第11章 电路的频率响应

本章重点

*网络函数的概念，幅频特性和相频特性的意义；

***RLC串联的谐振分析；**

RLC串联电路的频率响应及Q值、带宽、通频带；

***RLC并联电路的谐振分析；**

RC低通滤波器、 RC高通滤波器。

11.1 网络函数

单一正弦激励下，电路稳态响应的都为同频率的正弦量。

1. 定 义

电路的工作状态随频率而变化的现象，称为频率特性（频率响应）

响应与激励之间的函数关系称为 **网络函数**

$H(\mathrm{j}\omega)$ ⇒ $$H(\mathrm{j}\omega)=\frac{\dot{R}_k(\mathrm{j}\omega)}{\dot{E}_{\mathrm{S}j}(\mathrm{j}\omega)}$$

$\dot{R}_k(\mathrm{j}\omega)$ ⇒ 端口k的正弦稳态响应相量 $\dot{I}_k(\mathrm{j}\omega)$ 或 $\dot{U}_k(\mathrm{j}\omega)$

$\dot{E}_{\mathrm{S}j}(\mathrm{j}\omega)$ ⇒ 端口j处的输入变量（正弦激励）$\dot{I}_{\mathrm{S}j}(\mathrm{j}\omega)$ 或 $\dot{U}_{\mathrm{S}j}(\mathrm{j}\omega)$

网络函数与激励无关，是系统参数和结构决定的。

网络函数是一个复数。 $H(\mathrm{j}\omega)=|H(\mathrm{j}\omega)|\angle\varphi(\mathrm{j}\omega)$

2. 网络函数是一个复数

$$H(\mathrm{j}\omega)=\frac{\dot{R}_k(\mathrm{j}\omega)}{\dot{E}_{\mathrm{S}j}(\mathrm{j}\omega)}=\left|H(\mathrm{j}\omega)\right|\angle\varphi(\mathrm{j}\omega)$$

幅频特性：正弦量有效值或振幅值之比

相频特性：正弦量初相位之差

$\left.\begin{matrix} \\ \\ \end{matrix}\right\}$ 频响特性

已知网络函数，已知激励，可以求响应。

3. 网络函数的物理意义

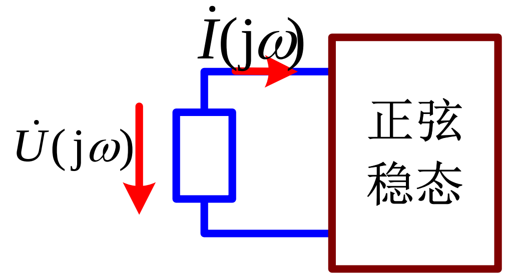
网络函数有多种类型

当激励和响应属于同一对端子时，称为**驱动点函数**。

当激励和响应不属于同一对端子时，称为**转移函数**。

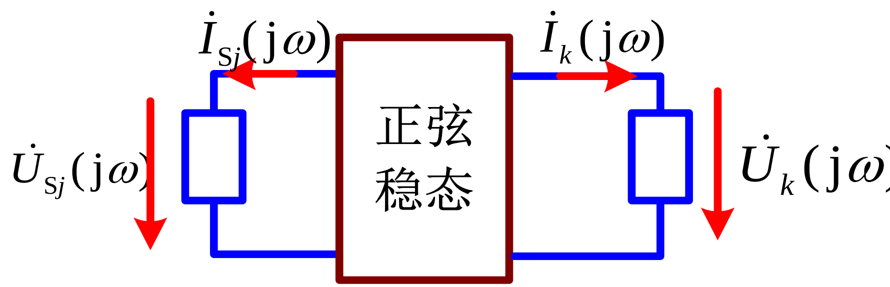
驱动点函数

- **驱动点阻抗** $Z = H(\mathrm{j}\omega) = \dfrac{\dot{U}(\mathrm{j}\omega)}{\dot{I}(\mathrm{j}\omega)}$
- **驱动点导纳** $Y = H(\mathrm{j}\omega) = \dfrac{\dot{I}(\mathrm{j}\omega)}{\dot{U}(\mathrm{j}\omega)}$



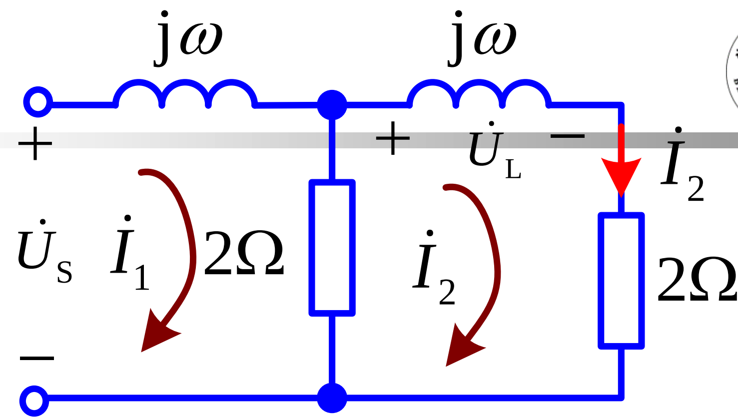
转移函数

- **转移阻抗** $H(\mathrm{j}\omega) = \dfrac{\dot{U}_k(\mathrm{j}\omega)}{\dot{I}_{\mathrm{S}j}(\mathrm{j}\omega)}$
- **转移导纳** $H(\mathrm{j}\omega) = \dfrac{\dot{I}_k(\mathrm{j}\omega)}{\dot{U}_{\mathrm{S}j}(\mathrm{j}\omega)}$
- **转移电压比** $H(\mathrm{j}\omega) = \dfrac{\dot{U}_k(\mathrm{j}\omega)}{\dot{U}_{\mathrm{S}j}(\mathrm{j}\omega)}$
- **转移电流比** $H(\mathrm{j}\omega) = \dfrac{\dot{I}_k(\mathrm{j}\omega)}{\dot{I}_{\mathrm{S}j}(\mathrm{j}\omega)}$



【例】

求电路的网络函数 $\dfrac{\dot I_2}{\dot U_S}$，$\dfrac{\dot U_L}{\dot U_S}$。



解

$$\begin{cases}(2+\mathrm{j}\omega)\dot I_1-2\dot I_2=\dot U_S\\-2\dot I_1+(4+\mathrm{j}\omega)\dot I_2=0\end{cases}$$

$$\dot I_2=\frac{2\dot U_S}{4+(\mathrm{j}\omega)^2+\mathrm{j}6\omega}$$

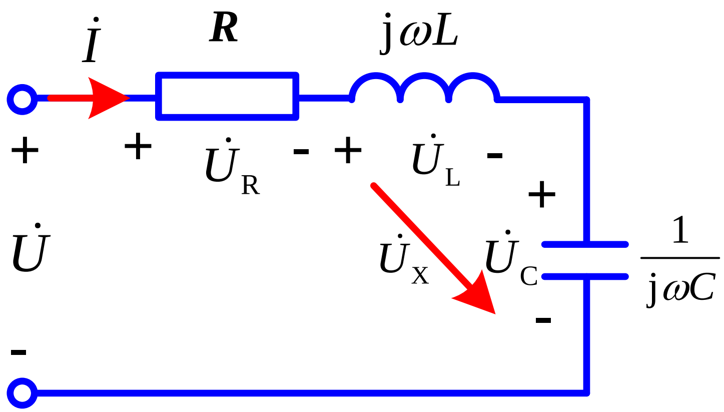
$$\frac{\dot I_2}{\dot U_S}=\frac{2}{(4-\omega^2)+\mathrm{j}6\omega}$$

转移导纳

$$\frac{\dot U_L}{\dot U_S}=\frac{\mathrm{j}2\omega}{(4-\omega^2)+\mathrm{j}6\omega}$$

转移电压比

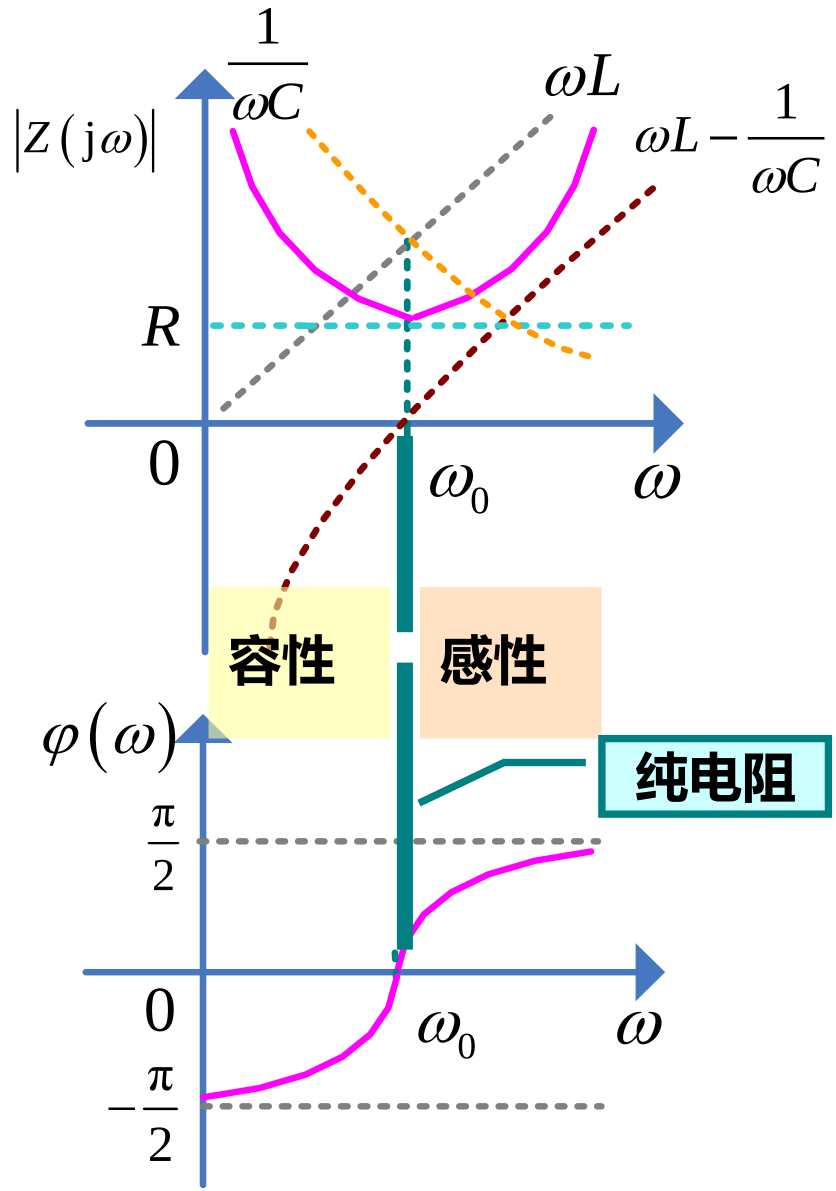
11.2 *RLC*串联电路的谐振

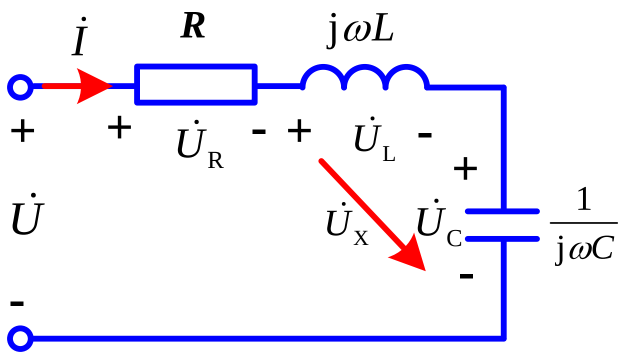


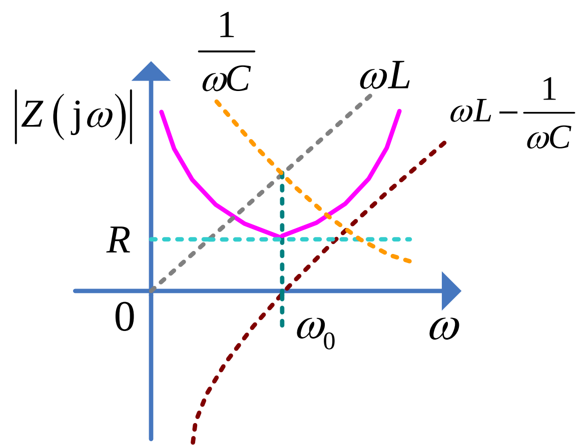
驱动点阻抗 $Z = R + \mathrm{j}\left(\omega L - \dfrac{1}{\omega C}\right)$

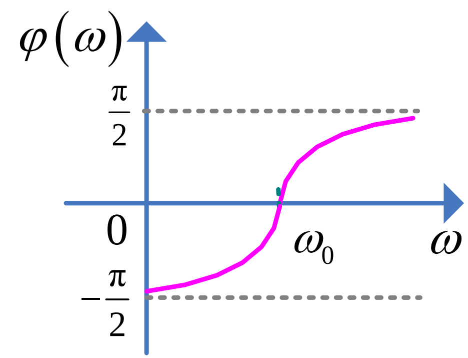
$$\left|Z(\mathrm{j}\omega)\right| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

$$\varphi(\mathrm{j}\omega) = \arctan\left(\frac{\omega L - \dfrac{1}{\omega C}}{R}\right)$$









$$Z=R+j\left(\omega L-\frac{1}{\omega C}\right)$$

1. 定义 端口电压、电流出现同相位的现象时，称电路发生了谐振；对于RLC串联电路，则称为串联谐振。

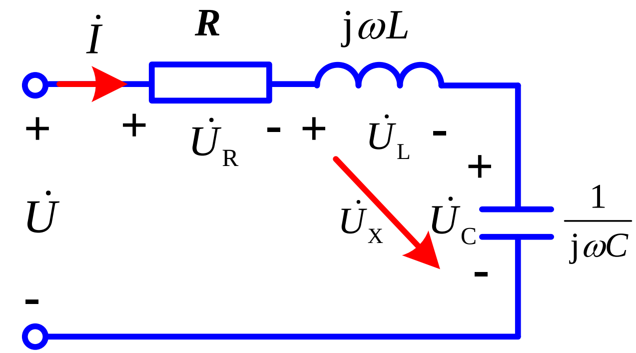
2. 条件

$$\boxed{\mathrm{Im}\left[Z(j\omega)\right]=0}$$

11.2 *RLC*串联电路的谐振

2. 条件

$$\mathrm{Im}\left[Z(\mathrm{j}\omega)\right]=0$$



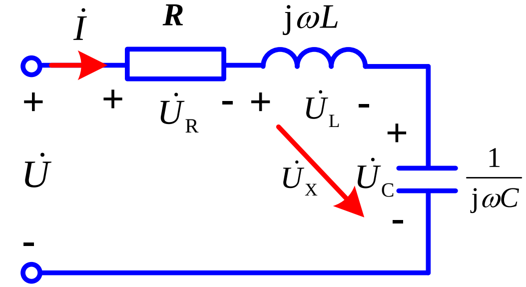
*由谐振条件得串联电路实现谐振的方式为:

(1) L、C 不变，改变 ω 达到谐振。

(2) 电源频率不变，改变 L 或 C (常改变 C) 达到谐振。

谐振角频率 $\omega_0=\dfrac{1}{\sqrt{LC}}$　　$f_0=\dfrac{1}{2\pi\sqrt{LC}}$ **谐振频率**

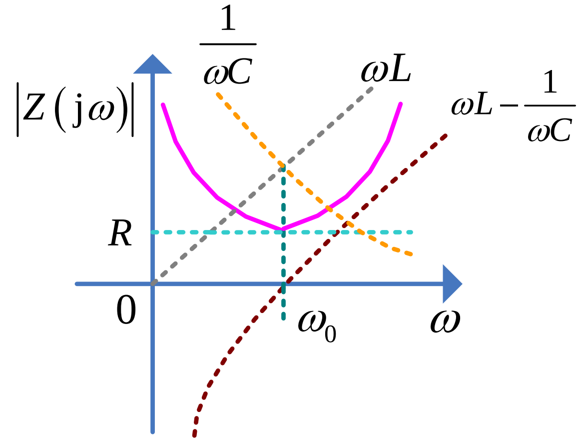
3. 特点 (阻抗、电流、电压、功率)



$$Z(\mathrm{j}\omega_0)=R+\mathrm{j}\left(\omega_0 L-\frac{1}{\omega_0 C}\right)=R$$

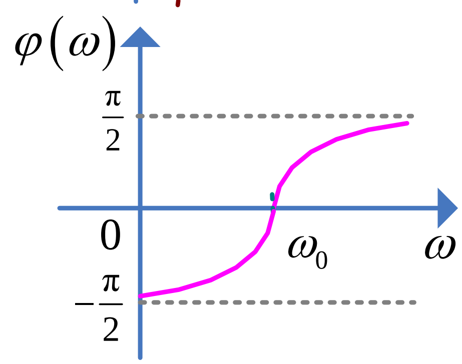
(1) $\dot U$、$\dot I$ **同相** $\varphi=0°$

$$Z=R \qquad |Z|=|Z|_{\min}=R$$

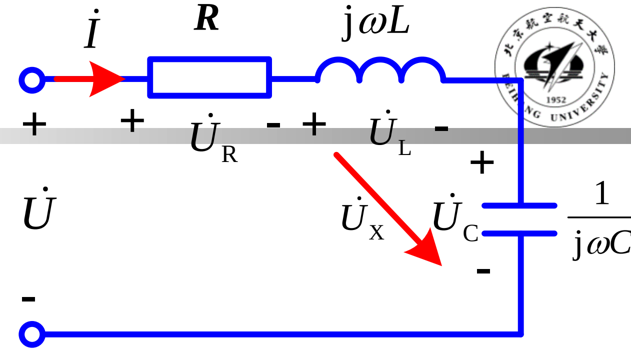


(2) 若U一定

$$I=\frac{U}{|Z|}=\frac{U}{R}=I_{\max}$$



(3) $\dot{U}_R = R\dot{I} = R\dfrac{\dot{U}}{R} = \dot{U}$

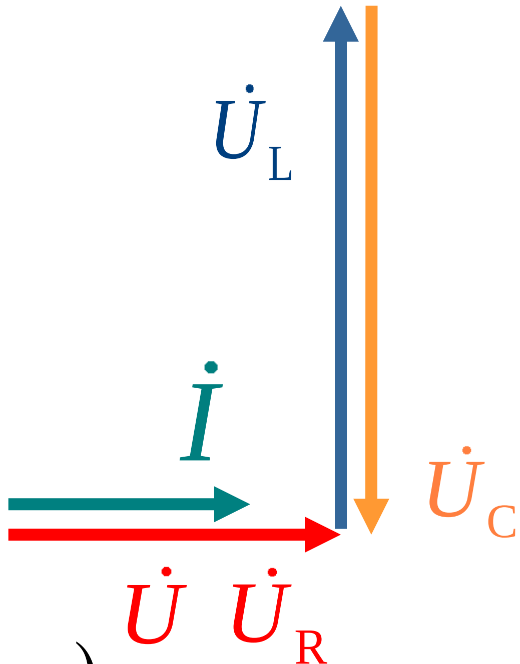


$$\dot{U}_X = \dot{U}_L + \dot{U}_C = 0$$

电压谐振　L串C部分视作短路

$$U_L = U_C$$

(4) $P = UI = RI^2 = \dfrac{U^2}{R}$



$$Q = Q_L + Q_C = 0$$

$$W_{存储}(j\omega_0) = W_L(j\omega_0) + W_C(j\omega_0)$$

$$W_{存储}(j\omega_0) = \frac{1}{2}LI_m^2(j\omega_0) = \frac{1}{2}CU_{Cm}^2(j\omega_0)$$

4. 品质因数Q

谐振时 $U_C = U_L = \omega_0 LI = \omega_0 L\dfrac{U}{R} = \dfrac{\omega_0 L}{R}U$

定义 $Q = \dfrac{U_L(\omega_0)}{U}$ $\Rightarrow$ $Q = \dfrac{\omega_0 L}{R} = \dfrac{1}{\omega_0 CR} = \dfrac{1}{R}\sqrt{\dfrac{L}{C}}$

$Q = \dfrac{Q_L(j\omega_0)}{P(j\omega_0)} = \dfrac{|Q_C(j\omega_0)|}{P(j\omega_0)}$ $\Leftarrow$ $Q = \dfrac{\omega_0 LI^2(j\omega_0)}{RI^2(j\omega_0)}$

$$W(j\omega_0) = \frac{1}{2}LI_m^2(j\omega_0) = \frac{1}{2}CU_{Cm}^2(j\omega_0) = CQ^2U_S^2(j\omega_0)$$

！Q综合反映了电路三个参数对谐振状态的影响！

驱动点阻抗 $Z = H(\mathrm{j}\omega) = \dfrac{\dot{U}(\mathrm{j}\omega)}{\dot{I}(\mathrm{j}\omega)}$

转移电压比 $H(\mathrm{j}\omega) = \dfrac{\dot{U}_\mathrm{R}(\mathrm{j}\omega)}{\dot{U}_\mathrm{S}(\mathrm{j}\omega)}$ $\quad H(\mathrm{j}\omega) = \dfrac{\dot{U}_\mathrm{L}(\mathrm{j}\omega)}{\dot{U}_\mathrm{S}(\mathrm{j}\omega)}$ $\quad H(\mathrm{j}\omega) = \dfrac{\dot{U}_\mathrm{C}(\mathrm{j}\omega)}{\dot{U}_\mathrm{S}(\mathrm{j}\omega)}$

(1) 电阻电压频率特性

$$H_\mathrm{R}(\mathrm{j}\omega) = \frac{\dot{U}_\mathrm{R}(\mathrm{j}\omega)}{\dot{U}_\mathrm{S}(\mathrm{j}\omega)} = \frac{R}{R + \mathrm{j}\left(\omega L - \dfrac{1}{\omega C}\right)}$$

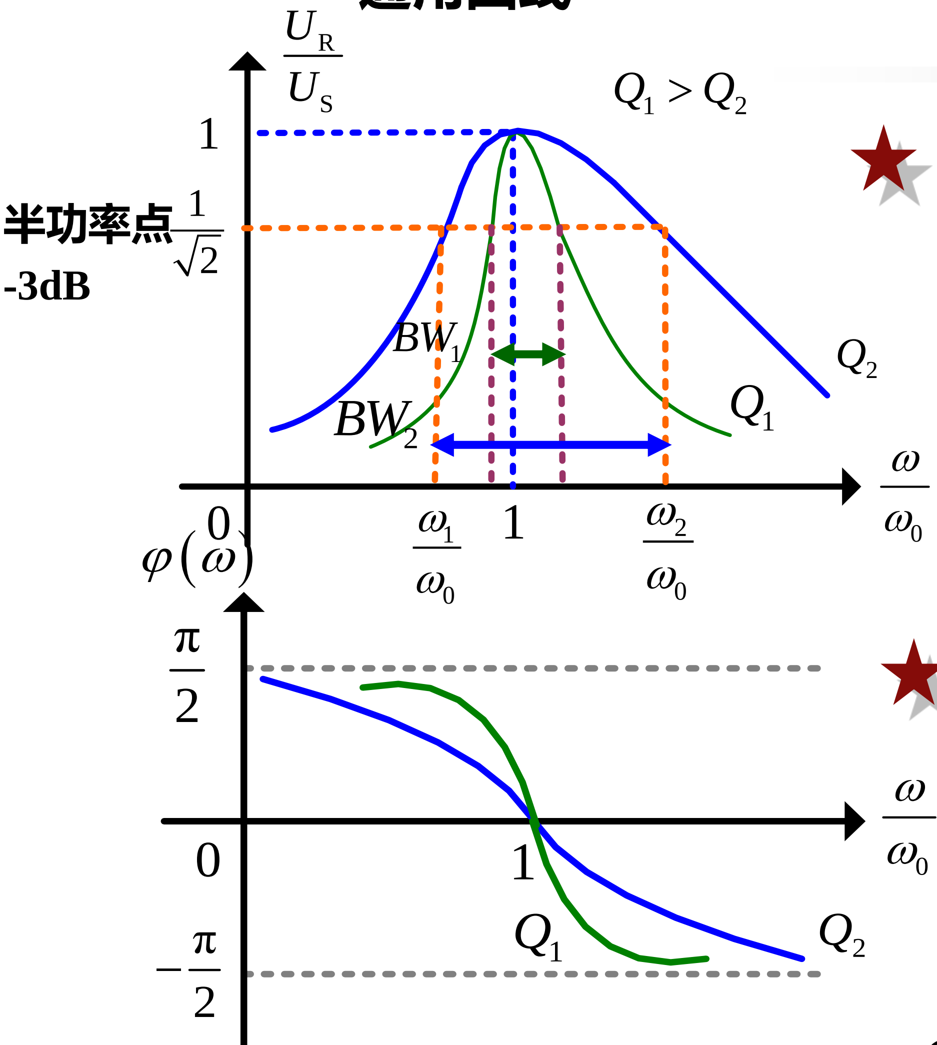
$$H_\mathrm{R}(\mathrm{j}\omega) = \frac{1}{1 + \mathrm{j}\left(\dfrac{\omega L}{R} - \dfrac{1}{R\omega C}\right)} = \frac{1}{1 + \mathrm{j}\left(\boxed{\dfrac{\omega}{\omega_0}}\boxed{\dfrac{\omega_0 L}{R}} - \boxed{\dfrac{1}{R\omega_0 C}}\boxed{\dfrac{\omega_0}{\omega}}\right)}$$

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR} \qquad \eta = \frac{\omega}{\omega_0}$$

$$H(\mathrm{j}\eta) = \frac{1}{1 + \mathrm{j}Q\left(\eta - \dfrac{1}{\eta}\right)}$$

$$\begin{cases} |H(\mathrm{j}\eta)| = \dfrac{1}{\sqrt{1 + Q^2\left(\eta - \dfrac{1}{\eta}\right)^2}} \\ \varphi(\mathrm{j}\eta) = -\arg\tan\left[Q\left(\eta - \dfrac{1}{\eta}\right)\right] \end{cases}$$

通用曲线



★
$$\begin{cases} |H(\mathrm{j}\eta)| = \dfrac{1}{\sqrt{1+Q^2\left(\eta-\dfrac{1}{\eta}\right)^2}} \\ \varphi(\mathrm{j}\eta) = -\arg\tan\left[Q\left(\eta-\dfrac{1}{\eta}\right)\right] \end{cases}$$

频率选择性：Q 越大越好

抑制能力：Q 越大抑制能力越强

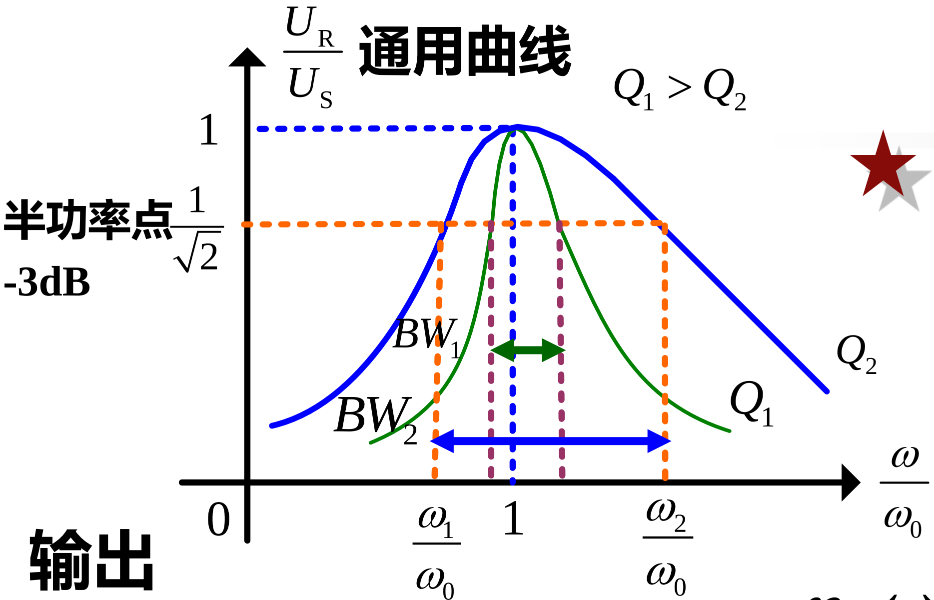
★ **通频带（通带）**

品质因数试验方法

$$Q = \frac{\omega_0}{\omega_2-\omega_1} = \frac{f_0}{f_2-f_1} = \frac{1}{\eta_2-\eta_1} = \frac{\omega_0}{BW}$$

通频带带宽

！Q反映电路选择性的好坏！



$$\begin{cases} |H(j\eta)| = \dfrac{1}{\sqrt{1+Q^2\left(\eta-\dfrac{1}{\eta}\right)^2}} \\ \varphi(j\eta) = -\arg\tan\left[Q\left(\eta-\dfrac{1}{\eta}\right)\right] \end{cases}$$

输出幅值指标 $|H| \geq \dfrac{1}{\sqrt{2}}$ $\quad |H| = \dfrac{1}{\sqrt{2}}$

$\eta_1 \leftrightarrow \omega_1 \leftrightarrow f_1$

$\eta_2 \leftrightarrow \omega_2 \leftrightarrow f_2$

截止频率 转折频率

$$\eta_1 = -\frac{1}{2Q} + \sqrt{\left(\frac{1}{2Q}\right)^2 + 1}$$

$$\eta_2 = \frac{1}{2Q} + \sqrt{\left(\frac{1}{2Q}\right)^2 + 1}$$

通频带（通带） $\omega_1 \leq \omega \leq \omega_2 \quad f_1 \leq f \leq f_2$

带宽 $BW = \begin{cases} \omega_2 - \omega_1 \\ f_2 - f_1 \\ \eta_2 - \eta_1 \end{cases} \quad Q = \dfrac{\omega_0}{BW} \sim \dfrac{f_0}{BW} \sim \dfrac{1}{BW}$

波特图 $\begin{cases} H_{dB} = 20\lg|H(j\omega)| \\ \lg\omega \end{cases} \quad \begin{cases} \varphi(j\omega) \\ \lg\omega \end{cases}$

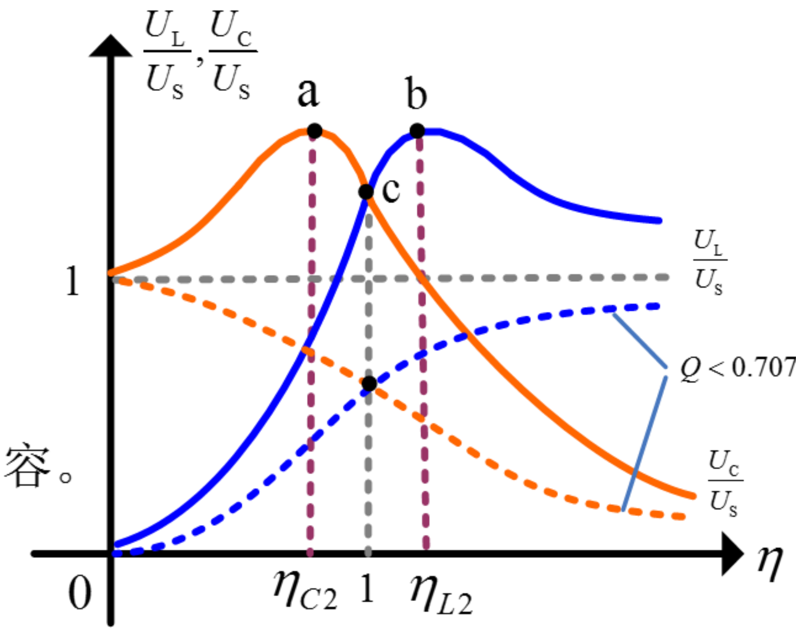
(2) 电感电压和电容电压频率特性

$$H_{\mathrm{C}}(\mathrm{j}\eta)=\frac{\dot{U}_{\mathrm{C}}(\mathrm{j}\eta)}{\dot{U}_{\mathrm{S}}(\mathrm{j}1)}=\frac{-\mathrm{j}Q}{\eta+\mathrm{j}Q\left(\eta^{2}-1\right)}$$

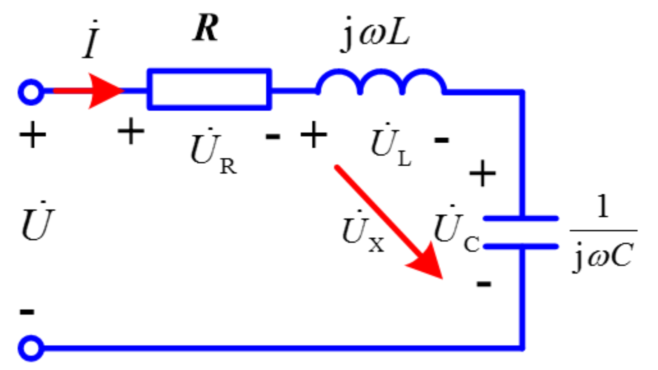
低通频率特性

若Q >> 1,则$U_C >> U_S$,可应用于无线电系统;

而电力系统应避免谐振，以免U_C过大，击毁电容。



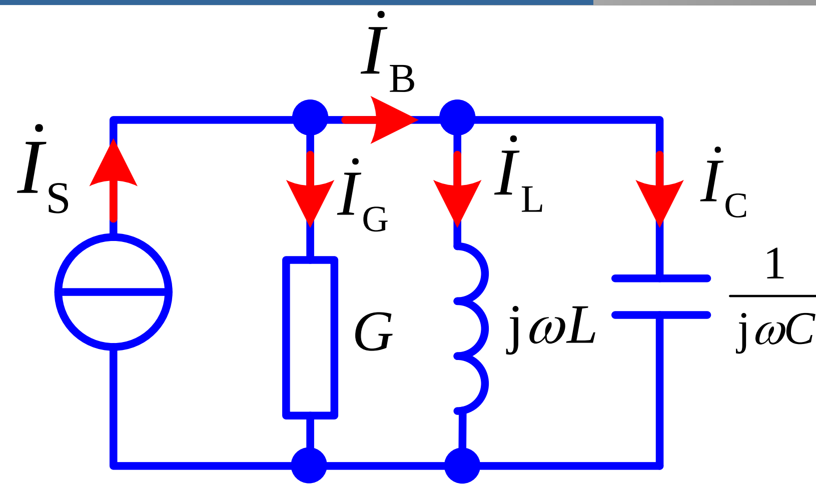
$$H_{\mathrm{L}}(\mathrm{j}\eta)=\frac{\dot{U}_{\mathrm{L}}(\mathrm{j}\eta)}{\dot{U}_{\mathrm{S}}(\mathrm{j}1)}=\frac{\mathrm{j}Q}{\frac{1}{\eta}+\mathrm{j}Q\left(1-\frac{1}{\eta^{2}}\right)}$$



高通频率特性

11.4 RLC并联谐振电路

$$Y = G + \mathrm{j}\left(\omega C - \frac{1}{\omega L}\right)$$



1. 定义

端口电压、电流出现同相位的现象时，称电路发生了谐振；对于RLC并联电路，则称为并联谐振。

2. 条件

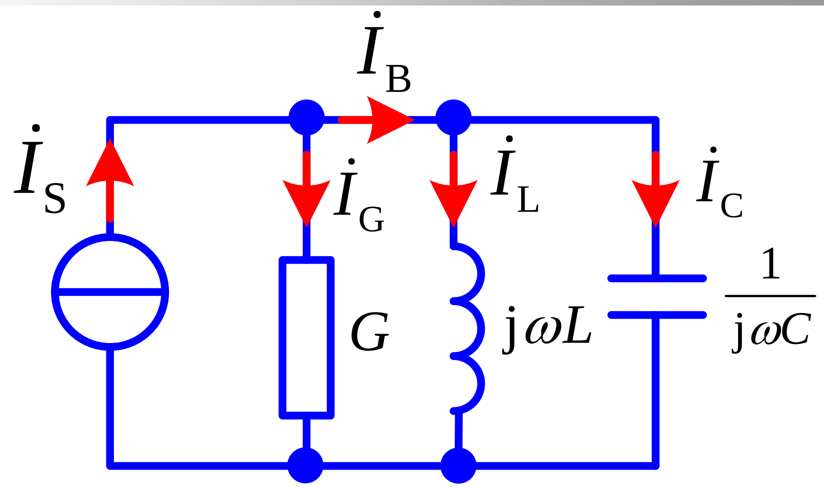
$$\mathrm{Im}\left[Y\left(\mathrm{j}\omega\right)\right] = 0$$

谐振角频率 $\omega_0 = \dfrac{1}{\sqrt{LC}}$

$f_0 = \dfrac{1}{2\pi\sqrt{LC}}$ **谐振频率**

3. 特点 (导纳、电压、电流、功率)

(1) $\dot{U}$、$\dot{I}$ 同相，$\varphi = 0°$



$$Y = G$$

$$|Y| = |Y|_{\min} = G$$

$$|Z| = \frac{1}{|Y|} = |Z|_{\max}$$

$$Y = G + j(\omega C - \frac{1}{\omega L})$$

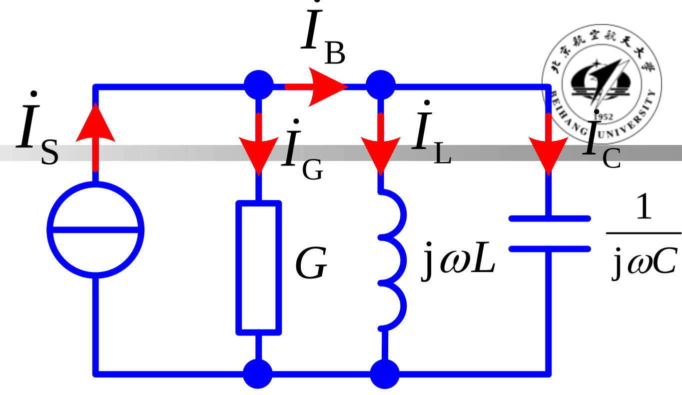
(2) 若I一定

$$U = I|Z| = IR = U_{\max}$$

(3) $\dot{I}_B = \dot{I}_L + \dot{I}_C = 0$

$I_L = I_C$

$I_S = I_G$



$$Y = G + j(\omega C - \frac{1}{\omega L})$$

电流谐振　L并C视作开路

(4) $P = UI = RI^2 = \dfrac{U^2}{R}$

$$Q = Q_L + Q_C = 0$$

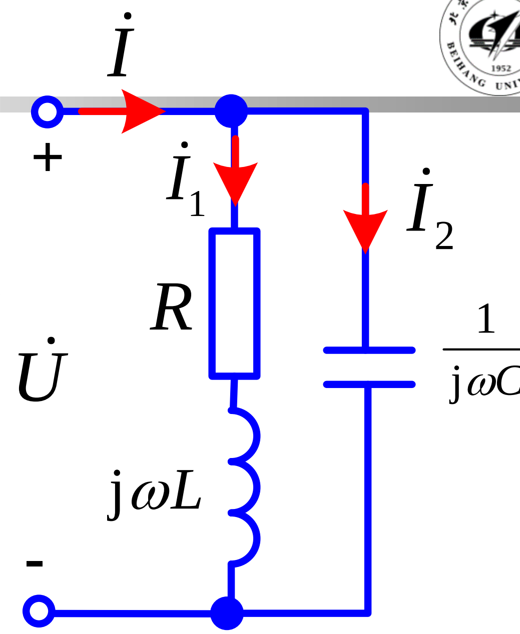
$$Y=\frac{1}{R+\mathrm{j}\omega L}+\mathrm{j}\omega C$$

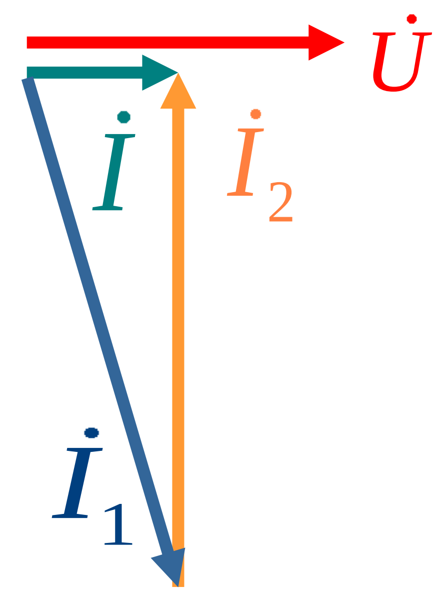
$$=\frac{R}{R^2+(\omega L)^2}-\mathrm{j}\frac{\omega L}{R^2+(\omega L)^2}+\mathrm{j}\omega C$$

$$\mathrm{Im}[Y]=0$$

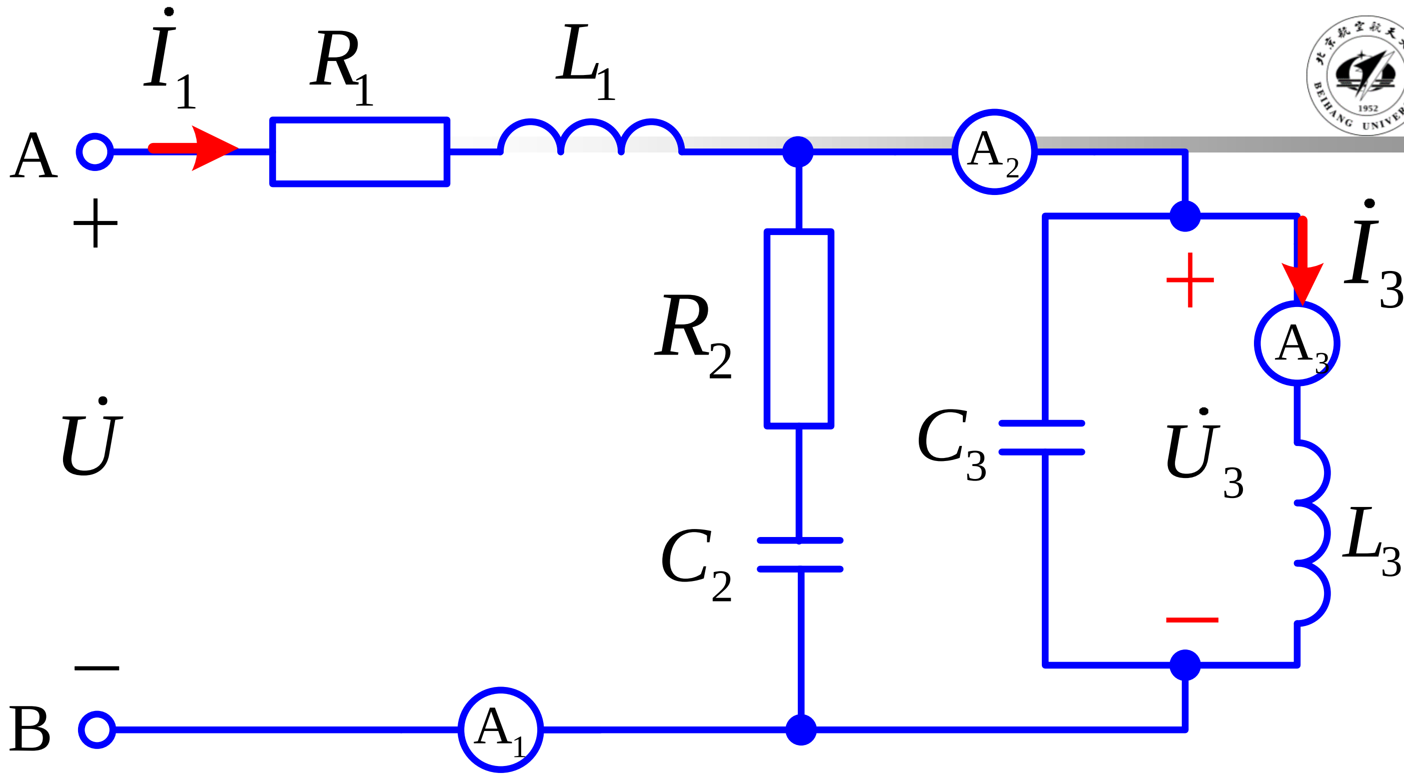
$$\omega C-\frac{\omega L}{R^2+(\omega L)^2}=0$$

$$\omega_0=\frac{1}{\sqrt{LC}}\sqrt{1-\frac{CR^2}{L}}$$





【例】



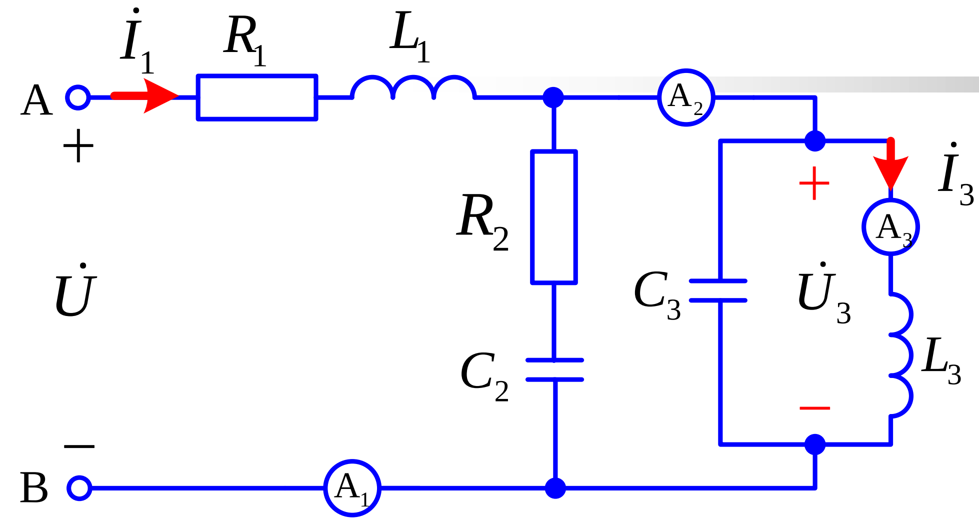
已知： $R_1 = 50\Omega$ $R_2 = 50\Omega$ $L_1 = 200\text{mH}$ $C_2 = 5\mu\text{F}$

$L_3 = 100\text{mH}$ $C_3 = 10\mu\text{F}$ $U = 200\text{V}$

电流表A2指示为零，所有电流表内阻忽略不计

求：（1）A1，A3的读数

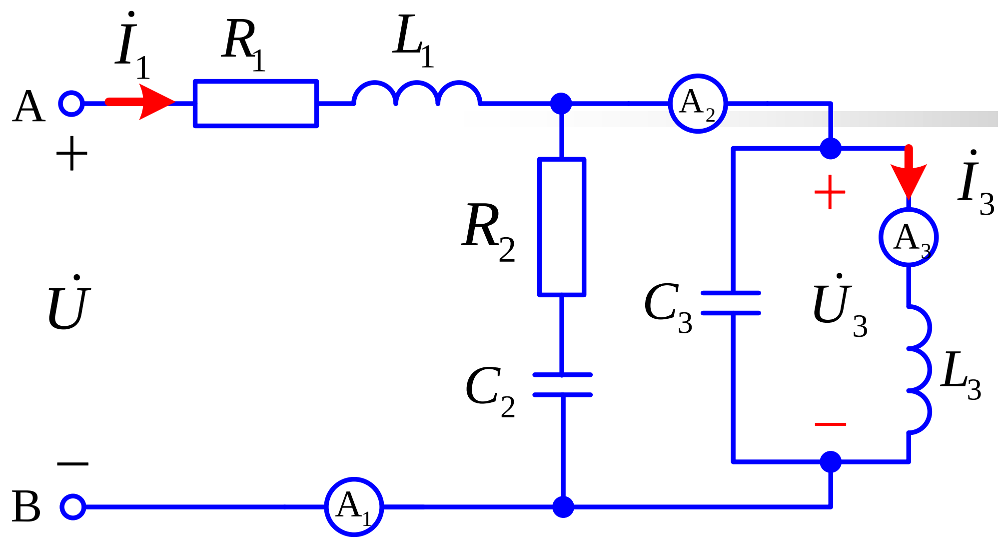
（2）输入AB端的功率和功率因数。



解

(1) $$\omega C_3 = \frac{1}{\omega L_3}$$

$$\omega = \frac{1}{\sqrt{L_3 C_3}} = \frac{1}{\sqrt{100\times 10^{-3}\times 10\times 10^{-6}}} = 10^3\,\text{rad/s}$$

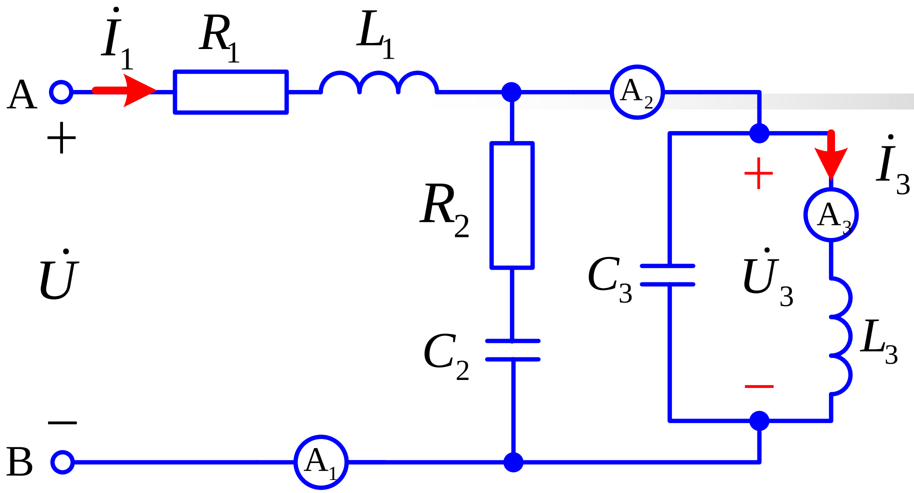


$$Z=(R_1+R_2)+\mathrm{j}\left(\omega L_1-\frac{1}{\omega C_2}\right)$$

$$=50+50+\mathrm{j}\left(10^3\times200\times10^{-3}-\frac{1}{10^3\times5\times10^{-6}}\right)$$

$$=100\angle0^0\Omega$$

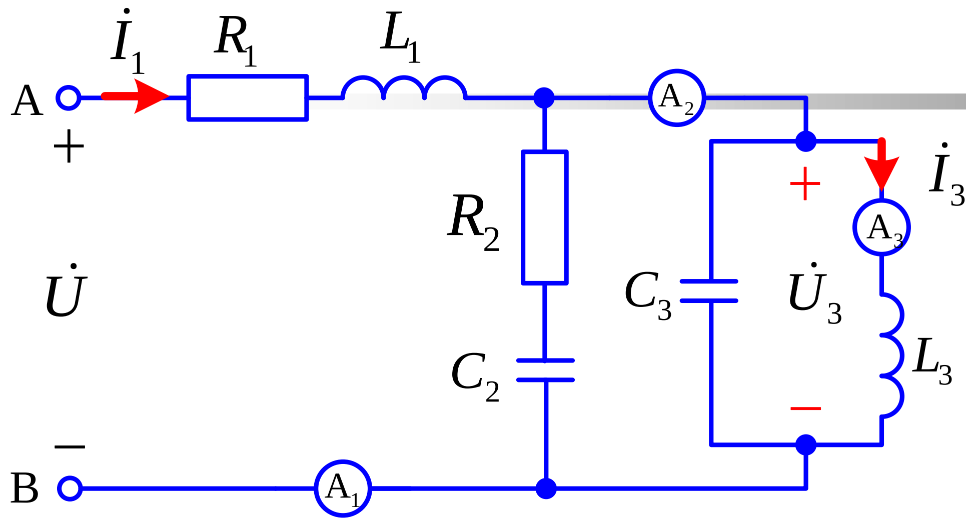
$$I_1=\frac{U}{|Z|}=\frac{200}{100}=2\mathrm{A}$$



$$U_3 = I_1\left|Z_2\right| = I_1\sqrt{R_2{}^2 + \left(\frac{1}{\omega C_2}\right)^2} = 412.3\text{V}$$

$$I_3 = \frac{U_3}{\omega L_3} = \frac{412.3}{10^3 \times 100 \times 10^{-3}} = 4.12\text{A}$$

(2)



$$\varphi = 0^\circ$$

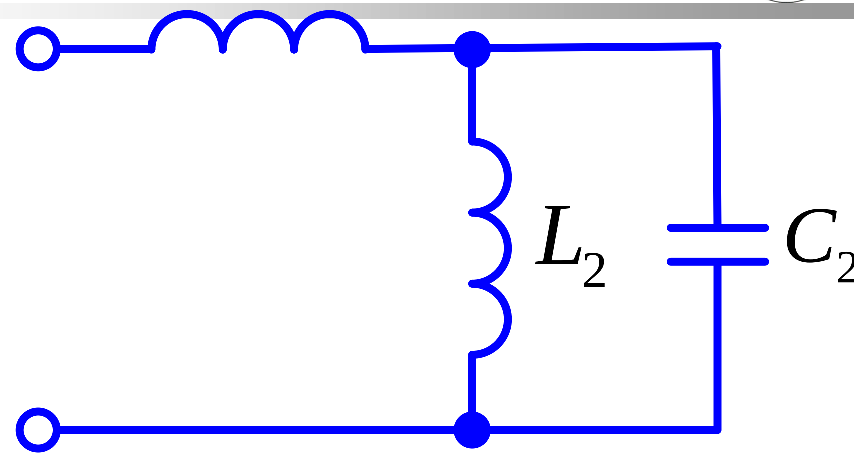
$$\cos\varphi = 1$$

$$P = UI_1\cos\varphi = 200\times 2 = 400\text{W}$$

或 $P = I_1^2(R_1+R_2) = 2^2\times(50+50) = 400\text{W}$

【例】

分析图示电路的串并联谐振。



解 **既有串联谐振，也有并联谐振。**

先求 $Z, \mathrm{I_m}[Z]=0$, **串联谐振**

再求 $Y, \mathrm{I_m}[Y]=0$, **并联谐振**

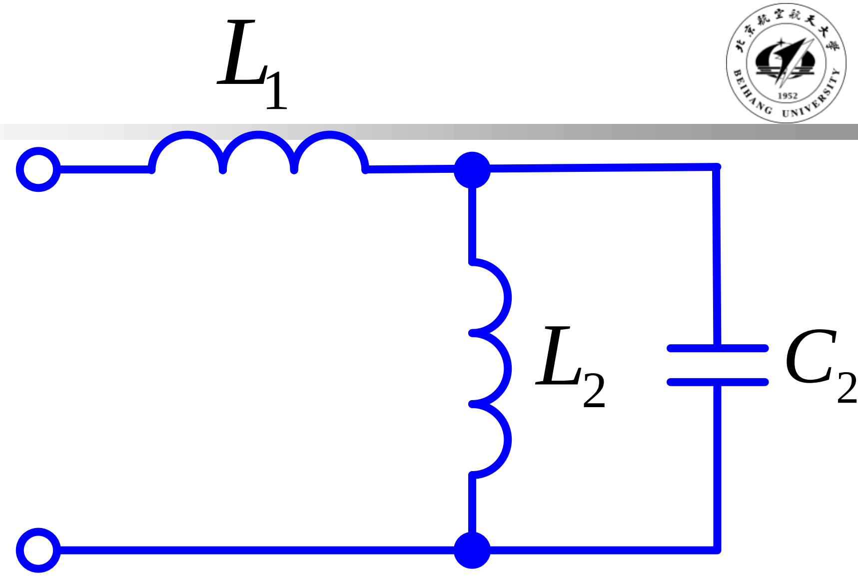
$$Z=\mathrm{j}\omega L_1+\frac{\mathrm{j}\omega L_2\left(-\mathrm{j}\dfrac{1}{\omega C_2}\right)}{\mathrm{j}\omega L_2-\mathrm{j}\dfrac{1}{\omega C_2}}=\mathrm{j}\frac{\omega^3 L_1 L_2 C_2-\omega\left(L_1+L_2\right)}{\omega^2 L_2 C_2-1}$$

串联谐振 $\mathrm{I_m}[Z]=0$

$$\omega_{01}=\sqrt{\frac{L_1+L_2}{L_1L_2C_2}}$$

并联谐振 $\mathrm{I_m}[Y]=0$

$$\omega_{02}=\sqrt{\frac{1}{L_2C_2}}$$



谐振特点：电流电压同相；LC间能量交换，与外部没有能量交换

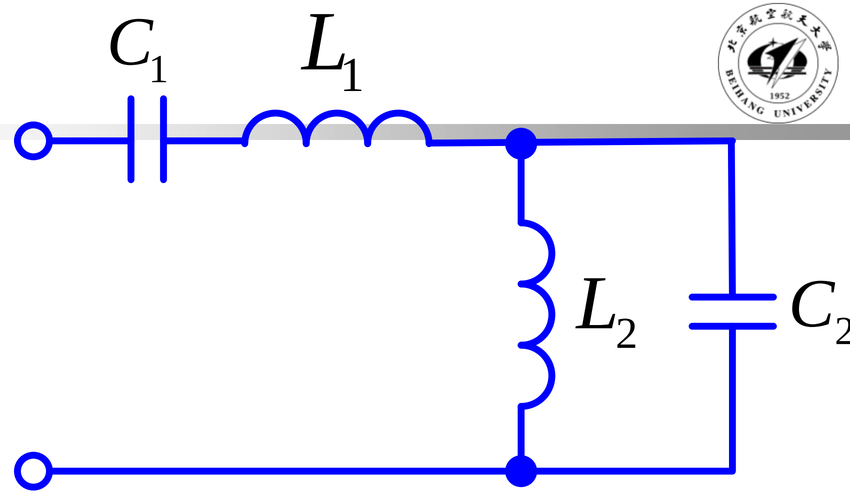
低频段，并联环节呈感性，整个电路呈感性；

ω上升，达到ω_{02}，发生并联谐振；

ω 继续上升，并联环节呈容性，当 $\omega=\omega_{01}$ 时，发生串联谐振。

【练习】

分析图示电路的串并联谐振。



解 **既有串联谐振，**
也有并联谐振。

求 $Z, \mathrm{I_m}[Z]=0,$ **串联谐振**

求 $Y, \mathrm{I_m}[Y]=0,$ **并联谐振**

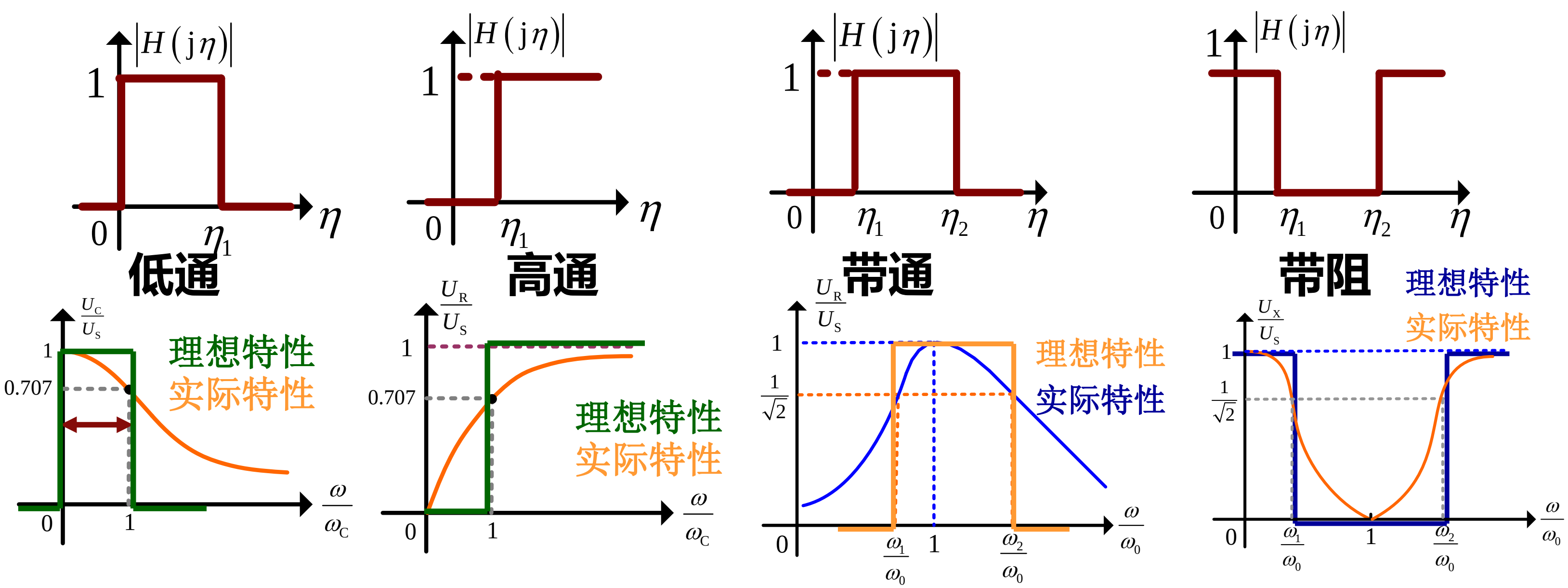
C_2, L_2 **并联，并联谐振**

C_1, L_1 **串联**, C_2, L_2 **并联，整个电路串联谐振**

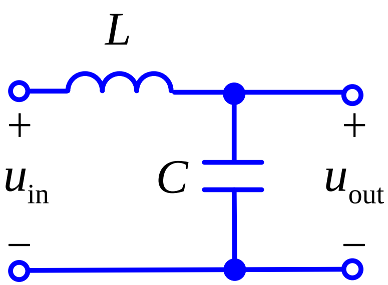
11.5 滤波器简介

滤波器是具有频率选择作用的网络

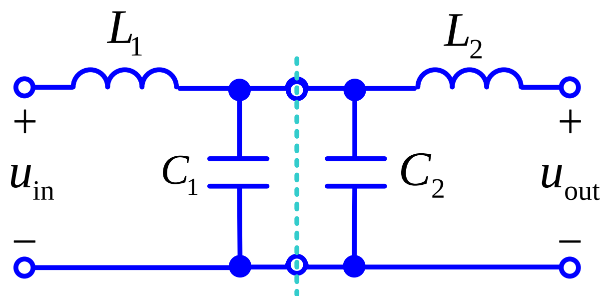
- 频率特性 / 幅频特性：低通、高通、带通、带阻
- 函数形式：2阶、3阶、巴特沃思、切比雪夫等
- 组成元件：有源滤波器、无源滤波器
- 重要概念：通频带、阻带、带宽、中心频率、上截止频率、下截止频率、转折频率



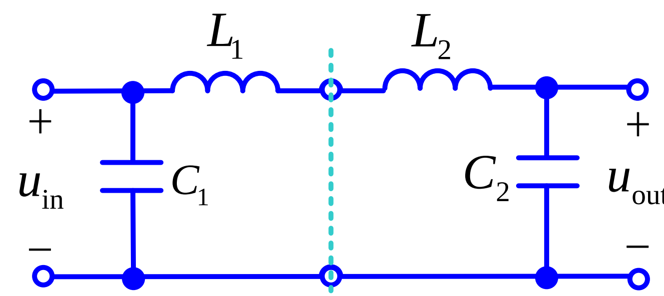
低通滤波器Low Pass Filter(LPF)



2阶

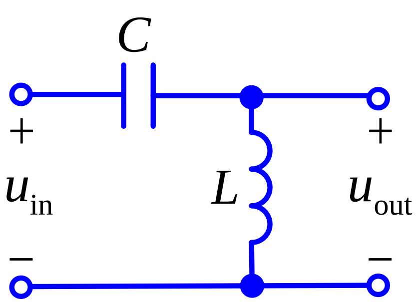


3阶

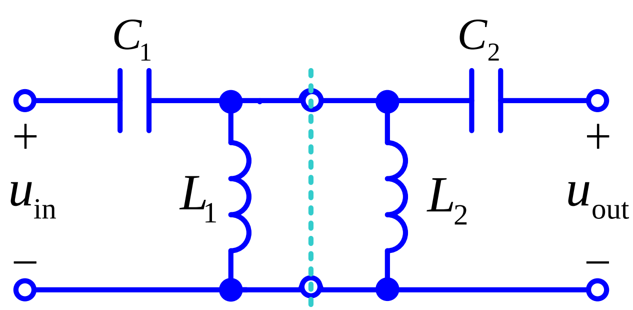


3阶

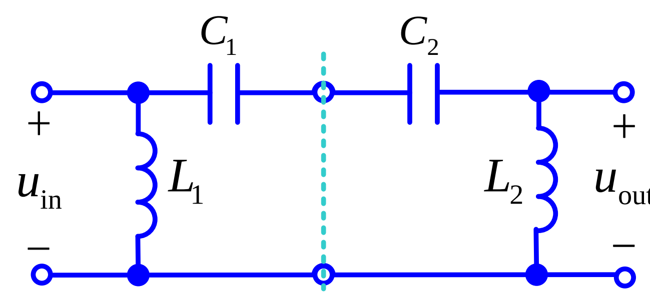
高通滤波器High Pass Filter(HPF)



2阶



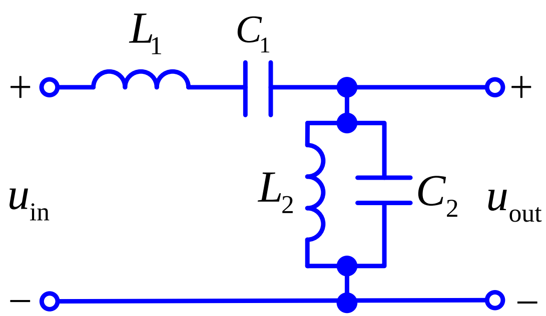
3阶

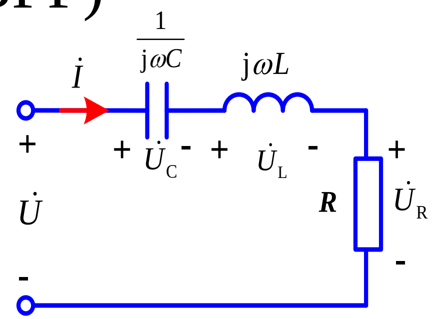


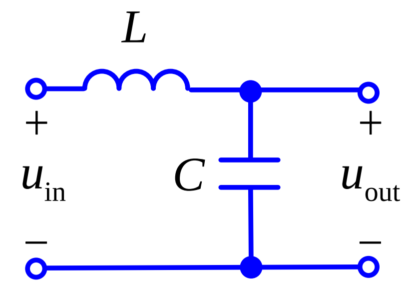
3阶

11.5 滤波器简介 有源滤波器 无源滤波器

带通滤波器Band Pass Filter(BPF)

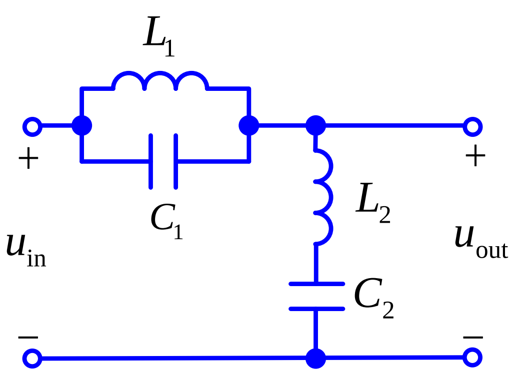


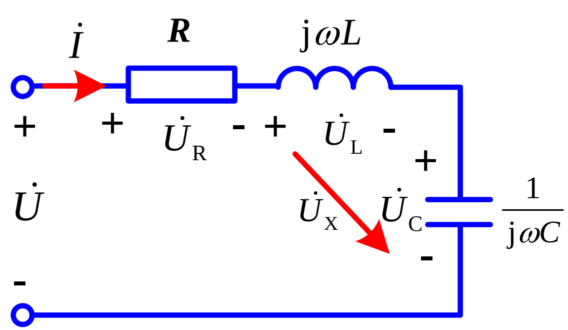


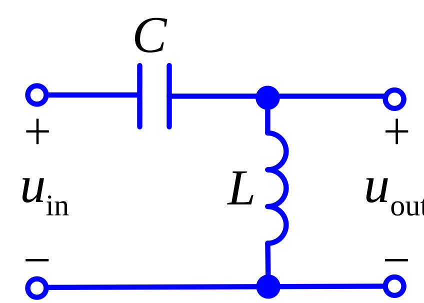


LPF

带阻滤波器Band Reject Filter(BRF)

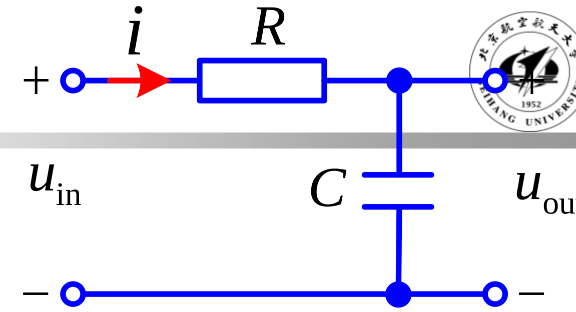




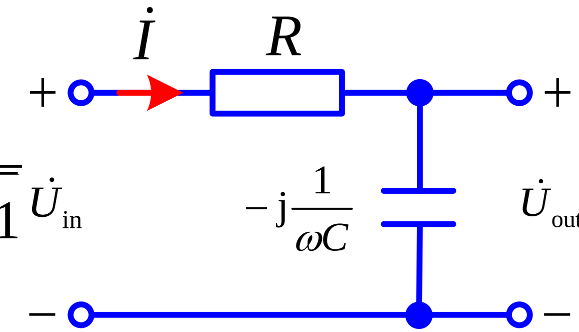


HPF

(1) *RC*低通滤波器

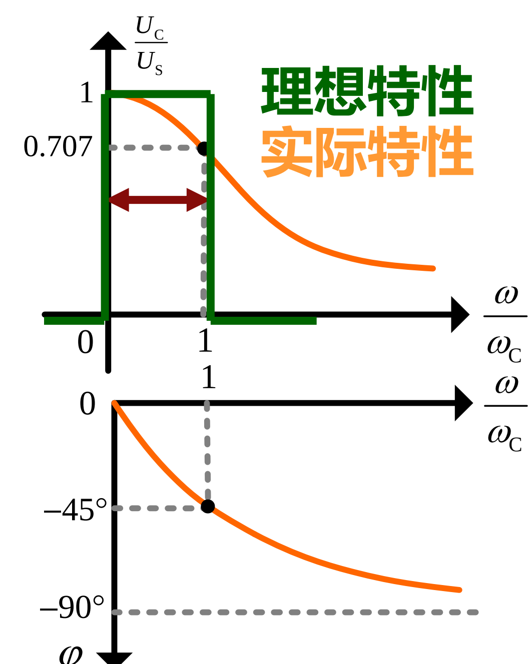


$$\dot{U}_{out}=\frac{-\mathrm{j}\dfrac{1}{\omega C}}{R-\mathrm{j}\dfrac{1}{\omega C}}\dot{U}_{in}=\frac{1-\mathrm{j}R\omega C}{\left(R\omega C\right)^{2}+1}\dot{U}_{in}$$



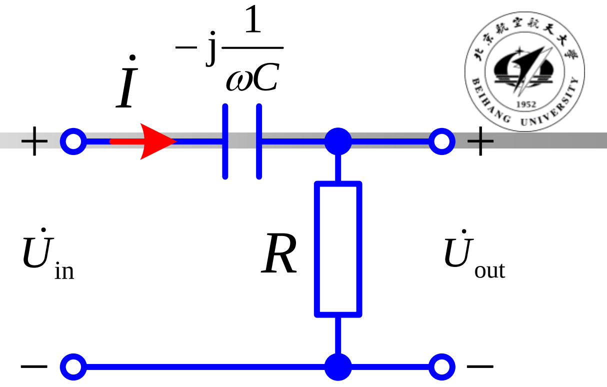
$$U_{out}=\frac{1}{\sqrt{\left(R\omega C\right)^{2}+1}}U_{in}\qquad\left|H(\mathrm{j}\omega)\right|=\frac{U_{out}}{U_{in}}=\frac{1}{\sqrt{\left(R\omega C\right)^{2}+1}}$$

$$\omega_C=\frac{1}{\tau}=\frac{1}{RC}\qquad\left|H(\mathrm{j}\omega)\right|=\frac{1}{\sqrt{\left(\dfrac{\omega}{\omega_C}\right)^{2}+1}}$$



是一个截止频率为ω_C低通滤波器。

(2) *RC*高通滤波器

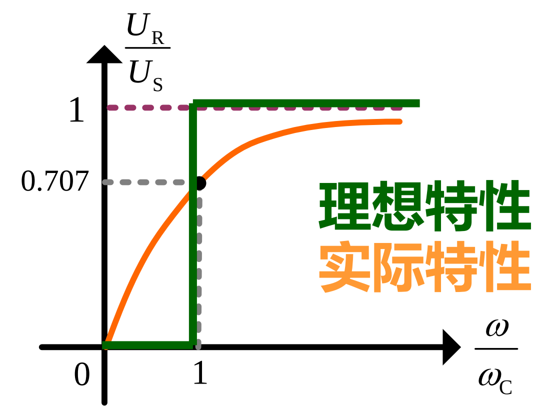


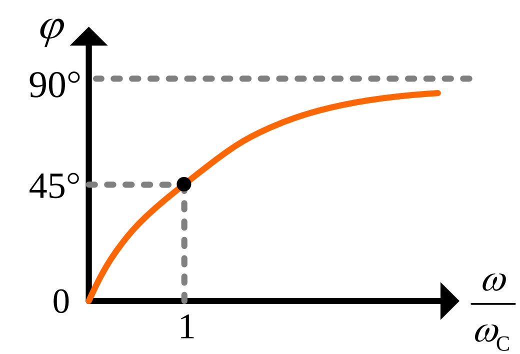
$$\dot{U}_{\mathrm{out}}=\frac{R}{R-\mathrm{j}\dfrac{1}{\omega C}}\dot{U}_{\mathrm{in}}=\frac{R\omega C\left(R\omega C+\mathrm{j}\right)}{\left(R\omega C\right)^2+1}\dot{U}_{\mathrm{in}}$$

$$U_{\mathrm{out}}=\frac{R\omega C}{\sqrt{\left(R\omega C\right)^2+1}}U_{\mathrm{in}}=\frac{1}{\sqrt{1+\left(\dfrac{1}{R\omega C}\right)^2}}U_{\mathrm{in}}$$

$$\left|H(\mathrm{j}\omega)\right|=\frac{U_{\mathrm{out}}}{U_{\mathrm{in}}}=\frac{1}{\sqrt{1+\left(\dfrac{1}{R\omega C}\right)^2}}$$

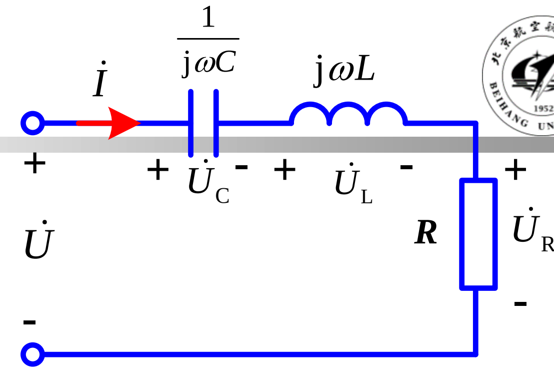
$$\omega_{\mathrm{C}}=\frac{1}{\tau}=\frac{1}{RC}\qquad \left|H(\mathrm{j}\omega)\right|=\frac{1}{\sqrt{\left(\dfrac{\omega_{\mathrm{C}}}{\omega}\right)^2+1}}$$





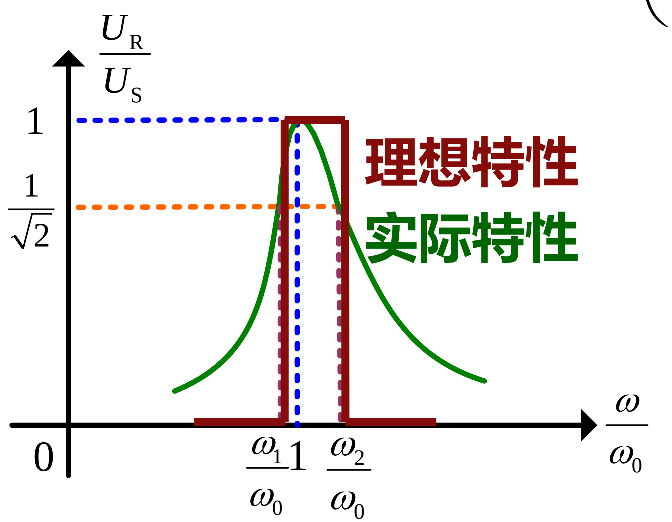
是一个截止频率为ω_{C}高通滤波器。

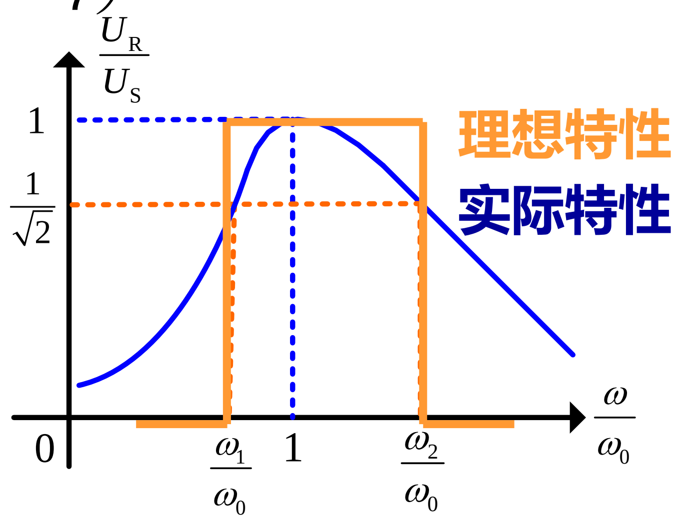
(3) *RLC*带通滤波器



$$H_R(\mathrm{j}\omega)=\frac{\dot{U}_R(\mathrm{j}\omega)}{\dot{U}_S(\mathrm{j}\omega)}=\frac{R}{R+\mathrm{j}\left(\omega L-\dfrac{1}{\omega C}\right)}$$

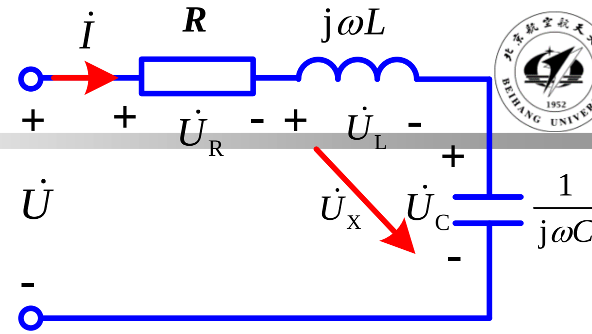
$$\eta=\frac{\omega}{\omega_0}\qquad H(\mathrm{j}\eta)=\frac{1}{1+\mathrm{j}Q\left(\eta-\dfrac{1}{\eta}\right)}$$





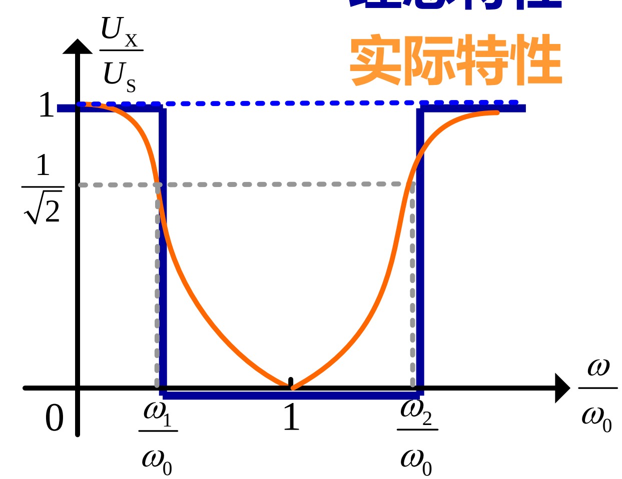
通频带为ω_1,ω_2之间，带通滤波器。

(4) *RLC*带阻滤波器



$$H_X(\mathrm{j}\omega)=\frac{\dot{U}_X(\mathrm{j}\omega)}{\dot{U}_S(\mathrm{j}\omega)}=\frac{\mathrm{j}\left(\omega L-\dfrac{1}{\omega C}\right)}{R+\mathrm{j}\left(\omega L-\dfrac{1}{\omega C}\right)}$$

$$\eta=\frac{\omega}{\omega_0}\qquad H(\mathrm{j}\eta)=\frac{\mathrm{j}Q\left(\eta-\dfrac{1}{\eta}\right)}{1+\mathrm{j}Q\left(\eta-\dfrac{1}{\eta}\right)}$$

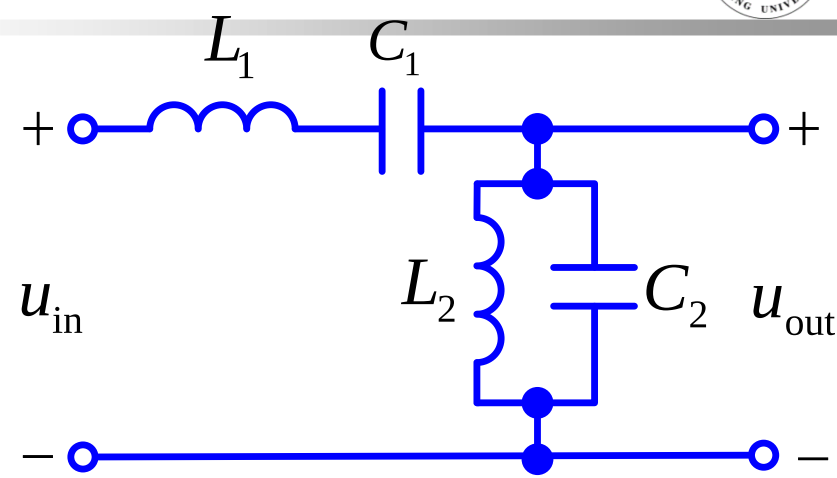


阻频带为ω_1,ω_2之间，带阻滤波器。

思考:

u_{in} 中有多个频率谐波信号，

希望 u_{out} 中只有一种频率信号无衰减，分析电路工作状态。



$$\left.\begin{array}{ll} L_1C_1 & \text{串联谐振} \\ L_2C_2 & \text{并联谐振} \end{array}\right\}\text{其谐振频率是输出信号频率。}$$