Huazhong University
of Science & Technology

Electronic Circuit of Communications

School of Electronic Information
and Commnications

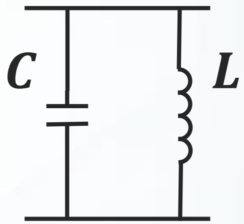
Jiaqing Huang

Coupling Circuits

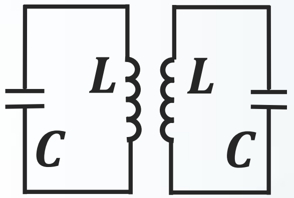
Frequency Selective Circuits

- Resonance
  - Series Resonance

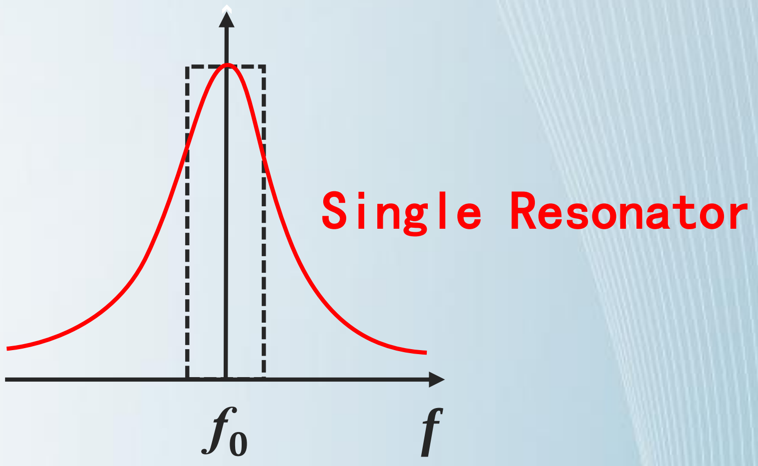
  - Parallel Resonance

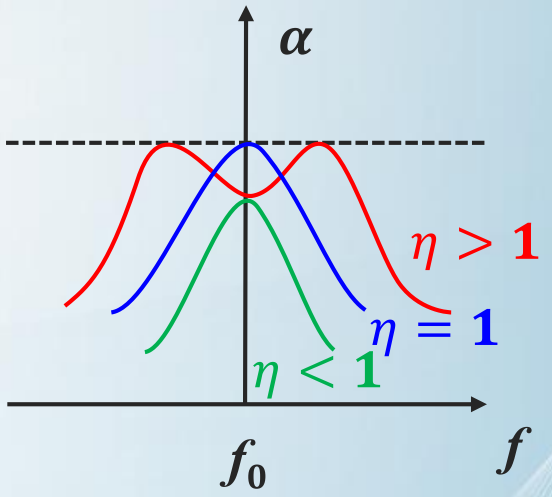


  - Coupling Resonance



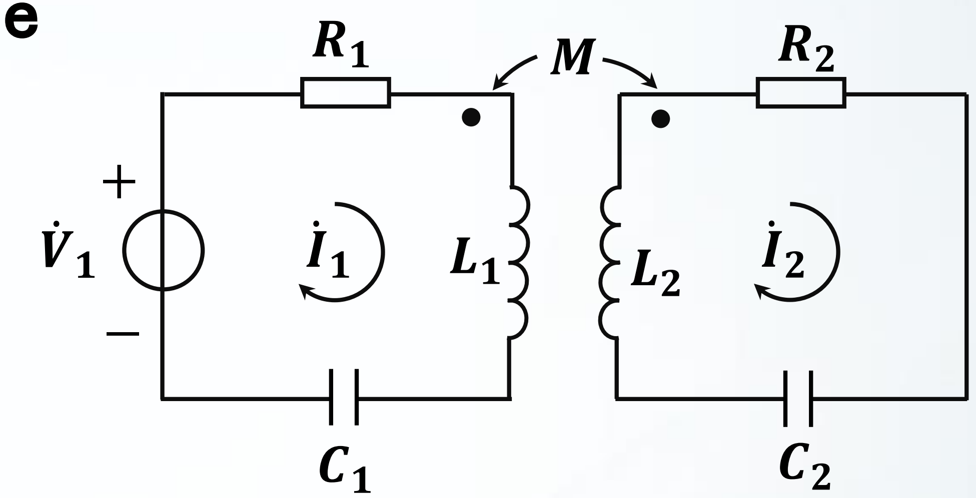
- Filter
  - Quartz Crystal Filter
  - Ceramic filter
  - SAWF





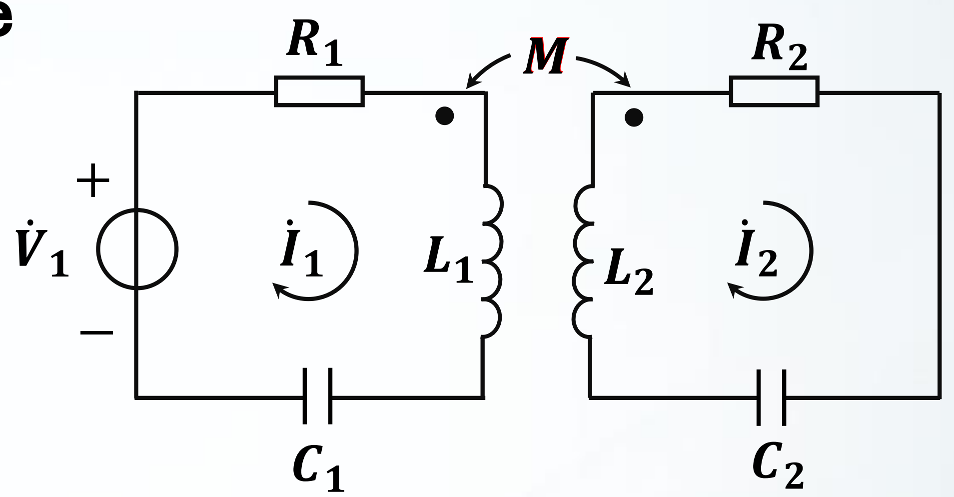
η : coupling factor

Coupling Resonance



Inductive Coupling Resonance

Coupling Resonance



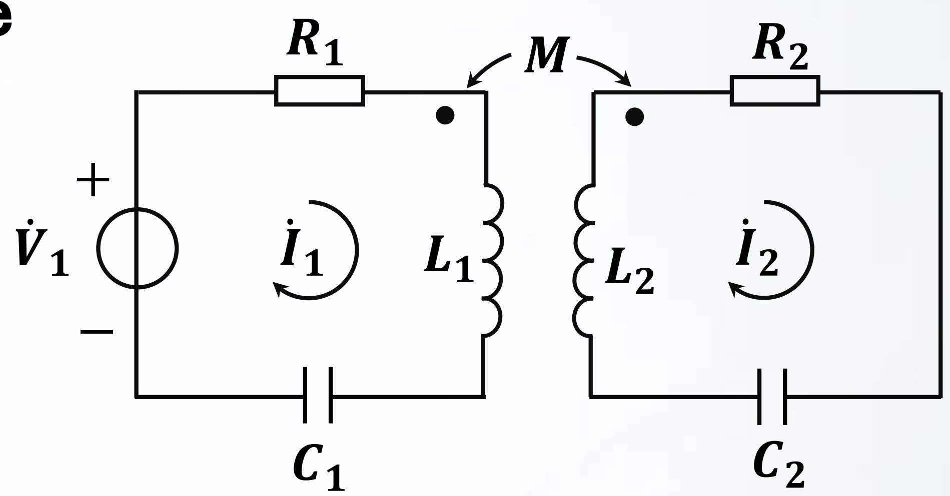
Inductive Coupling Resonance

De-coupling

$\Downarrow$

Primary Equivalent Circuit + Secondary Equivalent Circuit

Coupling Resonance



Primary Circuit

$$\dot{V}_1 = Z_{11}\dot{I}_1 - j\omega M\dot{I}_2$$

$R_{11} + jX_{11} = Z_{11}$

Primary Circuit

$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \frac{(\omega M)^2}{Z_{22}}}$$

Secondary Circuit

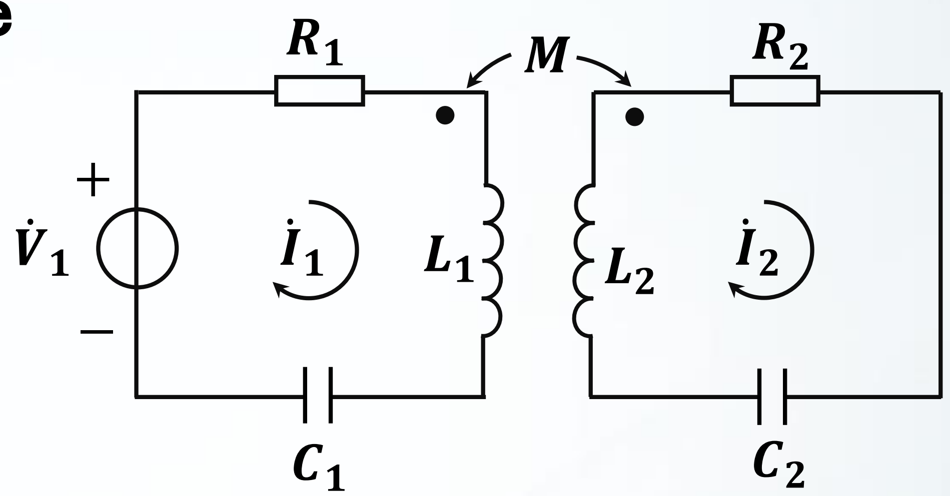
$$0 = Z_{22}\dot{I}_2 - j\omega M\dot{I}_1$$

$Z_{22} = R_{22} + jX_{22}$

Secondary Circuit

$$\dot{I}_2 = \frac{j\omega M\frac{\dot{V}_1}{Z_{11}}}{Z_{22} + \frac{(\omega M)^2}{Z_{11}}}$$

Coupling Resonance



Primary Circuit

$$\dot{V}_1 = Z_{11}\dot{I}_1 - j\omega M\dot{I}_2$$

Secondary Circuit

$$0 = Z_{22}\dot{I}_2 - j\omega M\dot{I}_1$$

$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \dfrac{(\omega M)^2}{Z_{22}}}$$

$$\dot{I}_2 = \frac{j\omega M\dfrac{\dot{V}_1}{Z_{11}}}{Z_{22} + \dfrac{(\omega M)^2}{Z_{11}}}$$

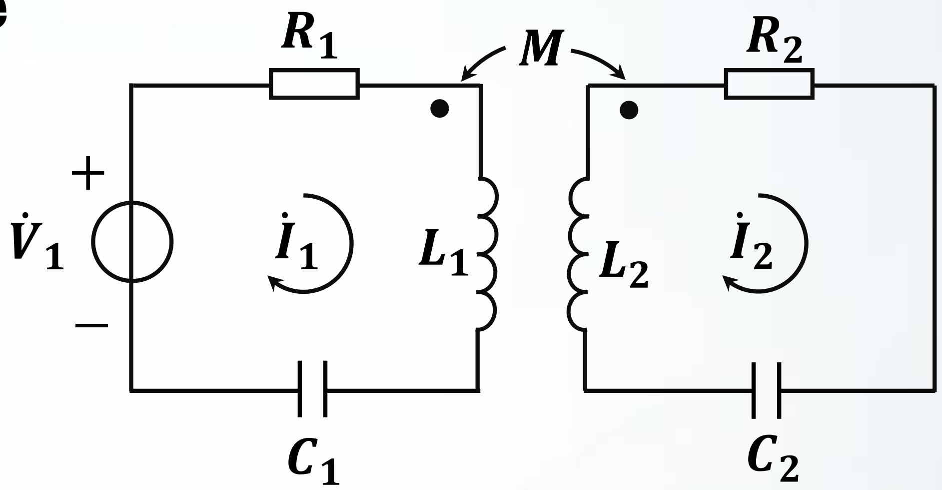
$R_{11} + jX_{11} = Z_{11}$

Primary Circuit

$Z_{22} = R_{22} + jX_{22}$

Secondary Circuit

Coupling Resonance



$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \boxed{\dfrac{(\omega M)^2}{Z_{22}}}}$$

$$\dot{I}_2 = \frac{j\omega M \dfrac{\dot{V}_1}{Z_{11}}}{Z_{22} + \dfrac{(\omega M)^2}{Z_{11}}}$$

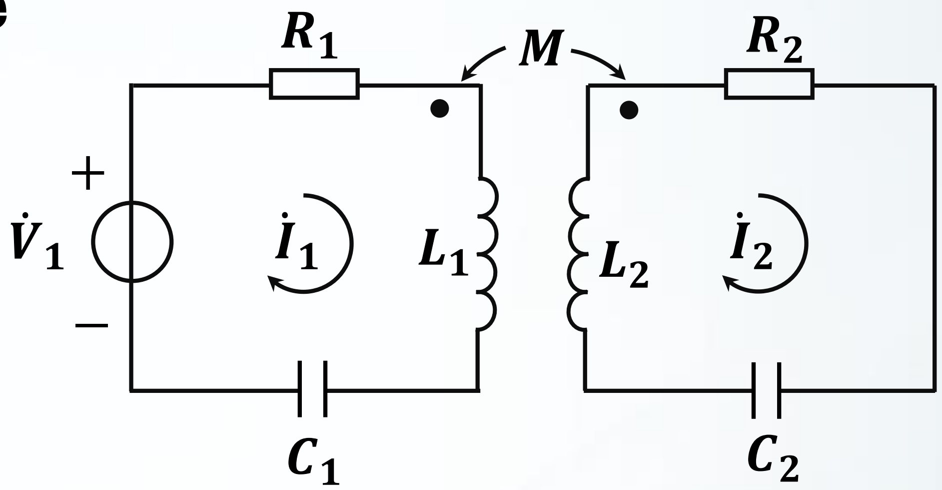
$R_{11} + jX_{11} = Z_{11}$

Primary Circuit

$Z_{22} = R_{22} + jX_{22}$

Secondary Circuit

Coupling Resonance



$$\frac{(\omega M)^2}{Z_{22}} = Z_{f1} = R_{f1} + jX_{f1}$$ Reflected Impedance

$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \frac{(\omega M)^2}{Z_{22}}}$$

$$\dot{I}_2 = \frac{j\omega M \frac{\dot{V}_1}{Z_{11}}}{Z_{22} + \frac{(\omega M)^2}{Z_{11}}}$$

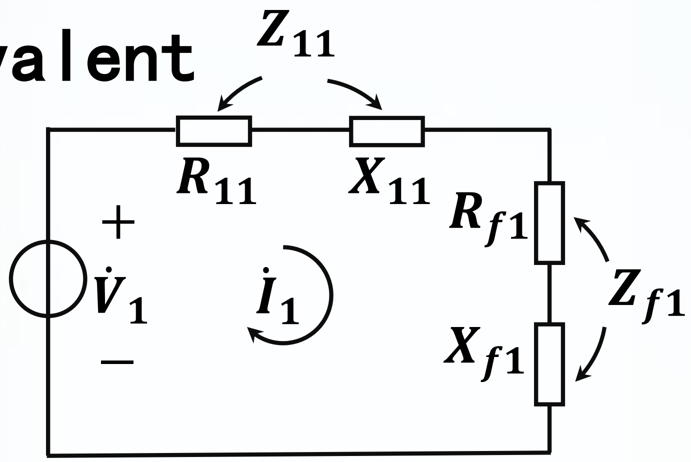
$R_{11} + jX_{11} = Z_{11}$

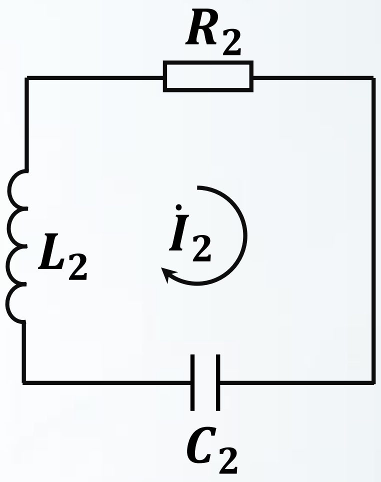
Primary Circuit

$Z_{22} = R_{22} + jX_{22}$

Secondary Circuit

Primary Equivalent Circuit





(a) Primary Equivalent Circuit

$$\frac{(\omega M)^2}{Z_{22}} = Z_{f1} = R_{f1} + jX_{f1}$$ Reflected Impedance

Note： Z_{f1} Not solid impedance, but effect

$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \boxed{\frac{(\omega M)^2}{Z_{22}}}}$$

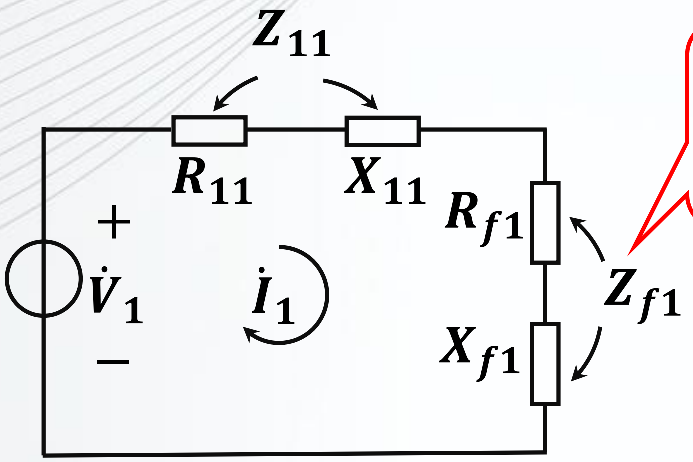
$$\dot{I}_2 = \frac{j\omega M \frac{\dot{V}_1}{Z_{11}}}{Z_{22} + \frac{(\omega M)^2}{Z_{11}}}$$

$R_{11} + jX_{11} = Z_{11}$

Primary Circuit

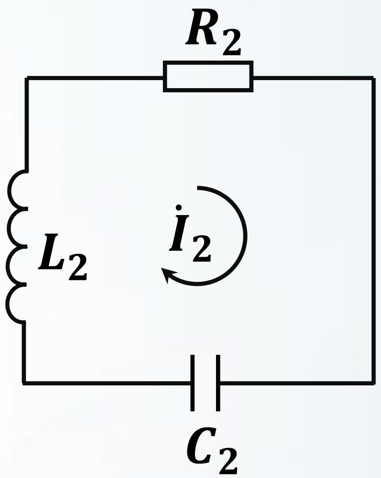
$Z_{22} = R_{22} + jX_{22}$

Secondary Circuit



$$Z_{f1} = \frac{(\omega M)^2}{Z_{22}}$$

(a) Primary Equivalent Circuit



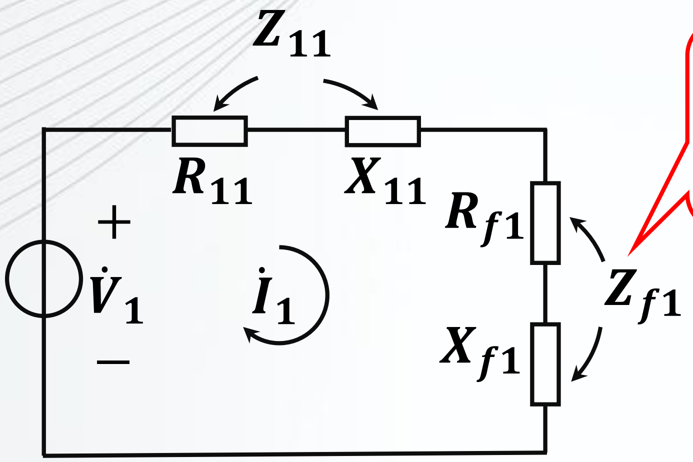
$$Z_{f1} = \frac{(\omega M)^2}{Z_{22}}$$ Reflected Impedance

$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \boxed{\frac{(\omega M)^2}{Z_{22}}}}$$

$$\dot{I}_2 = \frac{j\omega M \frac{\dot{V}_1}{Z_{11}}}{Z_{22} + \frac{(\omega M)^2}{Z_{11}}}$$

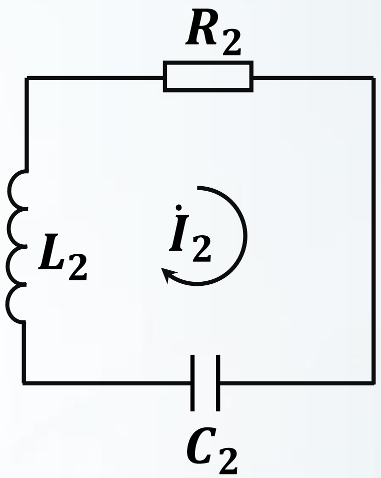
$$Z_{22} = R_{22} + jX_{22}$$

Secondary Circuit



(a) Primary Equivalent Circuit

$$Z_{f1} = \frac{(\omega M)^2}{Z_{22}}$$



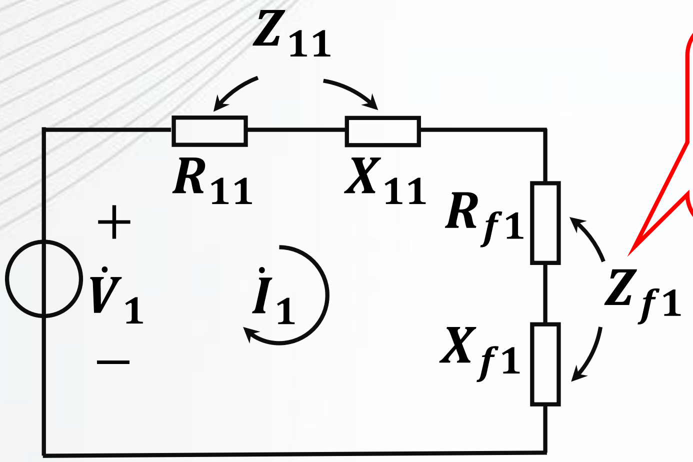
$$\begin{cases} Z_{f1} = \dfrac{(\omega M)^2}{Z_{22}} & \text{Reflected Impedance} \\ Z_{f2} = \dfrac{(\omega M)^2}{Z_{11}} & \text{Reflected Impedance} \end{cases}$$

$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \dfrac{(\omega M)^2}{Z_{22}}} \qquad \dot{I}_2 = \frac{j\omega M \dfrac{\dot{V}_1}{Z_{11}}}{Z_{22} + \boxed{\dfrac{(\omega M)^2}{Z_{11}}}}$$

$Z_{22} = R_{22} + jX_{22}$

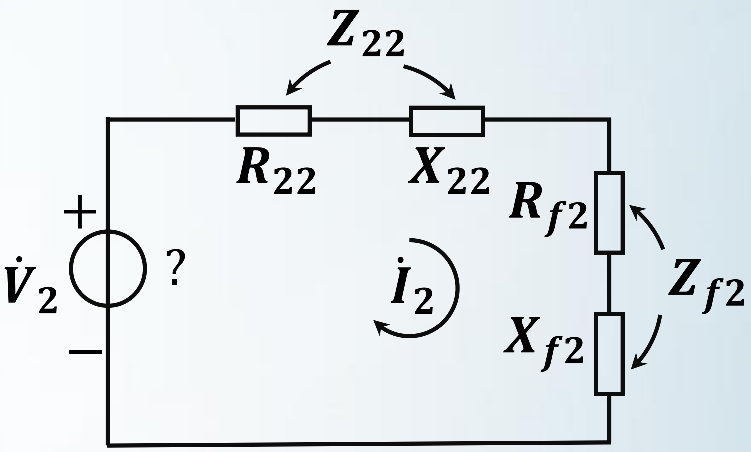
Secondary Circuit

Secondary Equivalent Circuit



$$Z_{f1} = \frac{(\omega M)^2}{Z_{22}}$$

(a) Primary Equivalent Circuit



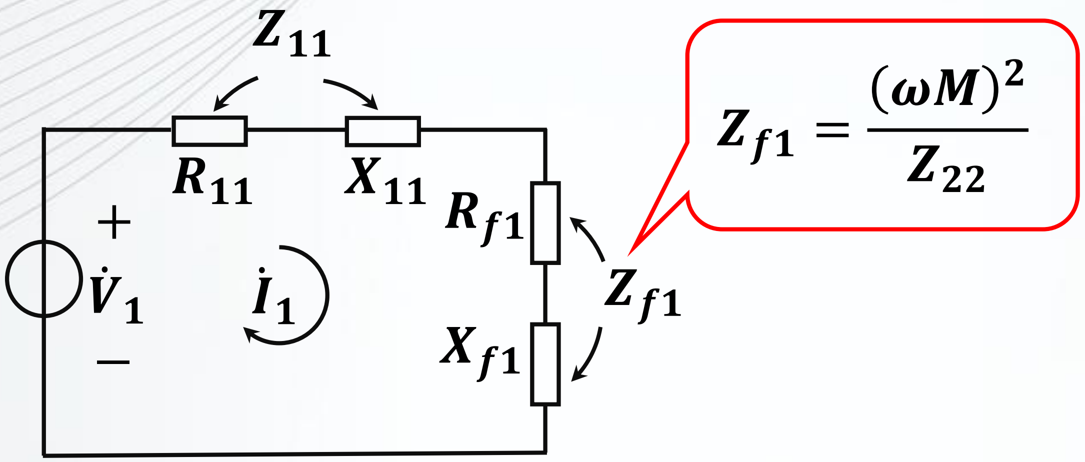
(b) Secondary Equivalent Circuit

$$\begin{cases} Z_{f1} = \dfrac{(\omega M)^2}{Z_{22}} & \text{Reflected Impedance} \\ Z_{f2} = \dfrac{(\omega M)^2}{Z_{11}} & \text{Reflected Impedance} \end{cases}$$

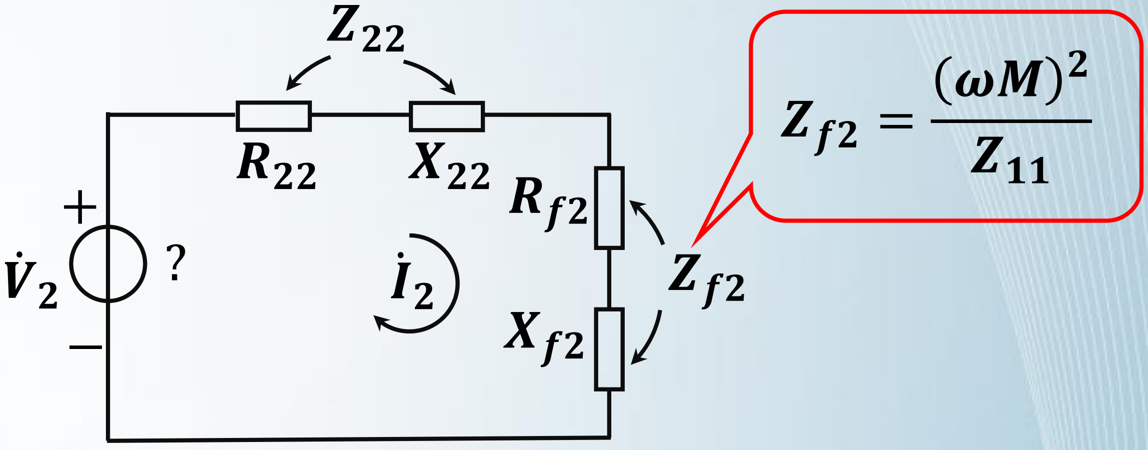
$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \dfrac{(\omega M)^2}{Z_{22}}} \qquad \dot{I}_2 = \frac{j\omega M \dfrac{\dot{V}_1}{Z_{11}}}{Z_{22} + \boxed{\dfrac{(\omega M)^2}{Z_{11}}}}$$

$Z_{22} = R_{22} + jX_{22}$

Secondary Circuit



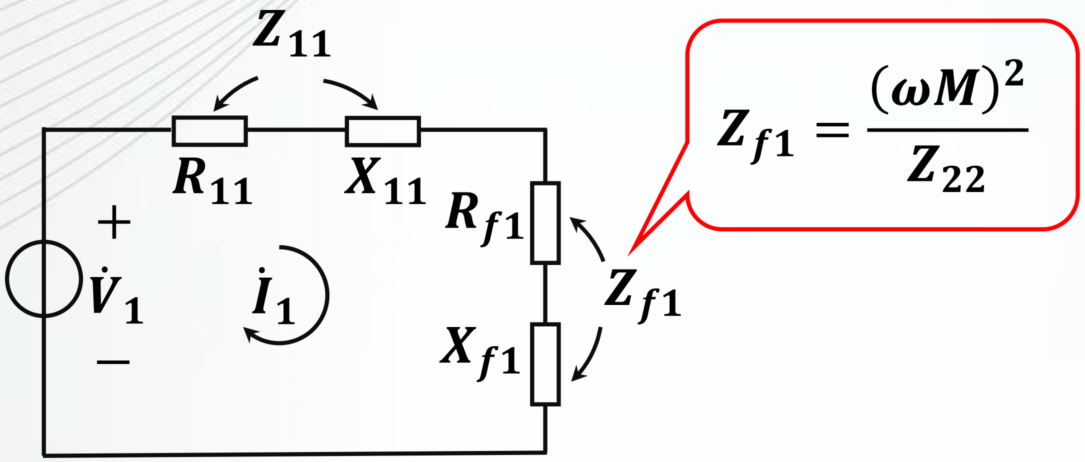
(a) Primary Equivalent Circuit



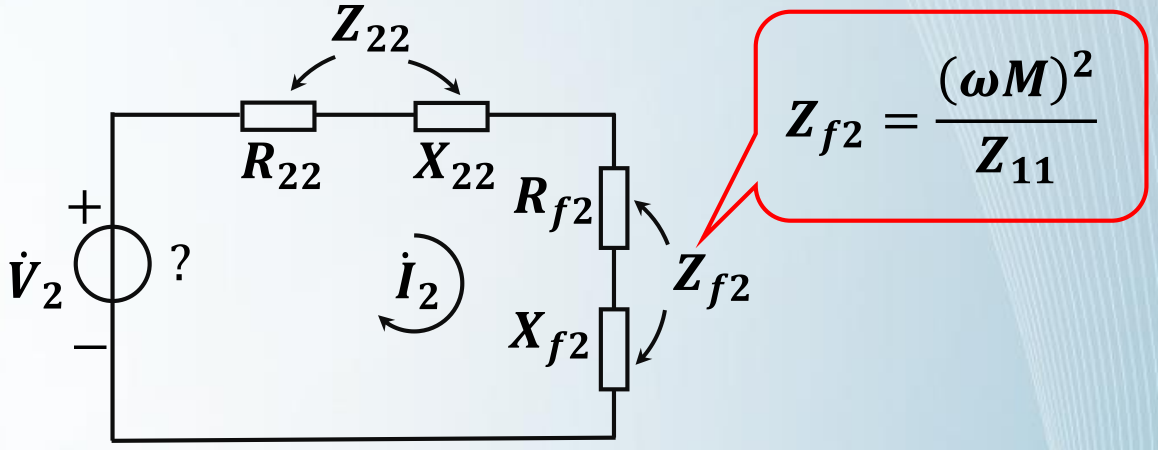
(b) Secondary Equivalent Circuit

$$\begin{cases} Z_{f1} = \dfrac{(\omega M)^2}{Z_{22}} & \text{Reflected Impedance} \\ Z_{f2} = \dfrac{(\omega M)^2}{Z_{11}} & \text{Reflected Impedance} \end{cases}$$

$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \dfrac{(\omega M)^2}{Z_{22}}} \qquad \dot{I}_2 = \frac{j\omega M \dfrac{\dot{V}_1}{Z_{11}}}{Z_{22} + \boxed{\dfrac{(\omega M)^2}{Z_{11}}}}$$



(a) Primary Equivalent Circuit



(b) Secondary Equivalent Circuit

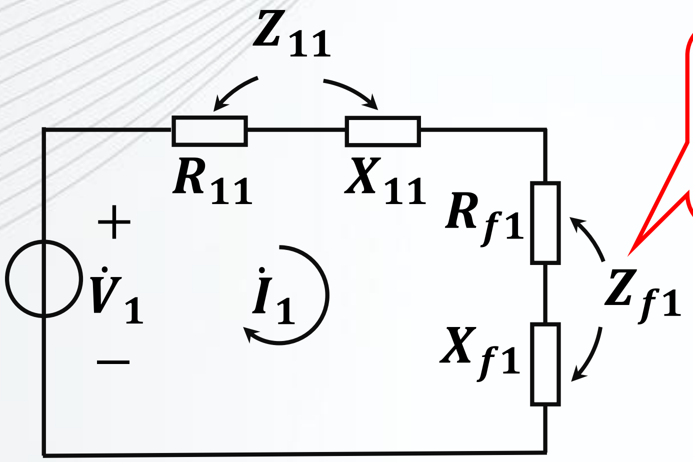
Secondary circuit is OPEN

$\frac{\dot{V}_1}{Z_{11}}$ L_2 induced electromotive force

$$\dot{V}_2 = j\omega M \boxed{\frac{\dot{V}_1}{Z_{11}}}$$

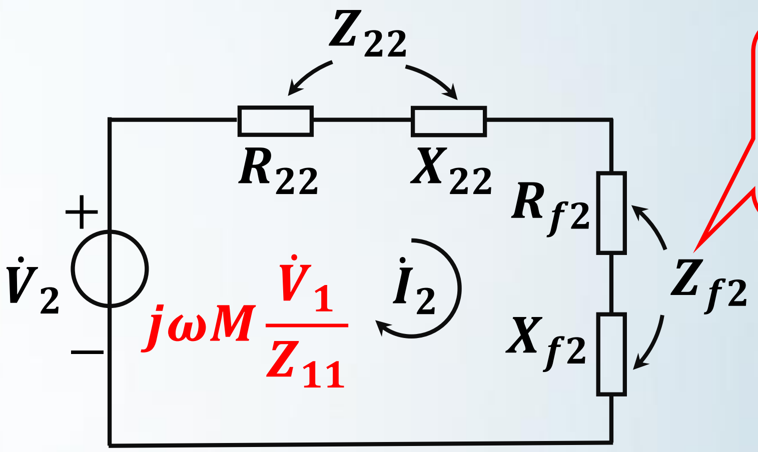
$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \frac{(\omega M)^2}{Z_{22}}}$$

$$\dot{I}_2 = \frac{\boxed{j\omega M \frac{\dot{V}_1}{Z_{11}}}}{Z_{22} + \frac{(\omega M)^2}{Z_{11}}}$$



$$Z_{f1} = \frac{(\omega M)^2}{Z_{22}}$$

(a) Primary Equivalent Circuit



$$Z_{f2} = \frac{(\omega M)^2}{Z_{11}}$$

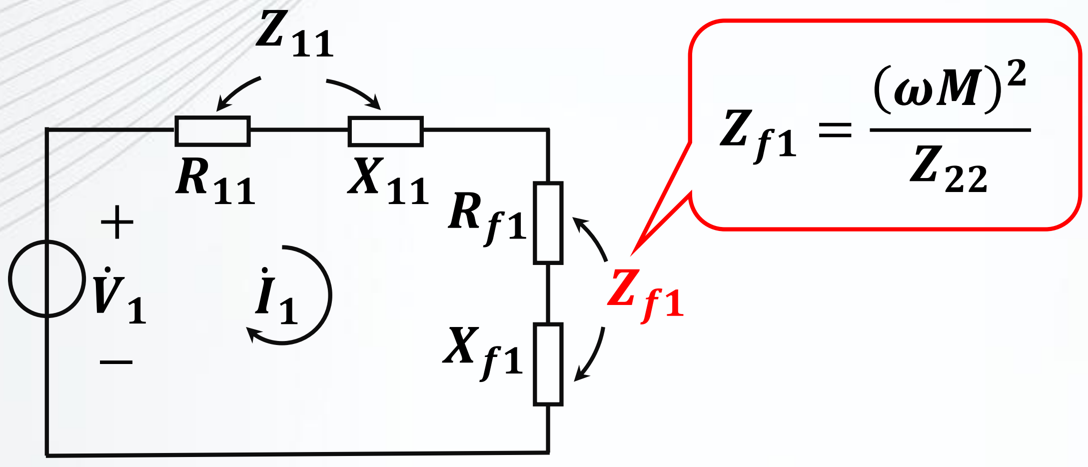
(b) Secondary Equivalent Circuit

Secondary circuit is OPEN

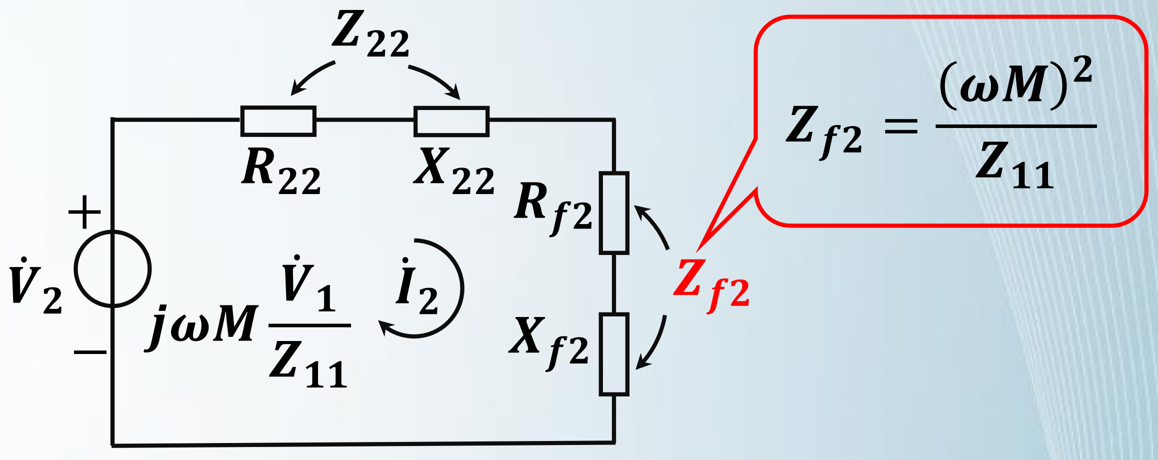
$\frac{\dot{V}_1}{Z_{11}}$ L_2 induced electromotive force

$$\dot{V}_2 = j\omega M\boxed{\frac{\dot{V}_1}{Z_{11}}}$$

$$\dot{I}_1 = \frac{\dot{V}_1}{Z_{11} + \frac{(\omega M)^2}{Z_{22}}} \qquad \dot{I}_2 = \frac{\boxed{j\omega M\frac{\dot{V}_1}{Z_{11}}}}{Z_{22} + \frac{(\omega M)^2}{Z_{11}}}$$



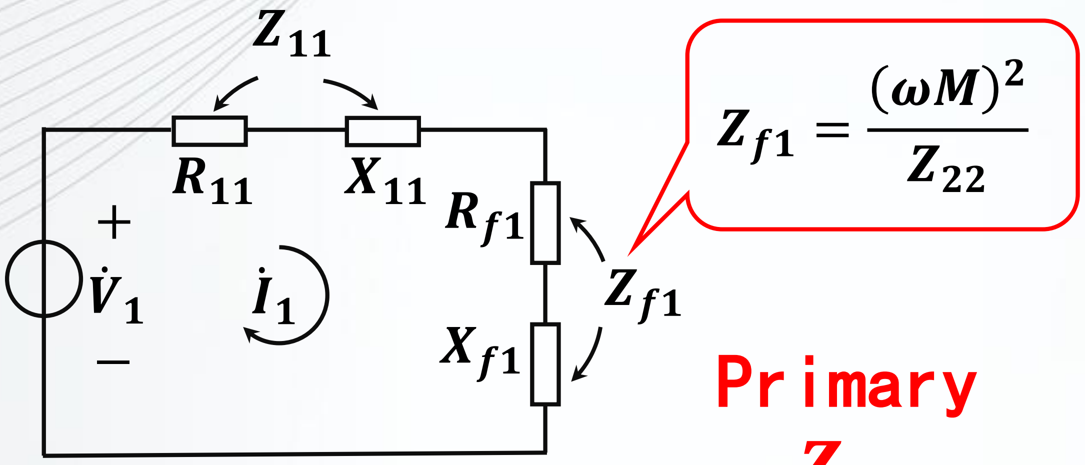
(a) Primary Equivalent Circuit



(b) Secondary Equivalent Circuit

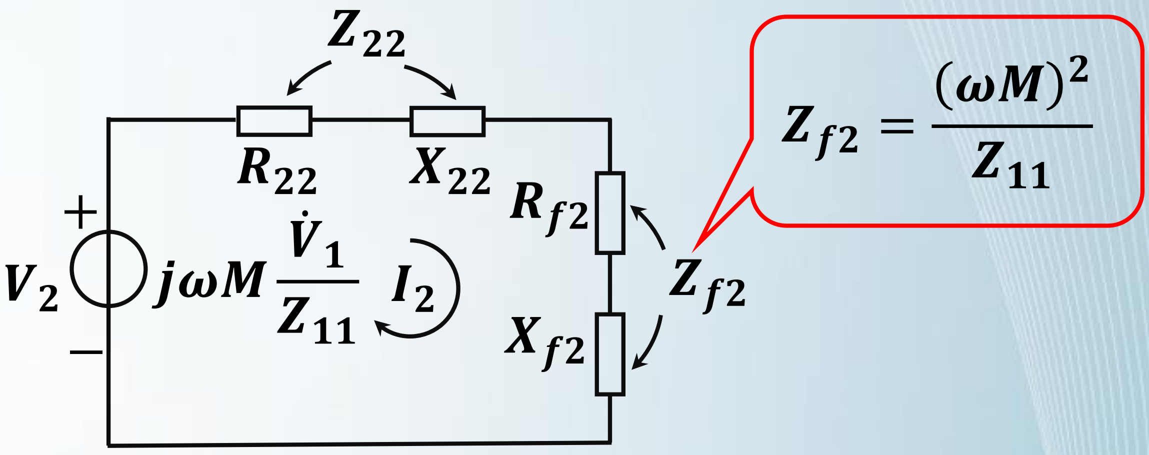
Reflected Impedance :

- Appear in **Equivalent** Circuits
- No solid impedance
- Denote mutual effect



(a) Primary Equivalent Circuit

Primary Z_{f1}



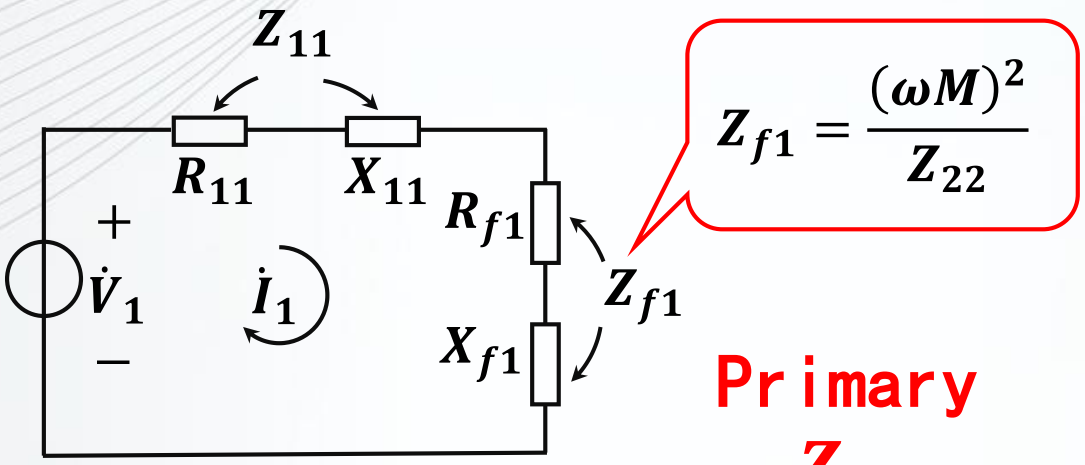
(b) Secondary Equivalent Circuit

$$Z_{f1} = R_{f1} + jX_{f1} = \frac{(\omega M)^2}{R_{22} + jX_{22}}$$

$$= \frac{(\omega M)^2}{R_{22}{}^2 + X_{22}{}^2} R_{22} + j \frac{-(\omega M)^2}{R_{22}{}^2 + X_{22}{}^2} X_{22}$$

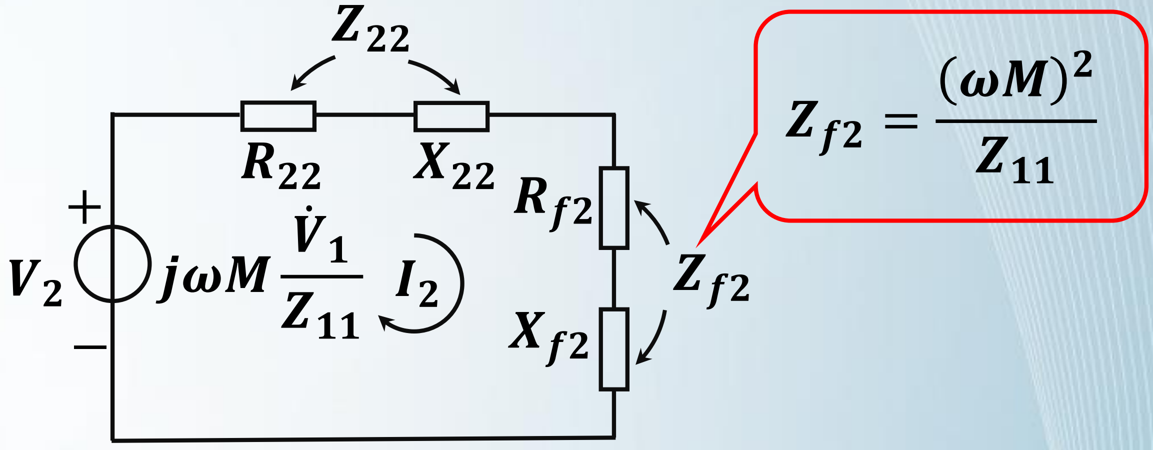
$$\begin{cases} R_{f1} = \dfrac{(\omega M)^2}{R_{22}{}^2 + X_{22}{}^2} R_{22} \\ X_{f1} = \dfrac{-(\omega M)^2}{R_{22}{}^2 + X_{22}{}^2} X_{22} \end{cases}$$

Negative



Primary Z_{f1}

(a) Primary Equivalent Circuit



(b) Secondary Equivalent Circuit

$$Z_{f1} = R_{f1} + jX_{f1} = \frac{(\omega M)^2}{R_{22} + jX_{22}}$$

$$= \frac{(\omega M)^2}{{R_{22}}^2 + {X_{22}}^2} R_{22} + j \frac{-(\omega M)^2}{{R_{22}}^2 + {X_{22}}^2} X_{22}$$

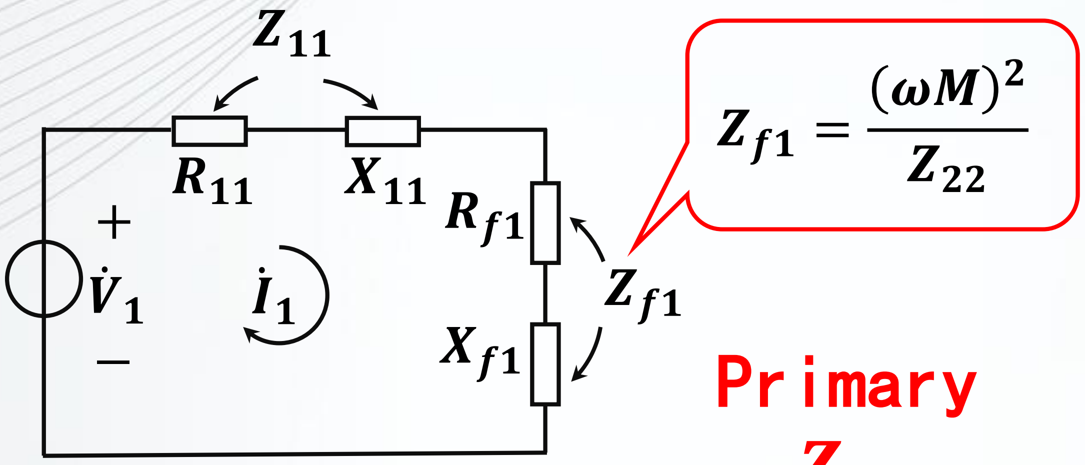
$$\begin{cases} R_{f1} = \dfrac{(\omega M)^2}{{R_{22}}^2 + {X_{22}}^2} R_{22} \\ X_{f1} = \dfrac{-(\omega M)^2}{{R_{22}}^2 + {X_{22}}^2} X_{22} \end{cases}$$

→Positive (Energy Loss)

→Opposite

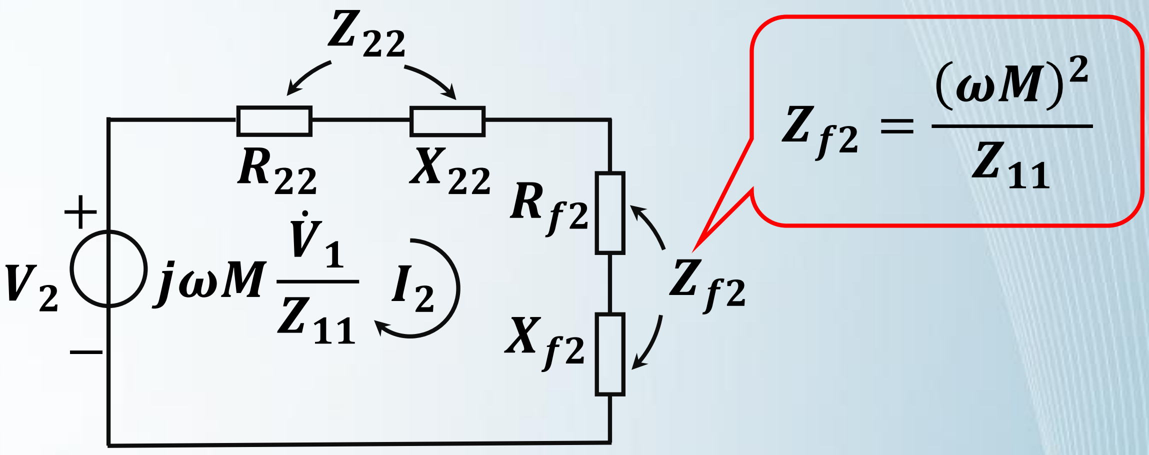
Negative

Exp: X_{22} Inductive (X_{22}>0), X_{f1} Capacitive(X_{f1}<0)



Primary Z_{f1}

(a) Primary Equivalent Circuit



(b) Secondary Equivalent Circuit

$$Z_{f1} = R_{f1} + jX_{f1} = \frac{(\omega M)^2}{R_{22} + jX_{22}}$$

$$= \frac{(\omega M)^2}{{R_{22}}^2 + {X_{22}}^2} R_{22} + j \frac{-(\omega M)^2}{{R_{22}}^2 + {X_{22}}^2} X_{22}$$

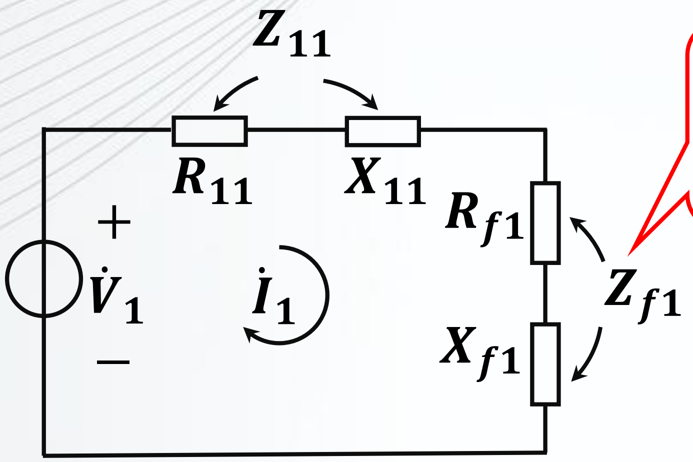
$$\begin{cases} R_{f1} = \dfrac{(\omega M)^2}{{R_{22}}^2 + {X_{22}}^2} R_{22} \\ X_{f1} = \dfrac{-(\omega M)^2}{{R_{22}}^2 + {X_{22}}^2} X_{22} \end{cases}$$

Negative

If $X_{11} = X_{22} = 0$

$\Rightarrow R_{f1} = \frac{(\omega M)^2}{R_{22}}$; $\quad X_{f1} = 0$

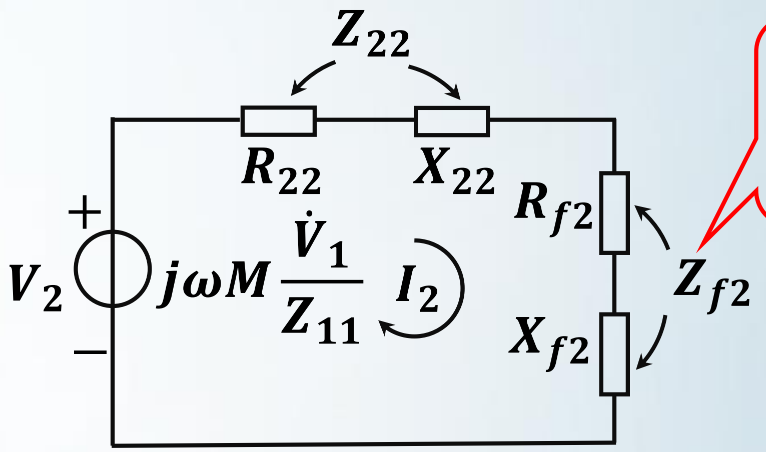
Pure resistance, R_{f1} & R_{22} are reciprocal



$$Z_{f1}=\frac{(\omega M)^2}{Z_{22}}$$

Primary Z_{f1}

(a) Primary Equivalent Circuit



$$Z_{f2}=\frac{(\omega M)^2}{Z_{11}}$$

(b) Secondary Equivalent Circuit

$$Z_{f1}=R_{f1}+jX_{f1}=\frac{(\omega M)^2}{R_{22}+jX_{22}}$$

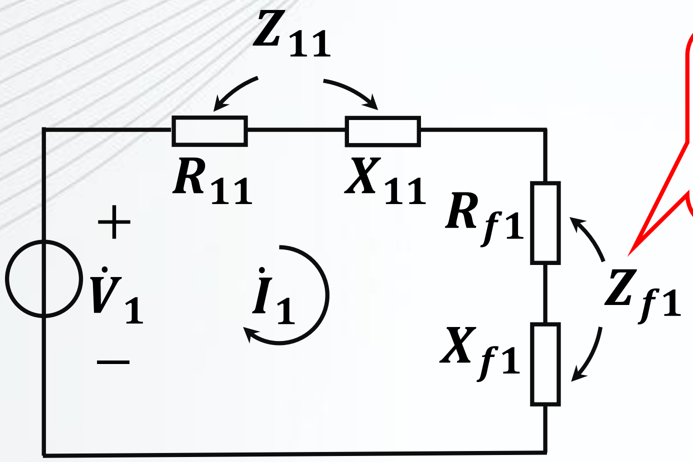
$$=\frac{(\omega M)^2}{{R_{22}}^2+{X_{22}}^2}R_{22}+j\frac{-(\omega M)^2}{{R_{22}}^2+{X_{22}}^2}X_{22}$$

$$\begin{cases} R_{f1}=\dfrac{(\omega M)^2}{{R_{22}}^2+{X_{22}}^2}R_{22} \\ X_{f1}=\dfrac{-(\omega M)^2}{{R_{22}}^2+{X_{22}}^2}X_{22} \end{cases}$$

Negative

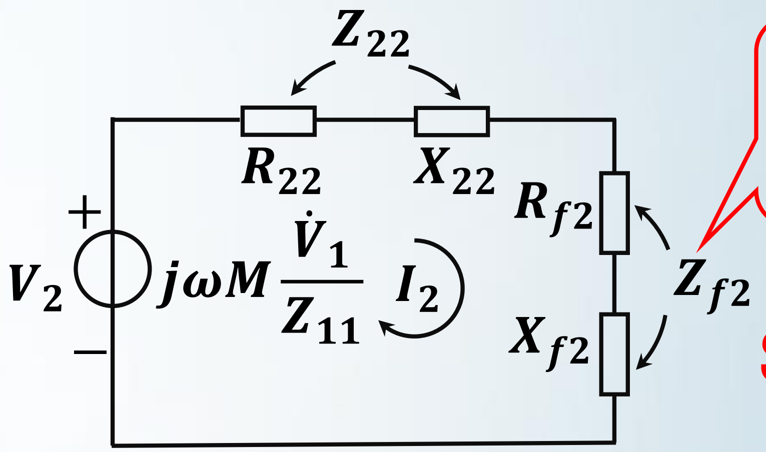
Proportional to $(\omega M)^2$

If $M=0$, $Z_{f1}=0$



$$Z_{f1} = \frac{(\omega M)^2}{Z_{22}}$$

(a) Primary Equivalent Circuit



$$Z_{f2} = \frac{(\omega M)^2}{Z_{11}}$$

Secondary Z_{f2}

(b) Secondary Equivalent Circuit

$$Z_{f2} = R_{f2} + jX_{f2} = \frac{(\omega M)^2}{R_{11} + jX_{11}}$$

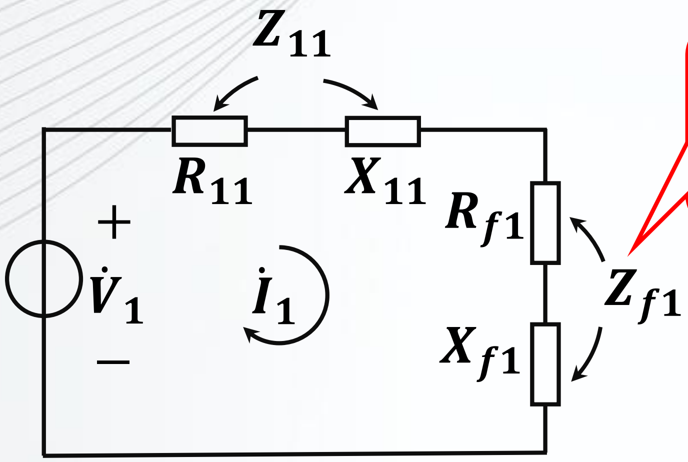
$$= \frac{(\omega M)^2}{R_{11}{}^2 + X_{11}{}^2} R_{11} + j \frac{-(\omega M)^2}{R_{11}{}^2 + X_{11}{}^2} X_{11}$$

Positive (Energy Loss) ← $R_{f2} = \frac{(\omega M)^2}{R_{11}{}^2 + X_{11}{}^2} R_{11}$

Opposite ← $X_{f2} = \frac{-(\omega M)^2}{R_{11}{}^2 + X_{11}{}^2} X_{11}$

Negative

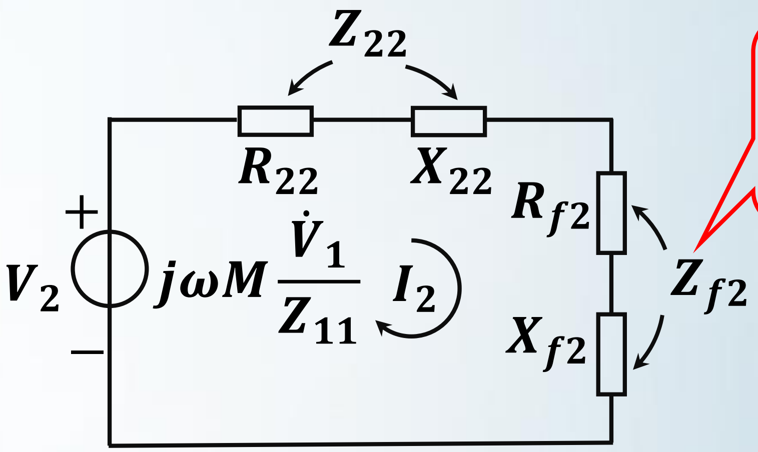
Exp: X_{11} Inductive(X_{11}>0), X_{f2}Capacitive(X_{f2}<0)



$$Z_{f1}=\frac{(\omega M)^2}{Z_{22}}$$

Primary Z_{f1}

(a) Primary Equivalent Circuit



$$Z_{f2}=\frac{(\omega M)^2}{Z_{11}}$$

Secondary Z_{f2}

(b) Secondary Equivalent Circuit

$$Z_{f2}=R_{f2}+jX_{f2}=\frac{(\omega M)^2}{R_{11}+jX_{11}}$$

$$=\frac{(\omega M)^2}{R_{11}{}^2+X_{11}{}^2}R_{11}+j\frac{-(\omega M)^2}{R_{11}{}^2+X_{11}{}^2}X_{11}$$

Applicable to pure reactance coupling system

$$\begin{cases} R_{f1}=\dfrac{(\omega M)^2}{R_{22}{}^2+X_{22}{}^2}R_{22} \\ X_{f1}=\dfrac{-(\omega M)^2}{R_{22}{}^2+X_{22}{}^2}X_{22} \end{cases}$$

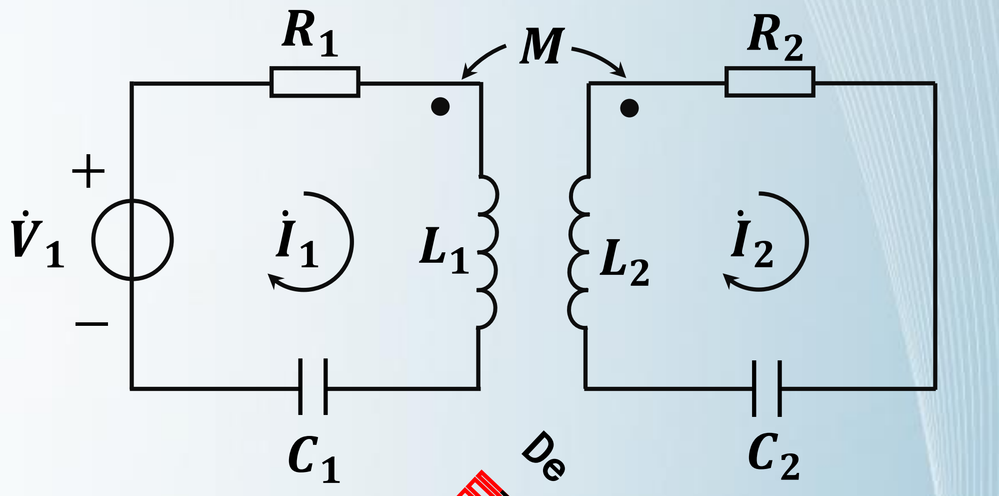
Negative

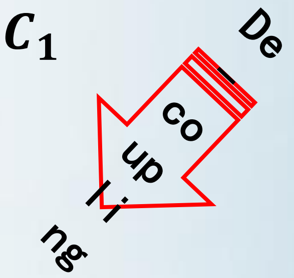
$$\begin{cases} R_{f2}=\dfrac{(\omega M)^2}{R_{11}{}^2+X_{11}{}^2}R_{11} \\ X_{f2}=\dfrac{-(\omega M)^2}{R_{11}{}^2+X_{11}{}^2}X_{11} \end{cases}$$

Negative

Coupling Circuit—Resonance

Primary Circuit Secondary Circuit





- Resonance: Reactance=0

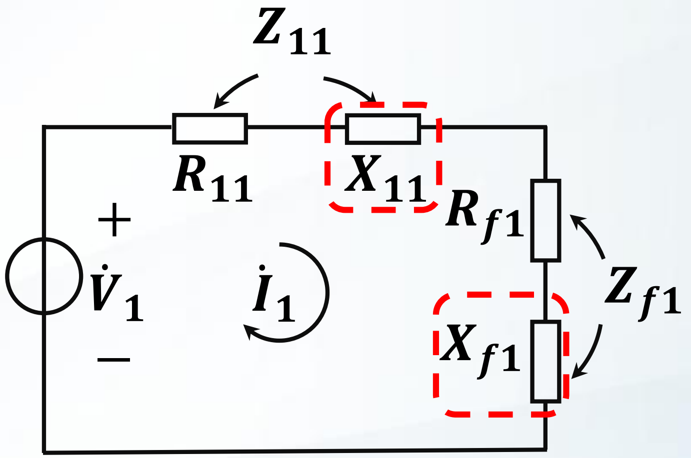
$$X_{11} = \omega L_1 - \frac{1}{\omega C_1}$$

Primary Resonance $(X_{11} = 0)$

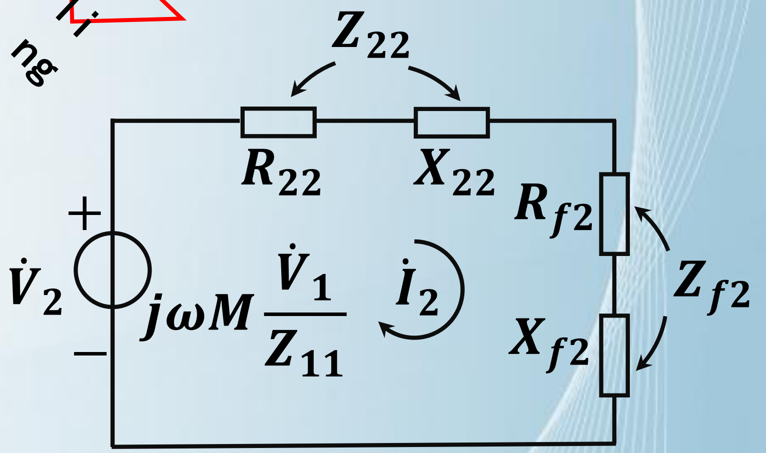
Primary Equivalent Resonance $(X_{11} + X_{f1} = 0)$

- Match: Optimal Power Transmission

$(R_{11} = R_{f1})$



Primary Equivalent Circuit

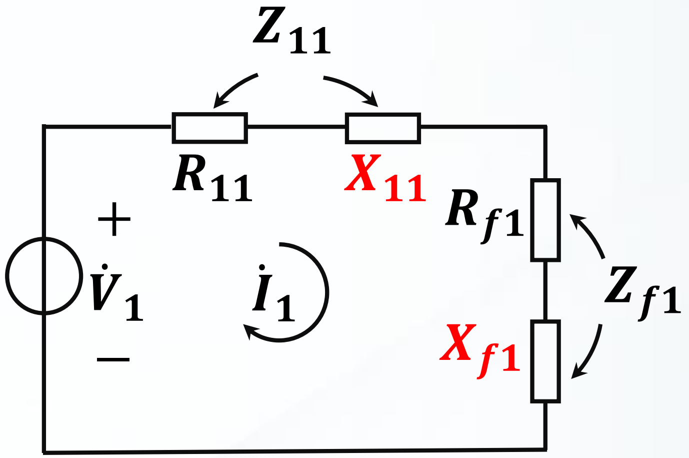
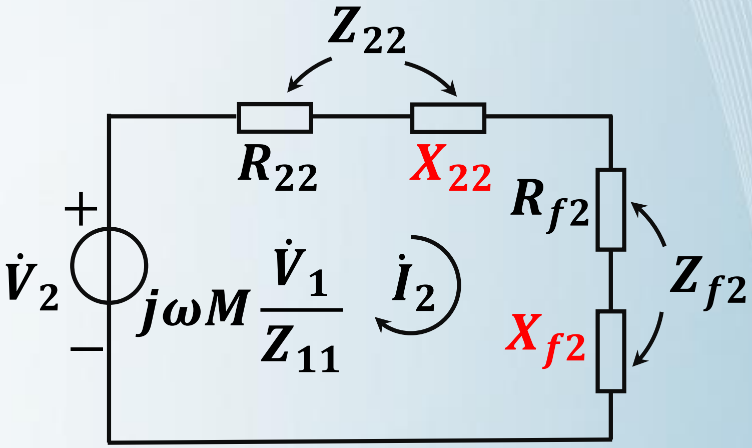


Secondary Equivalent Circuit

Coupling Circuit—Resonance (Classification)

1. Partial Resonance
   - Primary PR
   - Secondary PR
2. Complex Resonance
3. Complete Resonance (Best Complete Resonance)

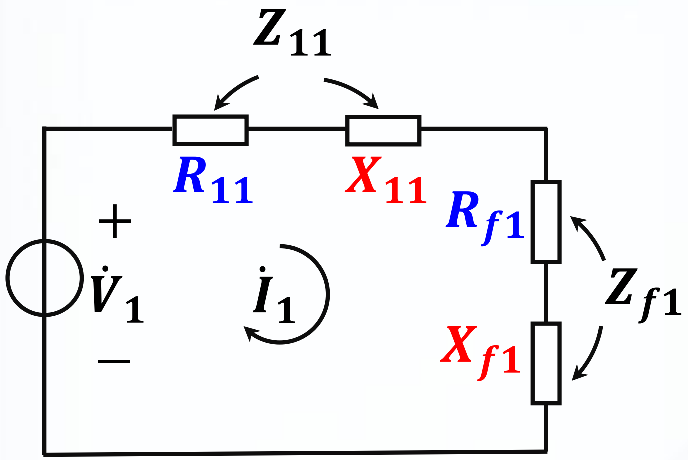
(1) Partial Resonance

	Primary Partial Resonance	Secondary Partial Resonance
Equivalent Circuit	 Primary Equivalent Circuit	 Secondary Equivalent Circuit
Definition	$X_{11} + X_{f1} = 0$	$X_{22} + X_{f2} = 0$
Physical Significance	Primary Equivalent Resonance $\neq$ Primary Resonance	Secondary Equivalent Resonance $\neq$ Secondary Resonance

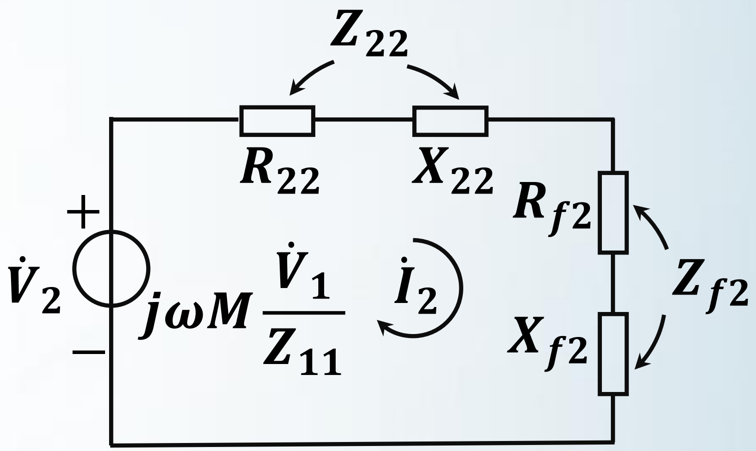
$(X_{11} = 0)$

$(X_{22} = 0)$

(2) Complex Resonance = Partial Resonance + Matching



(a) Primary Equivalent Circuit



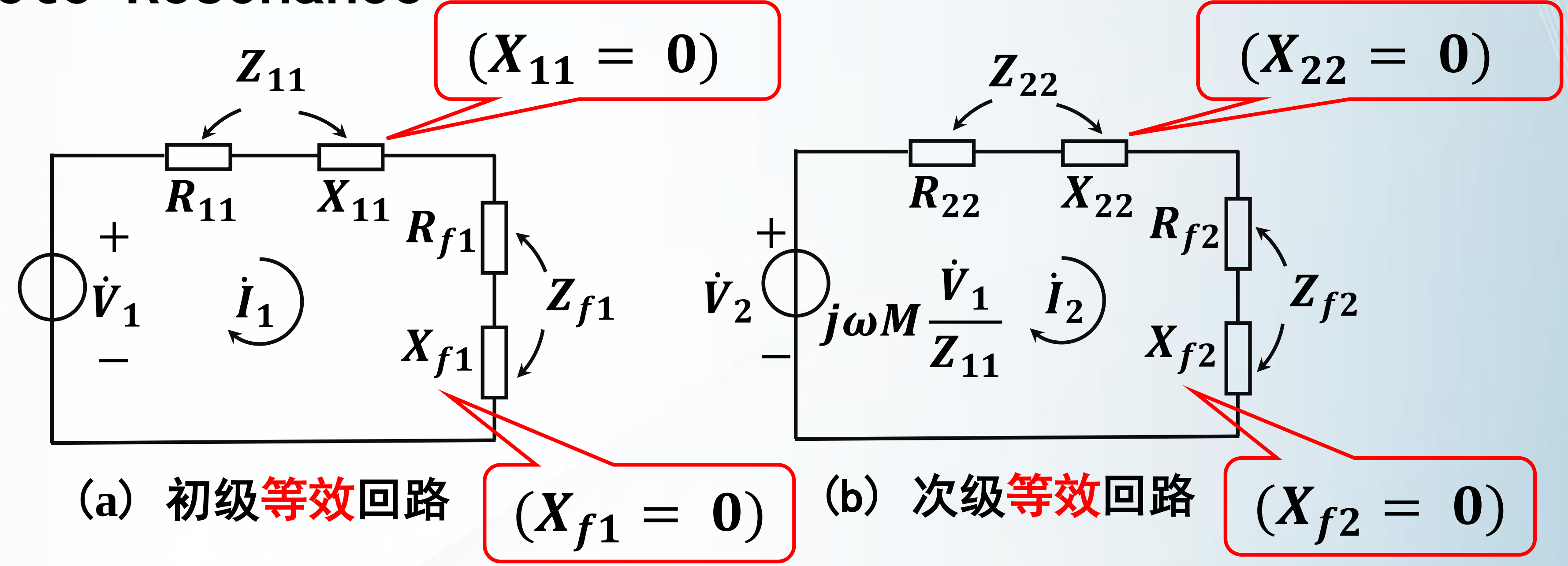
(b) Secondar Equivalent Circuit

Definition:

- Primary Equivalent Resonance ($X_{11}+X_{f1} = 0$) & Matching($R_{11} = R_{f1}$)

$\neq$ Primary Resonance ($X_{11} = 0$)

(3) Complete Resonance



(a) 初级等效回路　(b) 次级等效回路

- Complete Resonance ⇔ Primary Resonance$(X_{11} = 0)$& Secondary Resonance $(X_{22} = 0)$

$(X_{11} + X_{f1} = 0)$　　$(X_{22} + X_{f2} = 0)$

- Complete Resonance+ Matching$(R_{11} = R_{f1};\ R_{22} = R_{f2})$ ⇔ Optimal Complete Resonance

Summary—Coupling Circuit（Resonance）

- Partial、Complex、Complete（Optimal Complete）Resonance
  - Complex Resonance =Partial Resonance + Matching
  - Optimal Complete Resonance =Complete Resonance+ Matching（special case of complex resonance）

Q：Relationship