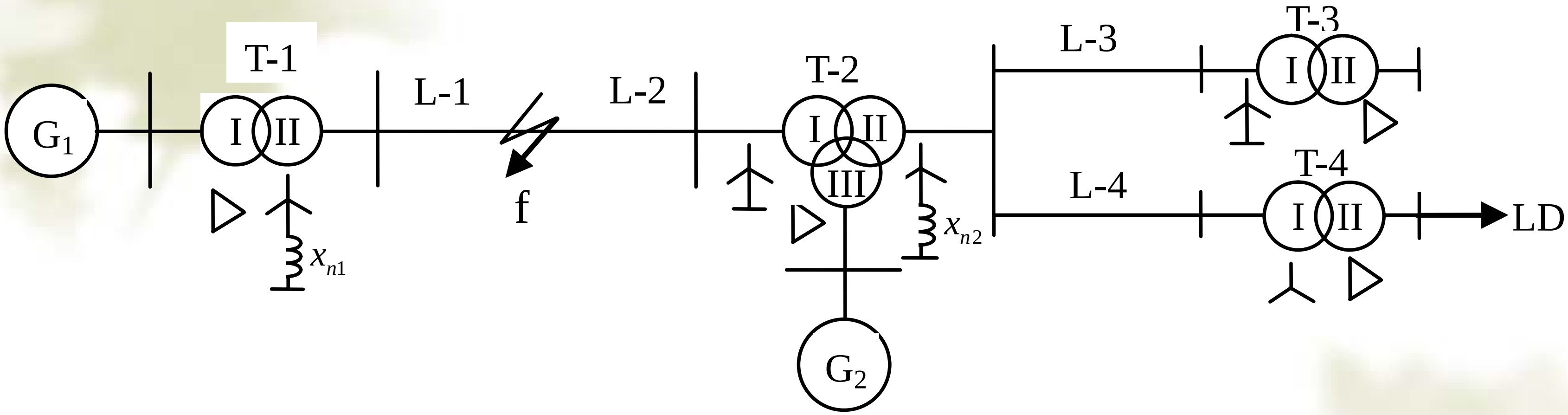
7-7电力系统各序网络的制定

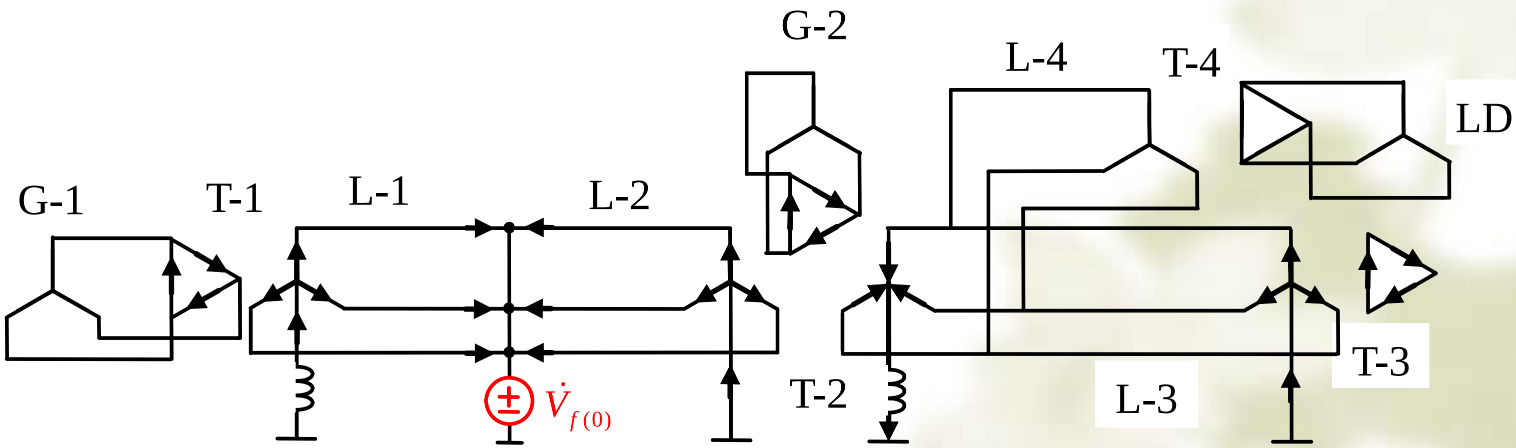
算例——负序网络



7-7电力系统各序网络的制定

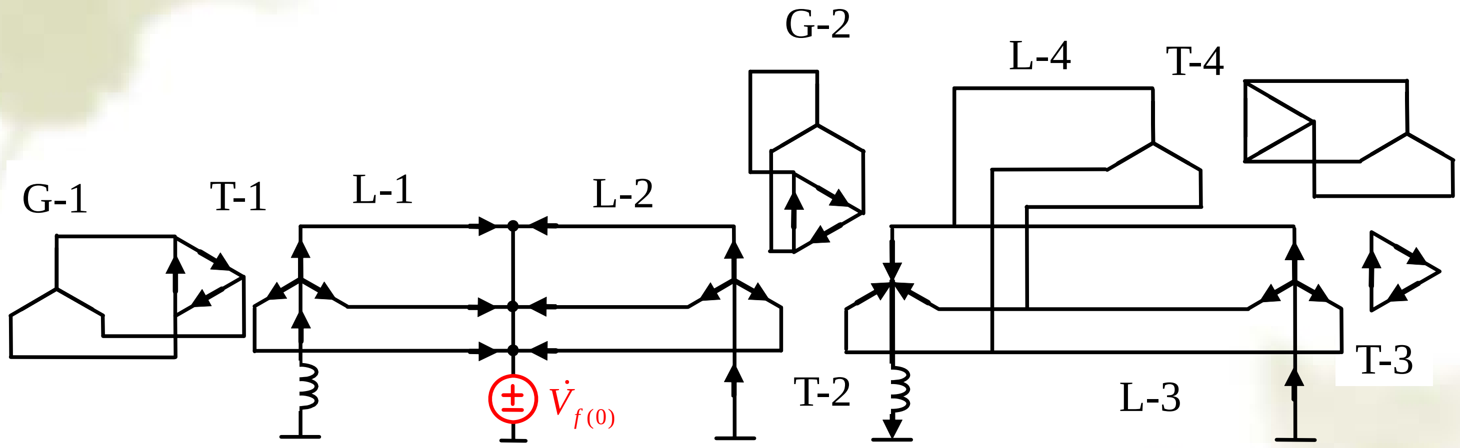
算例——零序网络

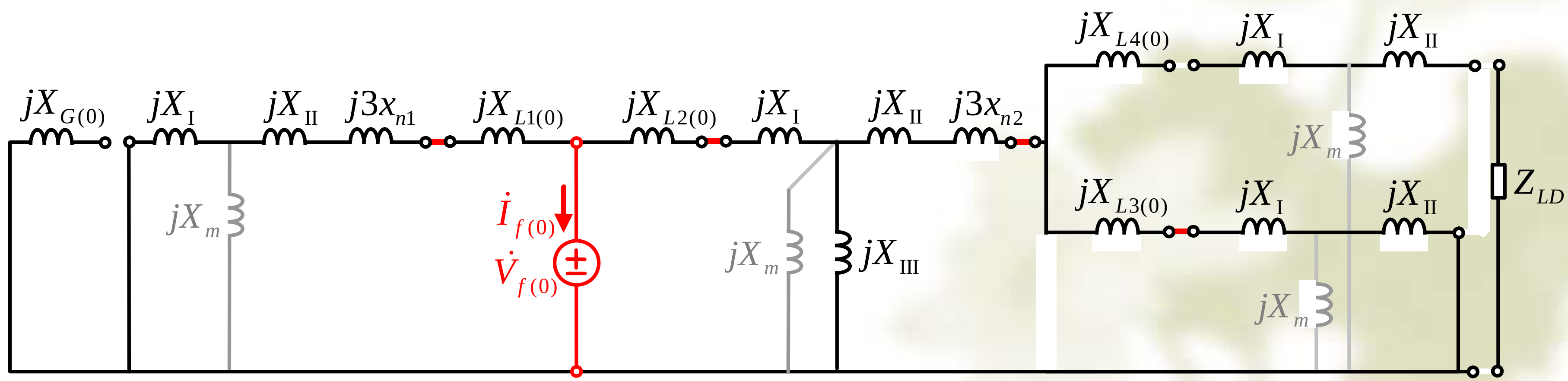




7-7电力系统各序网络的制定

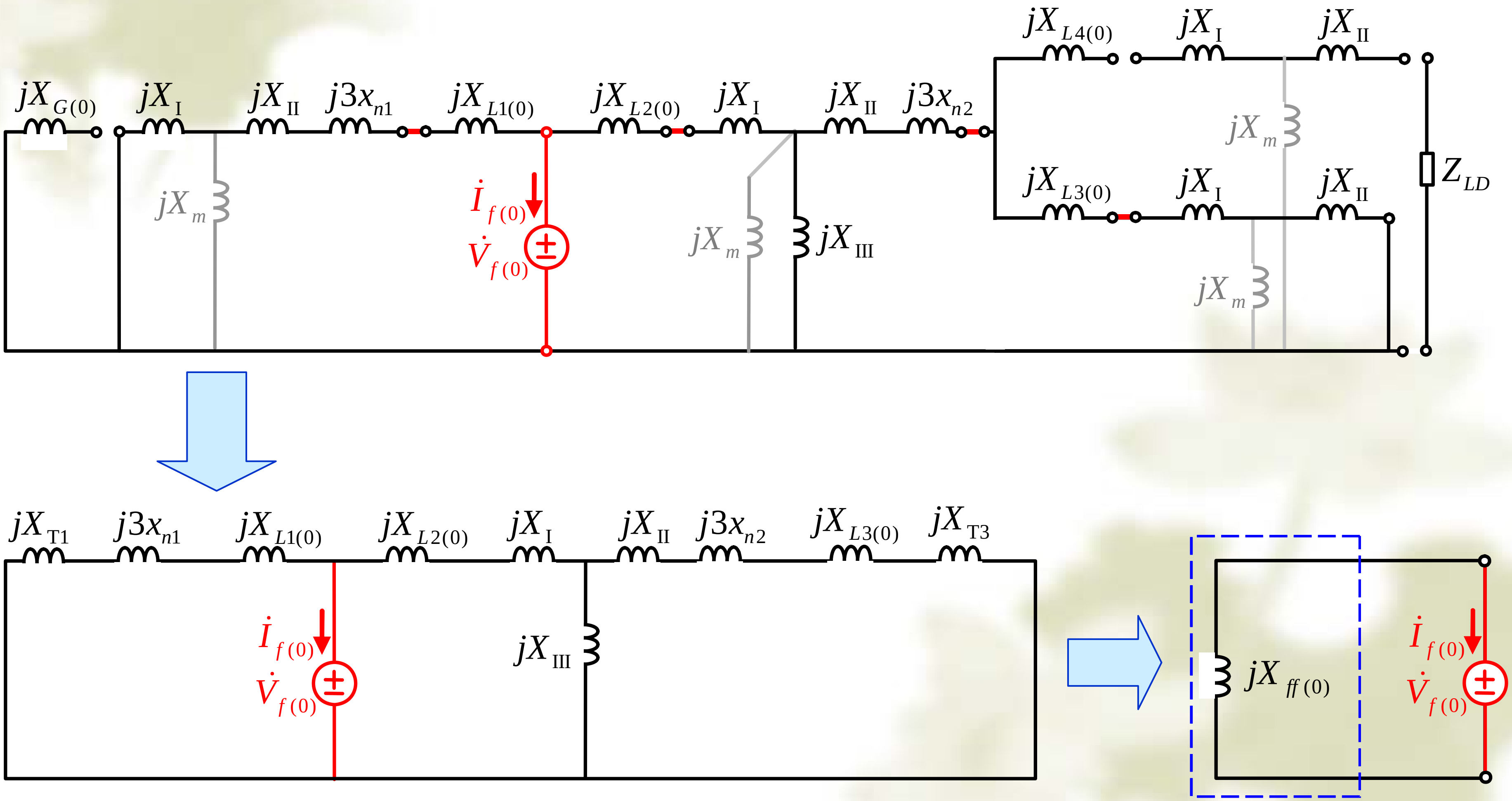
算例——零序网络





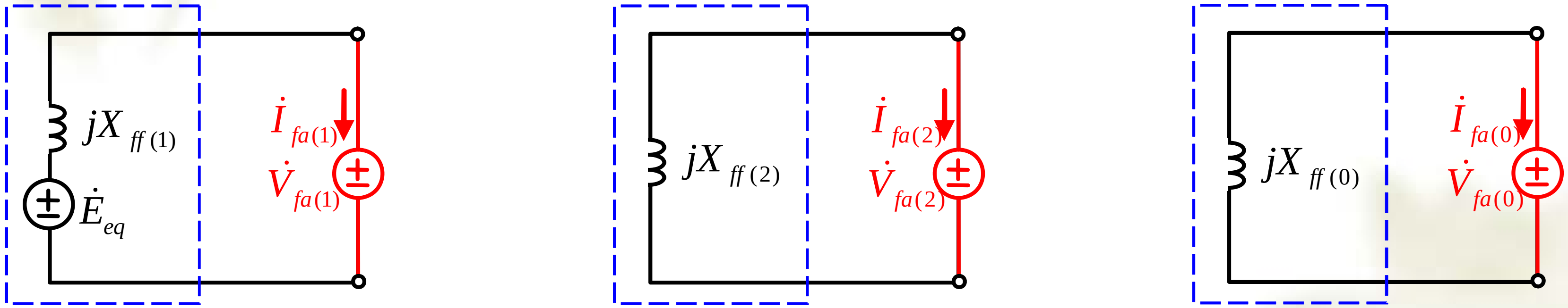
7-7电力系统各序网络的制定

算例——零序网络



7-7电力系统各序网络的制定

序网方程



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

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

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

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；

华中科技大学
Huazhong University of Science and Technology

习 题

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

To Be Continued