1.

A B Q

2.

3.

15 1

1.

G G

G(

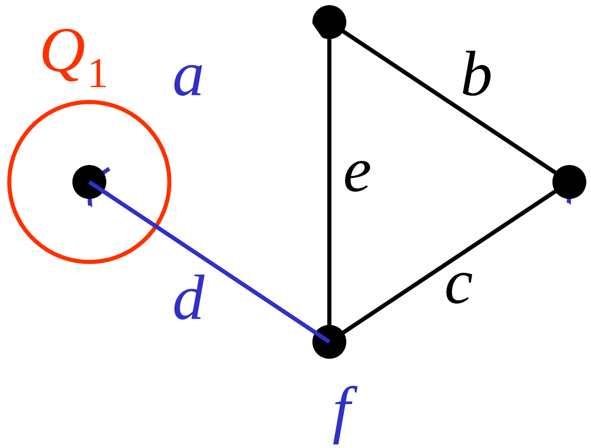
)

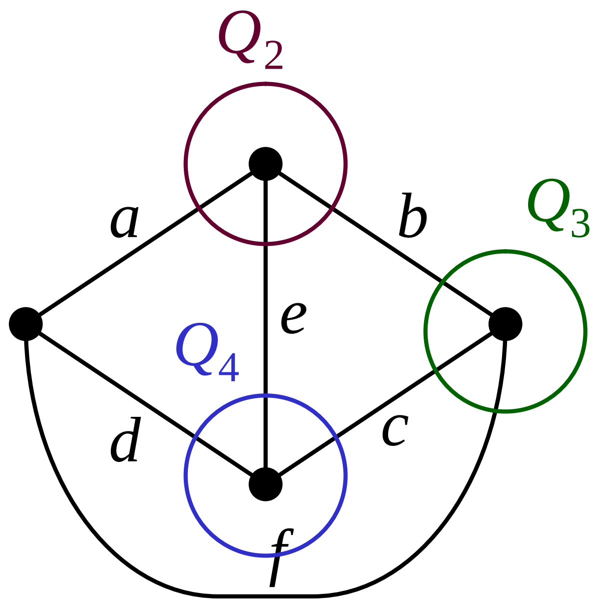
G

☞(a d f)

G

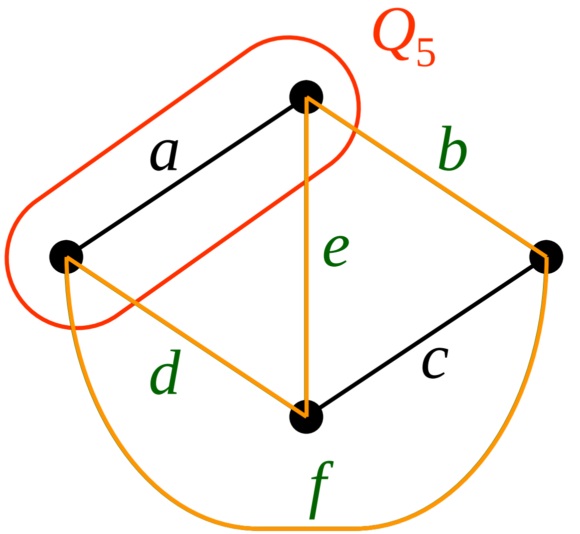
G

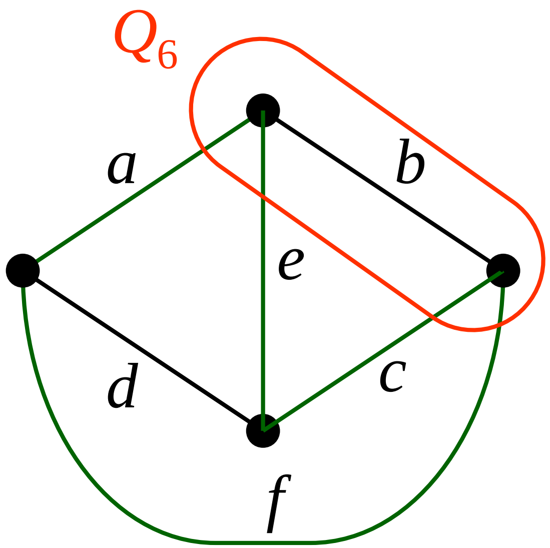


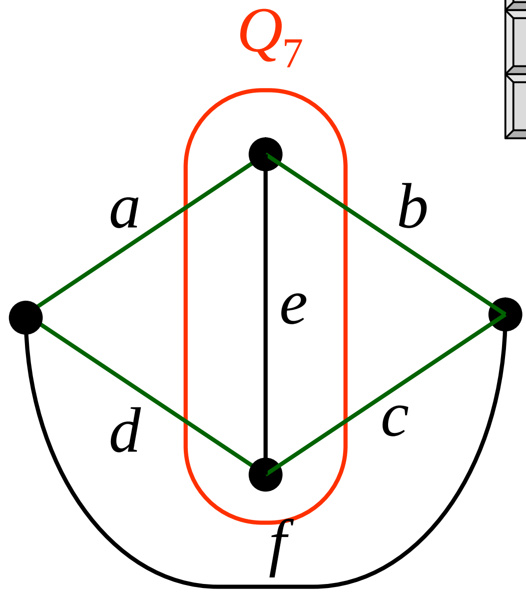


(a b e) (b c f) (c d e)

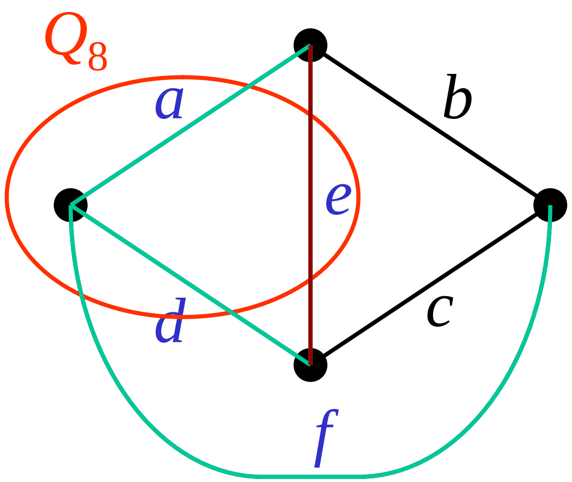
G G







(*b*, *d*, *e*, *f*) (*a*, *e*, *c*, *f*) (*a*, *b*, *c*, *d*)

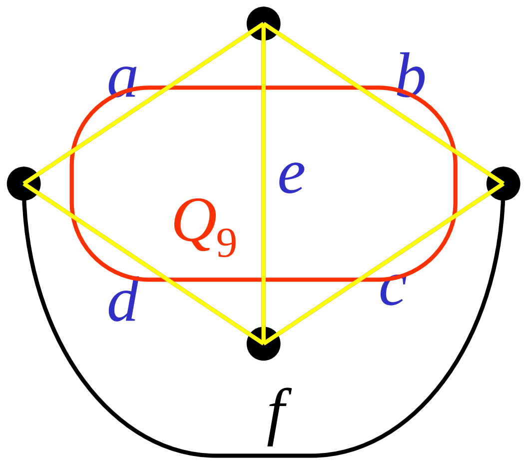


(*a*, *d*, *e*, *f*) G

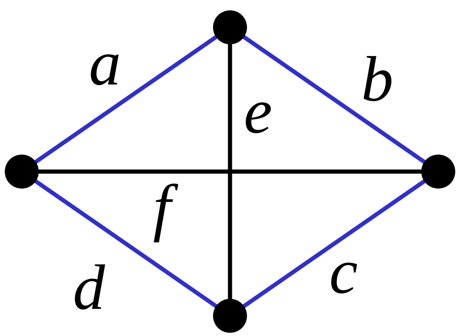
e G

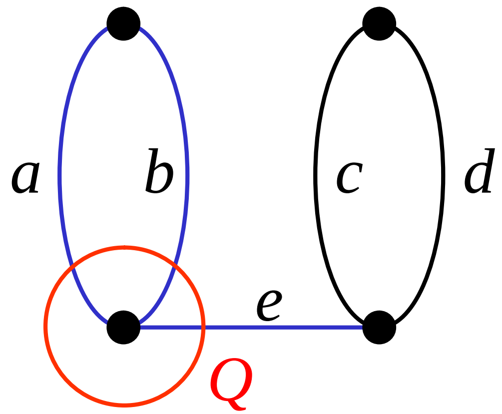
(a, b, c, d, e) G

G



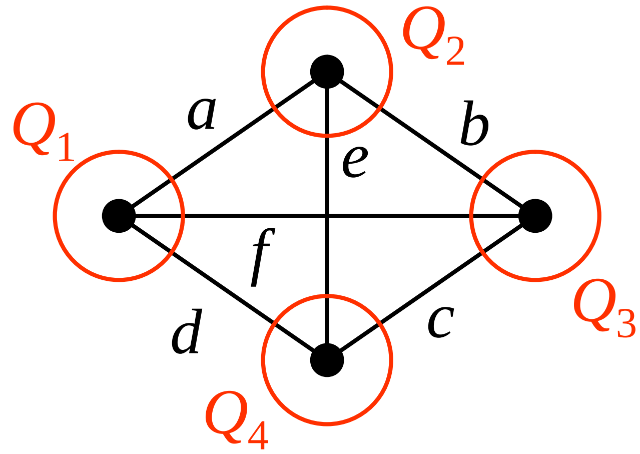
2.





Q

(a, b, c, d) (a, b, e)



3.

KCL

KCL

G

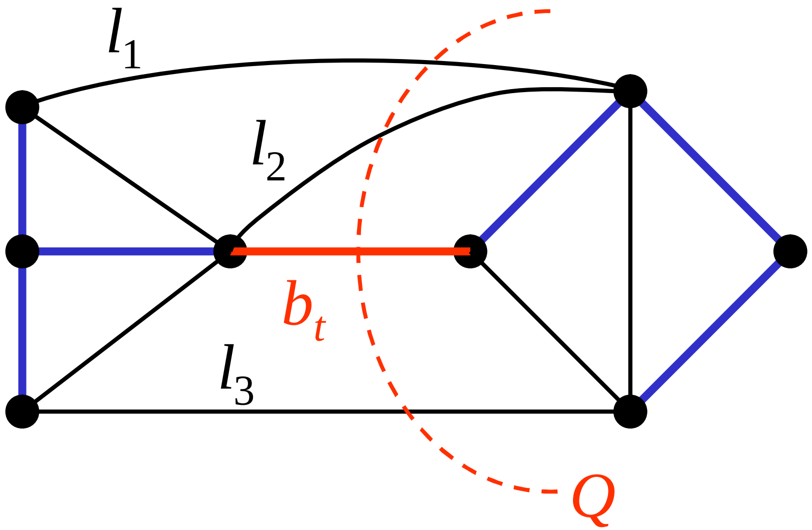
KCL

KCL KCL

(1)

KCL

(2)



-

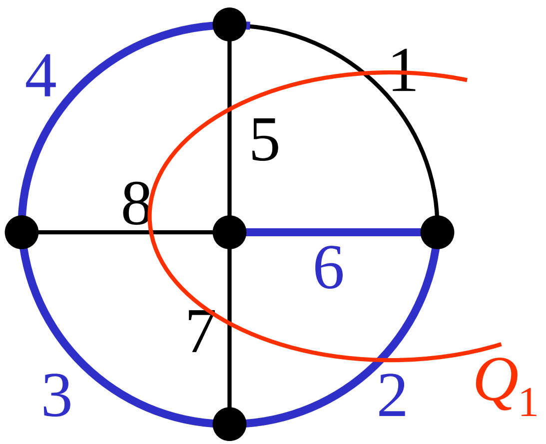
-

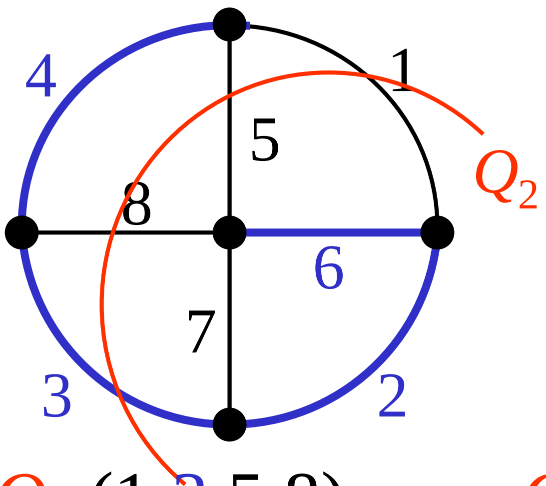
- n b

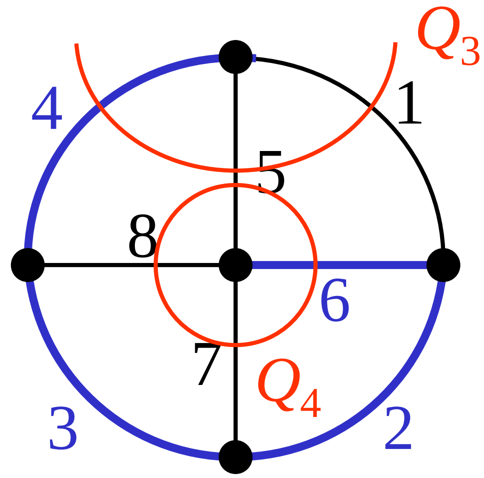
  $(n\ \ 1)$

- $(n\ \ 1)$

2,3,4,6

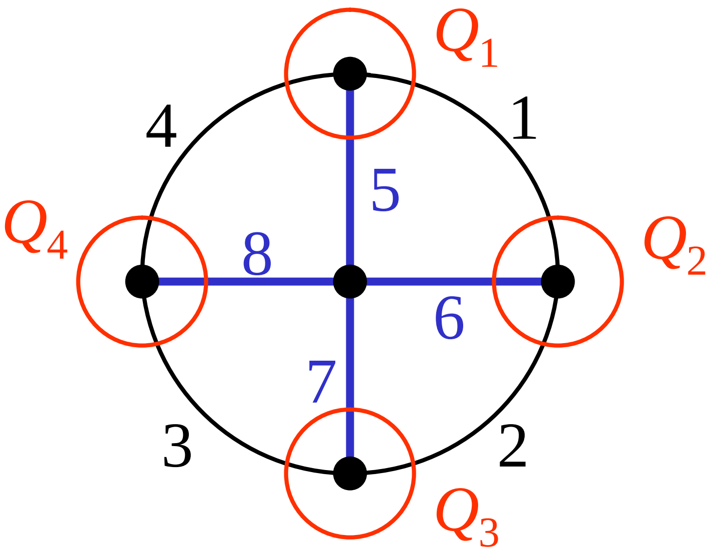






Q_1 (1,2,5,7,8) Q_2 (1,3,5,8) Q_3 (1,4,5) Q_4 (5,6,7,8)

5,6,7,8



15 2

1.

$(n \quad b)$

(1)$\boldsymbol{A}_a$

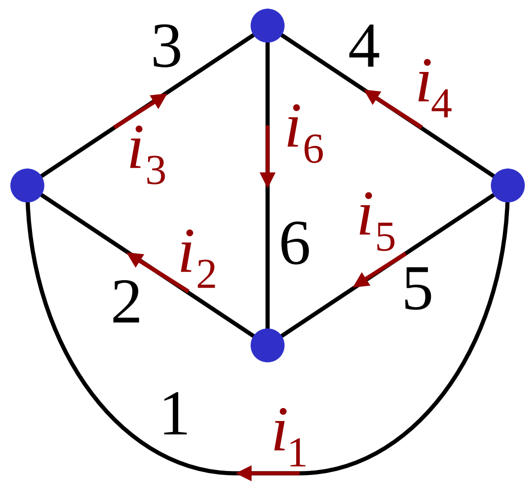
$a_{jk} = +1$ k j

$a_{jk} = -1$ k

j

$a_{jk} = 0$ k

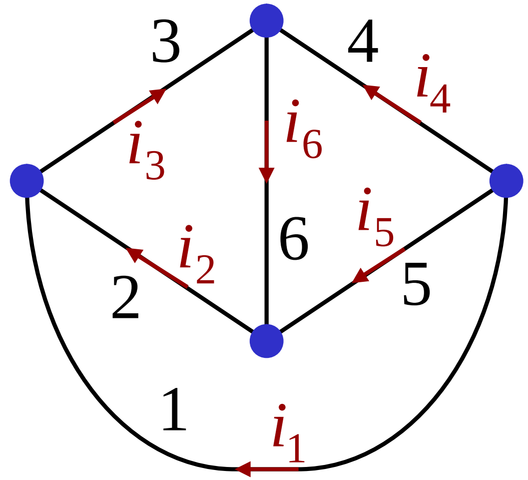
j



$\boldsymbol{A}_a =$

	1	2	3	4	5	6
1	1	1	+1	0	0	0
2	0	0	1	1	0	+1
3	+1	0	0	+1	+1	0
4	0	+1	0	0	1	1

$$\boldsymbol{A}=\begin{bmatrix}1&1&1&0&0&0\\0&0&1&1&0&1\\1&0&0&1&1&0\end{bmatrix}$$



(3) $\boldsymbol{A}$ KCL

$b(=6)$

$\boldsymbol{i}=[i_1, i_2, \cdots, i_6]^{\mathrm{T}}$

$$\boldsymbol{Ai}=\begin{bmatrix}1&1&1&0&0&0\\0&0&1&1&0&1\\1&0&0&1&1&0\end{bmatrix}\begin{bmatrix}i_1\\i_2\\\cdot\\\cdot\\\cdot\\i_6\end{bmatrix}=\begin{bmatrix}-i_1-i_2+i_3\\-i_3-i_4+i_6\\+i_1+i_4+i_5\end{bmatrix}=\begin{bmatrix}0\\0\\0\end{bmatrix}$$

$$\boldsymbol{Ai}=\begin{bmatrix}1\ \text{KCL}\\2\ \text{KCL}\\\cdots\cdots\\(n\ \ 1)\ \ \text{KCL}\end{bmatrix}\longrightarrow \boldsymbol{Ai}=\boldsymbol{0}$$

(4) $\boldsymbol{A}$ KVL

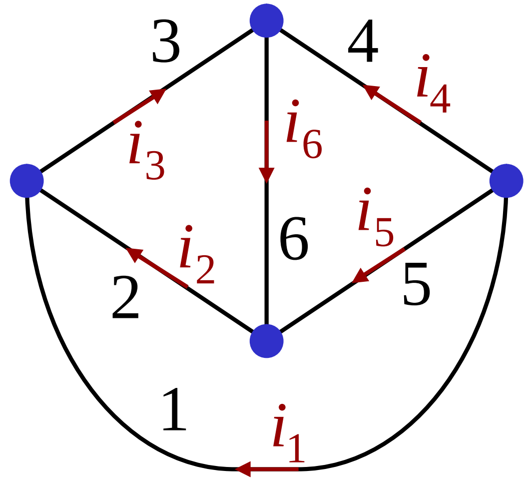
$b(=6)$

$\boldsymbol{u} = [u_1, u_2, \cdots, u_6]^{\mathrm{T}}$

( )

$(n\ \ 1=3)$

$\boldsymbol{u}_n = [u_{n1}, u_{n2}, u_{n3}]^{\mathrm{T}}$



$\boldsymbol{u} = \boldsymbol{A}^{\mathrm{T}}\boldsymbol{u}_n$

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{bmatrix} = \begin{bmatrix} u_{n1} + u_{n3} \\ u_{n1} \\ u_{n1}\ \ u_{n2} \\ u_{n2} + u_{n3} \\ u_{n3} \\ u_{n2} \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}}_{\boldsymbol{A}^{\mathrm{T}}} \begin{bmatrix} u_{n1} \\ u_{n2} \\ u_{n3} \end{bmatrix}$$

A

KVL

A

A KCL $\boldsymbol{Ai} = \mathbf{0}$

A KVL $\boldsymbol{u} = \boldsymbol{A}^{\mathrm{T}}\boldsymbol{u}_n$

2.

$(l \quad b)$

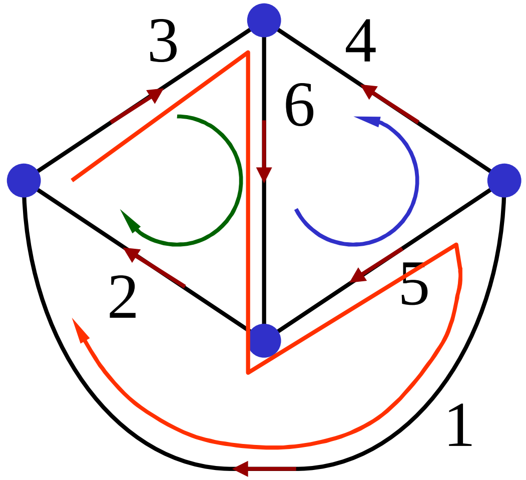
(1)*B*

$b_{jk}= +1 \qquad k \qquad j$

$b_{jk}= \quad 1 \qquad k \qquad j$

$b_{jk}= 0 \qquad k \qquad j$

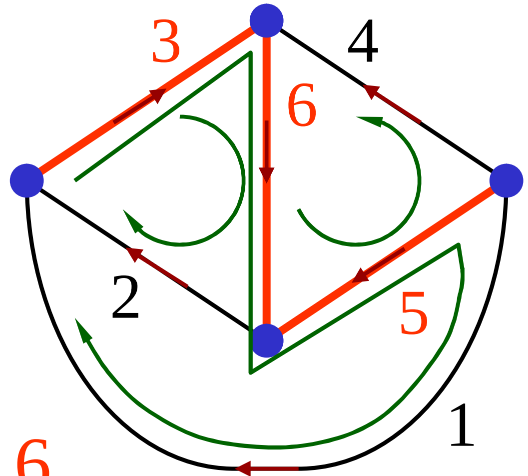
B =	1	2	3	4	5	6
1	1	0	1	0	1	1
2	0	1	1	0	0	1
3	0	0	0	1	1	1



(2) $\boldsymbol{B}_f$

$\boldsymbol{B}_f$

$\boldsymbol{B}_f$



$\boldsymbol{B}_f = [\ \mathbf{1}_l \quad \boldsymbol{B}_t\ ]$

$\boldsymbol{B}_f =$

	1	2	4	3	5	6
1	1	0	0	1	1	1
2	0	1	0	1	0	1
3	0	0	1	0	1	1

$\boldsymbol{Bu} = \mathbf{0}$

(3) $\boldsymbol{B}$ KVL

$u_1 + u_3 - u_5 + u_6 = 0$

$u_2 + u_3 + u_6 = 0$

$u_4 - u_5 + u_6 = 0$

$$\begin{bmatrix} 1 & 0 & 1 & 0 & -1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

(4) ***B*** KCL

3. $\boldsymbol{Q}$

$\boldsymbol{Q}$ $(n \;\; 1)$ b

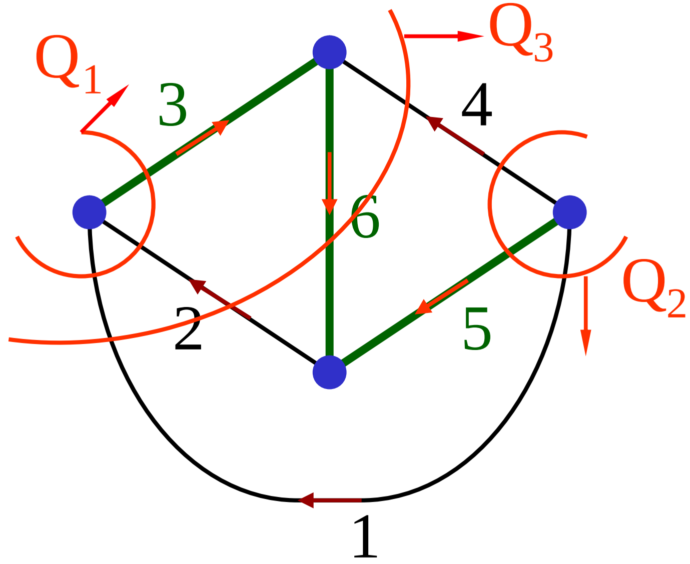
$q_{jk}= +1$ k j

$q_{jk}= \;\; 1$ k j

$q_{jk}= 0$ k j

$$\boldsymbol{Q} = \begin{array}{c} 1 \\ 2 \\ 3 \end{array} \overset{\begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array}}{\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}}$$

$\boldsymbol{Q}_f$

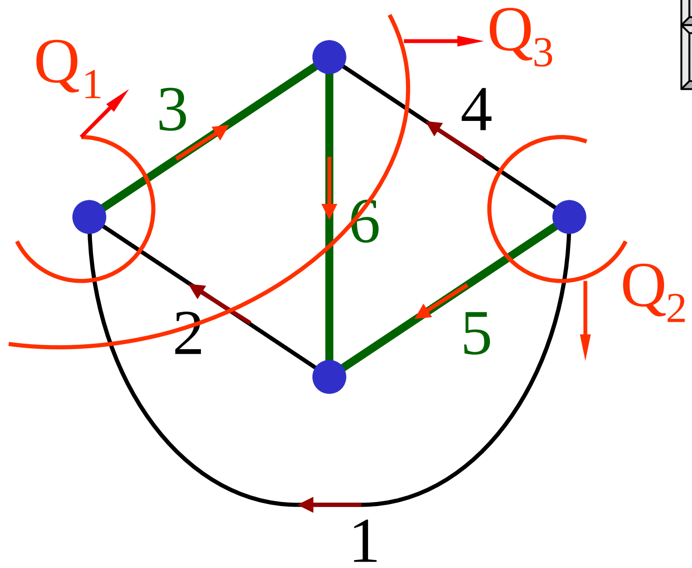


$\boldsymbol{Q}_f = [\; \mathbf{1}_t \quad \boldsymbol{Q}_l \;]$

(2) $\boldsymbol{Q}_f$ KVL

$$\boldsymbol{u} = \boldsymbol{Q}_f^{\mathrm{T}}\, \boldsymbol{u}_t$$

- $\boldsymbol{u}_t = [u_{t1}\ \ u_{t2}\ \ \cdots\ u_{t(n\ 1)}]^{\mathrm{T}}$



- $\boldsymbol{u}_t = [u_{t1}\ \ u_{t2}\ \ u_{t3}]^{\mathrm{T}}$

$$\boldsymbol{u} = [u_3\ \ u_5\ \ u_6\ \ u_1\ \ u_2\ \ u_4]^{\mathrm{T}}$$

$$\boldsymbol{u} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} u_{t1} \\ u_{t2} \\ u_{t3} \end{bmatrix} = \begin{bmatrix} u_{t1} \\ u_{t2} \\ u_{t3} \\ -u_{t1}+u_{t2}-u_{t3} \\ -u_{t1}-u_{t3} \\ u_{t2}-u_{t3} \end{bmatrix} \begin{matrix} =u_3 \\ =u_5 \\ =u_6 \\ =u_1 \\ =u_2 \\ =u_4 \end{matrix}$$

* 15 3 $\boldsymbol{A}$ $\boldsymbol{B}_f$ $\boldsymbol{Q}_f$

1. $\boldsymbol{A}\,\boldsymbol{i} = \boldsymbol{0}$ $\qquad \boldsymbol{Q}\,\boldsymbol{i} = \boldsymbol{0}$

   $\boldsymbol{u} = \boldsymbol{A}^{\mathrm{T}}\boldsymbol{u}_n$ $\qquad \boldsymbol{u} = \boldsymbol{Q}_f^{\mathrm{T}}\,\boldsymbol{u}_t$

   G $\boldsymbol{Q}_f = \boldsymbol{A}$

2. G $\boldsymbol{A}$ $\boldsymbol{B}$ $\boldsymbol{Q}$

$$\boldsymbol{A}\boldsymbol{B}^{\mathrm{T}} = \boldsymbol{0} \qquad \boldsymbol{B}\boldsymbol{A}^{\mathrm{T}} = \boldsymbol{0}$$

$$\boldsymbol{Q}\boldsymbol{B}^{\mathrm{T}} = \boldsymbol{0} \qquad \boldsymbol{B}\boldsymbol{Q}^{\mathrm{T}} = \boldsymbol{0}$$

3. $\boldsymbol{A}$ $\boldsymbol{B}_f$ $\boldsymbol{Q}_f$

$$\boldsymbol{B}_t^{\mathrm{T}} = \; \boldsymbol{A}_t\,{}^{1}\boldsymbol{A}_l \qquad \boldsymbol{Q}_l = \; \boldsymbol{B}_t^{\mathrm{T}} = \boldsymbol{A}_t\,{}^{1}\boldsymbol{A}_l$$

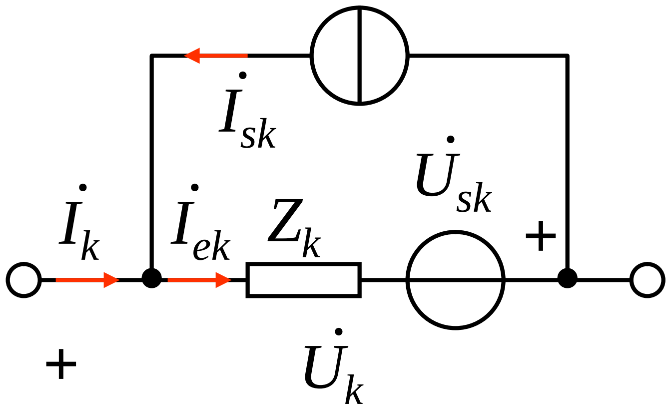
15 4

( )

(1) Z_k R L

C

(2)



$$\dot U_k = Z_k(\dot I_k + \dot I_{Sk}) \quad \dot U_{Sk}$$

k

$$\dot{\boldsymbol I} = [\ \dot I_1\ \ \dot I_2\ \ \cdots\ \dot I_b]^{\mathrm T}$$

$$\dot{\boldsymbol U} = [\dot U_1\ \ \dot U_2\ \cdots \dot U_b]^{\mathrm T}$$

$$\dot{\boldsymbol I}_{\boldsymbol S} = [\dot I_{S1}\ \dot I_{S2}\ \cdots \dot I_{Sb}]^{\mathrm T}$$

$$\dot{\boldsymbol U}_{\boldsymbol S} = [\ \ \dot U_{S1}\ \dot U_{S2} \cdots\ \dot U_{Sb}]^{\mathrm T}$$

$$\dot{\boldsymbol U} = \boldsymbol Z\ (\dot{\boldsymbol I} + \dot{\boldsymbol I}_{\boldsymbol S}) \quad \dot{\boldsymbol U}_{\boldsymbol S}$$

✓ 1

$\dot{U} = \mathbf{Z}\,(\dot{I} + \dot{I}_S)$ $\dot{U}_S$

$\mathbf{Z}$ $\mathbf{Z}$

$$\mathbf{Z} = \begin{bmatrix} Z_1 & & & \mathbf{0} \\ & Z_2 & & \\ & \mathbf{0} & \ddots & \\ & & & Z_b \end{bmatrix}$$

✓ 2

b 1 g

$\dot{U}_1 = Z_1\dot{I}_{e1}$ $\mathrm{j}\omega M_{12}\,\dot{I}_{e2}$ $\mathrm{j}\omega M_{13}\,\dot{I}_{e3}$ $\cdots$ $\mathrm{j}\omega M_{1g}\,\dot{I}_{eg}$ $\dot{U}_{S1}$

$\dot{U}_2 =$ $\mathrm{j}\omega M_{21}\dot{I}_{e1} + Z_2\,\dot{I}_{e2}$ $\mathrm{j}\omega M_{23}\,\dot{I}_{e3}$ $\cdots$ $\mathrm{j}\omega M_{2g}\,\dot{I}_{eg}$ $\dot{U}_{S2}$

$\cdots\ \cdots\ \cdots\ \cdots$

$\dot{U}_g =$ $\mathrm{j}\omega M_{g1}\dot{I}_{e1}$ $\mathrm{j}\omega M_{g2}\,\dot{I}_{e2}$ $\mathrm{j}\omega M_{g3}\,\dot{I}_{e3}$ $\cdots + Z_g\ \dot{I}_{eg}$ $\dot{U}_{Sg}$

$\dot{I}_{e1} = \dot{I}_1 + \dot{I}_{S1}$ $\dot{I}_{e2} = \dot{I}_2 + \dot{I}_{S2}$ $\cdots\ \cdots$ $M_{12} = M_{21}$ $\cdots\ \cdots$

$(g+1)$ b 1

$$
\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \vdots \\ \dot{U}_g \\ \dot{U}_{g+1} \\ \vdots \\ \dot{U}_b \end{bmatrix}
=
\begin{bmatrix}
Z_1 & j\omega M_{12} & \cdots & j\omega M_{1g} & 0 & \cdots & 0 \\
j\omega M_{21} & Z_2 & \cdots & j\omega M_{2g} & 0 & \cdots & 0 \\
\vdots & \vdots & & \vdots & \vdots & & \vdots \\
j\omega M_{g1} & j\omega M_{g2} & \cdots & Z_g & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 & Z_{g+1} & \cdots & 0 \\
\vdots & \vdots & & \vdots & \vdots & & \vdots \\
0 & 0 & \cdots & 0 & 0 & \cdots & Z_b
\end{bmatrix}
\begin{bmatrix} \dot{I}_1 + \dot{I}_{S!} \\ \dot{I}_2 + \dot{I}_{S2} \\ \vdots \\ \dot{I}_g + \dot{I}_{Sg} \\ \dot{I}_{g+1} + \dot{I}_{S(g+1)} \\ \vdots \\ \dot{I}_b + \dot{I}_{Sb} \end{bmatrix}
-
\begin{bmatrix} \dot{U}_{S1} \\ \dot{U}_{S2} \\ \vdots \\ \dot{U}_{Sg} \\ \dot{U}_{S(g+1)} \\ \vdots \\ \dot{U}_{Sb} \end{bmatrix}
$$

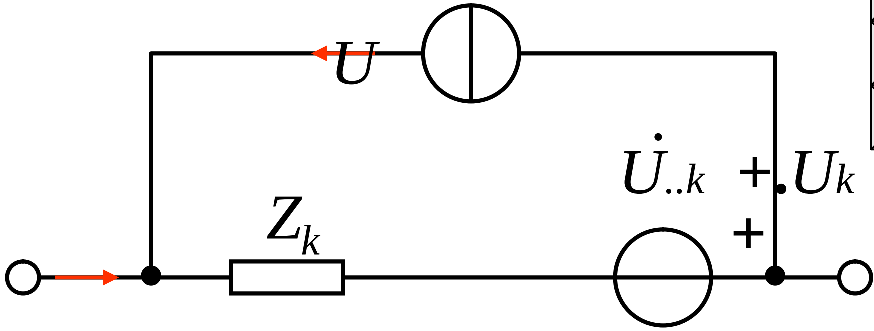
$\dot{\boldsymbol{U}} = \boldsymbol{Z}\,(\dot{\boldsymbol{I}} + \dot{\boldsymbol{I}}_S)\quad \dot{\boldsymbol{U}}_S$

$\boldsymbol{Z}$

✓ 3

-

-



-
- **Z**
-

( ) “+” “ ”

$\boldsymbol{B}$ KVL $\boldsymbol{B\dot{U}} = \mathbf{0}$

$$\dot{U} = Z(\dot{I} + \dot{I}_S) \quad \dot{U}_S$$

$$BZ\dot{I} + BZ\dot{I}_S \quad B\dot{U}_S = 0$$

$\boldsymbol{B}$ KCL $\dot{I} = B^{\mathrm{T}}\dot{I}_l$

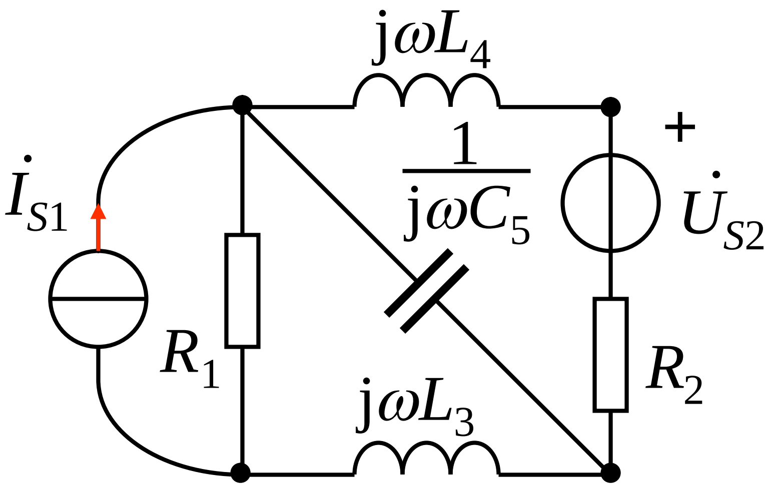
$$BZB^{\mathrm{T}}\dot{I} = B\dot{U}_S \quad BZ\dot{I}_S$$

BZB^{T} l $B\dot{U}_S$ BZ l

$Z_l = BZB^{\mathrm{T}}$ Z_l

Z_l

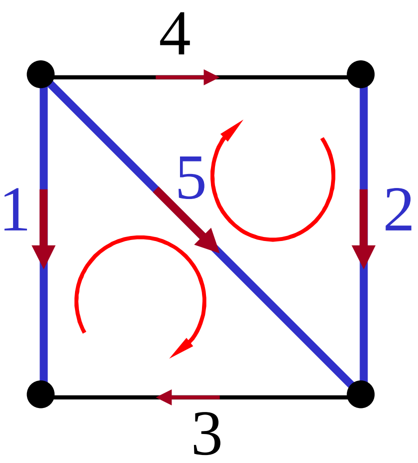
P401 15 1



(2)

(3) **B**

(1)



$$\boldsymbol{B}=\begin{bmatrix}1 & 0 & 1 & 0 & 1\\ 0 & 1 & 0 & 1 & 1\end{bmatrix}$$

$$\boldsymbol{Z}=\mathrm{diag}\left[R_1,\ R_2,\ \mathrm{j}\omega L_3,\ \mathrm{j}\omega L_4,\ \frac{1}{\mathrm{j}\omega C_5}\right]$$

$$\dot{\boldsymbol{U}}_{\boldsymbol{S}}=[0\ \ -\dot{U}_{S2}\ \ 0\ \ 0\ \ 0]^{\mathrm{T}}$$

$$\dot{\boldsymbol{I}}_{\boldsymbol{S}}=[\dot{I}_{S1}\ \ 0\ \ 0\ \ 0\ \ 0]^{\mathrm{T}}$$

(4) $\boldsymbol{Z}_l = \boldsymbol{B}\boldsymbol{Z}\boldsymbol{B}^{\mathrm{T}}$

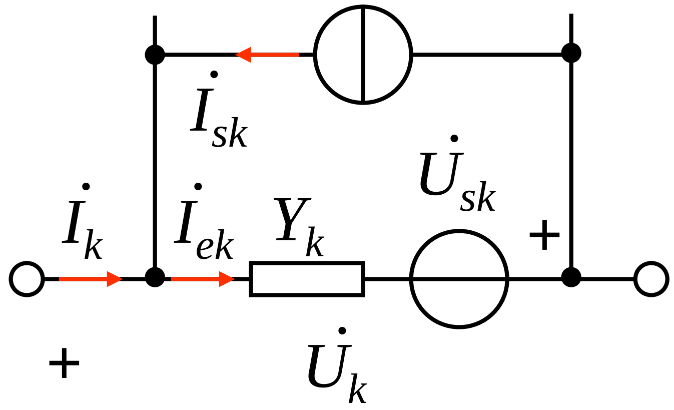
$$\boldsymbol{Z}_l = \boldsymbol{B}\boldsymbol{Z}\boldsymbol{B}^{\mathrm{T}}$$

$$= \begin{bmatrix} 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} R_1 & & & & \\ & R_2 & & & \\ & & \mathrm{j}\omega L_3 & & \\ & & & \mathrm{j}\omega L_4 & \\ & & & & \dfrac{1}{\mathrm{j}\omega C_5} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{bmatrix}$$

$$\begin{bmatrix} R_1 + \mathrm{j}\omega L_3 + \dfrac{1}{\mathrm{j}\omega C_5} & -\dfrac{1}{\mathrm{j}\omega C_5} \\ -\dfrac{1}{\mathrm{j}\omega C_5} & R_2 + \mathrm{j}\omega L_4 + \dfrac{1}{\mathrm{j}\omega C_5} \end{bmatrix} \begin{bmatrix} \dot{I}_{l1} \\ \dot{I}_{l2} \end{bmatrix} = \begin{bmatrix} R_1 \dot{I}_{S1} \\ \dot{U}_{S2} \end{bmatrix}$$

(5) $\boldsymbol{Z}_l$ $\dot{\boldsymbol{U}}_S$ $\dot{\boldsymbol{I}}_S$ $\boldsymbol{Z}_l \dot{\boldsymbol{I}} = \boldsymbol{B}\dot{\boldsymbol{U}}_S$ $\boldsymbol{B}\boldsymbol{Z}\dot{\boldsymbol{I}}_S$

15 5



✓ 1

k $\dot{I}_k = Y_k(\dot{U}_k + \dot{U}_{Sk}) \quad \dot{I}_{Sk}$

$$\dot{I} = Y(\dot{U} + \dot{U}_S) \quad \dot{I}_S$$

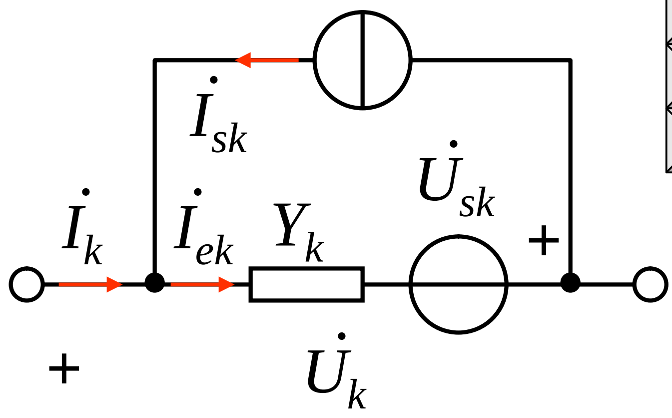
Y

Y

✓ 2

2

$\dot{U} = Z\,(\dot{I} + \dot{I}_S) \quad \dot{U}_S$



Z

Z

$Y\,\dot{U} = \dot{I} + \dot{I}_S \quad Y\dot{U}_S$

$\dot{I} = Y\,(\dot{U} \quad \dot{U}_S) \quad \dot{I}_S$

$Y = Z^{1}$

VCR 1

Y

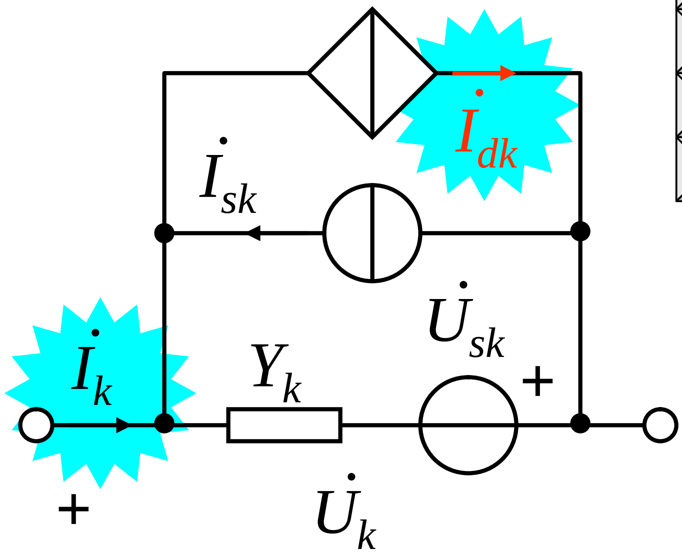
✓ 3

k j

( )

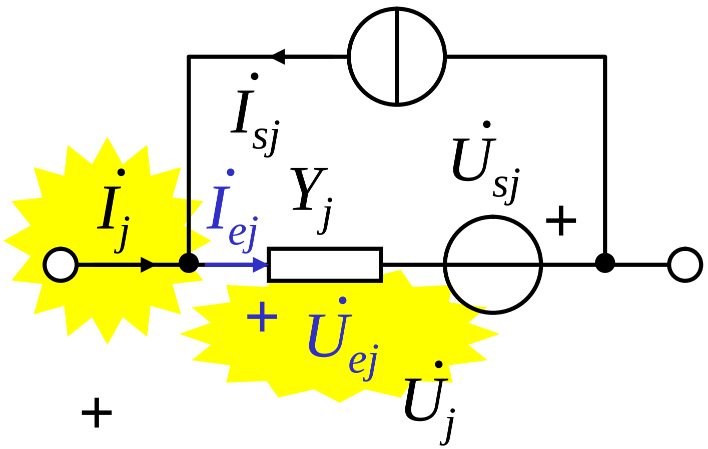
$\dot{I}_{dk} = g_{kj}\,\dot{U}_{ej}$ $\dot{I}_{dk} = \beta_{kj}\,\dot{I}_{ej}$

$\dot{I}_{ej} = Y_j\,\dot{U}_{ej}$ $\dot{I}_{dk} = \beta_{kj}\,Y_j\,\dot{U}_{ej}$



VCCS

Y_{kj} $Y_{kj} = \begin{cases} g_{kj} \\ \beta_{kj}\,Y_j \end{cases}$



k

$$\dot{I}_k = Y_k(\dot{U}_k + \dot{U}_{Sk}) + \dot{I}_{dk} \quad \dot{I}_{Sk}$$

$$\dot{I}_{dk} = Y_{kj}\,\dot{U}_{ej} = Y_{kj}\,(\dot{U}_j + \dot{U}_{Sj})$$

$$\dot{I}_k = Y_k(\dot{U}_k + \dot{U}_{Sk}) + Y_{kj}(\dot{U}_j + \dot{U}_{sj}) \quad \dot{I}_{Sk}$$

$\dot{I}_k = Y_k(\dot{U}_k + \dot{U}_{Sk}) + Y_{kj}(\dot{U}_j + \dot{U}_{sj}) \quad \dot{I}_{Sk}$ $\qquad b$

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \vdots \\ \dot{I}_j \\ \vdots \\ \dot{I}_k \\ \vdots \\ \dot{I}_b \end{bmatrix} = \begin{bmatrix} Y_1 & & & & & & \\ 0 & Y_2 & & & & \mathbf{0} & \\ \vdots & \vdots & \ddots & & & & \\ 0 & 0 & \cdots & Y_j & k & j & \\ \vdots & \vdots & & \vdots & \ddots & & \\ 0 & 0 & \cdots & Y_{kj} & \cdots & Y_k & \\ \vdots & \vdots & & \vdots & & \vdots & \ddots \\ 0 & 0 & \cdots & 0 & \cdots & 0 & \cdots & Y_b \end{bmatrix} \begin{bmatrix} \dot{U}_1 + \dot{U}_{S1} \\ \dot{U}_2 + \dot{U}_{S2} \\ \vdots \\ \dot{U}_j + \dot{U}_{Sj} \\ \vdots \\ \dot{U}_k + \dot{U}_{Sk} \\ \vdots \\ \dot{U}_b + \dot{U}_{Sb} \end{bmatrix} - \begin{bmatrix} \dot{I}_{S1} \\ \dot{I}_{S2} \\ \vdots \\ \dot{I}_{Sj} \\ \vdots \\ \dot{I}_{Sk} \\ \vdots \\ \dot{I}_{Sb} \end{bmatrix}$$

$\dot{\boldsymbol{I}} = \boldsymbol{Y}(\dot{\boldsymbol{U}} \quad \dot{\boldsymbol{U}}_S) \quad \dot{\boldsymbol{I}}_S$ $\qquad 1$

- $\boldsymbol{Y}$
- (2)

A

A KCL $A\dot{I} = 0$ A KVL $\dot{U} = A^{T}\dot{U}_{n}$

$$\dot{I} = Y(\dot{U}\quad \dot{U}_{S})\quad \dot{I}_{S}$$

$$\dot{I} = YA^{T}\dot{U}_{n}\quad Y\dot{U}_{S}\quad \dot{I}_{S}$$

A KCL $AYA^{T}\dot{U}_{n}\quad AY\dot{U}_{S}\quad A\dot{I}_{S} = 0$

$$AYA^{T}\dot{U}_{n} = A\dot{I}_{S}\quad AY\dot{U}_{S}$$

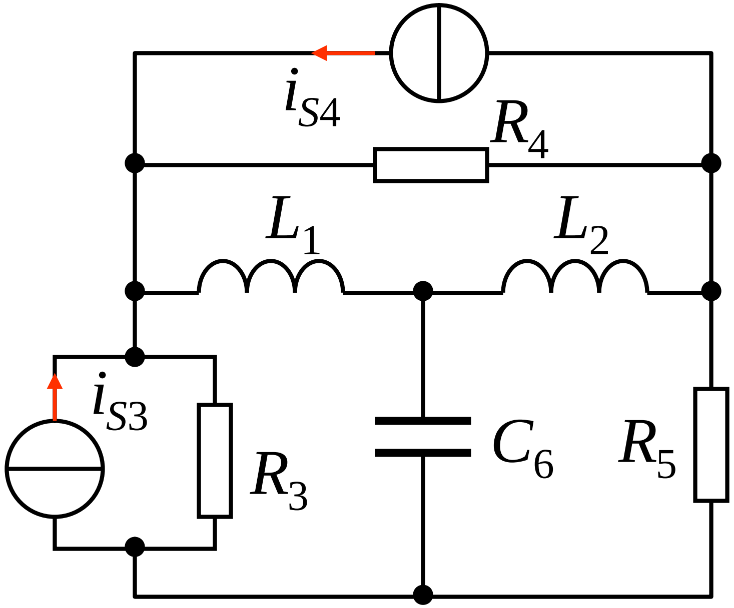
$Y_{n} = AYA^{T}$, $\dot{J}_{n} = A\dot{I}_{S}\quad AY\dot{U}_{S}$

$$Y_{n}\dot{U}_{n} = \dot{J}_{n}$$

Y_{n}

$\dot{J}_{n}$

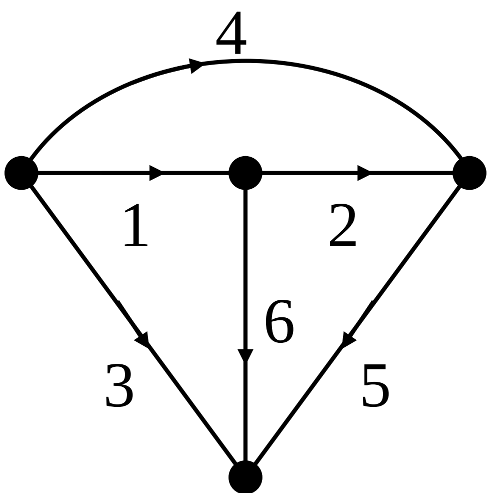
P405 15 2



(1)

(2) $\boldsymbol{A}$

$$\boldsymbol{A} = \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix}$$



$$\dot{\boldsymbol{U}}_s = \boldsymbol{0}, \quad \dot{\boldsymbol{I}}_s = [\,0 \;\; 0 \;\; \dot{I}_{S3} \;\; \dot{I}_{S4} \; 0 \;\; 0\,]^{\mathrm{T}}$$

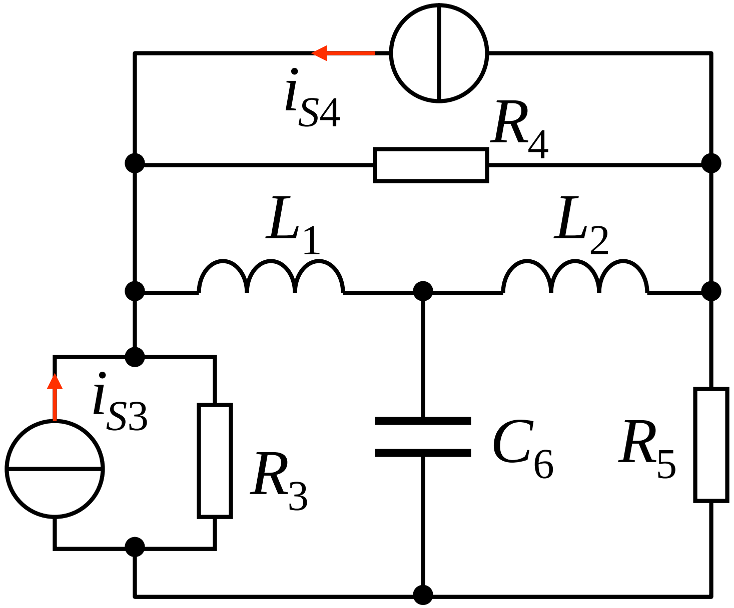
$$\boldsymbol{Y} = \mathrm{diag}\left[\frac{1}{\mathrm{j}\omega L_1}, \frac{1}{\mathrm{j}\omega L_2}, \frac{1}{R_3}, \frac{1}{R_4}, \frac{1}{R_5}, \; \mathrm{j}\omega C_6\right]$$

(3) $\boldsymbol{AYA}^{\mathrm{T}}$

$$\boldsymbol{AYA}^{\mathrm{T}}\dot{\boldsymbol{U}}_n = \boldsymbol{A}\dot{\boldsymbol{I}}_S \quad \boldsymbol{A}\boldsymbol{Y}\dot{\boldsymbol{U}}_S$$

$$\boldsymbol{AYA}^{\mathrm{T}}\dot{\boldsymbol{U}}_n = \boldsymbol{A}\dot{\boldsymbol{I}}_S$$

$$\begin{bmatrix} \frac{1}{R_3}+\frac{1}{R_4}+\frac{1}{j\omega L_1} & -\frac{1}{j\omega L_1} & -\frac{1}{R_4} \\ -\frac{1}{j\omega L_1} & \frac{1}{j\omega L_1}+\frac{1}{j\omega L_2}+j\omega C_6 & -\frac{1}{j\omega L_2} \\ -\frac{1}{R_4} & -\frac{1}{j\omega L_2} & \frac{1}{R_4}+\frac{1}{R_5}+\frac{1}{j\omega L_2} \end{bmatrix} \begin{bmatrix} \dot{U}_{n1} \\ \dot{U}_{n2} \\ \dot{U}_{n3} \end{bmatrix} = \begin{bmatrix} \dot{I}_{S3}+\dot{I}_{S4} \\ 0 \\ -\dot{I}_{S4} \end{bmatrix}$$



$$\boldsymbol{AYA}^{\mathrm{T}} \qquad \dot{\boldsymbol{U}}_n \qquad \boldsymbol{A}\dot{\boldsymbol{I}}_S$$

(　　　　　　　　　　)

P406 15 3

$$\dot{I}_{d2} = g_{21}\dot{U}_1 \,,\; \dot{I}_{d4} = \beta_{46}\dot{I}_6$$

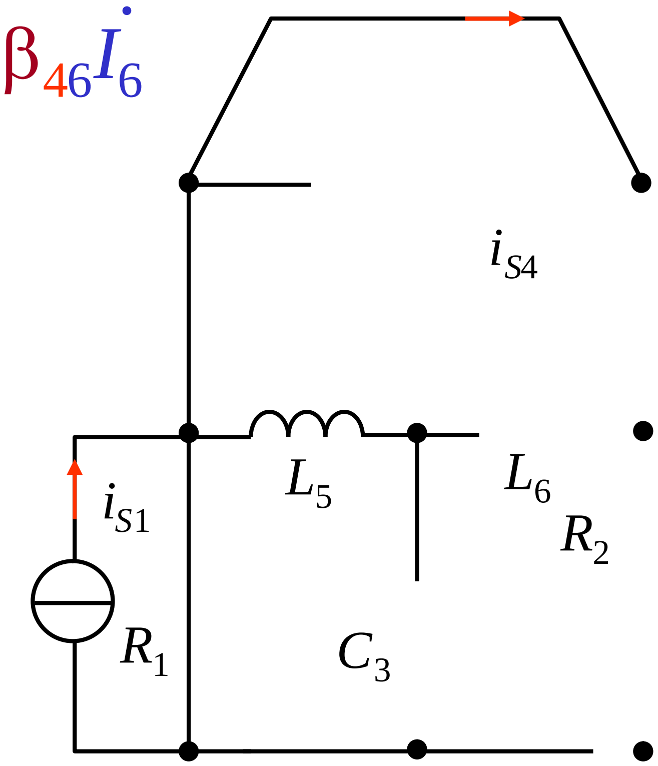
4

6

$$Y = \begin{bmatrix} \frac{1}{R_1} & & & & & \\ -g_{21} & \frac{1}{R_2} & & & \mathbf{0} & \\ & & \mathrm{j}\omega C_3 & & & \\ & & & \mathrm{j}\omega C_4 & 0 & \frac{\beta_{46}}{\mathrm{j}\omega L_6} \\ & \mathbf{0} & & & \frac{1}{\mathrm{j}\omega L_5} & 0 \\ & & & & 0 & \frac{1}{\mathrm{j}\omega L_6} \end{bmatrix}$$

2

1



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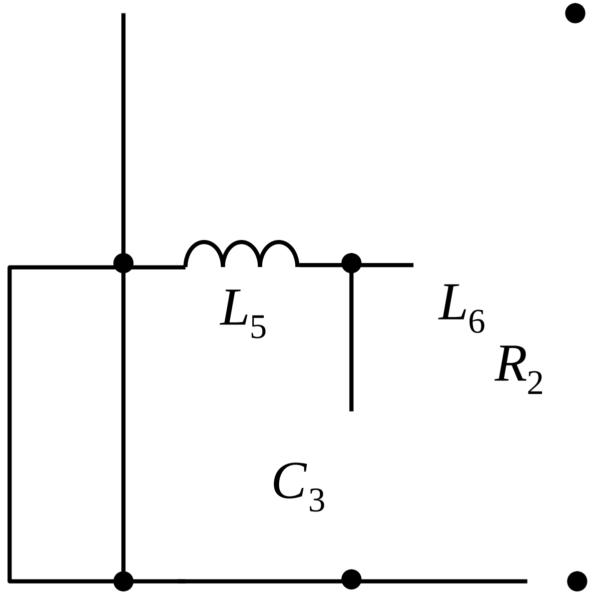
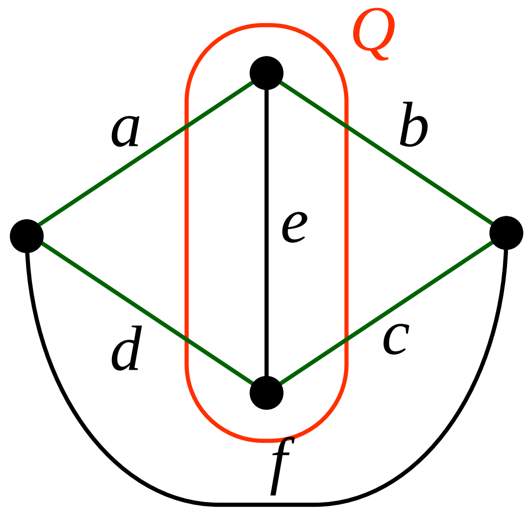
$$\dot{\boldsymbol{I}}_S = [\ \dot{I}_{S1}\quad 0\quad 0\quad -\dot{I}_{S4}\quad 0\quad 0\ ]^{\mathrm{T}}$$

$$\dot{\boldsymbol{U}}_S = [\ 0\quad -\dot{U}_{S2}\quad 0\quad \dot{U}_{S4}\quad 0\quad 0\ ]^{\mathrm{T}}$$



$$\dot{\boldsymbol{I}} = \boldsymbol{Y}\,(\dot{\boldsymbol{U}}\quad \dot{\boldsymbol{U}}_S)\quad \dot{\boldsymbol{I}}_S$$

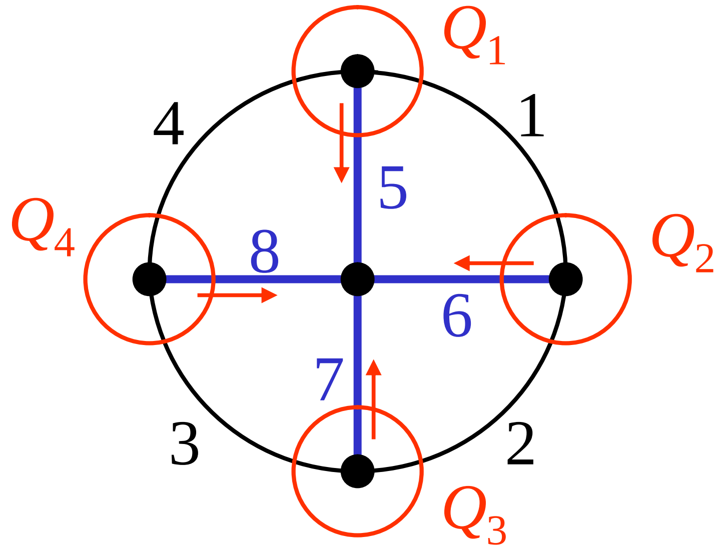
15 6



( )

$$\boldsymbol{u} = \boldsymbol{Q}_f^{\mathrm{T}} \boldsymbol{u}_t$$

$\boldsymbol{u}_t$



$$\dot{I} = Y(\dot{U} \quad \dot{U}_S) \quad \dot{I}_S$$

Q_f

Q_f KCL $Q_f \dot{I} = 0$ KVL $\dot{U} = Q_f^{T} \dot{U}_t$

$\dot{I} = Y(\dot{U} \quad \dot{U}_S) \quad \dot{I}_S$

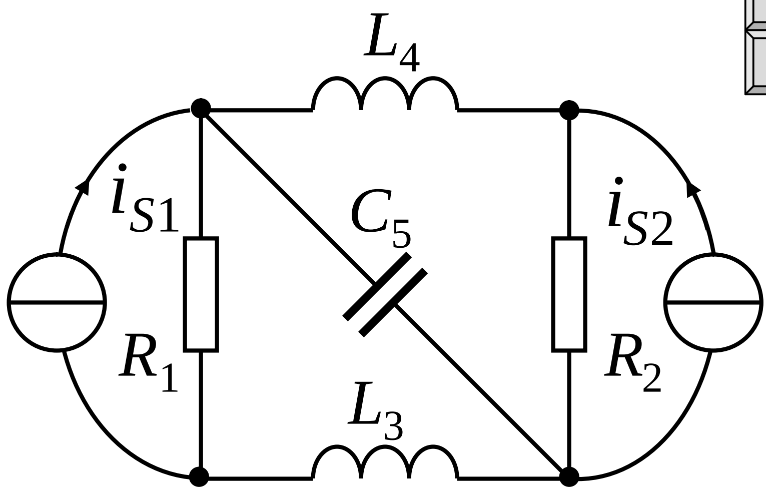
$\dot{I} = Y\, Q_f^{T} \dot{U}_t \quad Y\dot{U}_S \quad \dot{I}_S$

Q_f KCL

$Q_f Y Q_f^{T} \dot{U}_t = Q_f \dot{I}_S \quad Q_f Y \dot{U}_S$

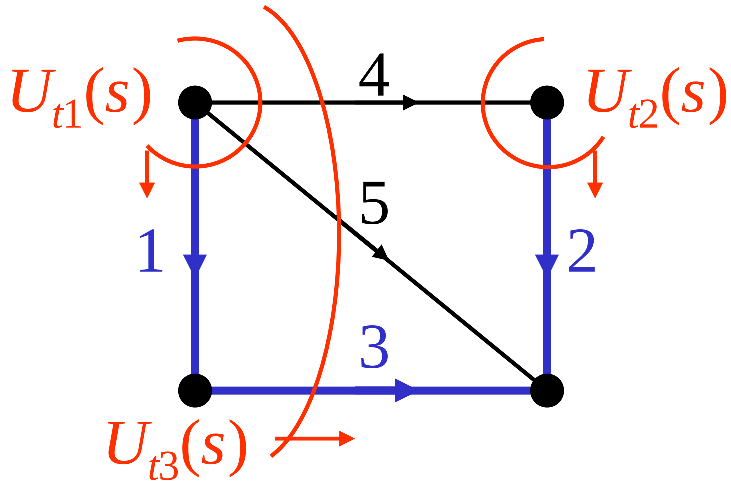
$Y_t = Q_f Y Q_f^{T}$ Y_t

P408 15 4



1 2 3

$U_{t1}(s)$ $U_{t2}(s)$ $U_{t3}(s)$



$\boldsymbol{Q}_f$

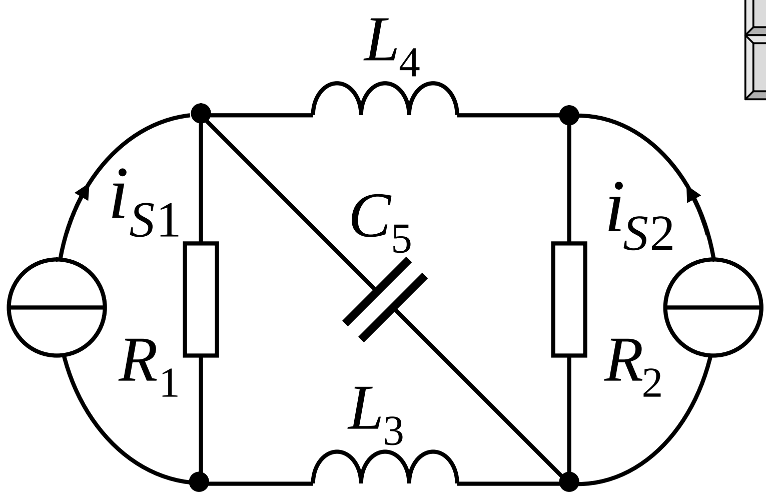
$$\boldsymbol{Q}_f = \begin{array}{c} \\ \end{array}\begin{matrix} 1 & 2 & 3 & 4 & 5 \\ \end{matrix}$$

$$\boldsymbol{Q}_f = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix} \begin{matrix} Q_1 \\ Q_2 \\ Q_3 \end{matrix}$$

$$\boldsymbol{U_S}(s) = 0$$

$$\boldsymbol{I_S}(s) = [I_{S1}(s) \;\; I_{S2}(s) \;\; 0 \;\; 0 \;\; 0]^{\mathrm{T}}$$

$$\boldsymbol{Y}(s) = \mathrm{diag}\left[\frac{1}{R_1}, \frac{1}{R_2}, \frac{1}{sL_3}, \frac{1}{sL_4}, sC_5\right]$$

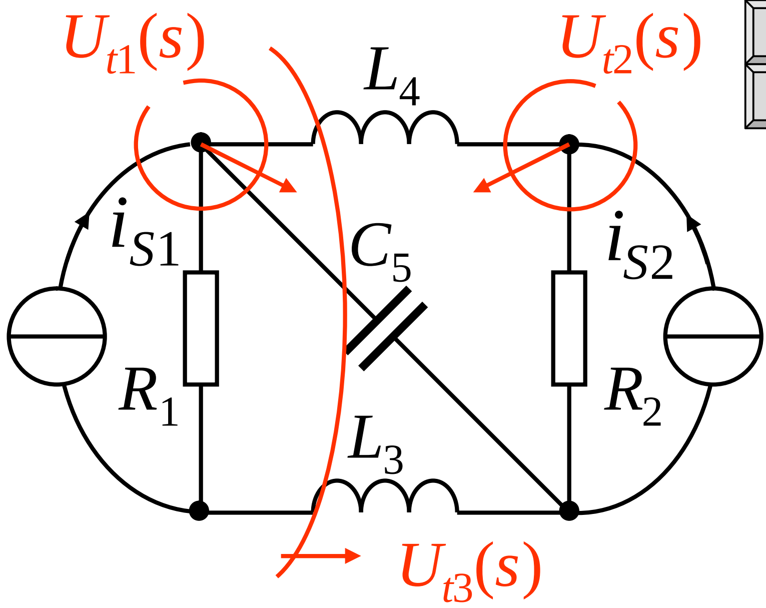


$$\boldsymbol{Q}_f \boldsymbol{Y}(s) \boldsymbol{Q}_f^{\mathrm{T}} \boldsymbol{U}_t(s) = \boldsymbol{Q}_f \boldsymbol{I_S}(s) - \boldsymbol{Q}_f \boldsymbol{Y}(s) \boldsymbol{U_S}(s)$$

$$\begin{bmatrix} \frac{1}{R_1} + \frac{1}{sL_4} + sC_5 & -\frac{1}{sL_4} & \frac{1}{sL_4} + sC_5 \\ -\frac{1}{sL_4} & \frac{1}{R_2} + \frac{1}{sL_4} & -\frac{1}{sL_4} \\ \frac{1}{sL_4} + sC_5 & -\frac{1}{sL_4} & \frac{1}{sL_3} + \frac{1}{sL_4} + sC_5 \end{bmatrix} \begin{bmatrix} U_{t1}(s) \\ U_{t2}(s) \\ U_{t3}(s) \end{bmatrix} = \begin{bmatrix} I_{S1}(s) \\ I_{S2}(s) \\ 0 \end{bmatrix}$$

$\boldsymbol{Y}_t$

Q_1 Q_2 Q_3



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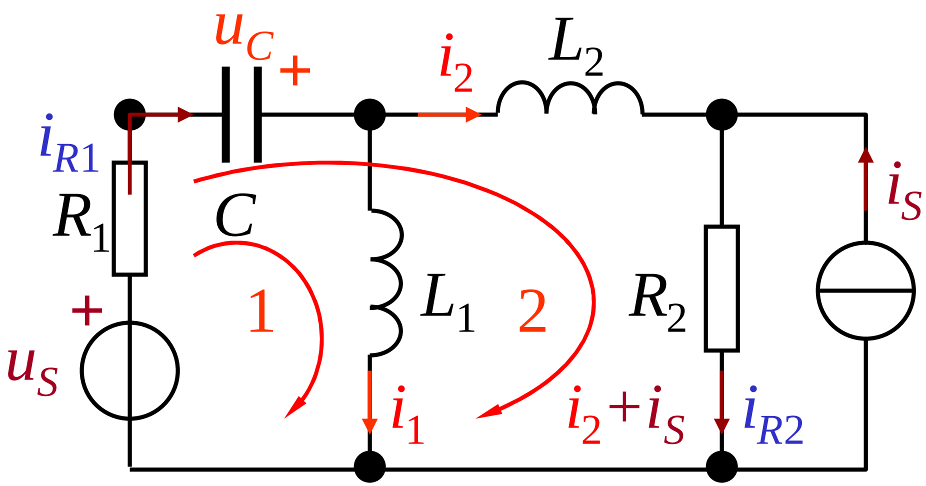
“+” “ ”

$$\begin{bmatrix} \frac{1}{R_1}+\frac{1}{sL_4}+sC_5 & -\frac{1}{sL_4} & \frac{1}{sL_4}+sC_5 \\ -\frac{1}{sL_4} & \frac{1}{R_2}+\frac{1}{sL_4} & -\frac{1}{sL_4} \\ \frac{1}{sL_4}+sC_5 & -\frac{1}{sL_4} & \frac{1}{sL_3}+\frac{1}{sL_4}+sC_5 \end{bmatrix} \begin{bmatrix} U_{t1}(s) \\ U_{t2}(s) \\ U_{t3}(s) \end{bmatrix} = \begin{bmatrix} I_{S1}(s) \\ I_{S2}(s) \\ 0 \end{bmatrix}$$



1.

$$C\frac{\mathrm{d}u_C}{\mathrm{d}t} = -i_1 - i_2$$

$$1 \quad L_1\frac{\mathrm{d}i_1}{\mathrm{d}t} = u_C - R_1\overbrace{(i_1+i_2)}^{i_{R1}} + u_S$$

(1) C

KCL

$$2 \quad L_2\frac{\mathrm{d}i_2}{\mathrm{d}t} = u_C - R_1(i_1+i_2) + u_S - R_2\underbrace{(i_2+i_S)}_{i_{R2}}$$

(2) L

KVL

(3) ( )

$$C\frac{\mathrm{d}u_C}{\mathrm{d}t} = -i_1 - i_2 \qquad (4)$$

$$L_1\frac{\mathrm{d}i_1}{\mathrm{d}t} = u_C - R_1(i_1+i_2) + u_S$$

$$L_2\frac{\mathrm{d}i_2}{\mathrm{d}t} = u_C - R_1(i_1+i_2) + u_S - R_2(i_2+i_S)$$

$$\begin{bmatrix} \frac{\mathrm{d}u_C}{\mathrm{d}t} \\ \frac{\mathrm{d}i_1}{\mathrm{d}t} \\ \frac{\mathrm{d}i_2}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{C} & -\frac{1}{C} \\ \frac{1}{L_1} & -\frac{R_1}{L_1} & -\frac{R_1}{L_1} \\ \frac{1}{L_2} & -\frac{R_1}{L_2} & -\frac{R_1+R_2}{L_2} \end{bmatrix} \begin{bmatrix} u_C \\ i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{1}{L_1} & 0 \\ \frac{1}{L_2} & -\frac{R_2}{L_2} \end{bmatrix} \begin{bmatrix} u_S \\ i_S \end{bmatrix}$$

2.

(1)

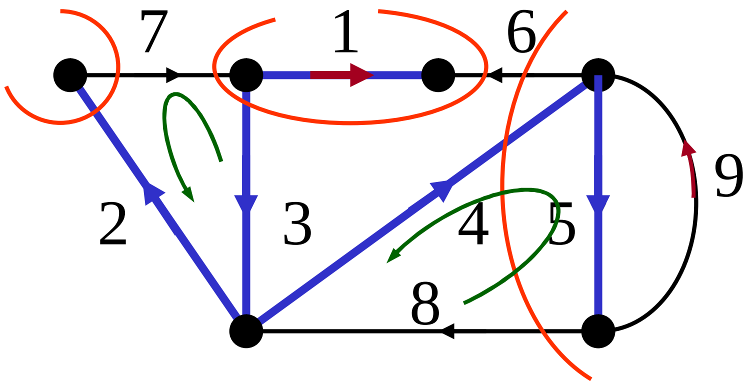
(2) KCL

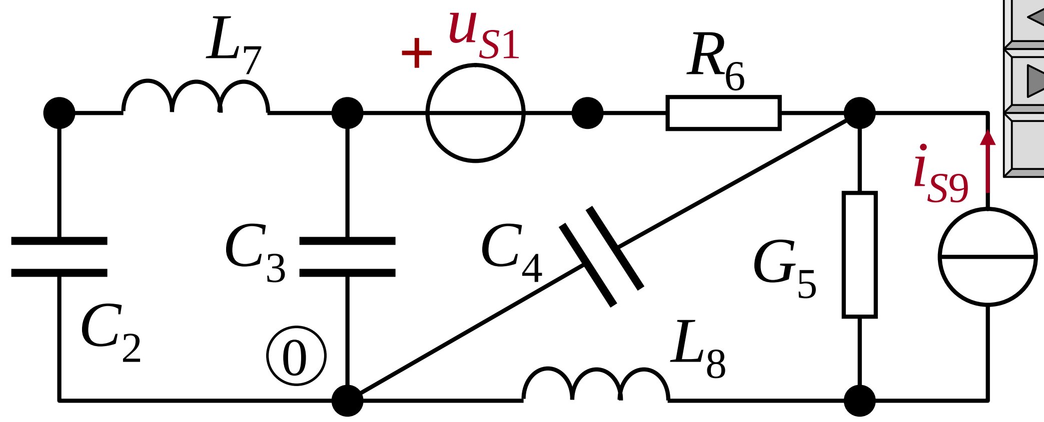
(3) KVL

(4)

(5)

:





KVL

$$L_7 \frac{\mathrm{d}i_7}{\mathrm{d}t} = -u_2 - u_3 \qquad L_8 \frac{\mathrm{d}i_8}{\mathrm{d}t} = -u_4 - u_5$$

KCL

$$C_2 \frac{\mathrm{d}u_2}{\mathrm{d}t} = i_7$$

$i_6 \quad u_5$

$$C_3 \frac{\mathrm{d}u_3}{\mathrm{d}t} = i_6 + i_7$$

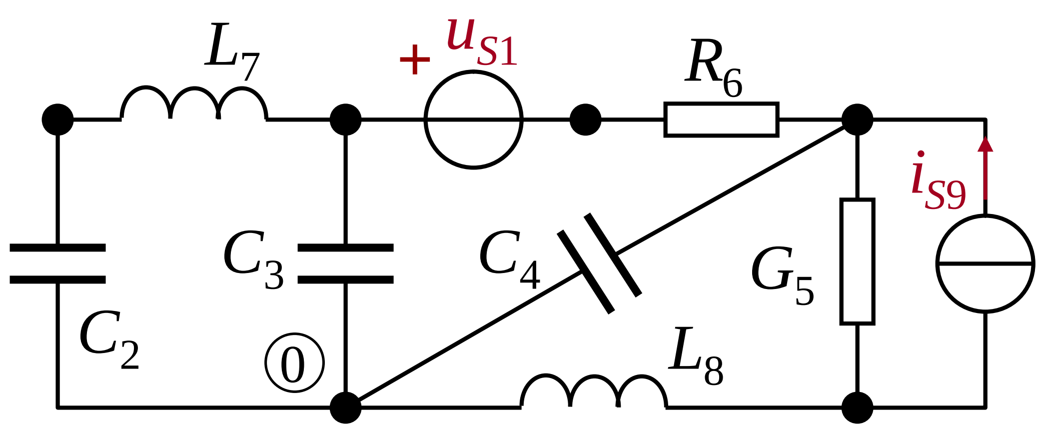
$$i_6 = \frac{1}{R_6} u_6 = \frac{1}{R_6} (-u_4 - u_3 + u_{S1})$$

$$u_5 = \frac{1}{G_5} i_5 = \frac{1}{G_5} (i_8 + i_9)$$

$$C_4 \frac{\mathrm{d}u_4}{\mathrm{d}t} = i_6 + i_8$$

$$\left.\begin{aligned}
\frac{\mathrm{d}u_2}{\mathrm{d}t} &= \frac{1}{C_2}\, i_7 \\
\frac{\mathrm{d}u_3}{\mathrm{d}t} &= -\frac{1}{C_3R_6}\, u_3 - \frac{1}{C_3R_6}\, u_4 + \frac{1}{C_3}\, i_7 + \frac{1}{C_3R_6}\, u_{S1} \\
\frac{\mathrm{d}u_4}{\mathrm{d}t} &= -\frac{1}{C_4R_6}\, u_3 - \frac{1}{C_4R_6}\, u_4 + \frac{1}{C_4}\, i_8 + \frac{1}{C_4R_6}\, u_{S1} \\
\frac{\mathrm{d}i_7}{\mathrm{d}t} &= -\frac{1}{L_7}\, u_2 - \frac{1}{L_7}\, u_3 \\
\frac{\mathrm{d}i_8}{\mathrm{d}t} &= -\frac{1}{L_8}\, u_4 - \frac{1}{G_5L_8}\, i_8 - \frac{1}{G_5L_8}\, i_{S9}
\end{aligned}\right\}$$

$u_2 = x_1$ $\quad u_3 = x_2$ $\quad u_4 = x_3$ $\quad i_7 = x_4$ $\quad i_8 = x_5$



$$
\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix}
=
\begin{bmatrix}
0 & 0 & 0 & \frac{1}{C_2} & 0 \\
0 & \frac{1}{C_3R_6} & \frac{1}{C_3R_6} & \frac{1}{C_3} & 0 \\
0 & \frac{1}{C_4R_6} & \frac{1}{C_4R_6} & 0 & \frac{1}{C_4} \\
\frac{1}{L_7} & \frac{1}{L_7} & 0 & 0 & 0 \\
0 & 0 & \frac{1}{L_8} & 0 & \frac{1}{G_5L_8}
\end{bmatrix}
\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}
+
\begin{bmatrix}
0 & 0 \\
\frac{1}{C_3R_6} & 0 \\
\frac{1}{C_4R_6} & 0 \\
0 & 0 \\
0 & \frac{1}{G_5L_8}
\end{bmatrix}
\begin{bmatrix} u_{S1} \\ i_{S9} \end{bmatrix}
$$