1.
  A   B   Q

2.

3.

1.

G

G

G(

)

G

☞ $(a \quad d \quad f)$

G

Q_1

a

e

b

d

c

f

Q_2

a

b

Q_3

e

Q_4

d

c

f

$(a \quad b \quad e) \quad (b \quad c \quad f) \quad (c \quad d \quad e)$

G   G

Q_5 Q_6 Q_7

a b a b a b

e e e

d c d c d c

f f f

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

Q_8

a b

e (a, d, e, f) G

d c

f e G

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

G

2.

Q_9

(a, b, c, d)

Q

(a, b, e)

3.

🗣️KCL

🕯️

KCL

🗣️

G

KCL

(1)

KCL

KCL   KCL

Q_2

Q_1 a b

e

f

d c Q_3

Q_4
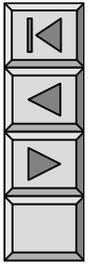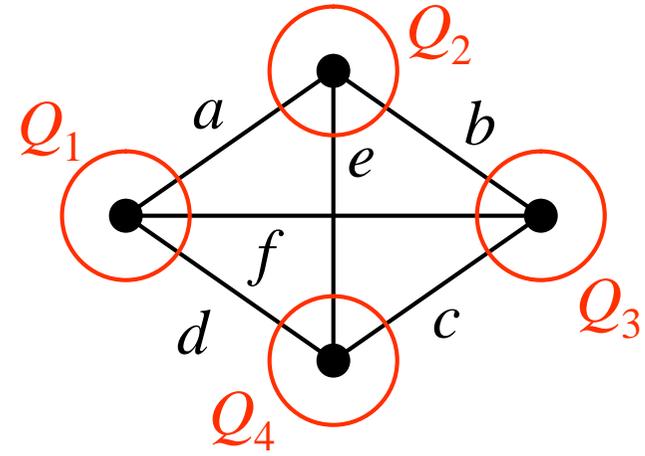
(2)

-
-
- n b

$(n \ 1)$

- $(n \ 1)$
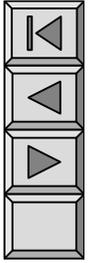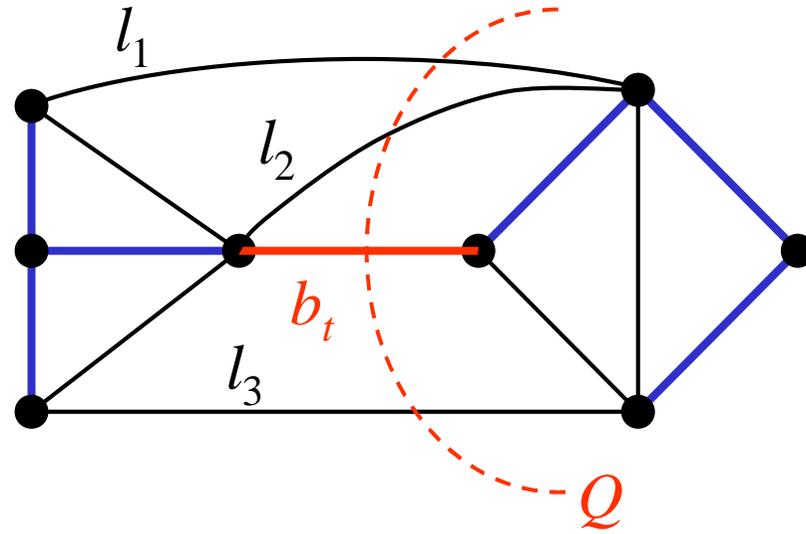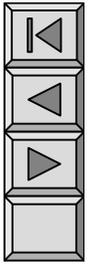
2,3,4,6
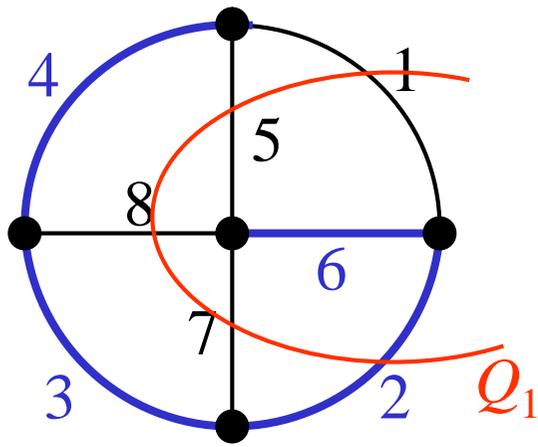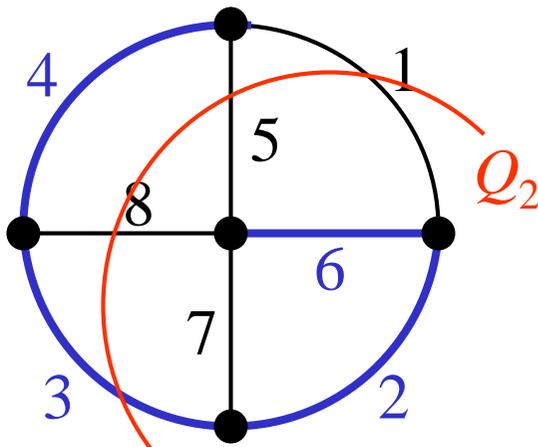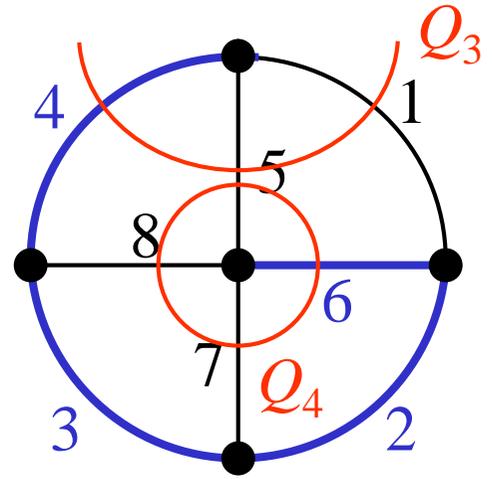
Q_1 (1,2,5,7,8) Q_2 (1,3,5,8) Q_3 (1,4,5) Q_4 (5,6,7,8)

5,6,7,8
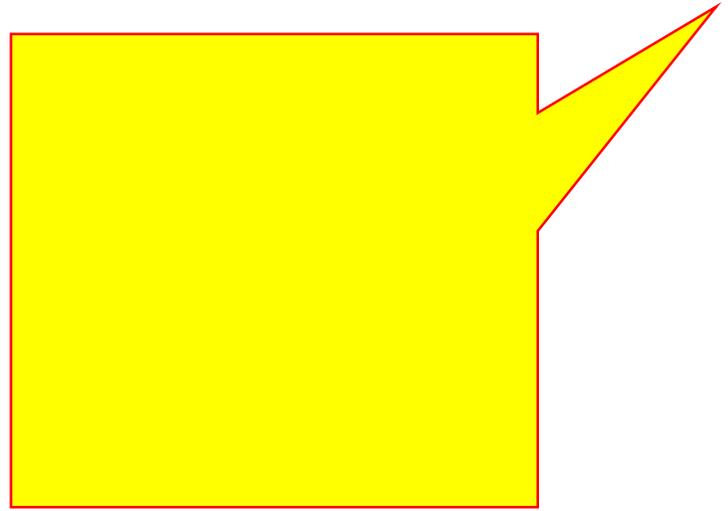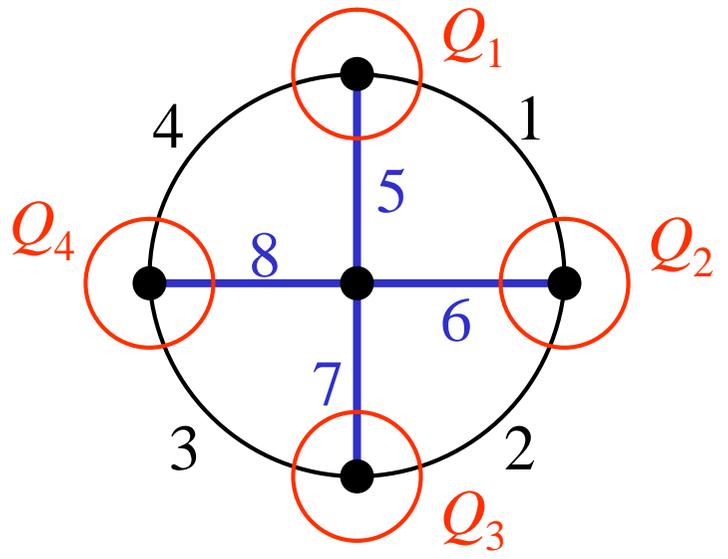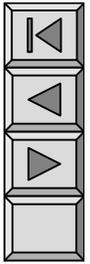
1.

$(n \quad b)$

$(1)\boldsymbol{A}_a$

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

$a_{jk} = -1 \qquad k$
$\quad j$

$a_{jk} = 0 \qquad\qquad k$
j
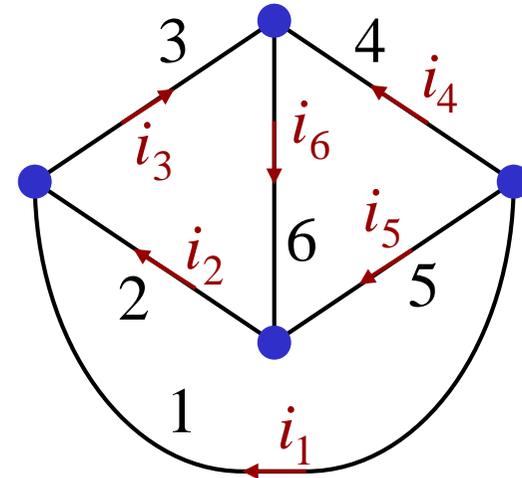
$$A_a = \begin{array}{c} {\color{red}1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6} \\ \begin{array}{c}{\color{blue}1}\\{\color{blue}2}\\{\color{blue}3}\\{\color{blue}4}\end{array}\left[\begin{array}{cccccc} 1 & 1 & +1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & +1 \\ +1 & 0 & 0 & +1 & +1 & 0 \\ 0 & +1 & 0 & 0 & 1 & 1 \end{array}\right]\end{array}$$
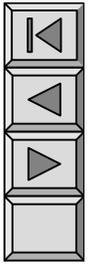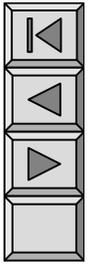
$$A = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}$$

(3)　A　　KCL

$b(=6)$

$$i = [i_1, i_2, \cdots, i_6]^{\mathrm{T}}$$
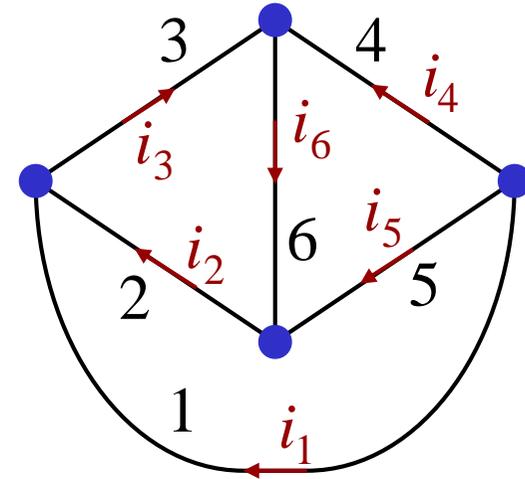
$$Ai = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ \cdot \\ \cdot \\ \cdot \\ i_6 \end{bmatrix} = \begin{bmatrix} -i_1 -i_2 +i_3 \\ -i_3 -i_4 +i_6 \\ +i_1 +i_4 +i_5 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

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

10

(4)　A　　　KVL

　　$b(=6)$

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

　　　　　　　　　（　　　）

$(n \ 1=3)$

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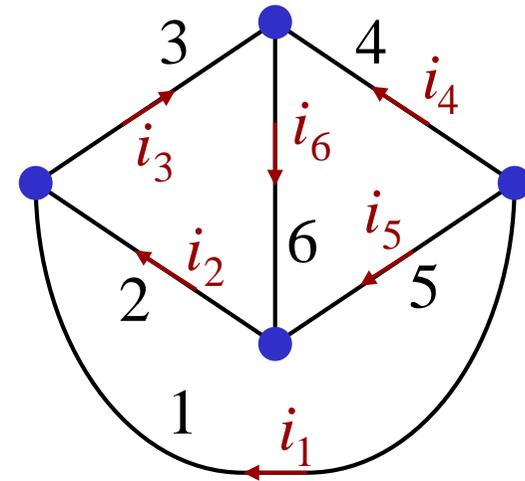
$$\boldsymbol{u} = \boldsymbol{A}^\mathrm{T} \boldsymbol{u}_n$$

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

$\boldsymbol{A}$

KVL
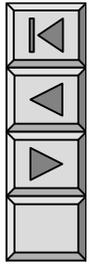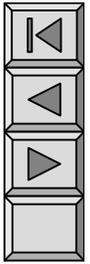
A

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

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

2.
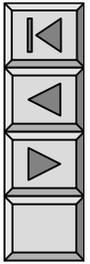
$$(l \quad b)$$

(1)$\boldsymbol{B}$

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

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

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

$$\boldsymbol{B} = \begin{array}{c} 1 \\ 2 \\ 3 \end{array} \begin{array}{|cccccc|} 1 & 2 & 3 & 4 & 5 & 6 \\ \hline 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{array}$$

(2)　　　　　　　　$\boldsymbol{B}_f$

$\boldsymbol{B}_f$

🕯 $\boldsymbol{B}_f$

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

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

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

(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
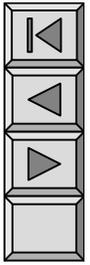
3.　　　　　Q

Q　　　　　$(n\ 1)\ \ b$

$q_{jk} = +1$　　　　k　　　　j

$q_{jk} = \ 1$　　　　k　　　　j

$q_{jk} = 0$　　　　k　　　　j

$$Q = \begin{array}{c} 1 \\ 2 \\ 3 \end{array}\begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}$$

(columns: 1 2 3 4 5 6)

Q_f
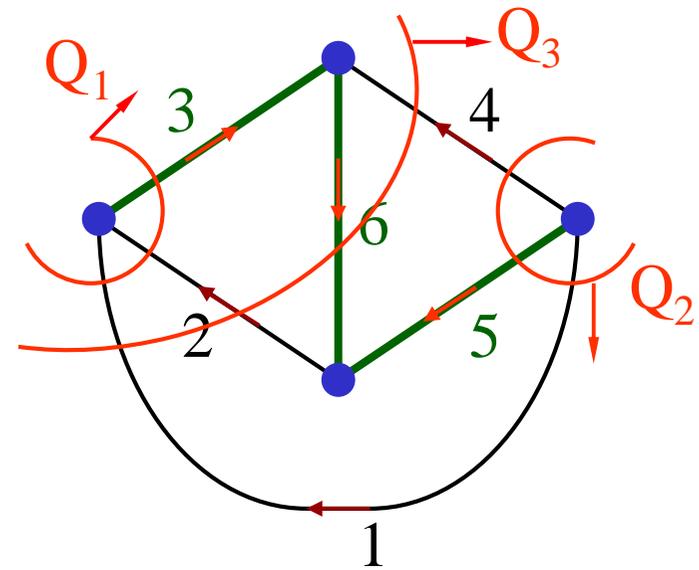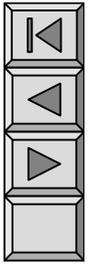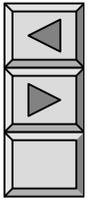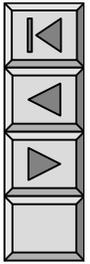
$Q_f = [\ \mathbf{1}_t \quad Q_l\ ]$

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

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

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

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

$$
\boldsymbol{u} =
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
1 & 1 & 1 \\
1 & 0 & 1 \\
0 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
u_{t1} \\
u_{t2} \\
u_{t3}
\end{bmatrix}
=
\begin{bmatrix}
u_{t1} \\
u_{t2} \\
u_{t3} \\
-u_{t1}+u_{t2}-u_{t3} \\
-u_{t1}-u_{t3} \\
u_{t2}-u_{t3}
\end{bmatrix}
\begin{matrix}
=u_3 \\
=u_5 \\
=u_6 \\
=u_1 \\
=u_2 \\
=u_4
\end{matrix}
$$
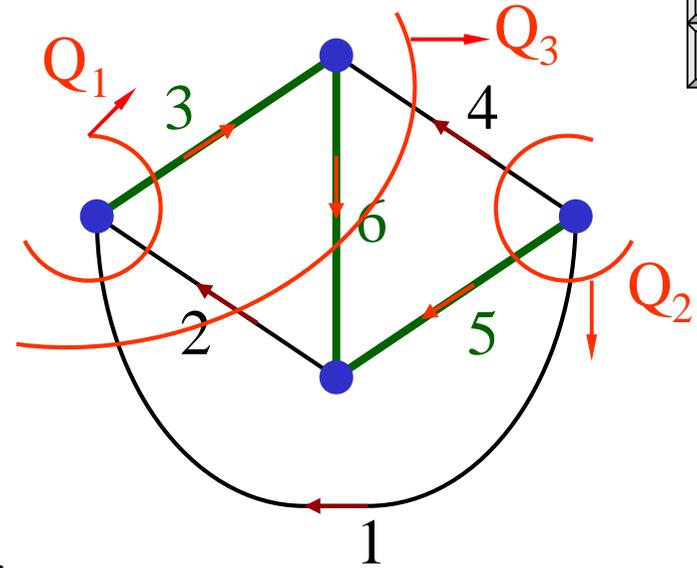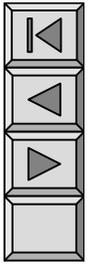
* 15 3 A B_f Q_f

1. $A\,i = 0$ $Q\,i = 0$

$u = A^{\mathrm{T}} u_n$ $u = Q_f^{\mathrm{T}} u_t$

G $Q_f = A$

2. G A B Q

$AB^{\mathrm{T}} = 0$ $BA^{\mathrm{T}} = 0$

$QB^{\mathrm{T}} = 0$ $BQ^{\mathrm{T}} = 0$

3. A B_f Q_f

$B_t^{\mathrm{T}} = A_t^{-1} A_l$ $Q_l = B_t^{\mathrm{T}} = A_t^{-1} A_l$

（　　）

(1)　　　　　　Z_k　　　　　R　L
　　C

(2)
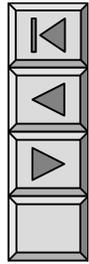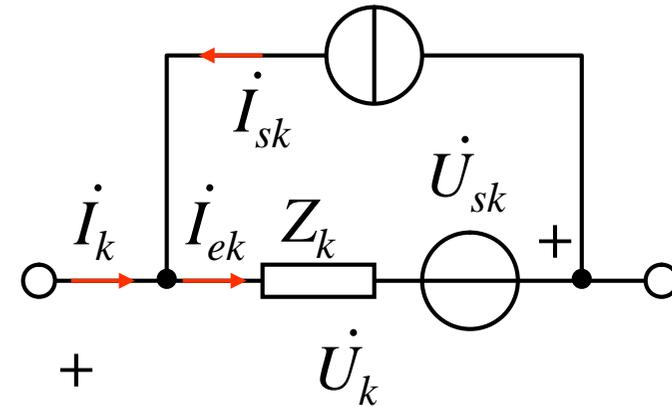
$$\dot{U}_k = Z_k(\dot{I}_k + \dot{I}_{Sk})\quad \dot{U}_{Sk}$$

$$k$$

$$\dot{\boldsymbol{I}} = [\ \dot{I}_1\ \ \dot{I}_2\ \ \cdots\ \ \dot{I}_b]^{\mathrm{T}}$$

$$\dot{\boldsymbol{U}} = [\dot{U}_1\ \ \dot{U}_2\ \cdots\ \dot{U}_b]^{\mathrm{T}}$$

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

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

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

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

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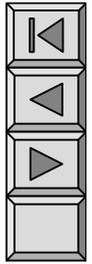
$$\mathbf{Z} = \begin{bmatrix} Z_1 & & & \mathbf{0} \\ & Z_2 & & \\ & & \ddots & \\ \mathbf{0} & & & Z_b \end{bmatrix}$$

✓ \quad 2

\qquad b \qquad\qquad 1 \quad g

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

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

$\cdots\cdots\cdots\cdots$

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

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

$(g+1)$ \quad b \hspace{10em} 1
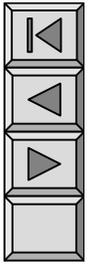
$$\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \vdots \\ \dot{U}_g \\ \dot{U}_{g+1} \\ \vdots \\ \dot{U}_b \end{bmatrix} = \begin{bmatrix} Z_1 & \mathrm{j}\omega M_{12} & \cdots & \mathrm{j}\omega M_{1g} & 0 & \cdots & 0 \\ \mathrm{j}\omega M_{21} & Z_2 & \cdots & \mathrm{j}\omega M_{2g} & 0 & \cdots & 0 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ \mathrm{j}\omega M_{g1} & \mathrm{j}\omega M_{g2} & \cdots & Z_g & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & Z_{g+1} & \cdots & 0 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & Z_b \end{bmatrix}$$

$$\begin{bmatrix} \dot{I}_1 + \dot{I}_{S!} \\ \dot{I}_2 + \dot{I}_{S2} \\ \vdots \\ \dot{I}_g + \dot{I}_{Sg} \\ \dot{I}_{g+1} + \dot{I}_{S(g+1)} \\ \vdots \\ \dot{I}_b + \dot{I}_{Sb} \end{bmatrix} - \begin{bmatrix} \dot{U}_{S1} \\ \dot{U}_{S2} \\ \vdots \\ \dot{U}_{Sg} \\ \dot{U}_{S(g+1)} \\ \vdots \\ \dot{U}_{Sb} \end{bmatrix}$$

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

$$\color{red}{\boldsymbol{Z}}$$

22

-

Z_k

$\dot{U}$

+

-

-

- **Z**

-

( ) "+" " "
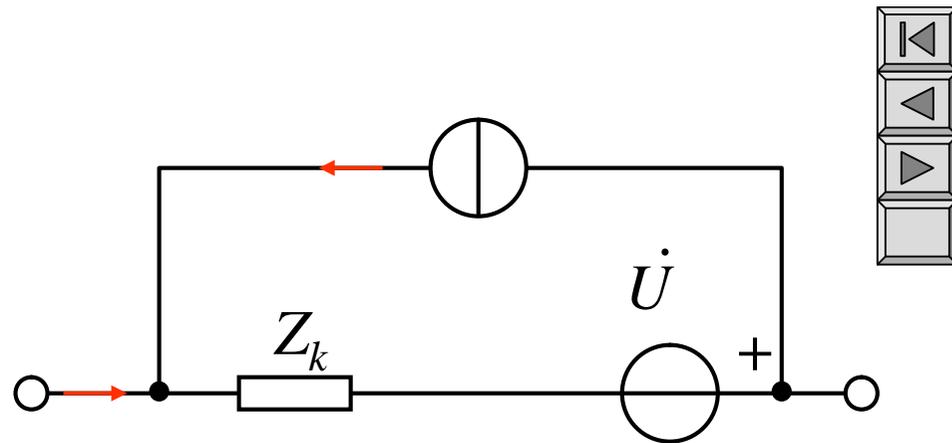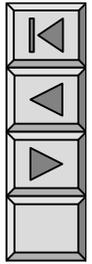
$\boldsymbol{B}$ KVL $\boldsymbol{B}\dot{\boldsymbol{U}} = \boldsymbol{0}$

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

$$\boldsymbol{B}\boldsymbol{Z}\,\dot{\boldsymbol{I}} + \boldsymbol{B}\boldsymbol{Z}\,\dot{\boldsymbol{I}}_S\quad \boldsymbol{B}\dot{\boldsymbol{U}}_S = \boldsymbol{0}$$

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

$$\boldsymbol{B}\boldsymbol{Z}\boldsymbol{B}^{\mathrm{T}}\dot{\boldsymbol{I}} = \boldsymbol{B}\dot{\boldsymbol{U}}_S\quad \boldsymbol{B}\boldsymbol{Z}\,\dot{\boldsymbol{I}}_S$$

$\boldsymbol{B}\boldsymbol{Z}\boldsymbol{B}^{\mathrm{T}}$ l $\boldsymbol{B}\dot{\boldsymbol{U}}_S$ $\boldsymbol{B}\boldsymbol{Z}$ l

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

$\mathbf{Z}_l$
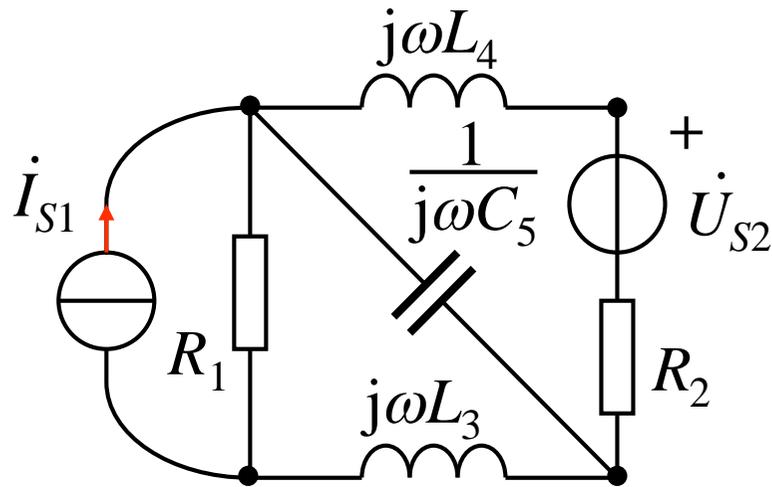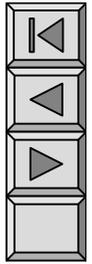
(2)

(3) B

(1)

$$B = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 \end{bmatrix}$$
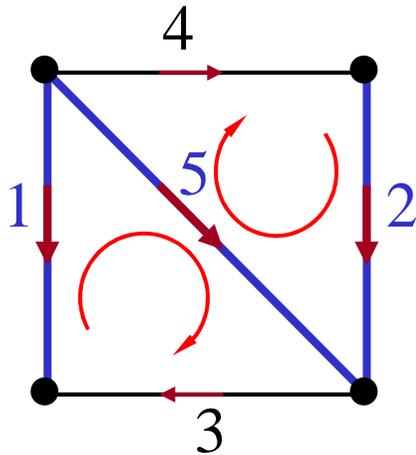
$$Z = \mathrm{diag}\,[R_1,\ R_2,\ \mathrm{j}\omega L_3,\ \mathrm{j}\omega L_4,\ \frac{1}{\mathrm{j}\omega C_5}]$$

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

$$\dot{I}_S = [\dot{I}_{S1}\ \ 0\ \ 0\ \ 0\ \ 0]^{\mathrm{T}}$$
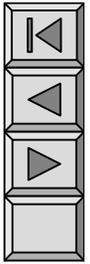
$$Z_l = BZB^{\mathrm{T}}$$

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

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

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

(5) Z_l $\dot{U}_S$ $\dot{I}_S$ $Z_l \dot{I} = B\dot{U}_S$ $BZ\,\dot{I}_S$
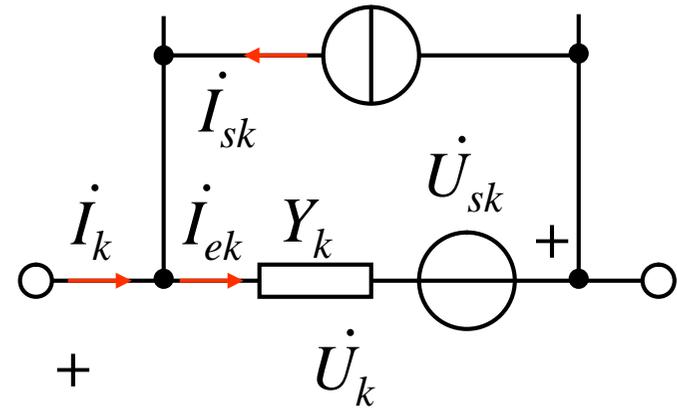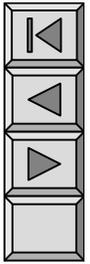
✓ 1

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

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

$\boldsymbol{Y}$

$\boldsymbol{Y}$

✓   2

2

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

Z   +
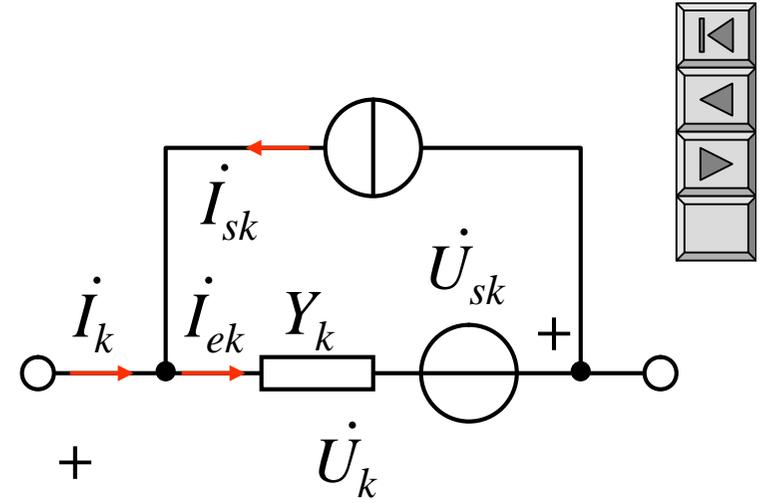
Z

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

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

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

VCR   1

Y

✔ 3

k   j

( )

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

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

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

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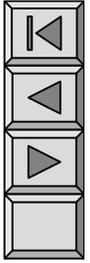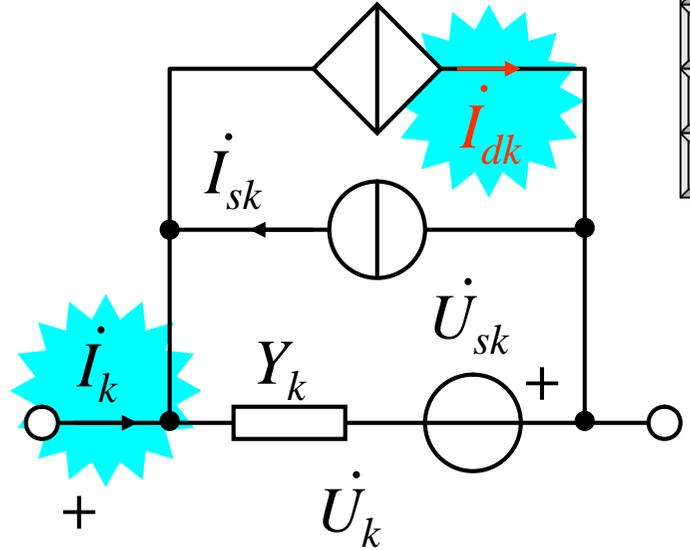
VCCS

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

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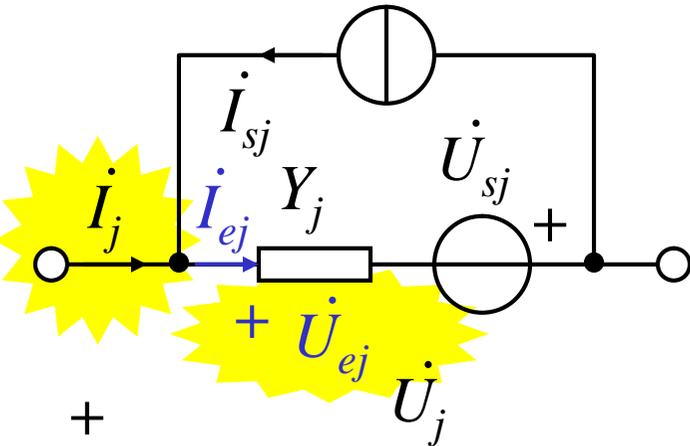
$$\dot{I}_k = Y_k(\dot{U}_k + \dot{U}_{Sk}) + \dot{I}_{dk} \quad \dot{I}_{Sk}$$

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

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

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

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

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

- $\boldsymbol{Y}$

- $(\qquad 2 \qquad)$
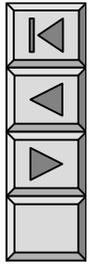
A KCL $A\dot{I} = 0$ A KVL $\dot{U} = A^{\mathrm{T}}\dot{U}_n$

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

$$\dot{I} = YA^{\mathrm{T}}\dot{U}_n \quad Y\dot{U}_S \quad \dot{I}_S$$

A KCL $AYA^{\mathrm{T}}\dot{U}_n \quad AY\dot{U}_S \quad A\dot{I}_S = 0$

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

$$Y_n = AYA^{\mathrm{T}}, \qquad \dot{J}_n = A\dot{I}_S \quad AY\dot{U}_S$$

$$Y_n\dot{U}_n = \dot{J}_n$$

Y_n

$\dot{J}_n$
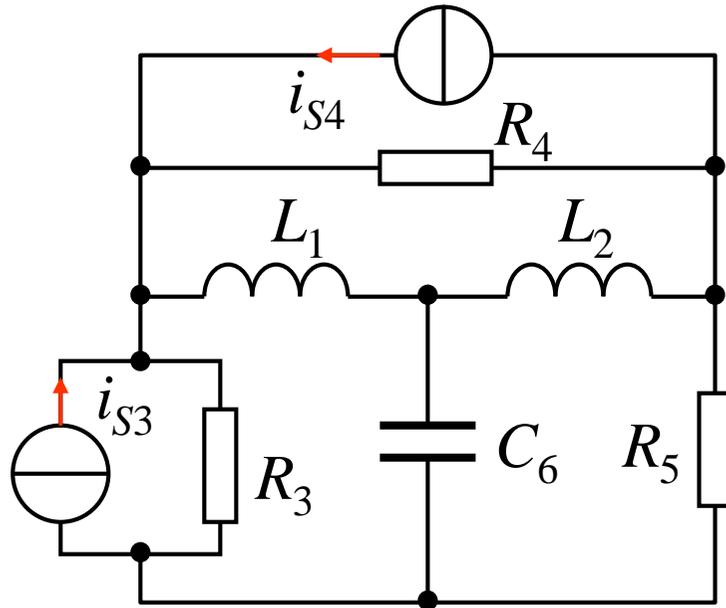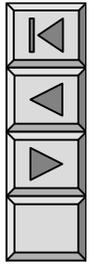
(1)

(2) $\boldsymbol{A}$

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

$$\dot{\boldsymbol{U}}_s = \boldsymbol{0}, \quad \dot{\boldsymbol{I}}_s = [\,0 \quad 0 \quad \dot{I}_{S3} \quad \dot{I}_{S4} \quad 0 \quad 0\,]^{\mathrm{T}}$$
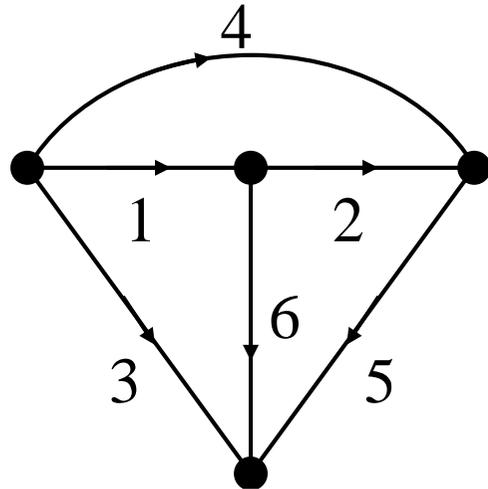
$$\boldsymbol{Y} = \mathrm{diag}[\,\frac{1}{\mathrm{j}\omega L_1},\ \frac{1}{\mathrm{j}\omega L_2},\ \frac{1}{R_3},\ \frac{1}{R_4},\ \frac{1}{R_5},\ \mathrm{j}\omega C_6\,]$$

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

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

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

$$\begin{bmatrix} \dfrac{1}{R_3}+\dfrac{1}{R_4}+\dfrac{1}{\mathrm{j}\omega L_1} & -\dfrac{1}{\mathrm{j}\omega L_1} & -\dfrac{1}{R_4} \\[2mm] -\dfrac{1}{\mathrm{j}\omega L_1} & \dfrac{1}{\mathrm{j}\omega L_1}+\dfrac{1}{\mathrm{j}\omega L_2}+\mathrm{j}\omega C_6 & -\dfrac{1}{\mathrm{j}\omega L_2} \\[2mm] -\dfrac{1}{R_4} & -\dfrac{1}{\mathrm{j}\omega L_2} & \dfrac{1}{R_4}+\dfrac{1}{R_5}+\dfrac{1}{\mathrm{j}\omega L_2} \end{bmatrix} \begin{bmatrix} \dot U_{n1} \\[2mm] \dot U_{n2} \\[2mm] \dot U_{n3} \end{bmatrix} = \begin{bmatrix} \dot I_{S3}+\dot I_{S4} \\[2mm] 0 \\[2mm] -\dot I_{S4} \end{bmatrix}$$

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

(   )
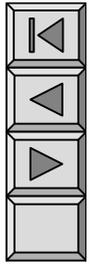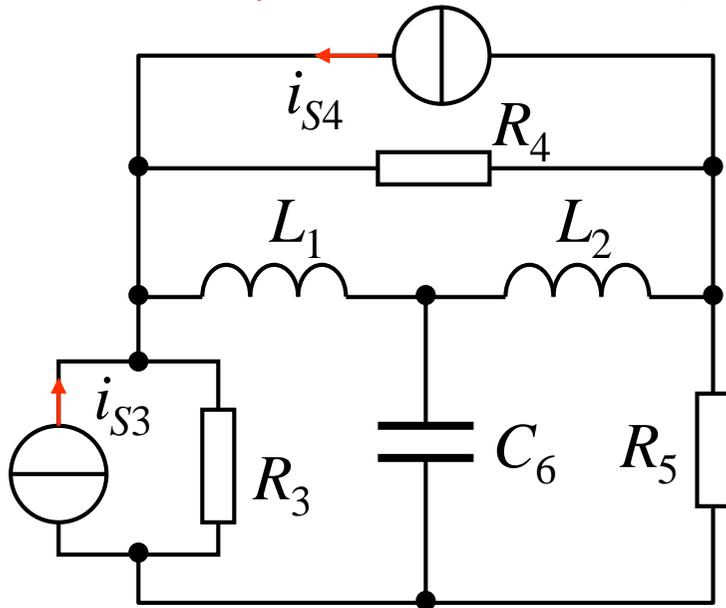
$$\dot{I}_{d2} = g_{21}\dot{U}_1 \ , \ \dot{I}_{d4} = \beta_{46}\dot{I}_6$$
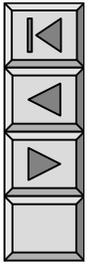
$$\boldsymbol{Y} = \begin{bmatrix} \dfrac{1}{R_1} & & \boldsymbol{0} & & \\ -g_{21} & \dfrac{1}{R_2} & & & \\ & j\omega C_3 & & & \\ & & j\omega C_4 & 0 & \dfrac{\beta_{46}}{j\omega L_6} \\ & & & \dfrac{1}{j\omega L_5} & 0 \\ \boldsymbol{0} & & & 0 & \dfrac{1}{j\omega L_6} \end{bmatrix}$$

4

6

2

1

✓

(   )   "+"   " "

34
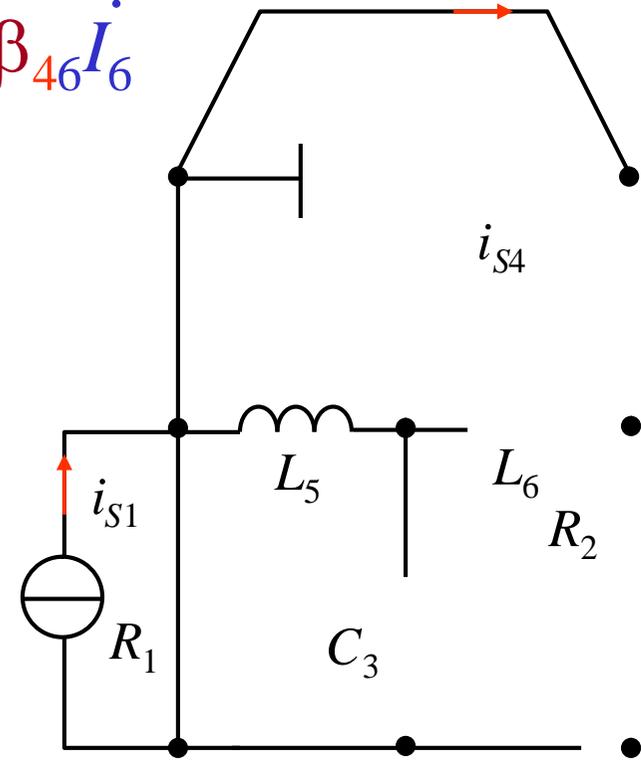
$$\dot{\boldsymbol{I}}_S = [\ \dot{I}_{S1}\quad 0\quad 0\quad -\dot{I}_{S4}\quad 0\quad 0\ ]^{\mathrm{T}}$$

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

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

L_5

L_6

R_2

(   )

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

$$\boldsymbol{u}_t$$
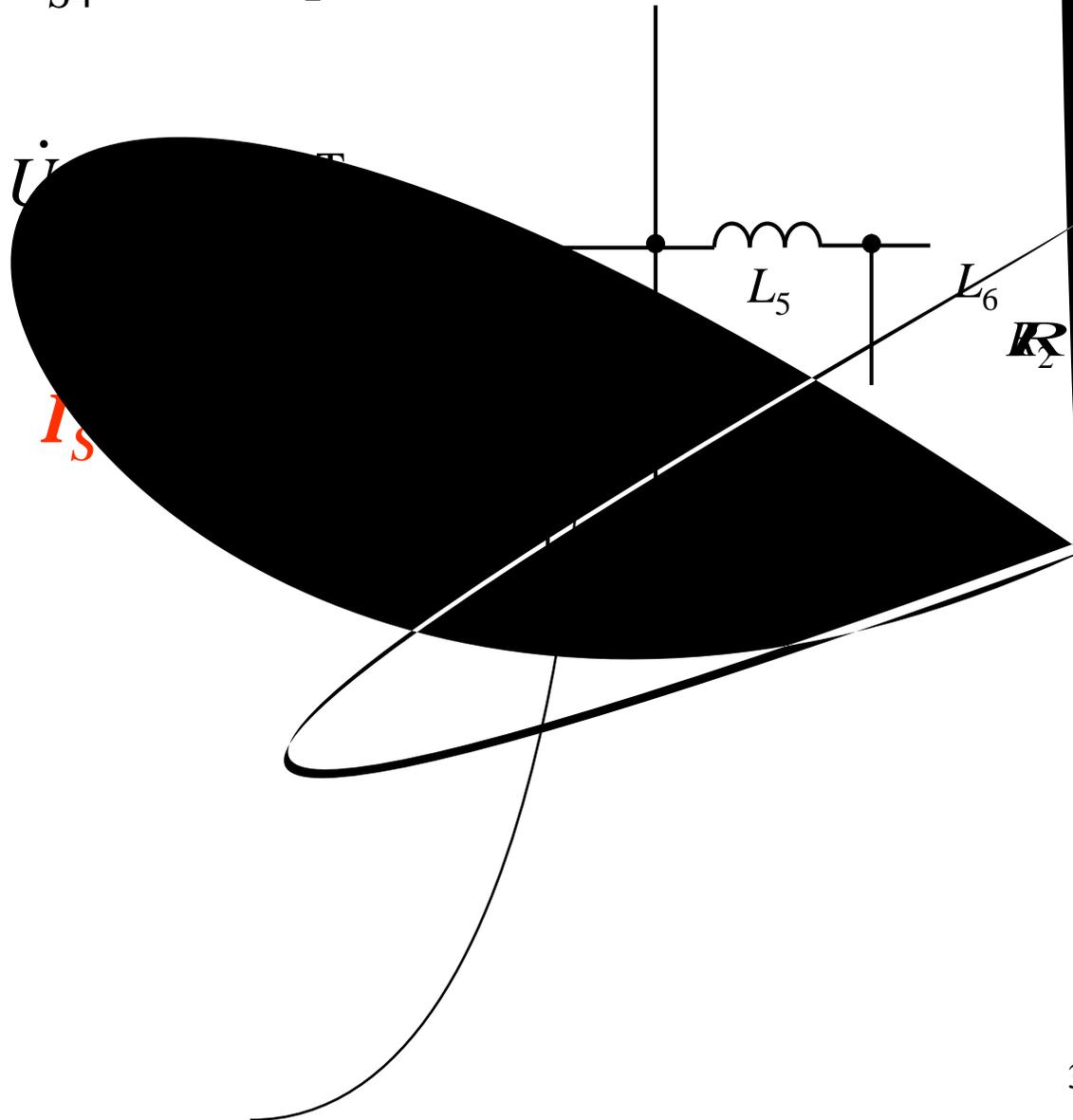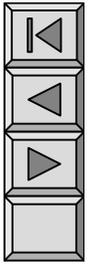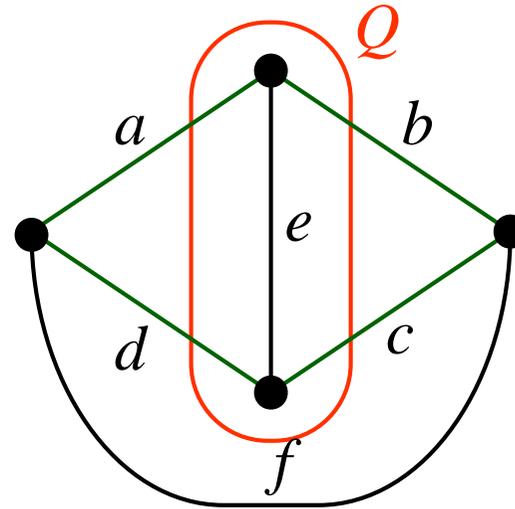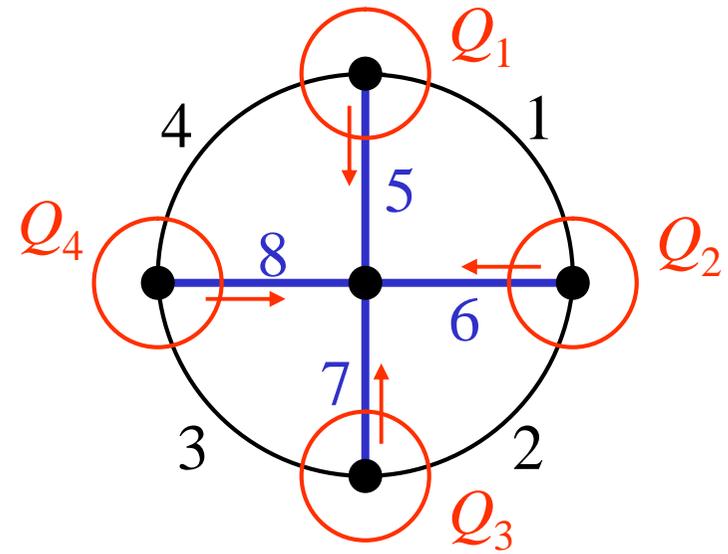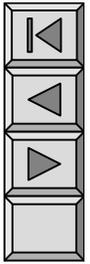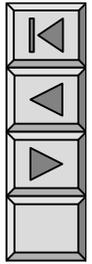
$$\dot{I} = Y(\dot{U} - \dot{U}_S) - \dot{I}_S$$

$\boldsymbol{Q}_f$ 　　　 KCL 　 $\boldsymbol{Q}_f \dot{\boldsymbol{I}} = \boldsymbol{0}$ 　　 KVL 　 $\dot{\boldsymbol{U}} = \boldsymbol{Q}_f^{\mathrm{T}} \dot{\boldsymbol{U}}_t$

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

$$\dot{\boldsymbol{I}} = Y \boldsymbol{Q}_f^{\mathrm{T}} \dot{\boldsymbol{U}}_t \quad Y \dot{\boldsymbol{U}}_S \quad \dot{\boldsymbol{I}}_S$$

$\boldsymbol{Q}_f$ 　　　　 KCL

$$\boldsymbol{Q}_f Y \boldsymbol{Q}_f^{\mathrm{T}} \dot{\boldsymbol{U}}_t = \boldsymbol{Q}_f \dot{\boldsymbol{I}}_S \quad \boldsymbol{Q}_f Y \dot{\boldsymbol{U}}_S$$

$$Y_t = \boldsymbol{Q}_f Y \boldsymbol{Q}_f^{\mathrm{T}} \qquad Y_t$$
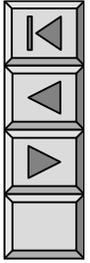
1   2   3

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

$$\boldsymbol{Q}_f$$
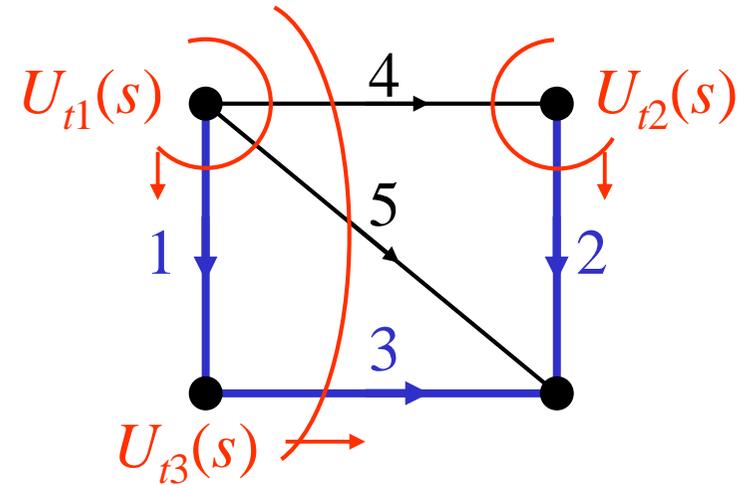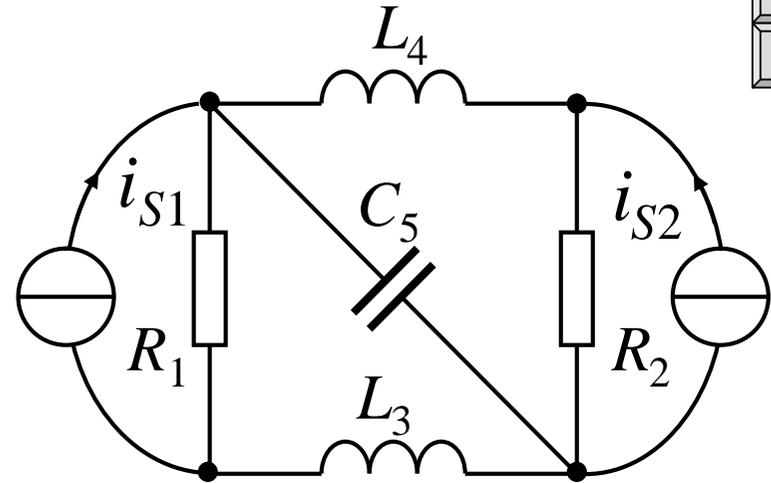
$$
\boldsymbol{Q}_f =
\begin{array}{c}
 \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\
\left[
\begin{array}{ccc|cc}
1 & 0 & 0 & 1 & 1 \\
0 & 1 & 0 & 1 & 0 \\
0 & 0 & 1 & 1 & 1
\end{array}
\right]
\begin{array}{c} Q_1 \\ Q_2 \\ Q_3 \end{array}
\end{array}
$$
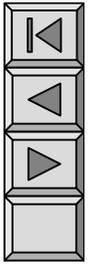
$$\boldsymbol{U}_S(s) = 0$$

$$\boldsymbol{I}_S(s) = [I_{S1}(s) \quad I_{S2}(s) \quad 0 \quad 0 \quad 0]^{\mathrm{T}}$$

$$\boldsymbol{Y}(s) = \mathrm{diag}\left[\frac{1}{R_1}, \; \frac{1}{R_2}, \; \frac{1}{sL_3}, \; \frac{1}{sL_4}, \; sC_5\right]$$
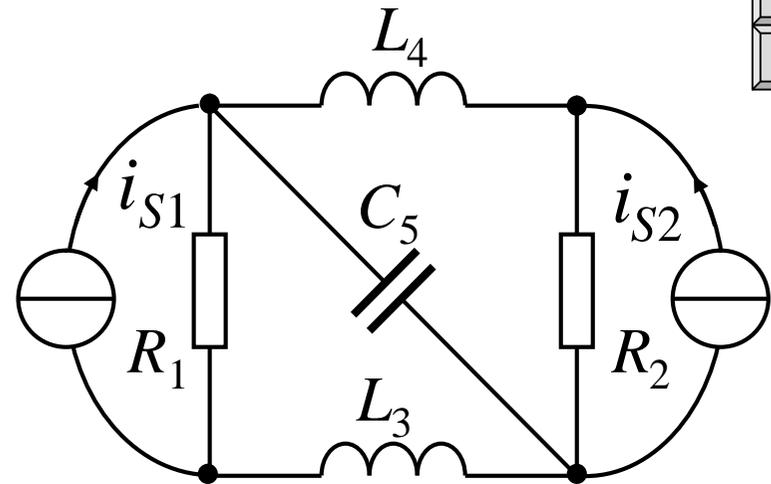
$$\boldsymbol{Q}_f\,\boldsymbol{Y}(s)\boldsymbol{Q}_f^{\mathrm{T}}\boldsymbol{U}_t(s) = \boldsymbol{Q}_f\boldsymbol{I}_S(s) - \boldsymbol{Q}_f\boldsymbol{Y}(s)\boldsymbol{U}_S(s)$$

$$
\begin{bmatrix}
\dfrac{1}{R_1} + \dfrac{1}{sL_4} + sC_5 & -\dfrac{1}{sL_4} & \dfrac{1}{sL_4} + sC_5 \\[2mm]
-\dfrac{1}{sL_4} & \dfrac{1}{R_2} + \dfrac{1}{sL_4} & -\dfrac{1}{sL_4} \\[2mm]
\dfrac{1}{sL_4} + sC_5 & -\dfrac{1}{sL_4} & \dfrac{1}{sL_3} + \dfrac{1}{sL_4} + sC_5
\end{bmatrix}
\begin{bmatrix}
U_{t1}(s) \\[2mm] U_{t2}(s) \\[2mm] U_{t3}(s)
\end{bmatrix}
=
\begin{bmatrix}
I_{S1}(s) \\[2mm] I_{S2}(s) \\[2mm] 0
\end{bmatrix}
$$

$\boldsymbol{Y}_t$

$Q_1 \quad Q_2 \quad Q_3$
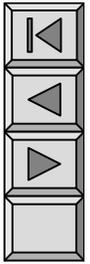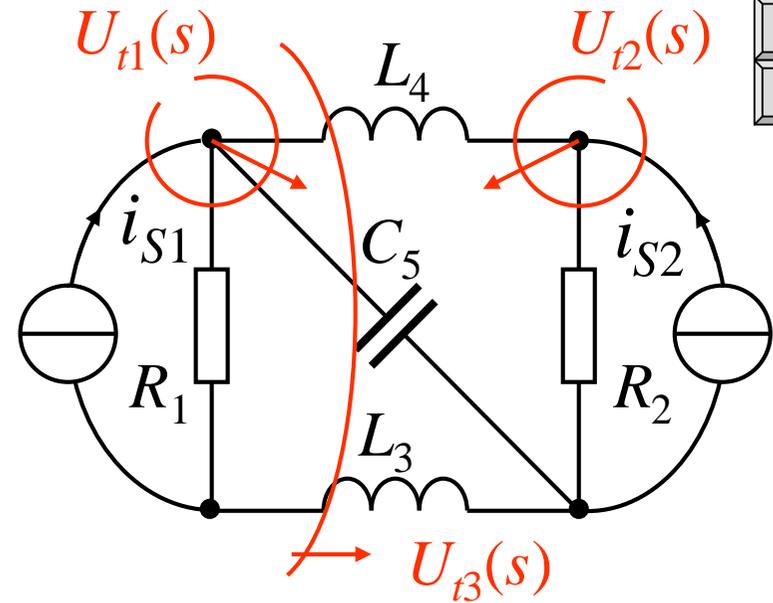
" "

"+"   " "

$$\begin{bmatrix} \dfrac{1}{R_1}+\dfrac{1}{sL_4}+sC_5 & -\dfrac{1}{sL_4} & \dfrac{1}{sL_4}+sC_5 \\[3mm] -\dfrac{1}{sL_4} & \dfrac{1}{R_2}+\dfrac{1}{sL_4} & -\dfrac{1}{sL_4} \\[3mm] \dfrac{1}{sL_4}+sC_5 & -\dfrac{1}{sL_4} & \dfrac{1}{sL_3}+\dfrac{1}{sL_4}+sC_5 \end{bmatrix} \begin{bmatrix} U_{t1}(s) \\[3mm] U_{t2}(s) \\[3mm] U_{t3}(s) \end{bmatrix} = \begin{bmatrix} I_{S1}(s) \\[3mm] I_{S2}(s) \\[3mm] 0 \end{bmatrix}_{41}$$
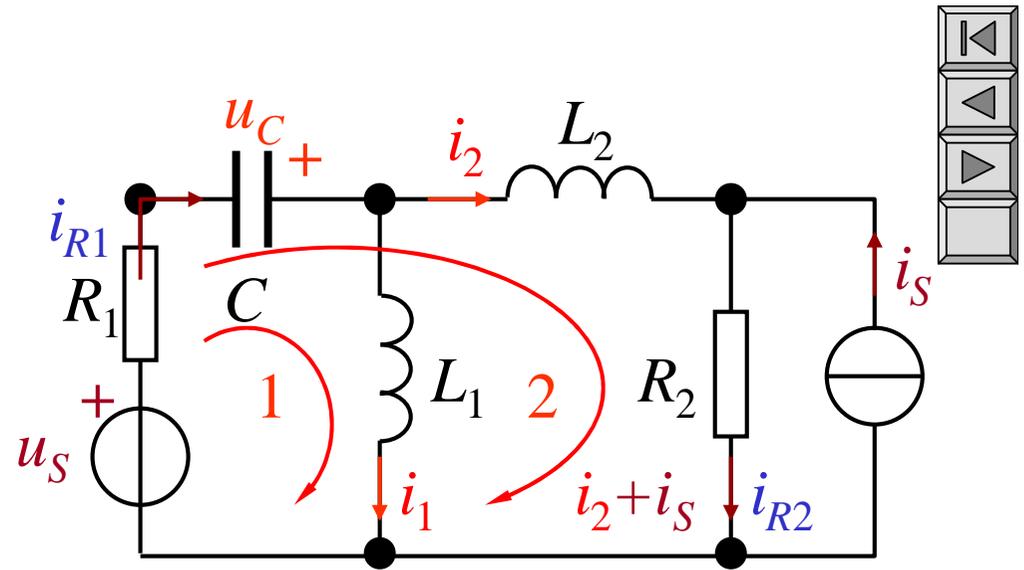
1.

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

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

(1)　　　　C

　KCL

(2)　　　　L

　KVL

(3)　　　　(　　　)

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

42
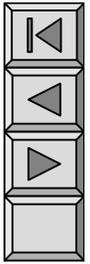
$$C\,\frac{\mathrm{d}u_C}{\mathrm{d}t} = -\,i_1 -\, i_2 \qquad (4)$$

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

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

$$\begin{bmatrix} \dfrac{\mathrm{d}u_C}{\mathrm{d}t} \\[2ex] \dfrac{\mathrm{d}i_1}{\mathrm{d}t} \\[2ex] \dfrac{\mathrm{d}i_2}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} 0 & -\dfrac{1}{C} & -\dfrac{1}{C} \\[2ex] \dfrac{1}{L_1} & -\dfrac{R_1}{L_1} & -\dfrac{R_1}{L_1} \\[2ex] \dfrac{1}{L_2} & -\dfrac{R_1}{L_2} & -\dfrac{R_1+R_2}{L_2} \end{bmatrix} \begin{bmatrix} u_C \\[2ex] i_1 \\[2ex] i_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\[2ex] \dfrac{1}{L_1} & 0 \\[2ex] \dfrac{1}{L_2} & -\dfrac{R_2}{L_2} \end{bmatrix} \begin{bmatrix} u_S \\[2ex] i_S \end{bmatrix}$$

2.

(1)

(2)　　　　　　　　KCL

(3)　　　　　　　　KVL

(4)

(5)

:

KVL

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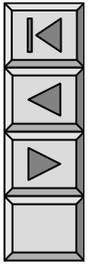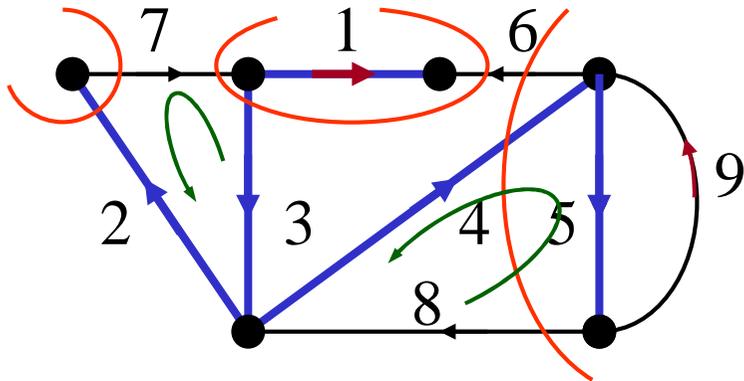
KCL

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

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

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

$$i_6 \qquad u_5$$

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

$$u_5 = \frac{1}{G_5} i_5 = \frac{1}{G_5} (i_8 + i_9)$$
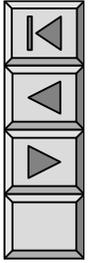
$$\frac{\mathrm{d}u_2}{\mathrm{d}t} = \frac{1}{C_2}\, i_7$$

$$\frac{\mathrm{d}u_3}{\mathrm{d}t} = -\frac{1}{C_3 R_6}\, u_3 - \frac{1}{C_3 R_6}\, u_4 + \frac{1}{C_3}\, i_7 + \frac{1}{C_3 R_6}\, u_{S1}$$

$$\frac{\mathrm{d}u_4}{\mathrm{d}t} = -\frac{1}{C_4 R_6}\, u_3 - \frac{1}{C_4 R_6}\, u_4 + \frac{1}{C_4}\, i_8 + \frac{1}{C_4 R_6}\, u_{S1}$$

$$\frac{\mathrm{d}i_7}{\mathrm{d}t} = -\frac{1}{L_7}\, u_2 - \frac{1}{L_7}\, u_3$$

$$\frac{\mathrm{d}i_8}{\mathrm{d}t} = -\frac{1}{L_8}\, u_4 - \frac{1}{G_5 L_8}\, i_8 - \frac{1}{G_5 L_8}\, i_{S9}$$

$$u_2 = x_1 \qquad u_3 = x_2 \qquad u_4 = x_3 \qquad i_7 = x_4 \qquad i_8 = x_5$$
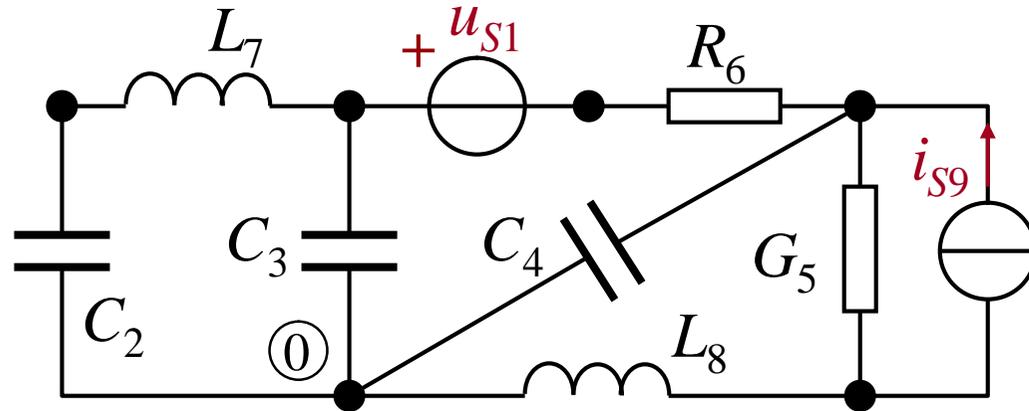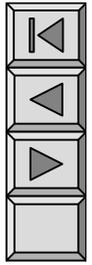
$$
\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix}
=
\begin{bmatrix}
0 & 0 & 0 & \dfrac{1}{C_2} & 0 \\[2ex]
0 & \dfrac{1}{C_3 R_6} & \dfrac{1}{C_3 R_6} & \dfrac{1}{C_3} & 0 \\[2ex]
0 & \dfrac{1}{C_4 R_6} & \dfrac{1}{C_4 R_6} & 0 & \dfrac{1}{C_4} \\[2ex]
\dfrac{1}{L_7} & \dfrac{1}{L_7} & 0 & 0 & 0 \\[2ex]
0 & 0 & \dfrac{1}{L_8} & 0 & \dfrac{1}{G_5 L_8}
\end{bmatrix}
\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}
+
\begin{bmatrix}
0 & 0 \\[2ex]
\dfrac{1}{C_3 R_6} & 0 \\[2ex]
\dfrac{1}{C_4 R_6} & 0 \\[2ex]
0 & 0 \\[2ex]
0 & \dfrac{1}{G_5 L_8}
\end{bmatrix}
\begin{bmatrix} u_{S1} \\ i_{S9} \end{bmatrix}
$$