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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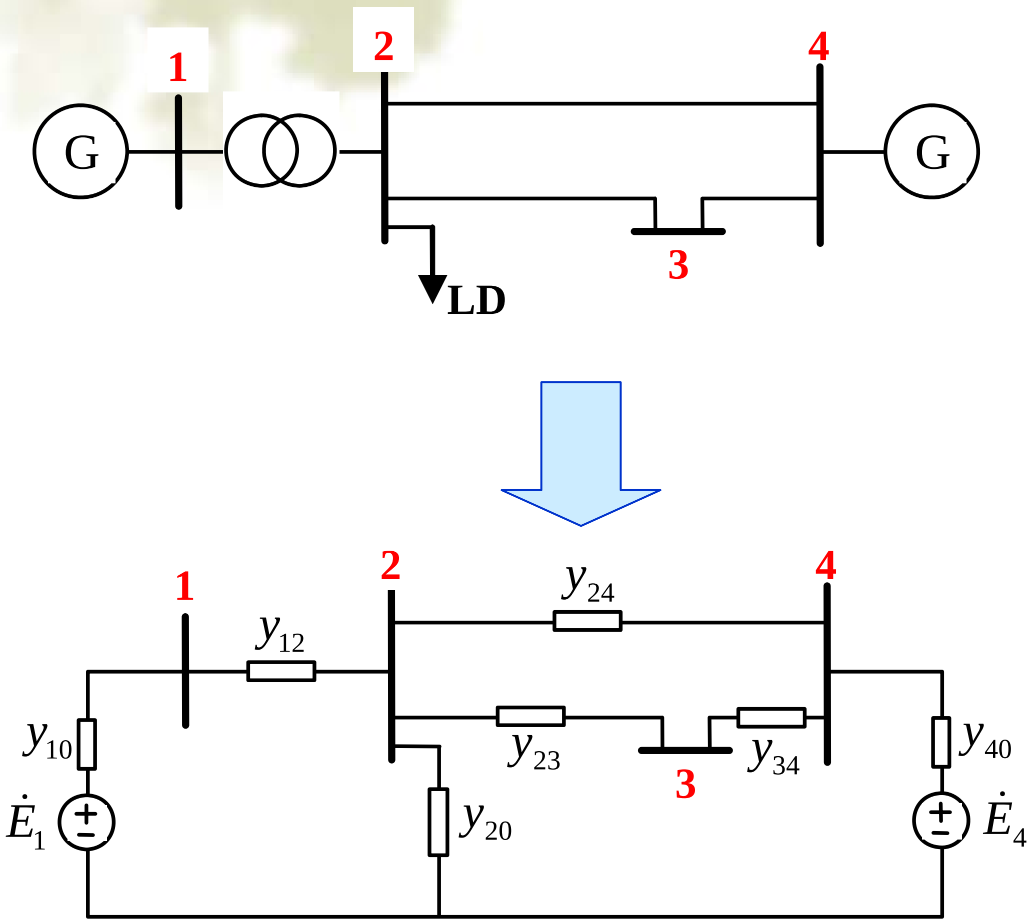
第四章 电力网络的数学模型

4-1 节点导纳矩阵

1. 用于短路计算的电力系统数学模型
2. 节点方程
3. 节点导纳矩阵元素的物理意义
4. Y阵的修改（网络结构变化、故障等）

4-1 节点导纳矩阵

1.用于短路计算的电力系统数学模型

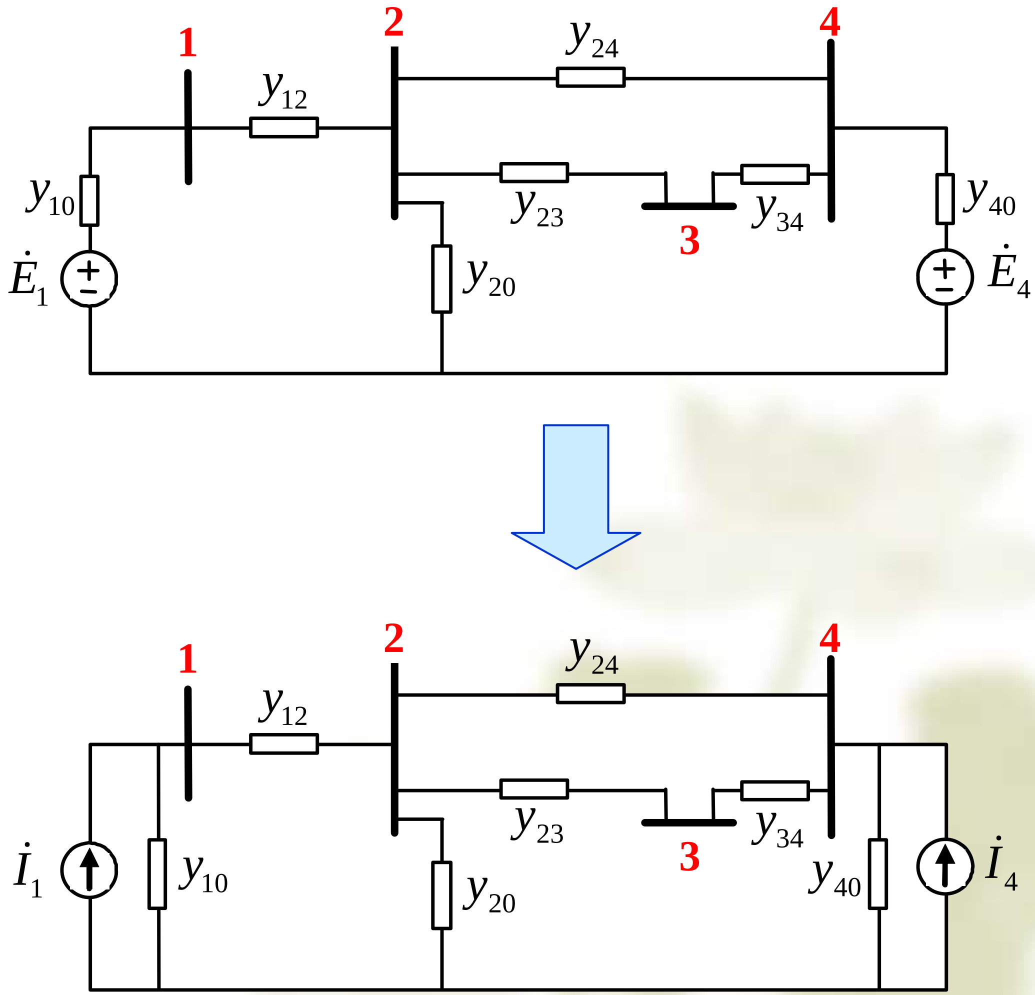


- 发电机：电势源支路
- 电力网络：一相等值电路，略去变压器励磁支路和线路电容
- 负荷：恒定阻抗
- 零电位参考节点不予编号

4-1 节点导纳矩阵

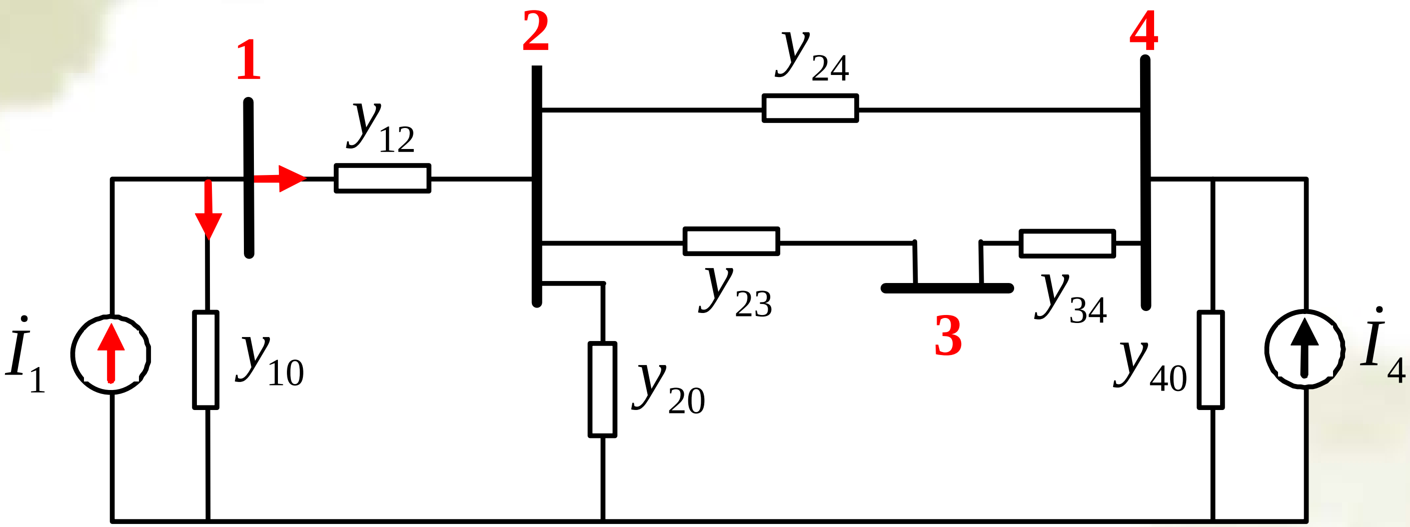
2.节点方程

电势源支路转换为电流源支路，根据KCL定律列写每一个节点的电流方程式。



4-1 节点导纳矩阵

2. 节点方程——节点1

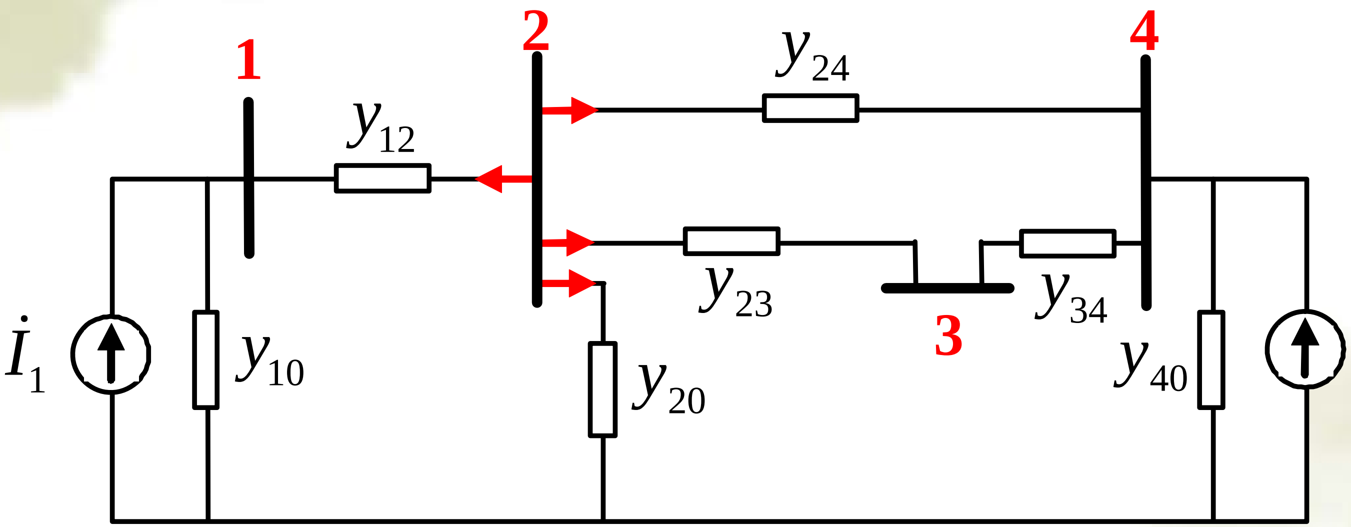


$$\dot{I}_1 = y_{10}\dot{V}_1 + y_{12}(\dot{V}_1 - \dot{V}_2)$$

$$\dot{I}_1 = (y_{10} + y_{12})\dot{V}_1 - y_{12}\dot{V}_2$$

4-1 节点导纳矩阵

2.节点方程——节点2

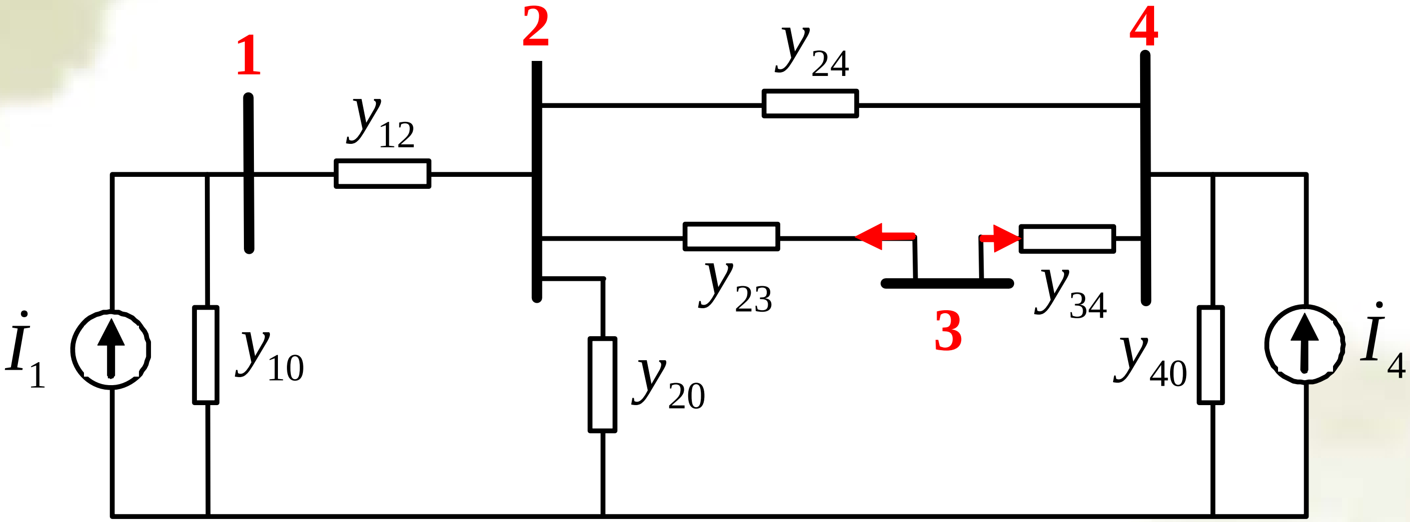


$$0 = y_{12}(\dot{V}_2 - \dot{V}_1) + y_{20}\dot{V}_2 + y_{23}(\dot{V}_2 - \dot{V}_3) + y_{24}(\dot{V}_2 - \dot{V}_4)$$

$$0 = -y_{12}\dot{V}_1 + \left(y_{12} + y_{20} + y_{23} + y_{24}\right)\dot{V}_2 - y_{23}\dot{V}_3 - y_{24}\dot{V}_4$$

4-1 节点导纳矩阵

2.节点方程——节点3

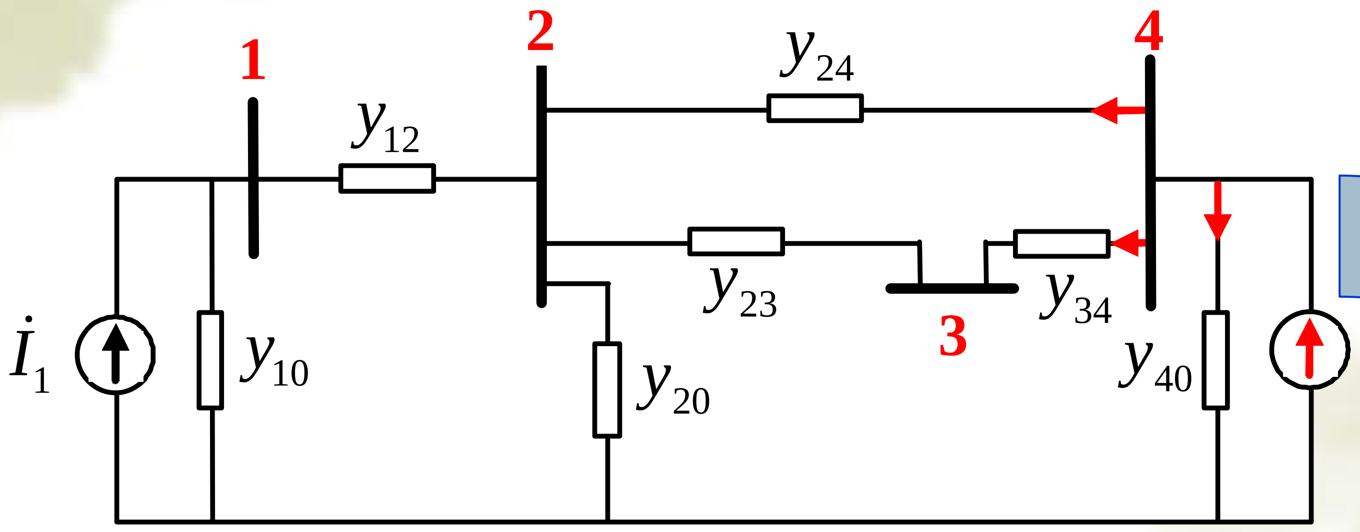


$$0 = y_{23}(\dot{V}_3 - \dot{V}_2) + y_{34}(\dot{V}_3 - \dot{V}_4)$$

$$0 = -y_{23}\dot{V}_2 + \left(y_{23} + y_{34}\right)\dot{V}_3 - y_{34}\dot{V}_4$$

4-1 节点导纳矩阵

2. 节点方程——节点4



$$\dot{I}_4 = y_{24}(\dot{V}_4 - \dot{V}_2) + y_{34}(\dot{V}_4 - \dot{V}_3) + y_{40}\dot{V}_4$$

$$\dot{I}_4 = -y_{24}\dot{V}_2 - y_{34}\dot{V}_3 + \left(y_{24} + y_{34} + y_{40}\right)\dot{V}_4$$

4-1 节点导纳矩阵

2.节点方程的矩阵形式

$$
\begin{cases}
\dot{I}_1 = (y_{10} + y_{12})\dot{V}_1 - y_{12}\dot{V}_2 \\
0 = -y_{12}\dot{V}_1 + (y_{12} + y_{20} + y_{23} + y_{24})\dot{V}_2 - y_{23}\dot{V}_3 - y_{24}\dot{V}_4 \\
0 = -y_{23}\dot{V}_3 + (y_{23} + y_{34})\dot{V}_3 - y_{34}\dot{V}_4 \\
\dot{I}_4 = -y_{24}\dot{V}_2 - y_{34}\dot{V}_3 + (y_{24} + y_{34} + y_{40})\dot{V}_4
\end{cases}
$$

$$
\begin{aligned}
Y_{12} &= Y_{21} = -y_{12} \\
Y_{23} &= Y_{32} = -y_{23} \\
Y_{24} &= Y_{42} = -y_{24} \\
Y_{34} &= Y_{43} = -y_{34}
\end{aligned}
$$

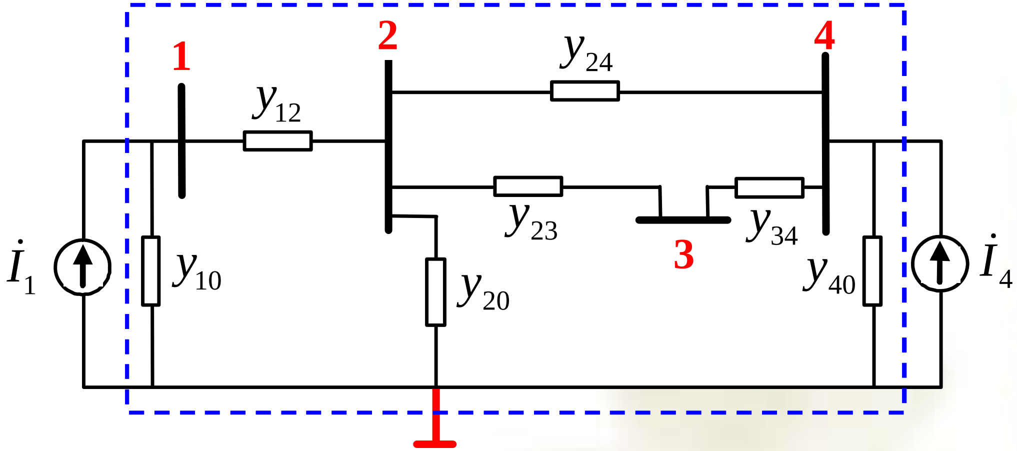
$$
\begin{bmatrix} \dot{I}_1 \\ 0 \\ 0 \\ \dot{I}_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & 0 & 0 \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ 0 & Y_{32} & Y_{33} & Y_{34} \\ 0 & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \dot{V}_3 \\ \dot{V}_4 \end{bmatrix}
$$

$$
\begin{aligned}
Y_{11} &= y_{10} + y_{12} \\
Y_{22} &= y_{12} + y_{20} + y_{23} + y_{24} \\
Y_{33} &= y_{23} + y_{34} \\
Y_{44} &= y_{24} + y_{34} + y_{40}
\end{aligned}
$$

4-1 节点导纳矩阵

2. 节点方程的矩阵形式

$$\begin{bmatrix} \dot{I}_1 \\ 0 \\ 0 \\ \dot{I}_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & 0 & 0 \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ 0 & Y_{32} & Y_{33} & Y_{34} \\ 0 & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \dot{V}_3 \\ \dot{V}_4 \end{bmatrix}$$



$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \\ \dot{I}_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{34} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \dot{V}_3 \\ \dot{V}_4 \end{bmatrix}$$

节点注入电流：$\dot{\mathbf{I}} = \begin{bmatrix} \dot{I}_1 & \dot{I}_2 & \dot{I}_3 & \dot{I}_4 \end{bmatrix}^{\mathrm{T}}$

节点电压：$\dot{\mathbf{V}} = \begin{bmatrix} \dot{V}_1 & \dot{V}_2 & \dot{V}_3 & \dot{V}_4 \end{bmatrix}^{\mathrm{T}}$

$$\Rightarrow \quad \dot{\mathbf{I}} = \mathbf{Y}\dot{\mathbf{V}}$$

4-1 节点导纳矩阵

2.节点方程—n个独立节点的电力网络数学模型

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \vdots \\ \dot{I}_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \vdots \\ \dot{V}_n \end{bmatrix}$$

线性代数方程

$$\dot{\mathbf{I}} = \mathbf{Y}\dot{\mathbf{V}}$$

Y_{ii} 节点i自导纳

Y_{ij} 节点ij间互导纳

$\mathbf{Y}$ 节点导纳矩阵

4-1 节点导纳矩阵

3.节点导纳矩阵元素的物理意义

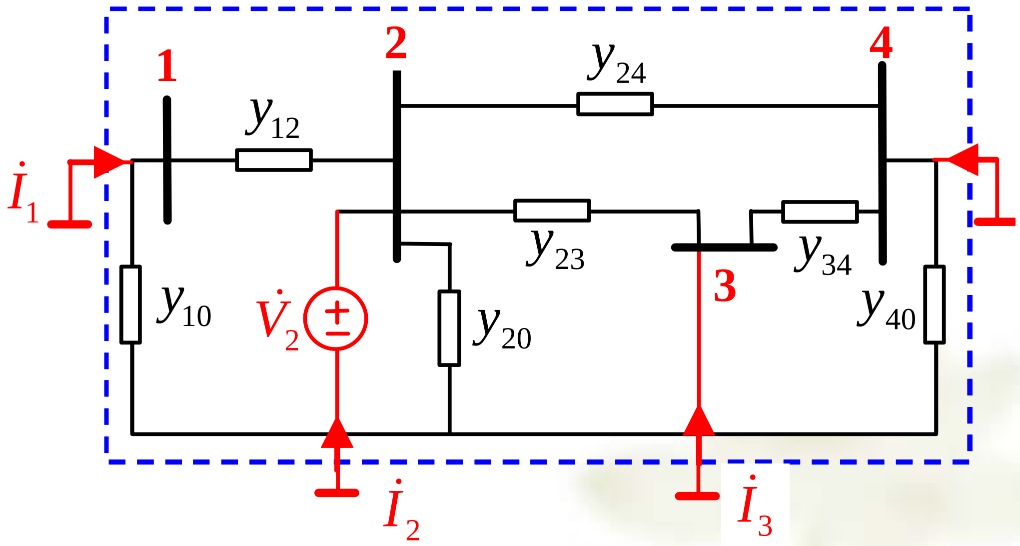
$$\dot{\mathbf{I}} = \mathbf{Y}\dot{\mathbf{V}}$$

$$\dot{V}_i \neq 0,\quad \dot{V}_j = 0,\quad (j \neq i)$$

$$\begin{cases} \dot{I}_i = \sum_{j=1}^{n} Y_{ij}\dot{V}_j \\ \dot{I}_j = \sum_{k}^{n} Y_{jk}\dot{V}_k \end{cases}$$

$$\dot{I}_i = Y_{ii}\dot{V}_i \Rightarrow Y_{ii} = \dot{I}_i / \dot{V}_i$$

$$\dot{I}_j = Y_{ji}\dot{V}_i \Rightarrow Y_{ji} = \dot{I}_j / \dot{V}_i$$



$$Y_{22} = \dot{I}_2 / \dot{V}_2 = y_{20} + y_{12} + y_{23} + y_{24}$$

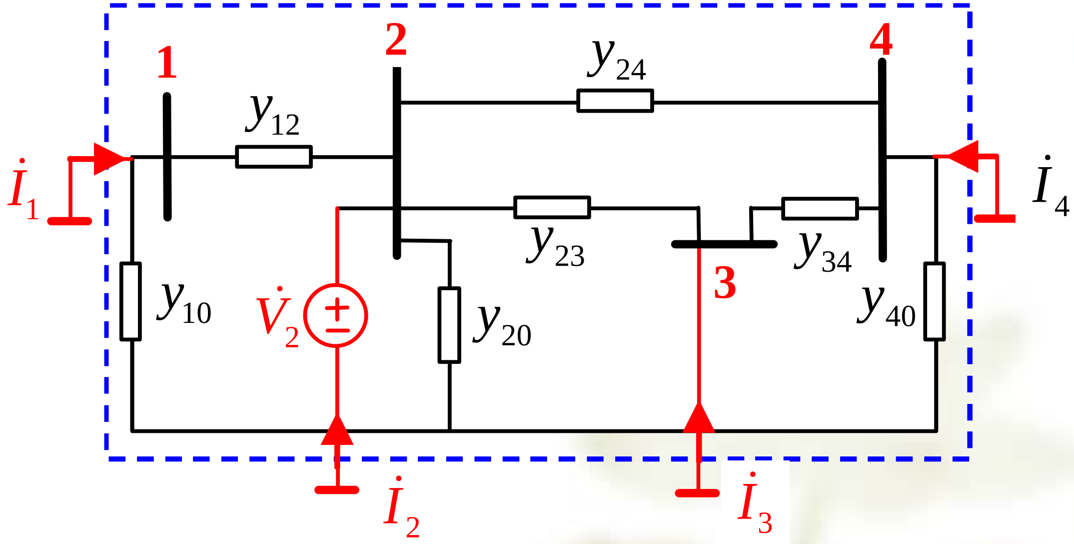
$$Y_{12} = \dot{I}_1 / \dot{V}_2 = -y_{12},\quad Y_{32} = \dot{I}_3 / \dot{V}_2 = -y_{23}$$

$$Y_{42} = \dot{I}_4 / \dot{V}_2 = -y_{24}$$

4-1 节点导纳矩阵

3.节点导纳矩阵元素的物理意义——自导纳

Y_{ii}:当网络中除节点i以外所有节点都接地时，从节点i注入网络的电流同施加于节点i的 电压之比



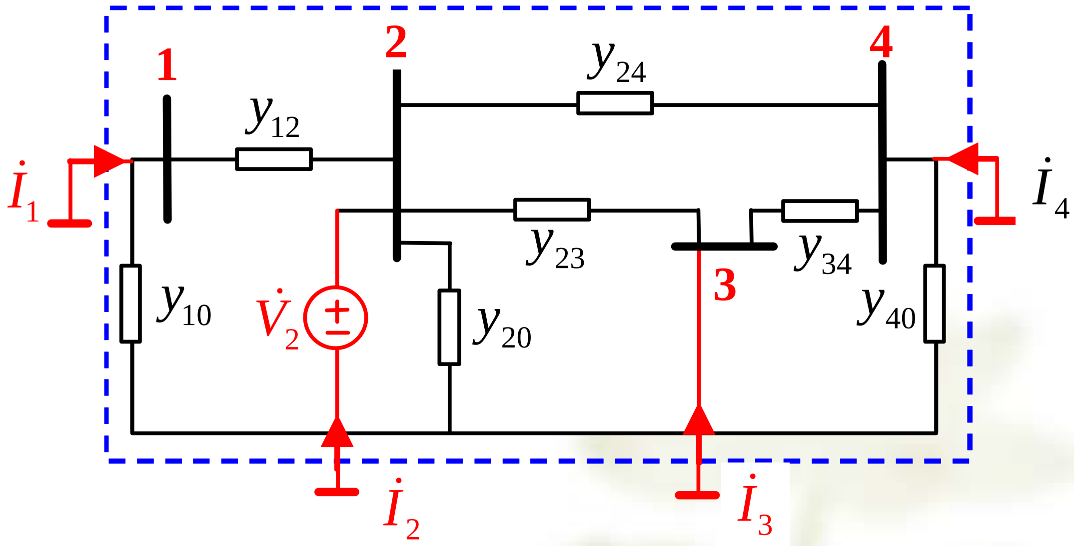
Y_{ii}:与节点i相连的所有支路导纳之和

$$Y_{22} = \dot{I}_2 / \dot{V}_2 = y_{20} + y_{12} + y_{23} + y_{24}$$

4-1 节点导纳矩阵

3.节点导纳矩阵元素的物理意义——互导纳

Y_{ji}：当网络中除节点i以外所有节点都接地时，从节点j注入网络的电流同施加于节点i的电压之比



节点j的电流实际上是自网络流出并进入地中的电流，所以Y_{jk}应等于节点j、i之间连接支路导纳的负值

$$Y_{12} = \dot{I}_1 / \dot{V}_2 = -y_{12}$$

$$Y_{32} = \dot{I}_3 / \dot{V}_2 = -y_{23}$$

$$Y_{42} = \dot{I}_4 / \dot{V}_2 = -y_{24}$$

4-1 节点导纳矩阵

3.节点导纳矩阵的特点

❖直观易求 ⇐ $Y_{ii}=y_{i0}+\sum y_{ij}$，$Y_{ij}=-\sum y_{ij}$

❖对称矩阵 ⇐ $Y_{ij}=Y_{ji}=-\sum y_{ij}$

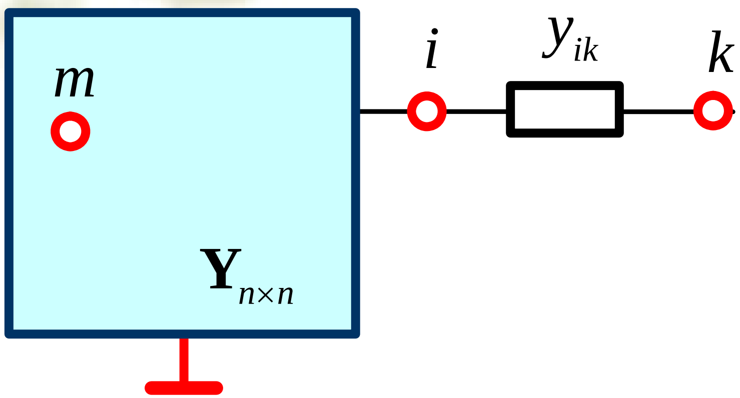
❖稀疏矩阵 ⇐ 如果ij之间没有直接支路连接，则 $Y_{ij}=Y_{ji}=0$

$\mathbf{Y}_{n\times n}$

❖设每个节点平均有10条出线，则节点导纳矩阵非零元素为11n个，稀疏度11/n

4-1 节点导纳矩阵

4. Y阵的修改——增加树支



$$\begin{bmatrix} Y_{11} & \cdots & Y_{1i} & \cdots & Y_{1n} & 0 \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Y_{i1} & \cdots & Y_{ii} & \cdots & Y_{in} & Y_{ik} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Y_{n1} & \cdots & Y_{ni} & \cdots & Y_{nn} & 0 \\ 0 & \cdots & Y_{ki} & \cdots & 0 & Y_{kk} \end{bmatrix}$$

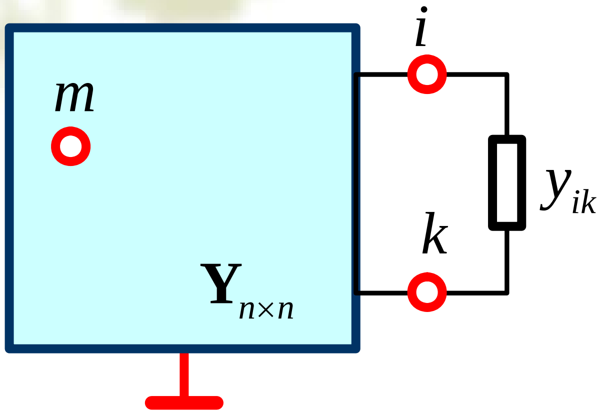
$$Y_{ii} = Y_{ii}^{(0)} + y_{ik}$$
$$Y_{kk} = y_{ik}$$
$$Y_{ik} = Y_{ki} = -y_{ik}$$

$$Y_{mk} = Y_{km} = 0$$
$$Y_{mi} = Y_{im} = Y_{im}^{(0)}$$

Y阵增加一行一列

4-1 节点导纳矩阵

4. Y阵的修改——增加连支



$$\begin{bmatrix} Y_{11} & \cdots & Y_{1i} & \cdots & Y_{1k} & \cdots & Y_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ Y_{i1} & \cdots & Y_{ii} & \cdots & Y_{ik} & \cdots & Y_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ Y_{k1} & \cdots & Y_{ki} & \cdots & Y_{kk} & \cdots & Y_{kn} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ Y_{n1} & \cdots & Y_{ni} & v & Y_{nk} & \cdots & Y_{nn} \end{bmatrix}$$

$$Y_{ii} = Y_{ii}^{(0)} + y_{ik}$$

$$Y_{kk} = Y_{kk}^{(0)} + y_{ik}$$

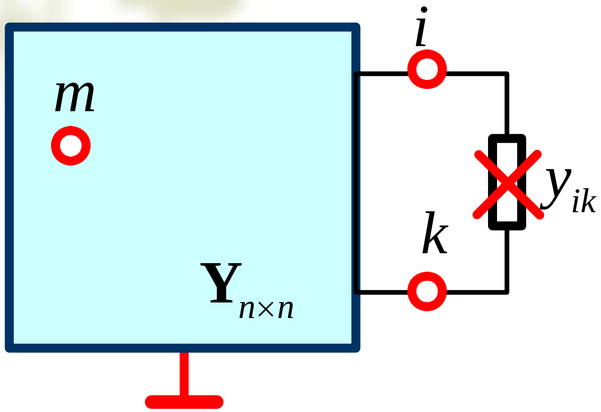
$$Y_{ik} = Y_{ki} = Y_{ik}^{(0)} - y_{ik}$$

Y阵阶数保持不变

$$Y_{mk} = Y_{km} = Y_{mk}^{(0)}, \quad Y_{mi} = Y_{im} = Y_{im}^{(0)}$$

4-1 节点导纳矩阵

4. Y阵的修改——删除连支



$$
\begin{bmatrix}
Y_{11} & \cdots & Y_{1i} & \cdots & Y_{1k} & \cdots & Y_{1n} \\
\vdots & \cdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
Y_{i1} & \cdots & Y_{ii} & \cdots & Y_{ik} & \cdots & Y_{in} \\
\vdots & \cdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
Y_{k1} & \cdots & Y_{ki} & \cdots & Y_{kk} & \cdots & Y_{kn} \\
\vdots & \cdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
Y_{n1} & \cdots & Y_{ni} & \cdots & Y_{nk} & \cdots & Y_{nn}
\end{bmatrix}
$$

$$Y_{ii} = Y_{ii}^{(0)} - y_{ik}$$

$$Y_{kk} = Y_{kk}^{(0)} - y_{ik}$$

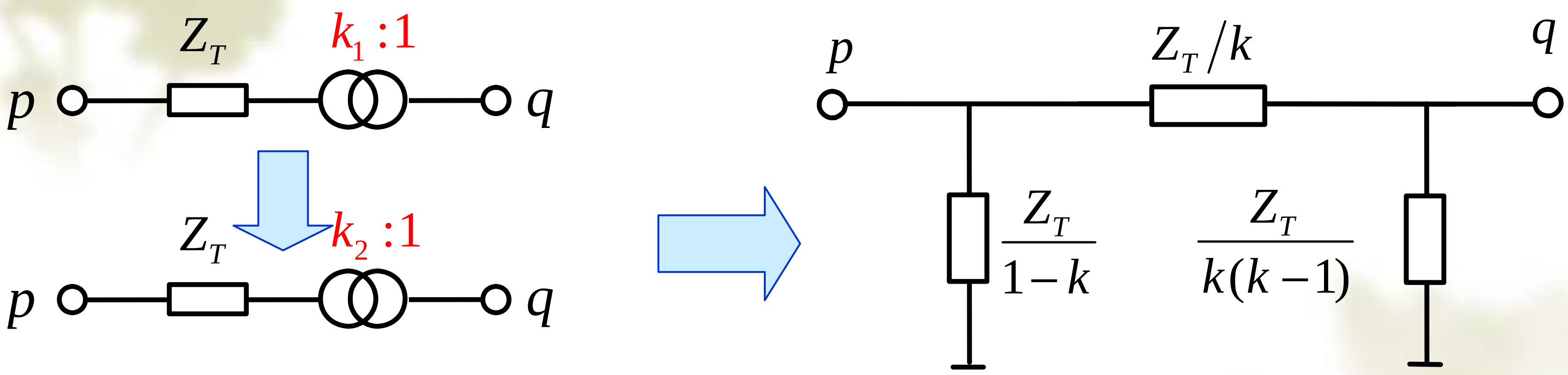
$$Y_{ik} = Y_{ki} = Y_{ik}^{(0)} + y_{ik}$$

Y阵阶数保持不变

$$Y_{mk} = Y_{km} = Y_{mk}^{(0)},\quad Y_{mi} = Y_{im} = Y_{im}^{(0)}$$

4-1 节点导纳矩阵

4. Y阵的修改——改变变压器变比



$$Y_{pp} = Y_{pp}^{(0)} - \Delta Y_{pp}^{(1)} + \Delta Y_{pp}^{(2)}$$

$$Y_{qq} = Y_{qq}^{(0)} - \Delta Y_{qq}^{(1)} + \Delta Y_{qq}^{(2)}$$

$$Y_{pq} = Y_{qp} = Y_{pq}^{(0)} - \Delta Y_{pq}^{(1)} + \Delta Y_{pq}^{(2)}$$

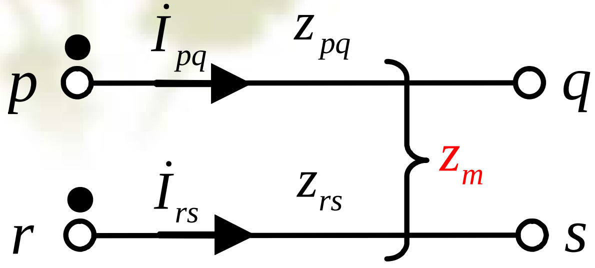
$$\Delta Y_{pp} = k/Z_T + (1-k)/Z_T = 1/Z_T$$

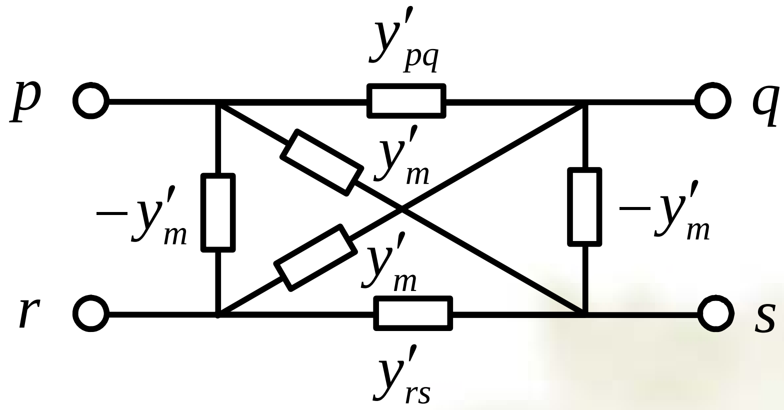
$$\Delta Y_{qq} = k/Z_T + k(k-1)/Z_T = k^2/Z_T$$

$$\Delta Y_{pq} = \Delta Y_{qp} = -k/Z_T$$

4-1 节点导纳矩阵

4. Y阵的修改——支路间存在互感



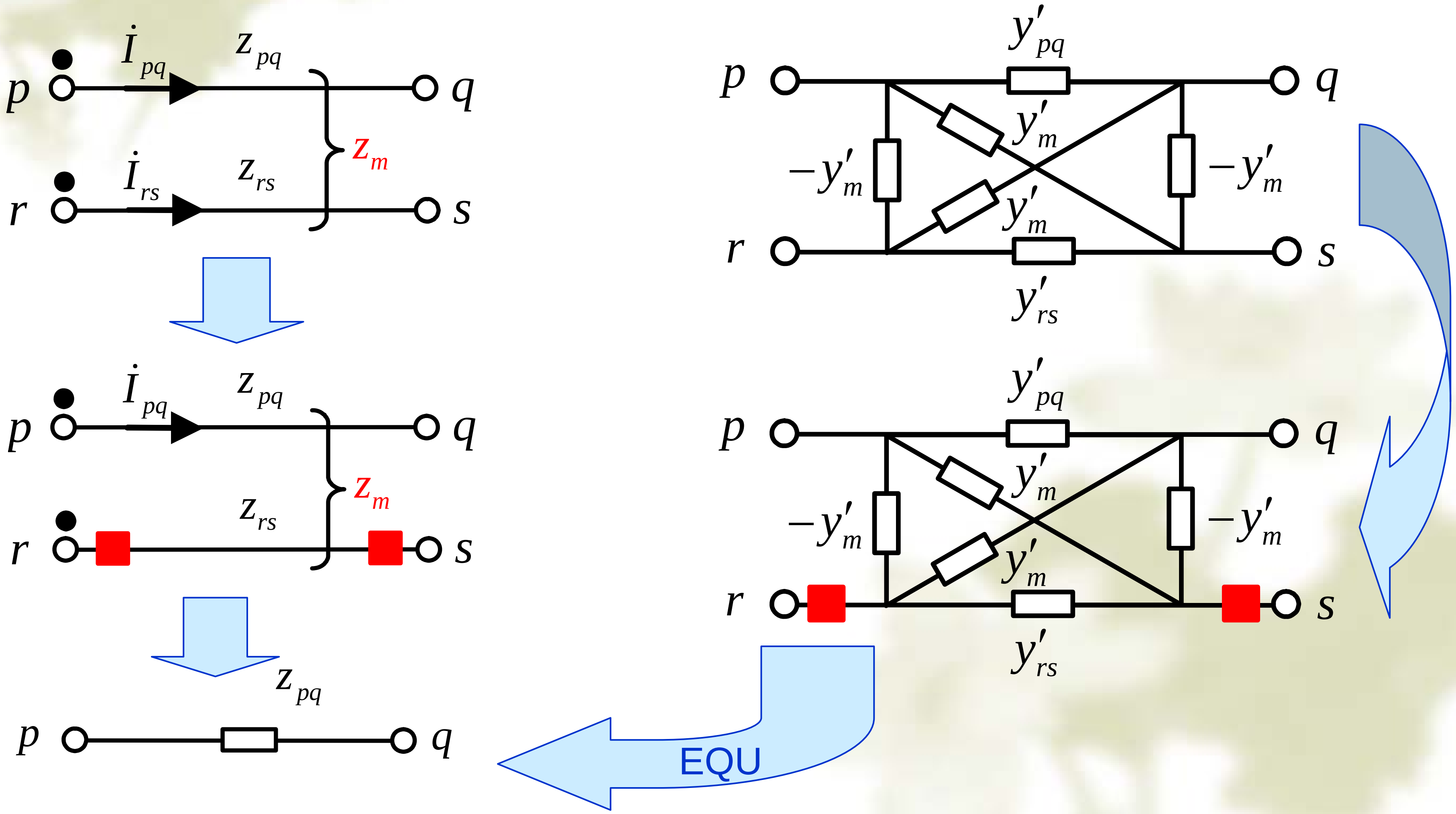


$$\begin{bmatrix}\dot V_p-\dot V_q\\ \dot V_r-\dot V_s\end{bmatrix}=\begin{bmatrix}z_{pq}&z_m\\ z_m&z_{rs}\end{bmatrix}\begin{bmatrix}\dot I_{pq}\\ \dot I_{rs}\end{bmatrix}$$

$$\begin{bmatrix}\dot I_{pq}\\ \dot I_{rs}\end{bmatrix}=\begin{bmatrix}y'_{pq}&y'_m\\ y'_m&y'_{rs}\end{bmatrix}\begin{bmatrix}\dot V_p-\dot V_q\\ \dot V_r-\dot V_s\end{bmatrix}$$

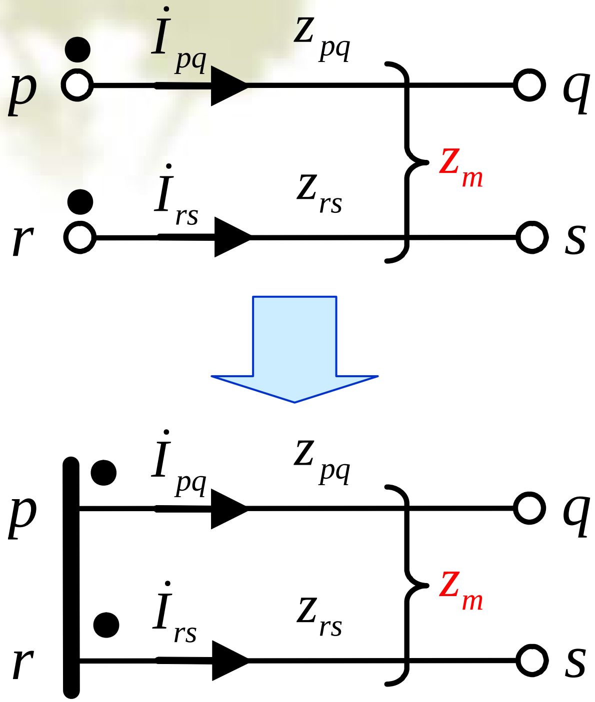
4-1 节点导纳矩阵

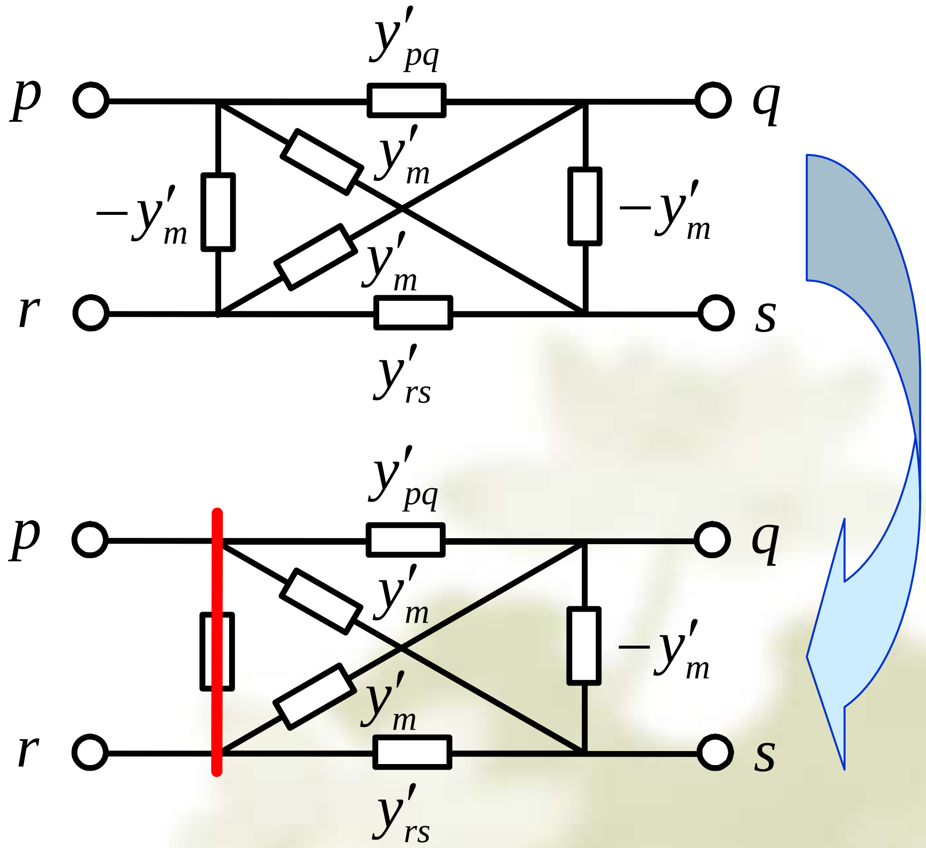
4. Y阵的修改——断开互感支路



4-1 节点导纳矩阵

4. Y阵的修改——一端互联的互感支路





4-3 节点阻抗矩阵

1. 节点阻抗矩阵

$$\begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \vdots \\ \dot{V}_n \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \vdots \\ \dot{I}_n \end{bmatrix}$$

$$\dot{\mathbf{I}} = \mathbf{Y}\dot{\mathbf{V}}$$

$$\dot{\mathbf{V}} = \mathbf{Z}\dot{\mathbf{I}}$$

Z_{ii} 节点i自阻抗

Z_{ij} 节点ij间互阻抗

节点阻抗矩阵

$$\mathbf{Z} = \mathbf{Y}^{-1}$$

4-3 节点阻抗矩阵

2. 节点阻抗矩阵元素的物理意义

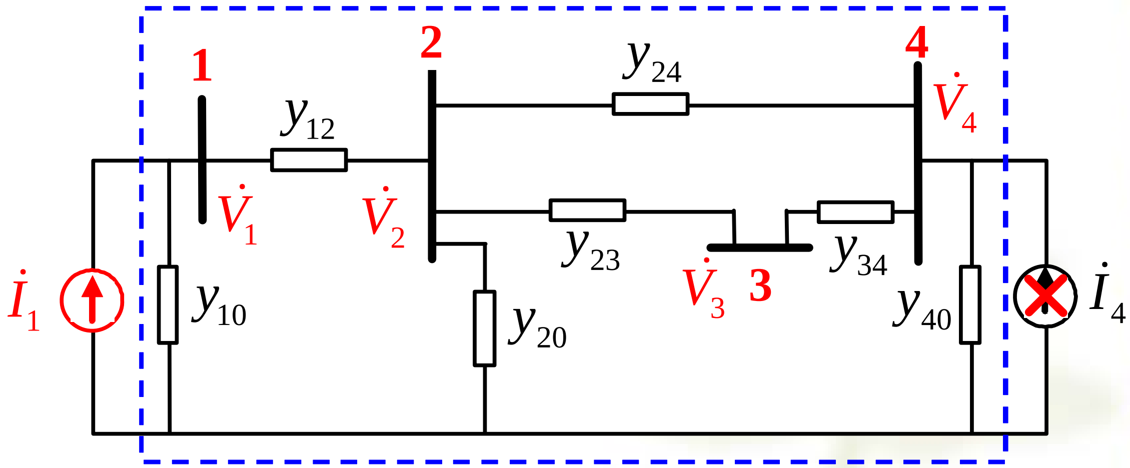
$$\dot{\mathbf{V}} = \mathbf{Z}\dot{\mathbf{I}}$$

$$\dot{I}_i \neq 0,\quad \dot{I}_j = 0,\quad (j \neq i)$$

$$\begin{cases} \dot{V}_i = \sum_{j=1}^{n} Z_{ij}\dot{I}_j \\ \dot{V}_j = \sum_{k}^{n} Z_{jk}\dot{I}_k \end{cases}$$

$$\dot{V}_i = Z_{ii}\dot{I}_i \Rightarrow Z_{ii} = \dot{V}_i / \dot{I}_i$$

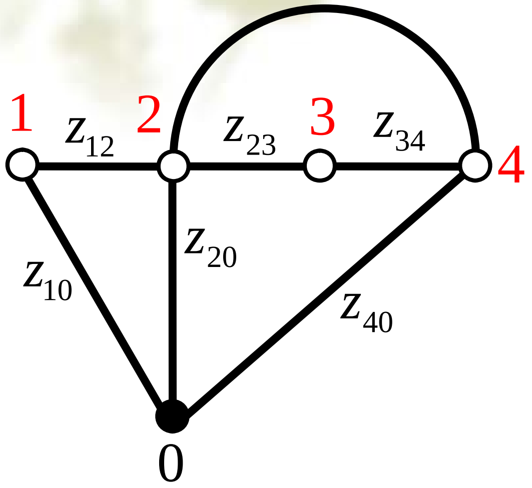
$$\dot{V}_j = Z_{ji}\dot{I}_i \Rightarrow Z_{ji} = \dot{V}_j / \dot{I}_i$$



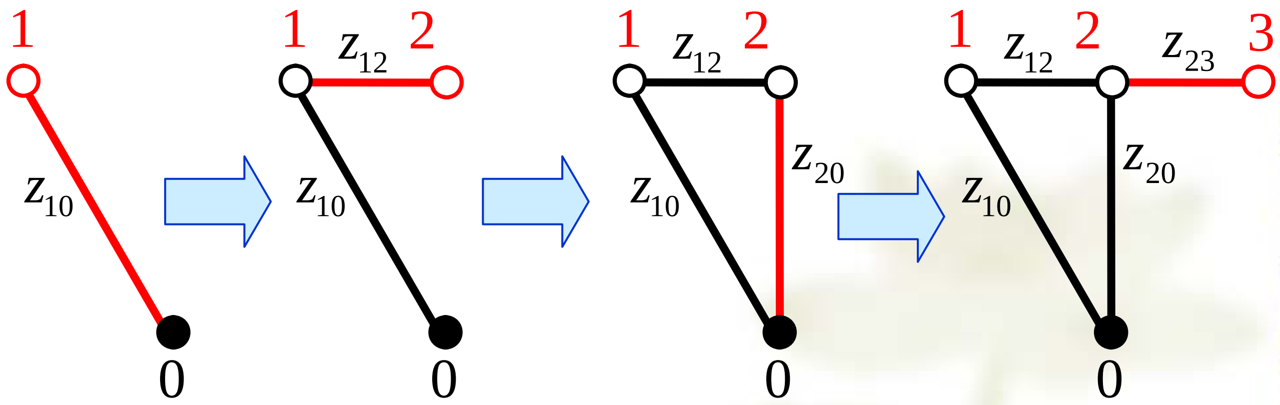
- ❖ 对称矩阵
- ❖ 满阵
- ❖ 计算复杂

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-基本过程



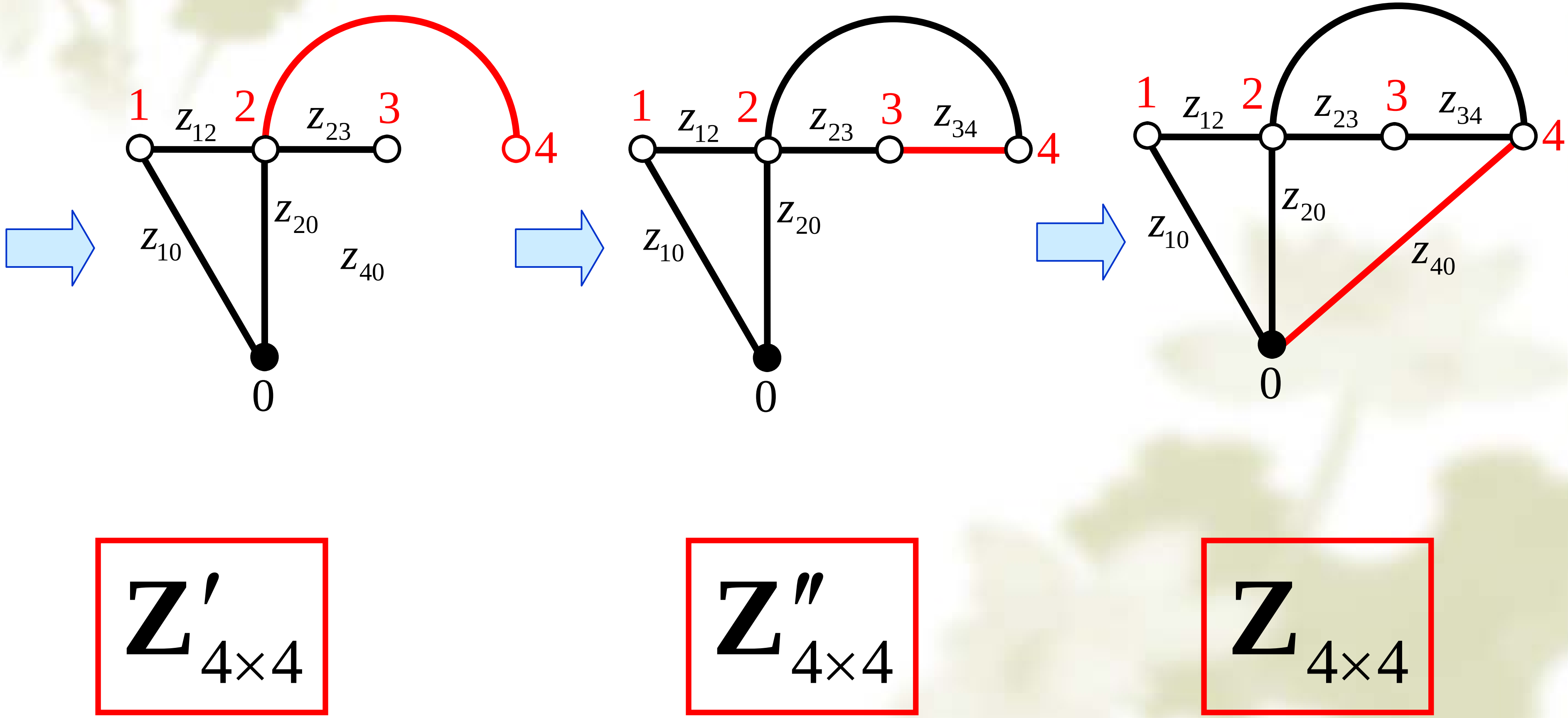
$\mathbf{Z}_{4\times4}$



$\mathbf{Z}_{1\times1}$ $\mathbf{Z}_{2\times2}$ $\mathbf{Z}'_{2\times2}$ $\mathbf{Z}_{3\times3}$

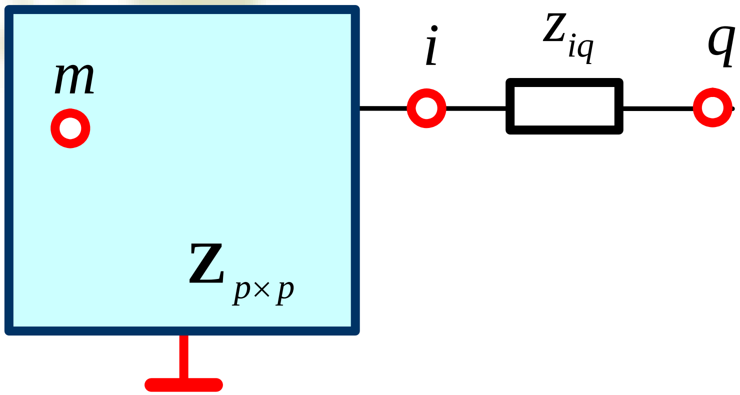
4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-基本过程



4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加树支



$$\mathbf{Z}_{p\times p}$$

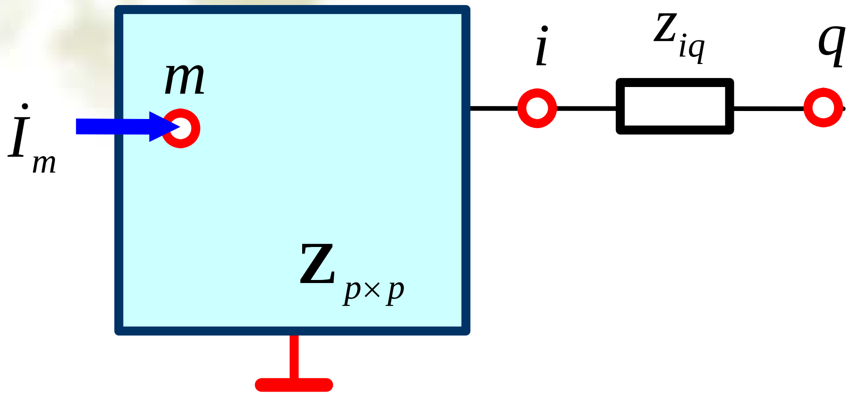
$$\mathbf{Z}_{(p+1)\times(p+1)}$$

$$\left[\begin{array}{ccccc|c} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1p} & Z_{1q} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{i1} & \cdots & Z_{ii} & \cdots & Z_{ip} & Z_{iq} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{p1} & \cdots & Z_{pi} & \cdots & Z_{pp} & Z_{pq} \\ \hline Z_{q1} & \cdots & Z_{qi} & \cdots & Z_{qp} & Z_{qq} \end{array}\right]$$

Z阵增加一行一列

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加树支



$$\begin{bmatrix} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1p} & Z_{1q} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{i1} & \cdots & Z_{ii} & \cdots & Z_{ip} & Z_{iq} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{p1} & \cdots & Z_{pi} & \cdots & Z_{pp} & Z_{pq} \\ Z_{q1} & \cdots & Z_{qi} & \cdots & Z_{qp} & Z_{qq} \end{bmatrix}$$

m节点单独注入电流$\dot{I}_m$

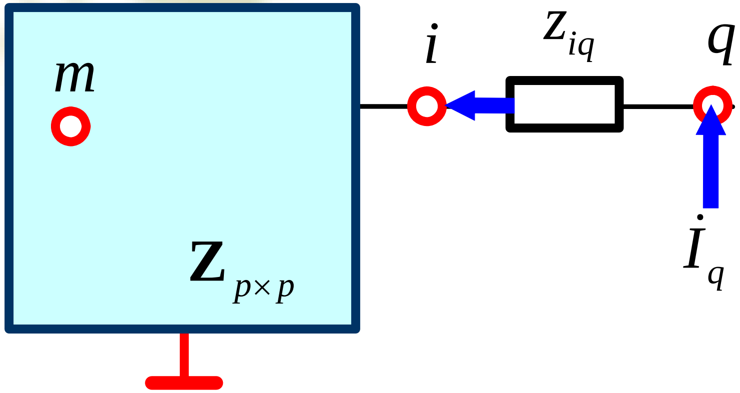
$$\dot{V}_i = Z_{im}\dot{I}_m$$

$$\dot{V}_q = Z_{qm}\dot{I}_m = \dot{V}_i = Z_{im}\dot{I}_m$$

$$Z_{qm} = Z_{im}$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加树支



$$\begin{bmatrix} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1p} & Z_{1q} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{i1} & \cdots & Z_{ii} & \cdots & Z_{ip} & Z_{iq} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{p1} & \cdots & Z_{pi} & \cdots & Z_{pp} & Z_{pq} \\ Z_{q1} & \cdots & Z_{qi} & \cdots & Z_{qp} & Z_{qq} \end{bmatrix}$$

q节点单独注入电流$\dot{I}_q$

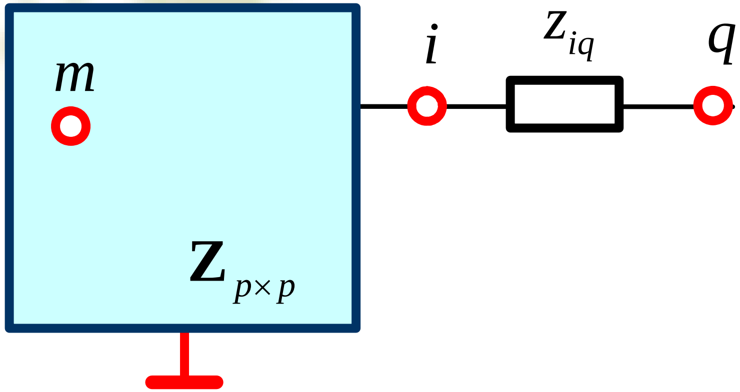
$$\dot{V}_m = Z_{mq}\dot{I}_q = Z_{mi}\dot{I}_q$$

$$\dot{V}_q = \dot{V}_i + z_{iq}\dot{I}_q = \left(Z_{ii} + z_{iq}\right)\dot{I}_q = Z_{qq}\dot{I}_q$$

$$Z_{mq} = Z_{mi}$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加树支



$$\begin{bmatrix} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1p} & Z_{1q} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{i1} & \cdots & Z_{ii} & \cdots & Z_{ip} & Z_{iq} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{p1} & \cdots & Z_{pi} & \cdots & Z_{pp} & Z_{pq} \\ Z_{q1} & \cdots & Z_{qi} & \cdots & Z_{qp} & Z_{qq} \end{bmatrix}$$

Z阵增加一行一列

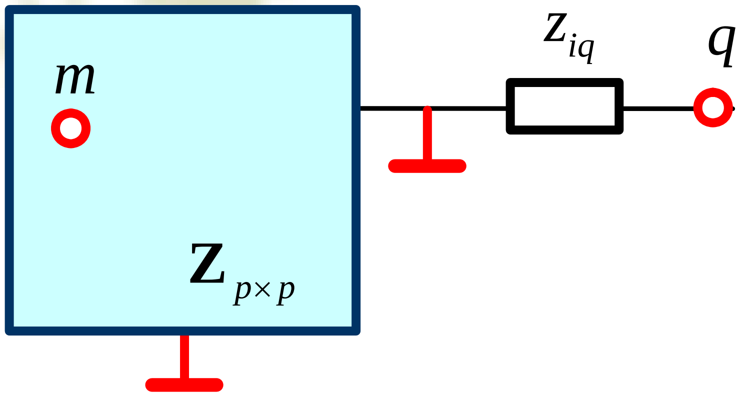
Z阵原有元素不变

$$Z_{mq} = Z_{mq} = Z_{mi},\left(m = 1, 2, \cdots, p\right)$$

$$Z_{qq} = Z_{ii} + z_{iq}$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加接地树支



$$
\begin{bmatrix}
Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1p} & Z_{1q} \\
\vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\
Z_{i1} & \cdots & Z_{ii} & \cdots & Z_{ip} & Z_{iq} \\
\vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\
Z_{p1} & \cdots & Z_{pi} & \cdots & Z_{pp} & Z_{pq} \\
Z_{q1} & \cdots & Z_{qi} & \cdots & Z_{qp} & Z_{qq}
\end{bmatrix}
$$

Z阵增加一行一列

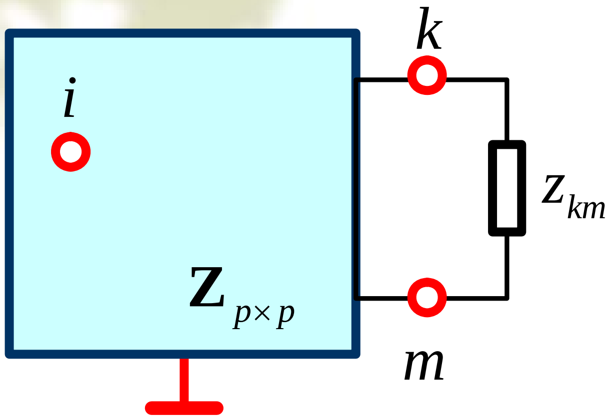
Z阵原有元素不变

$$Z_{mq} = Z_{qm} = 0, (m = 1, 2, \cdots, p)$$

$$Z_{qq} = z_{iq}$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加连支



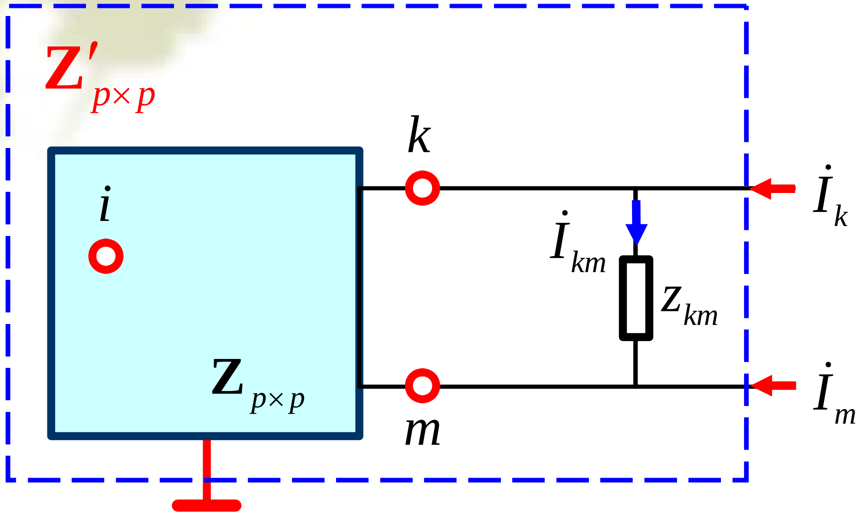
$$\mathbf{Z}_{p\times p} \Rightarrow \mathbf{Z}'_{p\times p}$$

$$\left[\begin{array}{ccccc|c}
Z'_{11} & \cdots & Z'_{1m} & \cdots & Z'_{1k} & \cdots \\
\vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\
Z'_{m1} & \cdots & Z'_{mm} & \cdots & Z'_{mk} & \cdots \\
\vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\
Z'_{k1} & \cdots & Z'_{km} & \cdots & Z'_{kk} & \cdots \\
\hline
\vdots & \cdots & \vdots & \cdots & \vdots & \vdots
\end{array}\right]$$

z_{km}支路会引起原网络电压电流分布的变化

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加连支

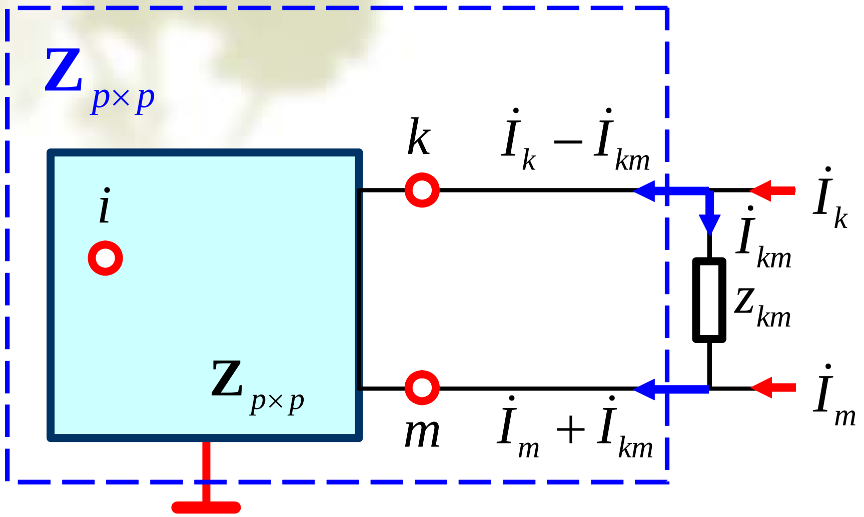


$$\dot{\mathbf{V}} = \mathbf{Z}'\dot{\mathbf{I}}$$

$$\dot{V}_i = \sum_{j=1}^{p} Z'_{ij}\dot{I}_j = Z'_{i1}\dot{I}_1 + \cdots + Z'_{ik}\dot{I}_k + \cdots + Z'_{im}\dot{I}_m + \cdots + Z'_{ip}\dot{I}_p$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加连支



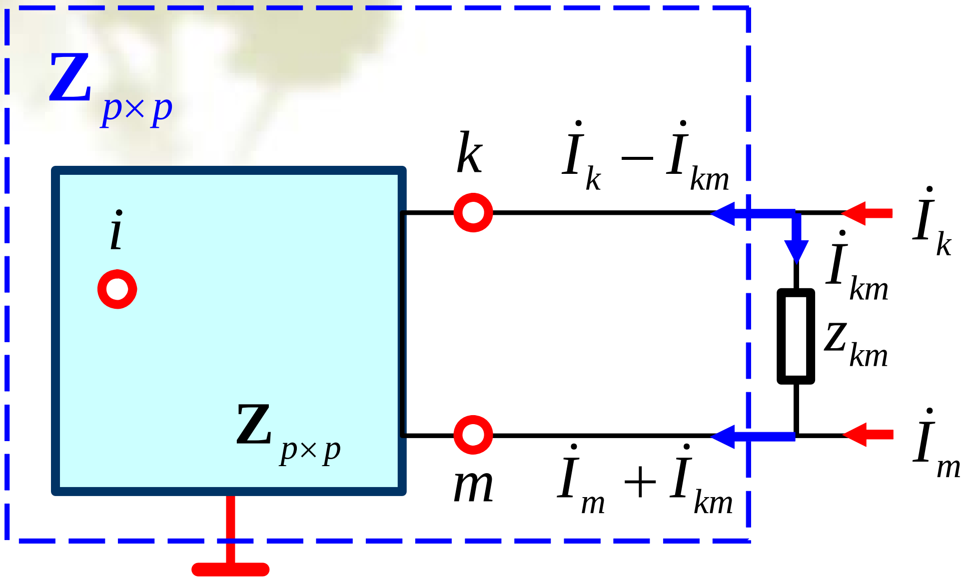
$$\dot{\mathbf{V}} = \mathbf{Z}\dot{\mathbf{I}}'$$

$$\dot{I}'_k = \dot{I}_k - \dot{I}_{km}$$
$$\dot{I}'_m = \dot{I}_m + \dot{I}_{km}$$
$$\dot{I}'_j = \dot{I}_j,\ j \neq k, m$$

$$\dot{V}_i = \sum_{j=1}^{p} Z_{ij}\dot{I}'_j = Z_{i1}\dot{I}_1 + \cdots + Z_{ik}\left(\dot{I}_k - \dot{I}_{km}\right) + \cdots + Z_{im}\left(\dot{I}_m + \dot{I}_{km}\right) + \cdots + Z_{ip}\dot{I}_p$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加连支



$$\dot{V}_k = \sum_{j=1}^{p} Z_{kj}\dot{I}_j - (Z_{kk} - Z_{km})\dot{I}_{km}$$

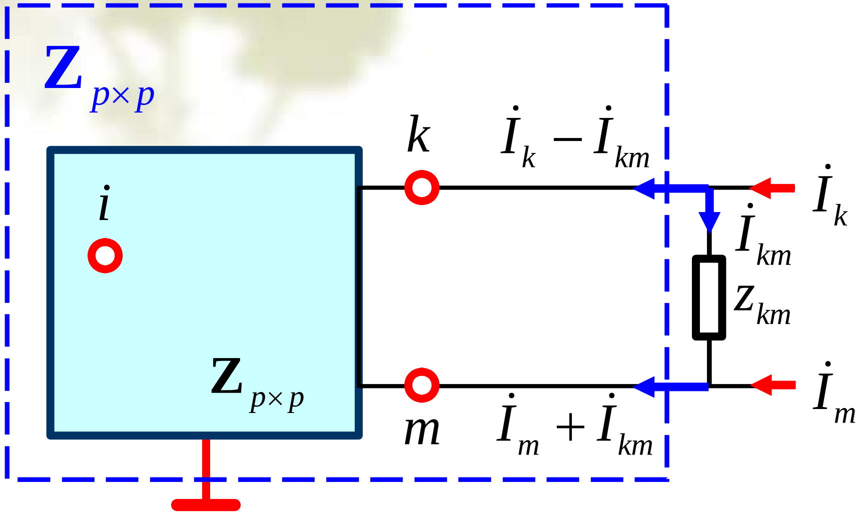
$$\dot{V}_m = \sum_{j=1}^{p} Z_{mj}\dot{I}_j - (Z_{mk} - Z_{mm})\dot{I}_{km}$$

$$\dot{V}_i = \sum_{j=1}^{p} Z_{ij}\dot{I}_j - (Z_{ik} - Z_{im})\dot{I}_{km}$$

$$\dot{V}_i = \sum_{j=1}^{p} Z_{ij}\dot{I}'_j = Z_{i1}\dot{I}_1 + \cdots + Z_{ik}\left(\dot{I}_k - \dot{I}_{km}\right) + \cdots + Z_{im}\left(\dot{I}_m + \dot{I}_{km}\right) + \cdots + Z_{ip}\dot{I}_p$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加连支



$$\dot{V}_k = \sum_{j=1}^{p} Z_{kj}\dot{I}_j - \left(Z_{kk} - Z_{km}\right)\dot{I}_{km}$$

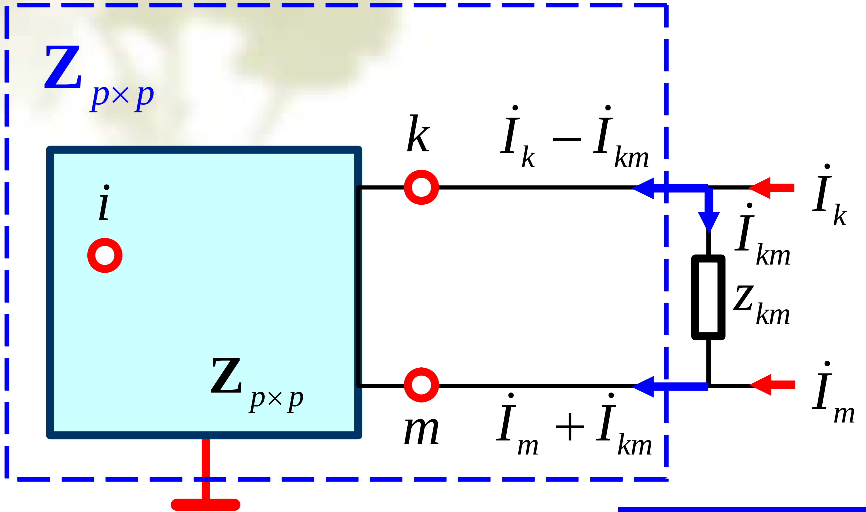
$$\dot{V}_m = \sum_{j=1}^{p} Z_{mj}\dot{I}_j - \left(Z_{mk} - Z_{mm}\right)\dot{I}_{km}$$

$$\dot{V}_k - \dot{V}_m = \sum_{j=1}^{p}\left(Z_{kj} - Z_{mj}\right)\dot{I}_j - \left(Z_{kk} - Z_{km} - Z_{mk} + Z_{mm}\right)\dot{I}_{km} = z_{km}\dot{I}_{km}$$

$$\dot{I}_{km} = \frac{1}{\left(Z_{kk} + Z_{mm} - 2Z_{km} + z_{km}\right)}\sum_{j=1}^{p}\left(Z_{kj} - Z_{mj}\right)\dot{I}_j$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加连支



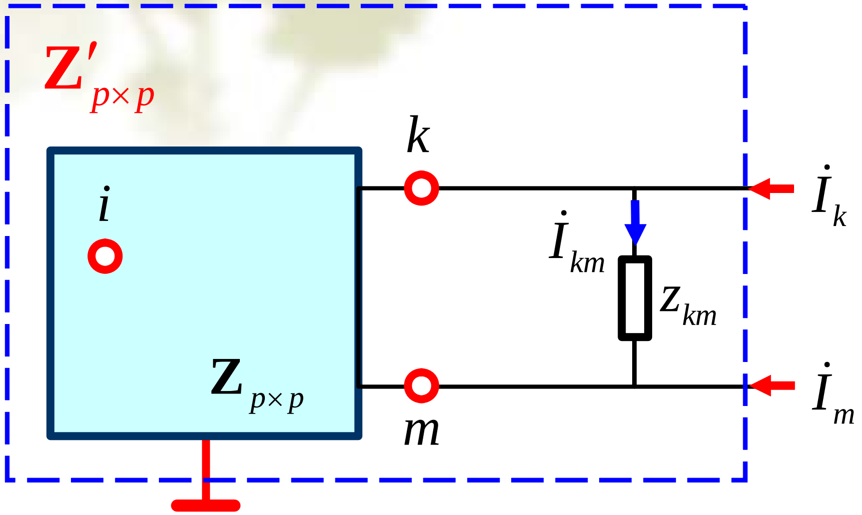
$$\dot{V}_i = \sum_{j=1}^{p} Z_{ij}\dot{I}_j - \left(Z_{ik} - Z_{im}\right)\dot{I}_{km}$$

$$\dot{I}_{km} = \frac{1}{\left(Z_{kk} + Z_{mm} - 2Z_{km} + z_{km}\right)}\sum_{j=1}^{p}\left(Z_{kj} - Z_{mj}\right)\dot{I}_j$$

$$\dot{V}_i = \sum_{j=1}^{p} Z_{ij}\dot{I}_j - \frac{\left(Z_{ik} - Z_{im}\right)}{\left(Z_{kk} + Z_{mm} - 2Z_{km} + z_{km}\right)}\sum_{j=1}^{p}\left(Z_{kj} - Z_{mj}\right)\dot{I}_j$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加连支



$$Z'_{ij} = Z_{ij} - \frac{(Z_{ik} - Z_{im})(Z_{kj} - Z_{mj})}{(Z_{kk} + Z_{mm} - 2Z_{km} + z_{km})}$$

$$(i, j = 1, 2, \cdots, p)$$

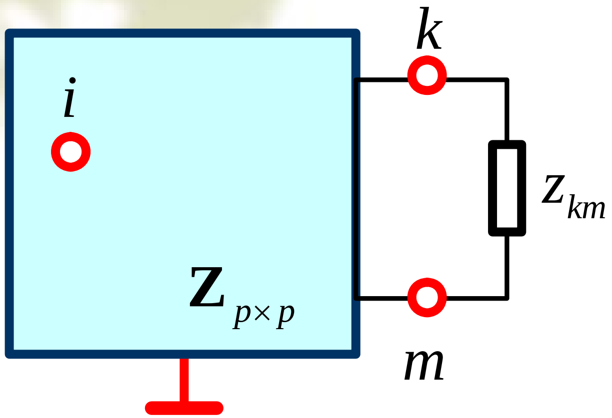
$$\dot{V}_i = \sum_{j=1}^{p} Z_{ij}\dot{I}_j - \frac{(Z_{ik} - Z_{im})}{(Z_{kk} + Z_{mm} - 2Z_{km} + z_{km})}\sum_{j=1}^{p}(Z_{kj} - Z_{mj})\dot{I}_j$$

$$\dot{V}_i = \sum_{j=1}^{p} Z'_{ij}\dot{I}_j$$

$$\dot{V}_i = \sum_{j=1}^{p}\left[Z_{ij} - \frac{(Z_{ik} - Z_{im})(Z_{kj} - Z_{mj})}{(Z_{kk} + Z_{mm} - 2Z_{km} + z_{km})}\right]\dot{I}_j$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加连支



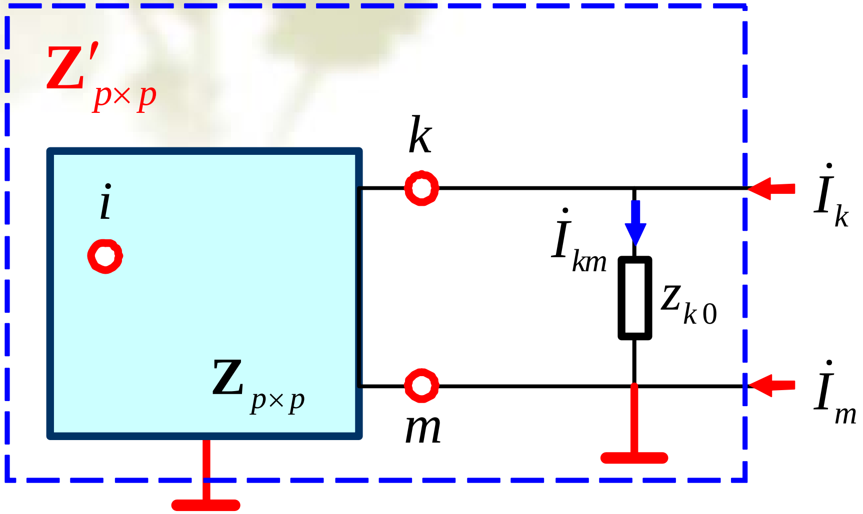
$$\mathbf{Z}_{p\times p} \Rightarrow \mathbf{Z}'_{p\times p}$$

$$\left[\begin{array}{ccccc|c}
Z'_{11} & \cdots & Z'_{1m} & \cdots & Z'_{1k} & \cdots \\
\vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\
Z'_{m1} & \cdots & Z'_{mm} & \cdots & Z'_{mk} & \cdots \\
\vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\
Z'_{k1} & \cdots & Z'_{km} & \cdots & Z'_{kk} & \cdots \\
\hline
\vdots & \cdots & \vdots & \cdots & \vdots & \vdots
\end{array}\right]$$

$$Z'_{ij} = Z_{ij} - \frac{\left(Z_{ik} - Z_{im}\right)\left(Z_{kj} - Z_{mj}\right)}{\left(Z_{kk} + Z_{mm} - 2Z_{km} + z_{km}\right)} \qquad \left(i, j = 1, 2, \cdots, p\right)$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加接地连支



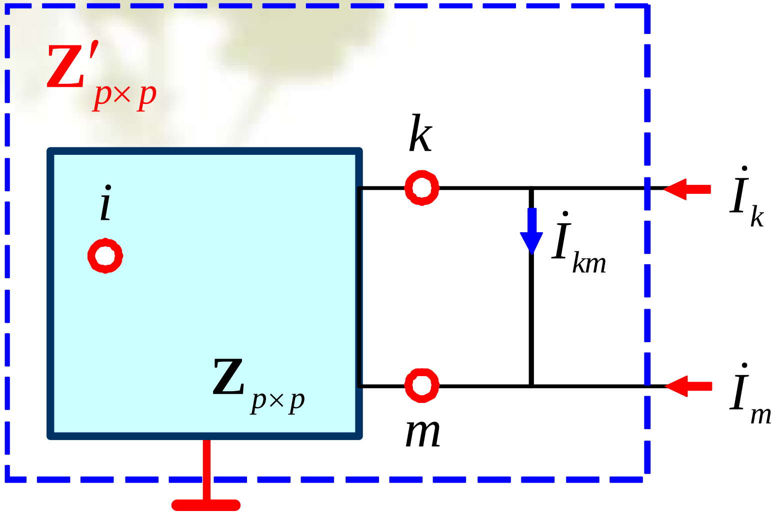
$$Z'_{ij} = Z_{ij} - \frac{(Z_{ik} - Z_{im})(Z_{kj} - Z_{mj})}{(Z_{kk} + Z_{mm} - 2Z_{km} + z_{km})} \quad (i, j = 1, 2, \cdots, p)$$

$$Z_{im} = Z_{mj} = Z_{km} = Z_{mm} = 0$$

$$Z'_{ij} = Z_{ij} - \frac{Z_{ik} Z_{kj}}{Z_{kk} + z_{k0}}, \quad (i, j = 1, 2, \cdots, p)$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加零阻抗连支



$$Z'_{ij}=Z_{ij}-\frac{\left(Z_{ik}-Z_{im}\right)\left(Z_{kj}-Z_{mj}\right)}{\left(Z_{kk}+Z_{mm}-2Z_{km}+z_{km}\right)}$$

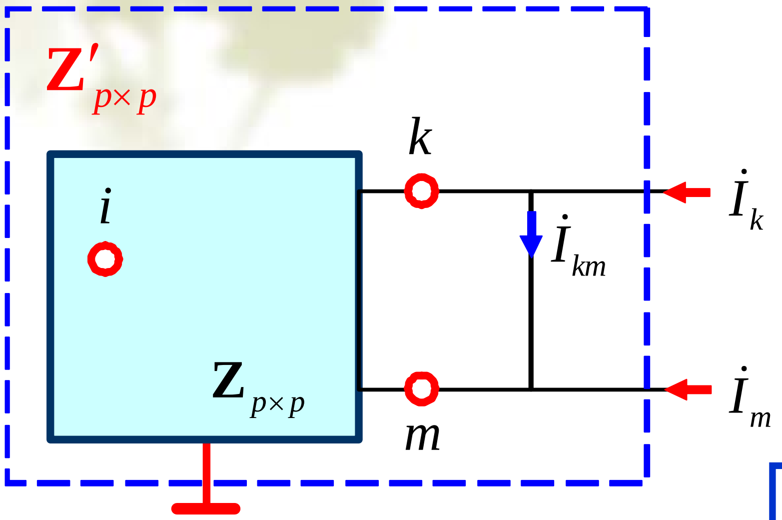
$$Z'_{ik}=Z_{ik}-\frac{\left(Z_{ik}-Z_{im}\right)\left(Z_{kk}-Z_{mk}\right)}{\left(Z_{kk}+Z_{mm}-2Z_{km}+z_{km}\right)}$$

$$Z'_{im}=Z_{im}-\frac{\left(Z_{ik}-Z_{im}\right)\left(Z_{km}-Z_{mm}\right)}{\left(Z_{kk}+Z_{mm}-2Z_{km}+z_{km}\right)}$$

$$Z'_{ik}-Z'_{im}=Z_{ik}-Z_{im}-\frac{\left(Z_{ik}-Z_{im}\right)\left(Z_{kk}-Z_{mk}\right)}{\left(Z_{kk}+Z_{mm}-2Z_{km}+z_{km}\right)}+\frac{\left(Z_{ik}-Z_{im}\right)\left(Z_{km}-Z_{mm}\right)}{\left(Z_{kk}+Z_{mm}-2Z_{km}+z_{km}\right)}$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加零阻抗连支



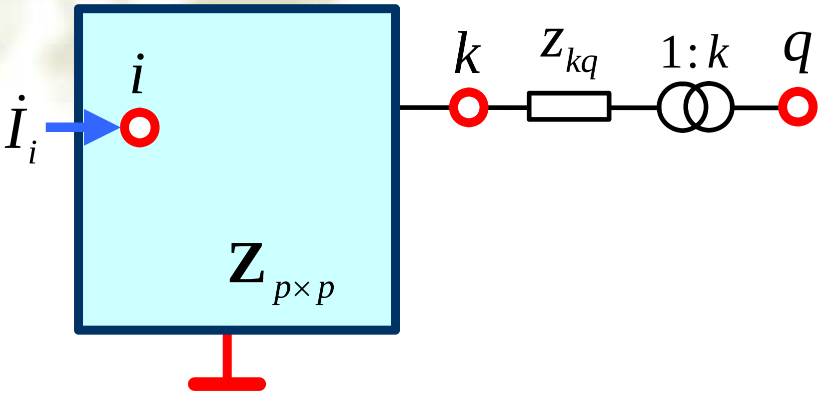
$z_{km}=0$,相当于k、m节点合并，则有$Z'_{ik}-Z'_{im}=0$，即第k列和第m列元素完全相等

$$Z'_{ik}-Z'_{im}=\left(Z_{ik}-Z_{im}\right)\left[1-\frac{\left(Z_{kk}-Z_{mk}\right)-\left(Z_{km}-Z_{mm}\right)}{\left(Z_{kk}+Z_{mm}-2Z_{km}+z_{km}\right)}\right]$$

$$Z'_{ik}-Z'_{im}=Z_{ik}-Z_{im}-\frac{\left(Z_{ik}-Z_{im}\right)\left(Z_{kk}-Z_{mk}\right)}{\left(Z_{kk}+Z_{mm}-2Z_{km}+z_{km}\right)}+\frac{\left(Z_{ik}-Z_{im}\right)\left(Z_{km}-Z_{mm}\right)}{\left(Z_{kk}+Z_{mm}-2Z_{km}+z_{km}\right)}$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加变压器树支



$$\left[\begin{array}{ccccc:c} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1p} & Z_{1q} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{k1} & \cdots & Z_{kk} & \cdots & Z_{kp} & Z_{kq} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{p1} & \cdots & Z_{pk} & \cdots & Z_{pp} & Z_{pq} \\ \hdashline Z_{q1} & \cdots & Z_{qk} & \cdots & Z_{qp} & Z_{qq} \end{array}\right]$$

i节点单独注入电流$\dot{I}_i$

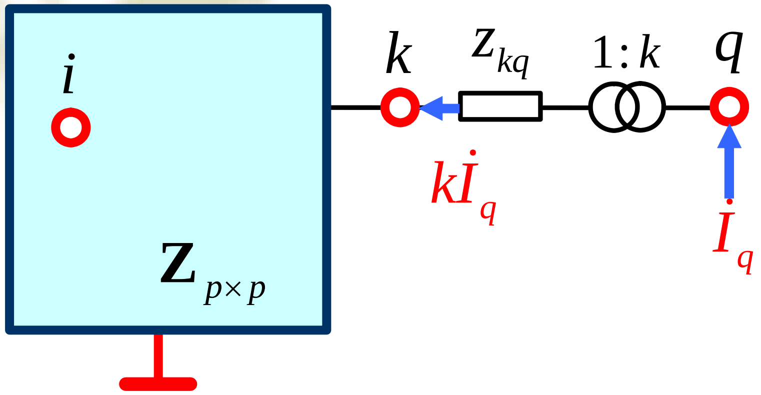
$$\dot{V}_k = Z_{ki}\dot{I}_i$$

$$\dot{V}_q = Z_{qi}\dot{I}_i = k\dot{V}_k = kZ_{ki}\dot{I}_i$$

$$\Rightarrow \quad Z_{qi} = kZ_{ki}$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加变压器树支



$$\begin{bmatrix} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1p} & Z_{1q} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{k1} & \cdots & Z_{kk} & \cdots & Z_{kp} & Z_{kq} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{p1} & \cdots & Z_{pk} & \cdots & Z_{pp} & Z_{pq} \\ Z_{q1} & \cdots & Z_{qk} & \cdots & Z_{qp} & Z_{qq} \end{bmatrix}$$

q节点单独注入电流$\dot{I}_q$

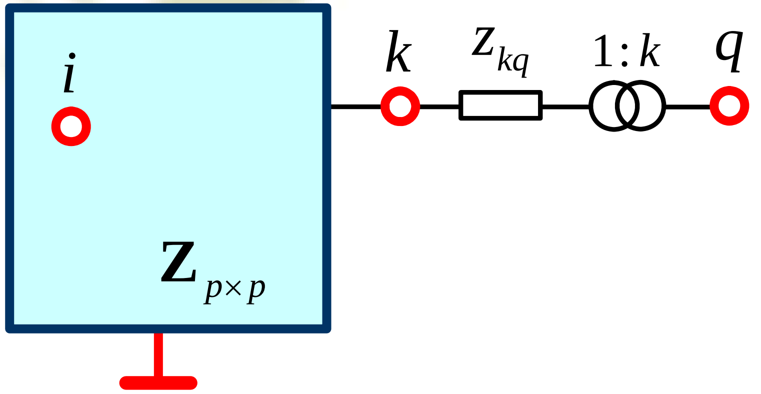
$$\dot{V}_i = Z_{iq}\dot{I}_q = kZ_{ik}\dot{I}_q$$

$$Z_{iq} = kZ_{ik}$$

$$\dot{V}_q = k\left(\dot{V}_k + z_{kq}k\dot{I}_q\right) = k^2\left(Z_{kk} + z_{kq}\right)\dot{I}_q = Z_{qq}\dot{I}_q$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加变压器树支



$$\begin{bmatrix} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1p} & Z_{1q} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{k1} & \cdots & Z_{kk} & \cdots & Z_{kp} & Z_{kq} \\ \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ Z_{p1} & \cdots & Z_{pk} & \cdots & Z_{pp} & Z_{pq} \\ Z_{q1} & \cdots & Z_{qk} & \cdots & Z_{qp} & Z_{qq} \end{bmatrix}$$

Z阵增加一行一列

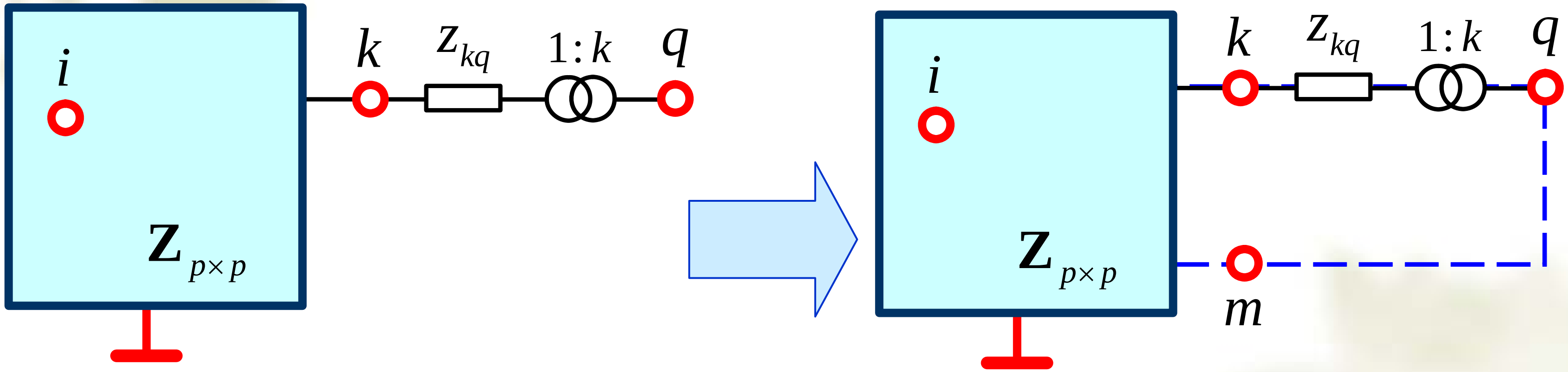
Z阵原有元素不变

$$Z_{iq} = Z_{qi} = kZ_{ki}, (i = 1, 2, \cdots, p)$$

$$Z_{qq} = k^2\left(Z_{kk} + z_{kq}\right)$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加变压器连支



$\mathbf{Z}_{p\times p} \Rightarrow \mathbf{Z}_{(p+1)\times(p+1)}$

$\mathbf{Z}'_{p\times p} \Leftarrow \mathbf{Z}'_{(p+1)\times(p+1)}$

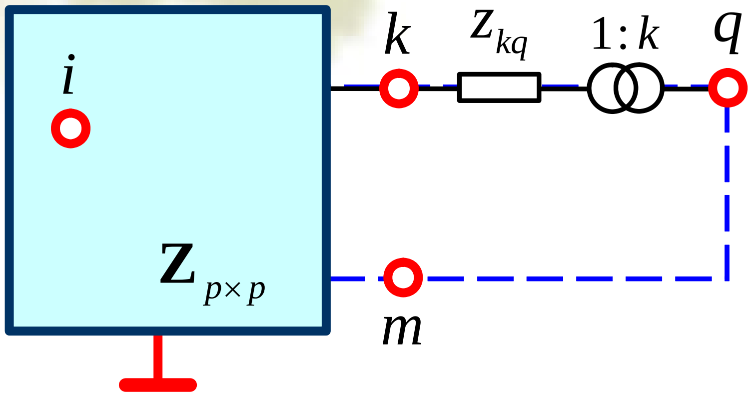
$$Z_{iq} = Z_{qi} = kZ_{ik}$$

$$Z_{qq} = k^2\left(Z_{kk} + z_{kq}\right)$$

$$Z'_{ij} = Z_{ij} - \frac{\left(Z_{iq} - Z_{im}\right)\left(Z_{qj} - Z_{mj}\right)}{\left(Z_{qq} + Z_{mm} - 2Z_{qm}\right)}$$

4-3 节点阻抗矩阵

3. 支路追加法生成Z阵-追加变压器连支



$$Z'_{ij} = Z_{ij} - \frac{\left(Z_{iq} - Z_{im}\right)\left(Z_{qj} - Z_{mj}\right)}{\left(Z_{qq} + Z_{mm} - 2Z_{qm}\right)}$$

$$Z_{iq} = Z_{qi} = kZ_{ik}, Z_{qq} = k^2\left(Z_{kk} + z_{kq}\right)$$

$$Z'_{ij} = Z_{ij} - \frac{\left(kZ_{ik} - Z_{im}\right)\left(kZ_{kj} - Z_{mj}\right)}{k^2\left(Z_{kk} + z_{kq}\right) + Z_{mm} - 2kZ_{mk}}, (i, j = 1, 2, \cdots, p)$$

$$\mathbf{Z}'_{p\times p}$$

4-3 节点阻抗矩阵

4. 由线性代数方程YZ=I计算Z阵

$$\begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \left[\begin{array}{c:c:c:c} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{array}\right] = \left[\begin{array}{c:c:c:c} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & 1 \end{array}\right]$$

$$\mathbf{Y}[\mathbf{Z}_1 \ \mathbf{Z}_2 \ \cdots \ \mathbf{Z}_n] = [\mathbf{e}_1 \ \mathbf{e}_2 \ \cdots \mathbf{e}_n]$$

$$\mathbf{Z}_j = \left[Z_{1j} \ Z_{2j} \ \cdots \ Z_{nj} \right]^{\mathrm{T}}$$

$$\mathbf{YZ}_j = \mathbf{e}_j, (j = 1, 2, \cdots, n)$$

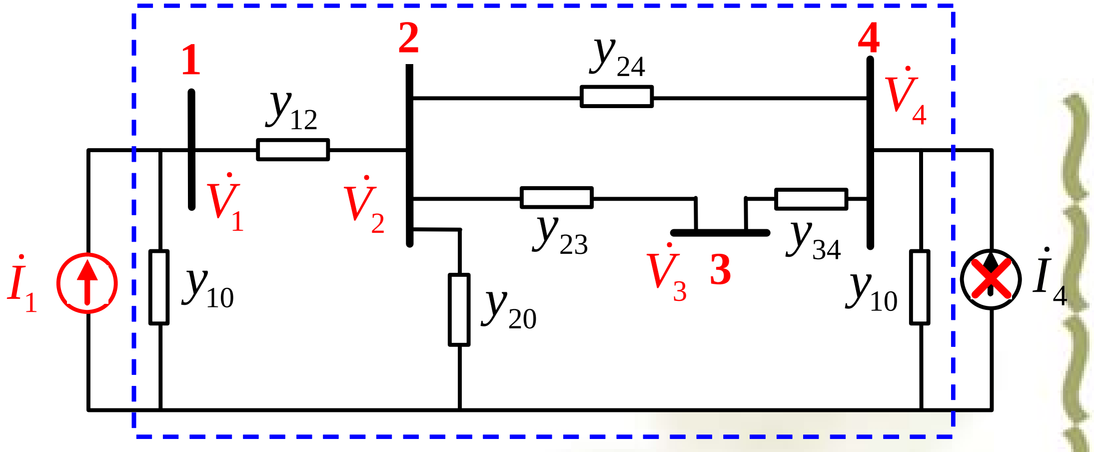
$$\mathbf{e}_j = [0 \ \cdots \ 1 \ \cdots \ 0]^{\mathrm{T}}$$

第*j*列

4-3 节点阻抗矩阵

4. 由线性代数方程YZ=I计算Z阵

$$\begin{bmatrix} Y_{11} & \cdots & Y_{1j} & \cdots & Y_{1n} \\ \vdots & & \vdots & & \vdots \\ Y_{j1} & \cdots & Y_{jj} & \cdots & Y_{jn} \\ \vdots & & \vdots & & \vdots \\ Y_{n1} & \cdots & Y_{nj} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} Z_{1j} \\ \vdots \\ Z_{jj} \\ \vdots \\ Z_{nj} \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{bmatrix}$$



$$\mathbf{YZ}_j = \mathbf{e}_j$$

$$\mathbf{Y\dot{V}} = \mathbf{\dot{I}}$$

$$\dot{I}_i = 0, \quad \dot{I}_j = 1, \quad (i \neq j)$$

$$\dot{V}_j = Z_{jj}\dot{I}_j = Z_{jj}$$

$$\dot{V}_i = Z_{ij}\dot{I}_j = Z_{ij}$$

方程的物理意义

4-3 节点阻抗矩阵

4. 由线性代数方程YZ=I计算Z阵

$$\begin{bmatrix} Y_{11} & \cdots & Y_{1j} & \cdots & Y_{1n} \\ \vdots & & \vdots & & \vdots \\ Y_{j1} & \cdots & Y_{jj} & \cdots & Y_{jn} \\ \vdots & & \vdots & & \vdots \\ Y_{n1} & \cdots & Y_{nj} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} Z_{1j} \\ \vdots \\ Z_{jj} \\ \vdots \\ Z_{nj} \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{bmatrix}$$

$$\mathbf{YZ}_j = \mathbf{e}_j \qquad \mathbf{LDUZ}_j = \mathbf{e}_j$$

$$\mathbf{Y} = \mathbf{LDU}$$

$$\begin{bmatrix} Y_{11} & \cdots & Y_{1j} & \cdots & Y_{1n} \\ \vdots & & \vdots & & \vdots \\ Y_{j1} & \cdots & Y_{jj} & \cdots & Y_{jn} \\ \vdots & & \vdots & & \vdots \\ Y_{n1} & \cdots & Y_{nj} & \cdots & Y_{nn} \end{bmatrix} = \begin{bmatrix} 1 & & & & \\ l_{21} & 1 & & & \\ l_{31} & l_{32} & 1 & & \\ \vdots & \vdots & \vdots & \ddots & \\ l_{n1} & l_{n2} & l_{n3} & \cdots & 1 \end{bmatrix} \begin{bmatrix} d_{11} & & & & \\ & d_{22} & & & \\ & & d_{33} & & \\ & & & \ddots & \\ & & & & d_{nn} \end{bmatrix} \begin{bmatrix} 1 & u_{12} & u_{13} & \cdots & u_{1n} \\ & 1 & u_{23} & \cdots & u_{2n} \\ & & 1 & \cdots & u_{3n} \\ & & & \ddots & \vdots \\ & & & & 1 \end{bmatrix}$$

4-3 节点阻抗矩阵

4. 由线性代数方程YZ=I计算Z阵

$$\mathbf{LDUZ}_j = \mathbf{e}_j$$

$$\mathbf{LF} = \mathbf{e}_j$$

$$f_i = \begin{cases} 0 & i < j \\ 1 & i = j \\ -\sum_{k=j}^{i-1} l_{ik} f_k, & i > j \end{cases}$$

$$\begin{bmatrix} 1 & & & & & & & & \\ l_{21} & 1 & & & & & & & \\ l_{31} & l_{32} & 1 & & & & & & \\ \vdots & \vdots & \vdots & \ddots & & & & & \\ l_{j1} & l_{j2} & l_{j3} & \cdots & 1 & & & & \\ \vdots & \vdots & \vdots & & \vdots & \ddots & & & \\ l_{i1} & l_{i2} & l_{i3} & \cdots & l_{ij} & \cdots & 1 & & \\ \vdots & \vdots & \vdots & & \vdots & & \vdots & \ddots & \\ l_{n1} & l_{n2} & l_{n3} & \cdots & l_{nj} & \cdots & l_{ni} & \cdots & 1 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_j \\ \vdots \\ f_i \\ \vdots \\ f_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

4-3 节点阻抗矩阵

4. 由线性代数方程YZ=I计算Z阵

$$\mathbf{LDUZ}_j = \mathbf{e}_j$$

$$\mathbf{DUZ}_j = \mathbf{F}$$

$$\mathbf{DH} = \mathbf{F}$$

$$\begin{bmatrix} d_{11} & & & & & & & & \\ & d_{22} & & & & & & & \\ & & d_{33} & & & & & & \\ & & & \ddots & & & & & \\ & & & & d_{jj} & & & & \\ & & & & & \ddots & & & \\ & & & & & & d_{ii} & & \\ & & & & & & & \ddots & \\ & & & & & & & & d_{nn} \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ \vdots \\ h_j \\ \vdots \\ h_i \\ \vdots \\ h_n \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_j \\ \vdots \\ f_i \\ \vdots \\ f_n \end{bmatrix}$$

$$h_i = \begin{cases} 0 & i < j \\ f_i / d_{ii} & i \geq j \end{cases}$$

4-3 节点阻抗矩阵

4. 由线性代数方程YZ=I计算Z阵

$$\mathbf{LDUZ}_j = \mathbf{e}_j$$

$$\mathbf{LF} = \mathbf{e}_j$$

$$\mathbf{DUZ}_j = \mathbf{F}$$

$$\mathbf{DH} = \mathbf{F}$$

$$\mathbf{UZ}_j = \mathbf{H}$$

$$\begin{bmatrix} 1 & u_{12} & u_{13} & \cdots & u_{1j} & \cdots & u_{1i} & \cdots & u_{1n} \\ & 1 & u_{23} & \cdots & u_{2j} & \cdots & u_{2i} & \cdots & u_{2n} \\ & & 1 & \cdots & u_{3j} & \cdots & u_{3i} & \cdots & u_{3n} \\ & & & \ddots & \vdots & & \vdots & & \vdots \\ & & & & 1 & & u_{ji} & \cdots & u_{jn} \\ & & & & & \ddots & \vdots & & \vdots \\ & & & & & & 1 & \cdots & u_{in} \\ & & & & & & & \ddots & \vdots \\ & & & & & & & & 1 \end{bmatrix} \begin{bmatrix} Z_{1j} \\ Z_{2j} \\ Z_{3j} \\ \vdots \\ Z_{jj} \\ \vdots \\ Z_{ij} \\ \vdots \\ Z_{nj} \end{bmatrix} = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ \vdots \\ h_j \\ \vdots \\ h_i \\ \vdots \\ h_n \end{bmatrix}$$

$$Z_{ij} = h_i - \sum_{k=i+1}^{n} u_{ik} Z_{kj}, \quad i = n, n-1, \cdots, 1$$

4-3 节点阻抗矩阵

4. 由线性代数方程YZ=I计算Z阵-因子表

$$\mathbf{L}^{\mathrm{T}} = \mathbf{U}$$

$$l_{ki} = u_{ik}$$

$$\begin{bmatrix} d_{11}^{-1} & u_{12} & u_{13} & \cdots & u_{1j} & \cdots & u_{1i} & \cdots & u_{1n} \\ & d_{22}^{-1} & u_{23} & \cdots & u_{2j} & \cdots & u_{2i} & \cdots & u_{2n} \\ & & d_{33}^{-1} & \cdots & u_{3j} & \cdots & u_{3i} & \cdots & u_{3n} \\ & & & \ddots & \vdots & & \vdots & & \vdots \\ & & & & d_{jj}^{-1} & & u_{ji} & \cdots & u_{jn} \\ & & & & & \ddots & \vdots & & \vdots \\ & & & & & & d_{ii}^{-1} & \cdots & u_{in} \\ & & & & & & & \ddots & \vdots \\ & & & & & & & & d_{nn}^{-1} \end{bmatrix}$$

本章小结

❖**Y**阵元素的物理意义；**Y**阵的特点、形成和修改；

❖**Z**阵元素的物理意义，根据Z阵元素的物理意义形成Z阵的方法；

❖利用线性代数方程$YZ_j=e_j$计算Z阵的某一列元素；

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习 题

Ex 4-1，4-2，4-4

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To Be Continued