Chapter 14
正弦稳态电路的频率响应

14.2 传递函数与频率响应

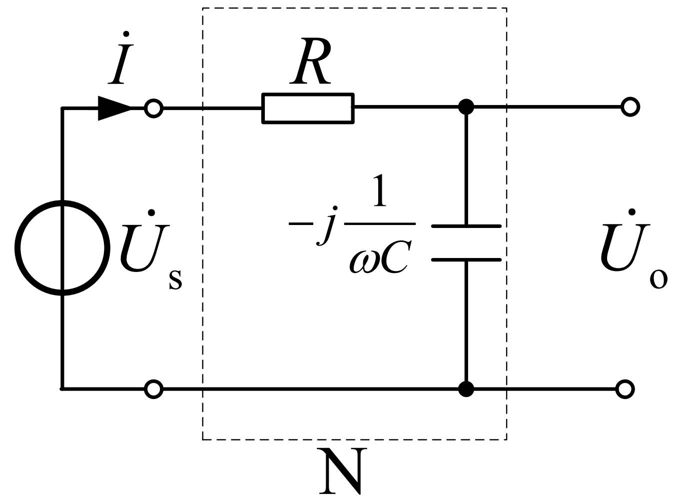
14.3 谐振电路

- 串联谐振
- 并联谐振

14.4 滤波器

频率响应：正弦稳态响应随激励频率的变化规律。

$$Z_{\text{in}} = R - \mathrm{j}\frac{1}{\omega C}$$



$$\dot{I} = \frac{\dot{U}_\mathrm{s}}{R - \mathrm{j}\dfrac{1}{\omega C}} = \frac{\mathrm{j}\omega C}{1 + \mathrm{j}\omega CR}\dot{U}_\mathrm{s}$$

$$\dot{U}_\mathrm{R} = \frac{\mathrm{j}\omega CR}{1 + \mathrm{j}\omega CR}\dot{U}_\mathrm{s} \qquad \dot{U}_\mathrm{C} = \frac{1}{1 + \mathrm{j}\omega CR}\dot{U}_\mathrm{s}$$

不同频率下工作状态不同！

$$\omega \to 0 \quad \frac{1}{\omega C} \to \infty,\ I \to 0,\ U_\mathrm{R} \to 0,\ U_\mathrm{C} \to U_\mathrm{s}$$

$$\omega \to \infty \quad \frac{1}{\omega C} \to 0,\ I \to \frac{U_\mathrm{s}}{R},\ U_\mathrm{R} \to U_\mathrm{s},\ U_\mathrm{C} \to 0$$

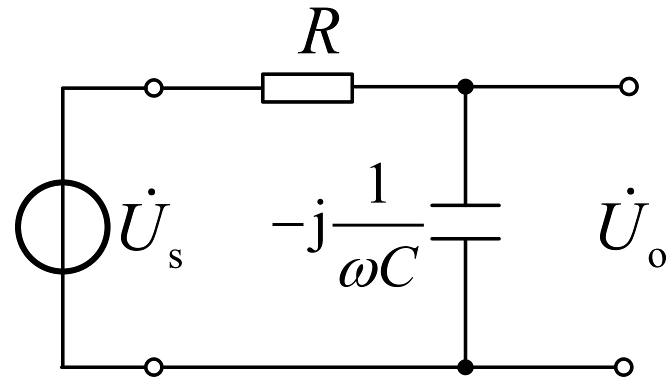
用什么手段来描述频率响应?

分析频率响应有何意义?

14.2 传递函数与频率响应

如何描述响应与激励频率之间的关系？ $\dot{U}_{\mathrm{o}} \sim \dot{U}_{\mathrm{S}},\omega$

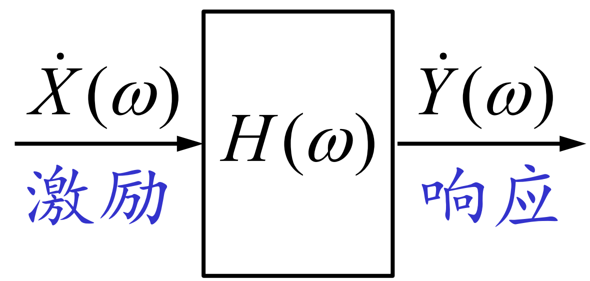
$$H(\omega)=\frac{\dot{U}_{\mathrm{o}}(\omega)}{\dot{U}_{\mathrm{s}}(\omega)}=\frac{-\mathrm{j}\frac{1}{\omega C}}{R-\mathrm{j}\frac{1}{\omega C}}=\frac{1}{1+\mathrm{j}\omega RC}$$



只包含频率

1. 传递函数 响应相量与激励相量的比值

$$H(\omega)=\frac{\dot{Y}(\omega)}{\dot{X}(\omega)}=\frac{\text{响应}}{\text{激励}}$$



- 传递函数与电路结构、参数、输入与输出变量类型、端口对的相对位置有关。

相同端口

不同端口

$$H(\omega)=\frac{\dot{U}_s(\omega)}{\dot{I}_s(\omega)} \qquad H(\omega)=\frac{\dot{U}_o(\omega)}{\dot{U}_s(\omega)} \qquad H(\omega)=\frac{\dot{I}_o(\omega)}{\dot{I}_s(\omega)}$$

$$H(\omega)=\frac{\dot{I}_s(\omega)}{\dot{U}_s(\omega)} \qquad H(\omega)=\frac{\dot{U}_o(\omega)}{\dot{I}_s(\omega)} \qquad H(\omega)=\frac{\dot{I}_o(\omega)}{\dot{U}_s(\omega)}$$

- 传递函数是一个复数，频率特性分为幅频特性和相频特性。

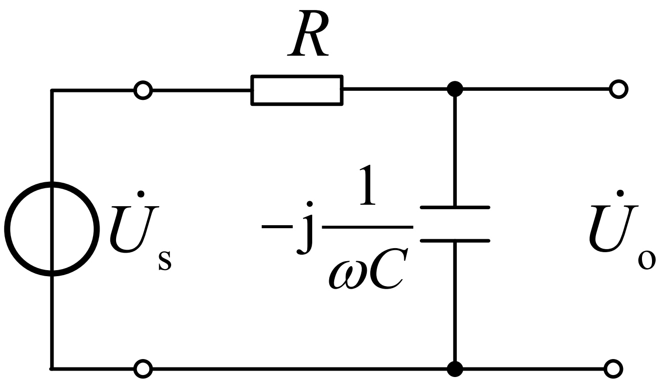
$$H(\omega)=|H(\omega)|\angle\varphi(\omega)$$

幅频响应　相频响应

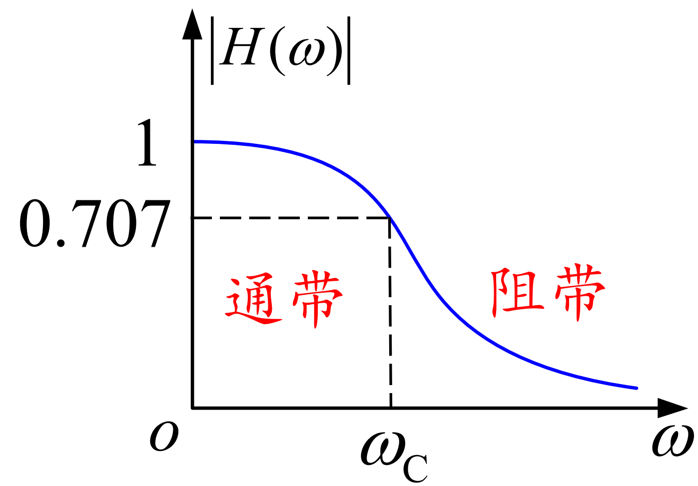
响应幅值与激励幅值之比

响应初相与激励初相之差

2. 频率响应 掌握电路对信号的频率选择性



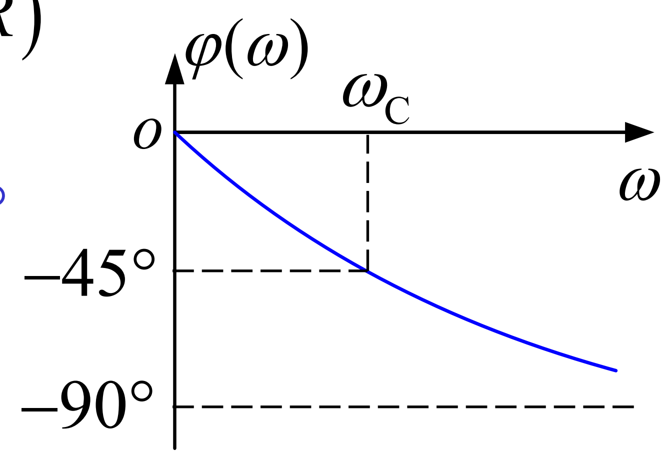
低通滤波器



$$H_C(\omega)=\frac{\dot{U}_o(\omega)}{\dot{U}_s(\omega)}=\frac{1}{1+j\omega RC}$$

$$\omega_C=\frac{1}{RC}$$

$$=\frac{1}{\sqrt{1+(\omega CR)^2}}\angle-\arctan(\omega CR)$$

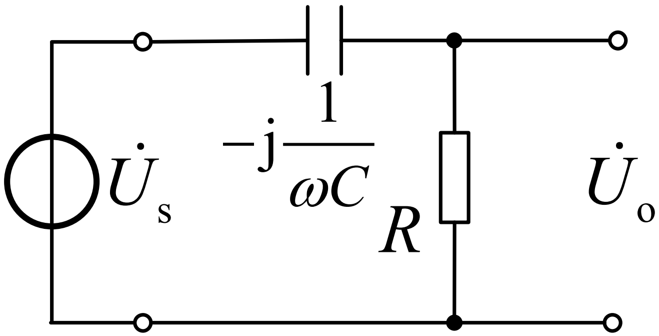


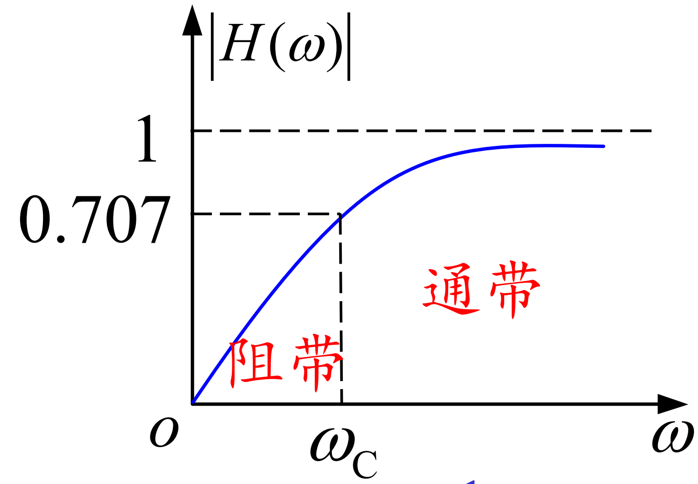
$H_C(0)=1\angle 0°$ $\quad H_C(\infty)=0\angle-90°$

$$H_C\left(\frac{1}{RC}\right)=0.707\angle-45°$$

2. 频率响应

高通滤波器





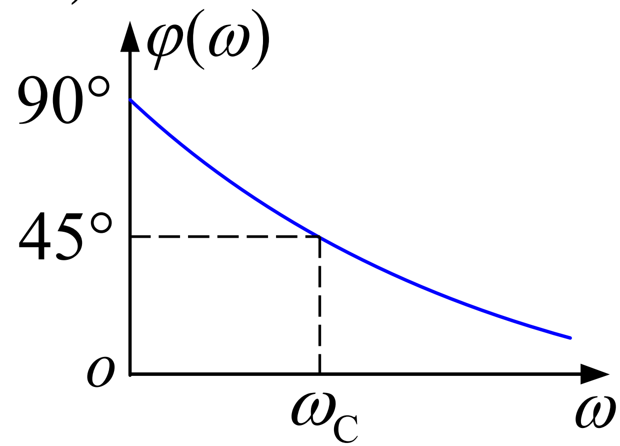
$$H_R(\omega)=\frac{\dot{U}_o(\omega)}{\dot{U}_s(\omega)}=\frac{j\omega RC}{1+j\omega RC}$$

$$=\frac{\omega RC}{\sqrt{1+(\omega CR)^2}}\angle 90^\circ-\arctan(\omega CR)$$

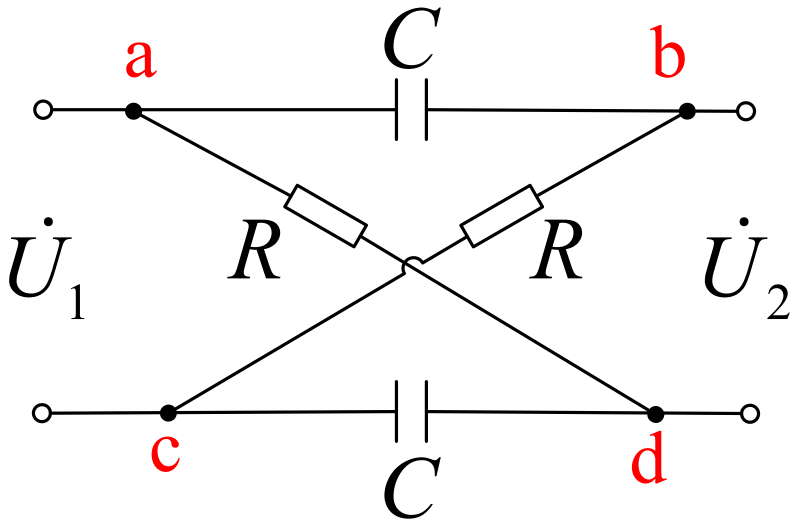
$$\omega_C=\frac{1}{RC}$$

$$H_R(0)=0\angle 90^\circ \qquad H_R(\infty)=1\angle 0^\circ$$

$$H_R\left(\frac{1}{RC}\right)=0.707\angle 45^\circ$$



例 图示电路中RC=1 s。求电压增益$\dot{U}_2/\dot{U}_1$



解 根据分压公式，有：

$$\dot{U}_2=\frac{R}{R+\dfrac{1}{\mathrm{j}\omega C}}\dot{U}_1-\frac{\dfrac{1}{\mathrm{j}\omega C}}{R+\dfrac{1}{\mathrm{j}\omega C}}\dot{U}_1=\frac{\mathrm{j}\omega CR-1}{1+\mathrm{j}\omega CR}\dot{U}_1=\frac{\mathrm{j}\omega-1}{1+\mathrm{j}\omega}\dot{U}_1$$

14.3 谐振电路

1. 谐振 正弦稳态下，电感和电容的阻抗完全互补

$$Z_{\text{in}} = R(\omega) + \mathrm{j}X(\omega) \qquad X(\omega) = 0$$

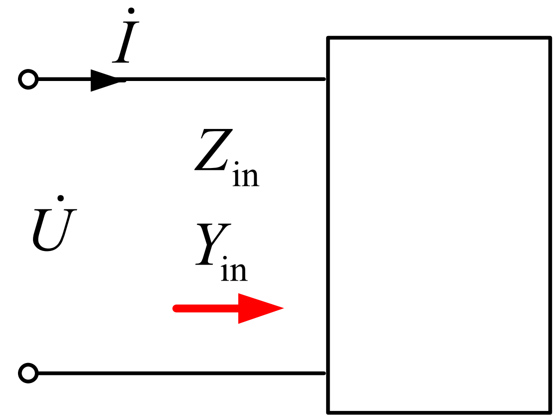
$$Y_{\text{in}} = G(\omega) + \mathrm{j}B(\omega) \qquad B(\omega) = 0$$

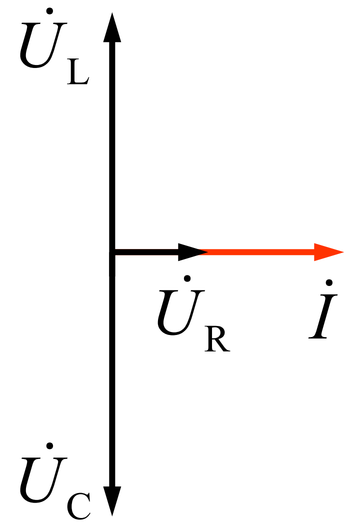
$\dot{U}$和 $\dot{I}$ 同相位

$P = UI \qquad Q = 0$

改变电源频率

改变电路L、C参数值

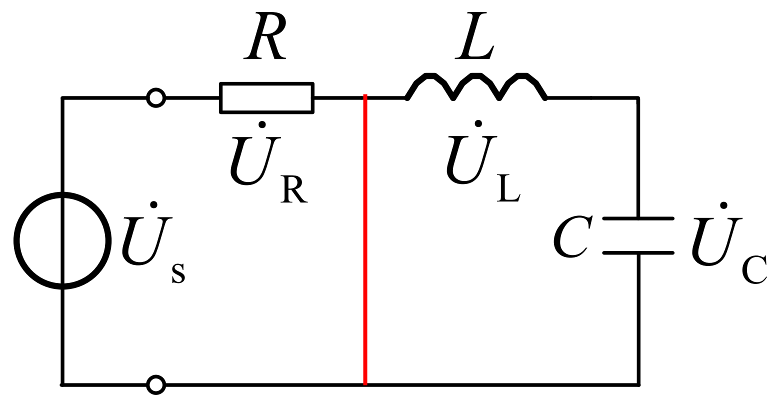




2. *RLC*串联谐振

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

$$\omega = \frac{1}{\sqrt{LC}} = \omega_0$$ **谐振频率**



对外相当于短路！

谐振特点：

(1) $|Z(\omega_0)| = R = |Z_{\min}(\omega)|$

(2) $\dot{U}_S$ 和 $\dot{I}_0$ 同相位

(3) $|\dot{I}_0| = \left|\frac{\dot{U}_S}{R}\right| = |\dot{I}_{\max}(\omega)|$

(4) $\dot{U}_{R0} = \dot{U}_S$

(5) $\dot{U}_{L0} = \mathrm{j}\omega_0 L\dot{I}_0 = \mathrm{j}\frac{\omega_0 L}{R}\dot{U}_S$

$$\dot{U}_{C0} = -\mathrm{j}\frac{1}{\omega_0 C}\dot{I}_0 = -\mathrm{j}\frac{1}{\omega_0 CR}\dot{U}_S$$

$$U_{L0} = U_{C0} = QU_S$$

***Q*：品质因数**

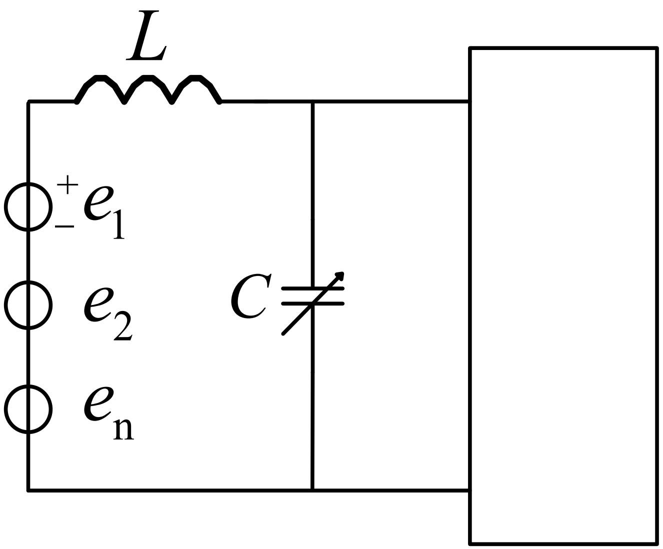
收音机

品质因数

$$Q=\frac{\omega_0 L}{R}=\frac{1}{\omega_0 CR}=\frac{1}{R}\sqrt{\frac{L}{C}}$$

$$U_{L0}=U_{C0}=QU_S$$

当Q>>1时，电容或电感上电压将远大于电源电压，称为过电压现象。

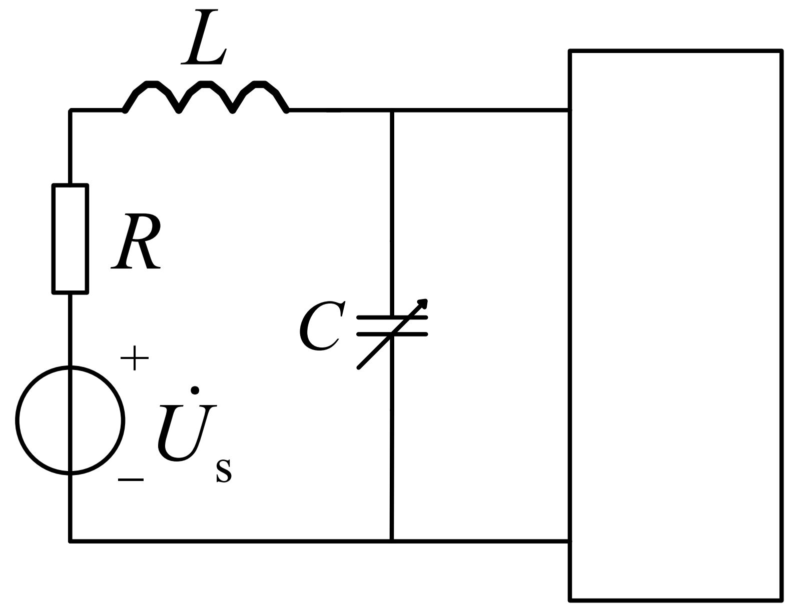


应用：电信系统的信号放大

例 某收音机输入回路L=0.3mH，R=10Ω，为收到中央电台560kHz信号，求（1）调谐电容C；（2）如输入电压为1.5μV，求谐振电流和电容电压。

解 （1）调谐电容C

$$C=\frac{1}{(2\pi f)^2 L}=269\ \text{pF}$$



（2）谐振电流和电容电压

$$I_0=\frac{U}{R}=0.15\ \mu\text{A}$$

$$U_C=I_0X_C=158.5\ \mu\text{V}\gg 1.5\ \mu\text{V}$$

（6）能量关系

储能 $w_0 = w_{L0} + w_{C0} = \frac{1}{2} L i_0{}^2 + \frac{1}{2} C u_{C0}{}^2$

$$= L I_0{}^2 (\cos \omega_0 t)^2 + C (\frac{I_0}{\omega_0 C})^2 [\cos(\omega_0 t - 90°)]^2$$

$$= L I_0{}^2 (\cos \omega_0 t)^2 + L I_0{}^2 (\sin \omega_0 t)^2 = L I_0{}^2$$

- 电感和电容能量按正弦规律变化，且最大值相等。L、C的电场能量和磁场能量作周期振荡性的交换，而不与电源进行能量交换；
- 总能量是不随时间变化的常量，且等于最大值。

（6）能量关系　储能 $w_0 = LI_0{}^2$

耗能 $w_{R0} = \int_0^{T_0} i_0{}^2 R\mathrm{dt} = I_0{}^2 R T_0 = I_0{}^2 R \dfrac{2\pi}{\omega_0} = 2\pi I_0{}^2 R\sqrt{LC}$

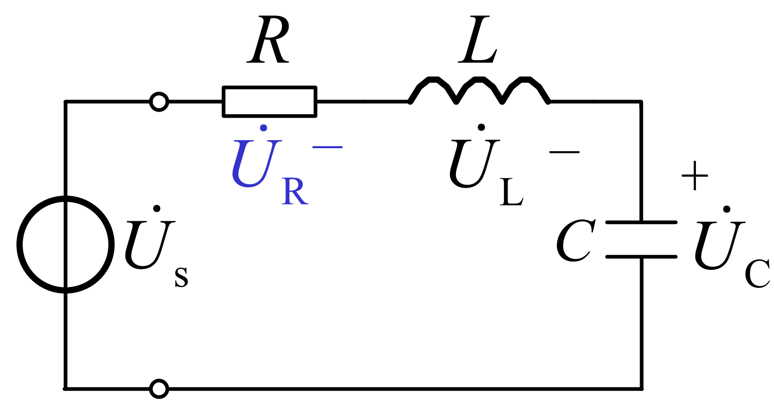
$$\frac{w_0}{w_{R0}} = \frac{1}{2\pi}\frac{\sqrt{L/C}}{R} = \frac{Q}{2\pi} \qquad Q = 2\pi\frac{\text{谐振电路存储的能量}}{\text{一个周期内消耗的能量}}$$

Q值反映了谐振回路中电磁振荡的程度，Q越大，总能量就越大，维持振荡所消耗的能量越小，振荡程度越剧烈，则振荡电路的“品质”越好。一般要求在发生谐振的回路中尽可能的提高Q值。

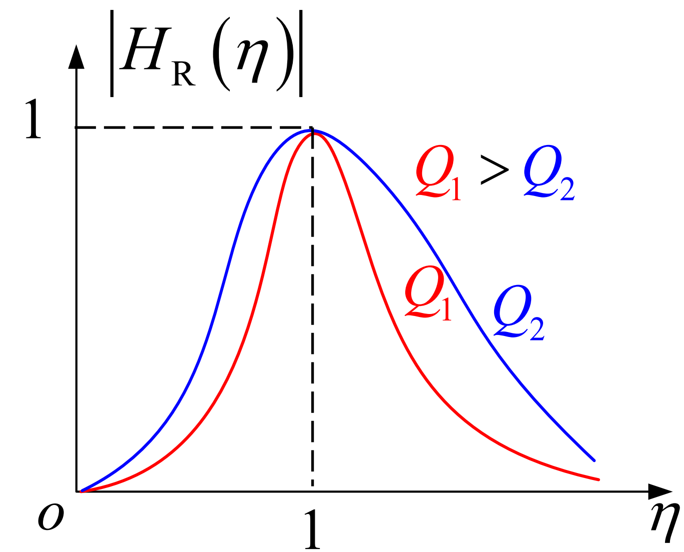
$$\left|H_R(\omega)\right| = \left|\frac{\dot{U}_R(\omega)}{\dot{U}_S(\omega)}\right| = \frac{R}{\left|R + j(\omega L - \dfrac{1}{\omega C})\right|}$$

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

$$= \frac{1}{\sqrt{1+Q^2\left(\dfrac{\omega}{\omega_0} - \dfrac{\omega_0}{\omega}\right)^2}}$$



$$\frac{\omega}{\omega_0} = \eta \qquad \left|H_R(\eta)\right| = \frac{1}{\sqrt{1+Q^2\left(\eta - \dfrac{1}{\eta}\right)^2}}$$



$\left|H_R(0)\right| = 0 \qquad \left|H_R(\infty)\right| = 0 \qquad \left|H_R(1)\right| = 1$

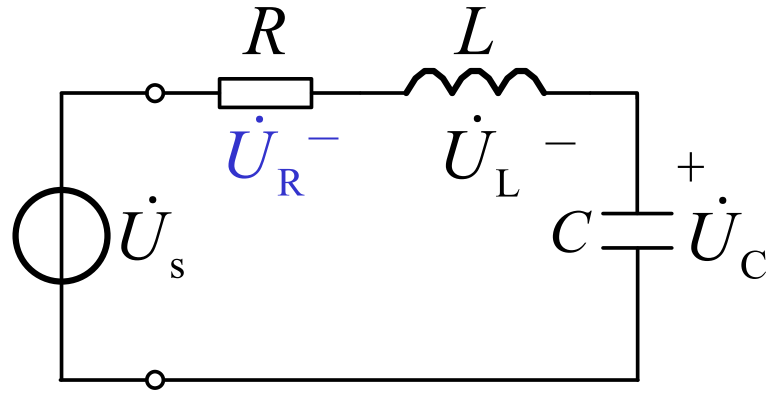
Q值越大，频率选择性越好

- 谐振电路具有选择性

在谐振点响应出现峰值，当ω偏离ω_0时，输出下降。即**串联谐振电路对不同频率信号有不同的响应，对谐振信号响应最大**，而对远离谐振频率的信号具有抑制能力。这种对不同输入信号的选择能力称为“选择性”。

- 谐振电路的选择性与Q成正比

Q越大，谐振曲线越陡。电路对非谐振频率信号的抑制能力强，所以选择性好。因此，**Q是反映谐振电路性质的一个重要指标。**



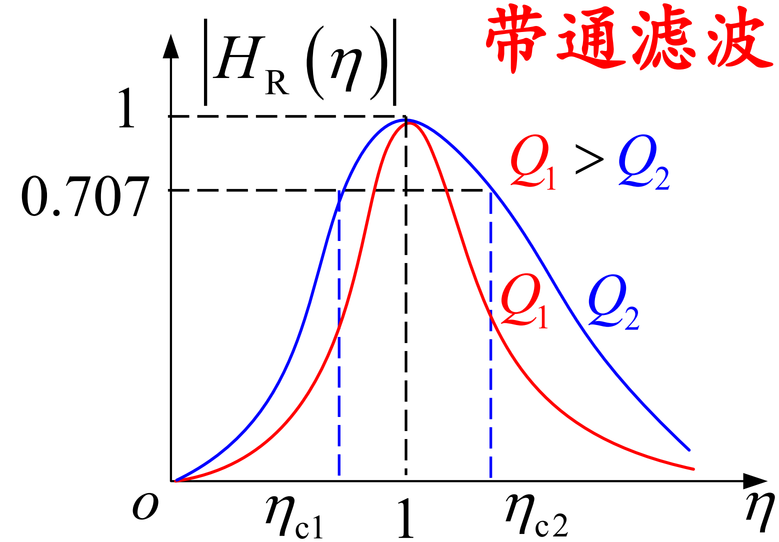
- 在谐振点电路消耗的有功功率最大；
- 当$|H_R(\eta)|$下降至0.707倍时，信号就被截止了。

$$|H_R(\eta_{c1,c2})| = \frac{1}{\sqrt{2}} = 0.707$$

截止频率 （半功率频率）

$$\omega_{c1,c2} = \eta_{c1,c2}\omega_0$$

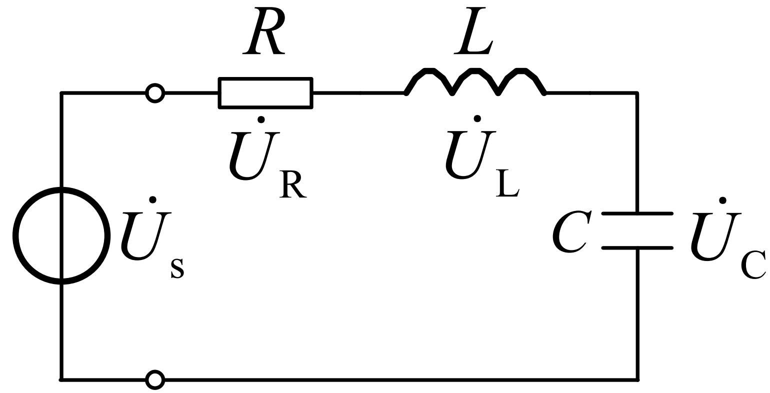
带通滤波器



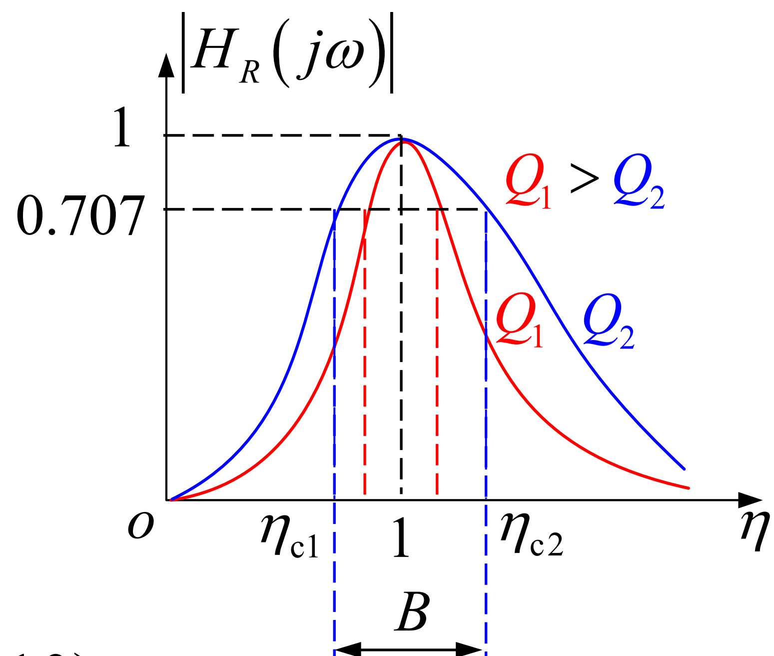
从有功功率角度：

$$P(\omega_{c1,c2}) = \frac{U_R^2}{R} = \frac{(U_S/\sqrt{2})^2}{R} = \frac{1}{2}\frac{U_S^2}{R} = \frac{1}{2}P(\omega_0)$$

$$\left|H_R(\eta)\right| = \frac{1}{\sqrt{1+Q^2\left(\eta-\dfrac{1}{\eta}\right)^2}} = \frac{\sqrt{2}}{2}$$



$$\begin{cases} \eta_{c1} = -\dfrac{1}{2Q} + \sqrt{\left(\dfrac{1}{2Q}\right)^2 + 1} \\[2ex] \eta_{c2} = \dfrac{1}{2Q} + \sqrt{\left(\dfrac{1}{2Q}\right)^2 + 1} \end{cases}$$



带宽 $B = (\eta_{c2} - \eta_{c1})\omega_0 = \dfrac{\omega_0}{Q}$

截止频率 $\omega_{c1,c2} \approx \omega_0 \mp \dfrac{1}{2}B \quad (Q \geq 10)$

RLC串联谐振的频率响应

谐振频率	$\omega_0=\dfrac{1}{\sqrt{LC}}=\sqrt{\omega_{c1}\omega_{c2}}$
品质因数	$Q=\dfrac{X_{L0}(X_{C0})}{R}=\dfrac{1}{R}\sqrt{\dfrac{L}{C}}=\dfrac{U_{L0}(U_{C0})}{U_S}=2\pi\dfrac{w_0}{w_{R0}}=\dfrac{\omega_0}{B}$
截止频率	$\omega_{c1,c2}=\mp\dfrac{\omega_0}{2Q}+\omega_0\sqrt{1+(\dfrac{1}{2Q})^2}=\mp\dfrac{R}{2L}+\sqrt{(\dfrac{R}{2L})^2+\dfrac{1}{LC}}$ $\omega_{c1,c2}\approx\omega_0\mp\dfrac{B}{2}\ (Q\geq 10)$
带宽	$B=\omega_{c2}-\omega_{c1}=\dfrac{\omega_0}{Q}=\dfrac{R}{L}$

例 设计一个RLC串联电路，使得带宽B=20 rad/s，$\omega_0 = 1000$ rad/s。（1）求该电路的Q值；（2）若C=5 μF，求L和R的值；（3）求截止频率。

解

$$B = \frac{\omega_0}{Q} \quad \rightarrow Q = \frac{\omega_0}{B} = \frac{1000}{20} = 50$$

$$\omega_0 = \frac{1}{\sqrt{LC}} = 1000 \quad \rightarrow L = 200\ \text{mH}$$

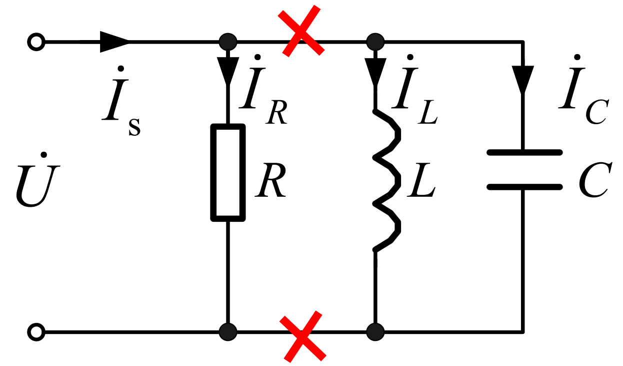
$$Q = \frac{\omega_0 L}{R} \quad \rightarrow R = \frac{\omega_0 L}{Q} = 4\ \Omega$$

$$\omega_{c1,c2} \approx \omega_0 \mp \frac{B}{2} = 990\ \text{rad / s},\ 1010\ \text{rad / s}$$

3. RLC并联谐振

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

$$\omega = \frac{1}{\sqrt{LC}} = \omega_0$$ 谐振频率



对外相当于开路！

谐振特点：

(1) $|Y(\omega_0)| = G = |Y_{\min}(\omega)|$

(2) $\dot{U}_S$ 和 $\dot{I}_0$ 同相位

(3) $|\dot{U}_0| = \left|\frac{\dot{I}_S}{G}\right| = |\dot{U}_{\max}(\omega)|$

(4) $\dot{U}_{R0} = \dot{I}_S / G$

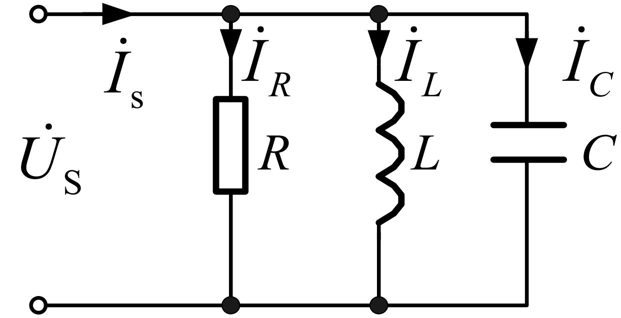
(5) $\dot{I}_{L0} = -\mathrm{j}\frac{1}{\omega_0 L}\dot{U}_0 = -\mathrm{j}\frac{1}{G\omega_0 L}\dot{I}_s$

$$\dot{I}_{C0} = \mathrm{j}\omega_0 C\dot{U}_0 = \mathrm{j}\frac{\omega_0 C}{G}\dot{I}_s$$

$$I_{L0} = I_{C0} = QI_S$$

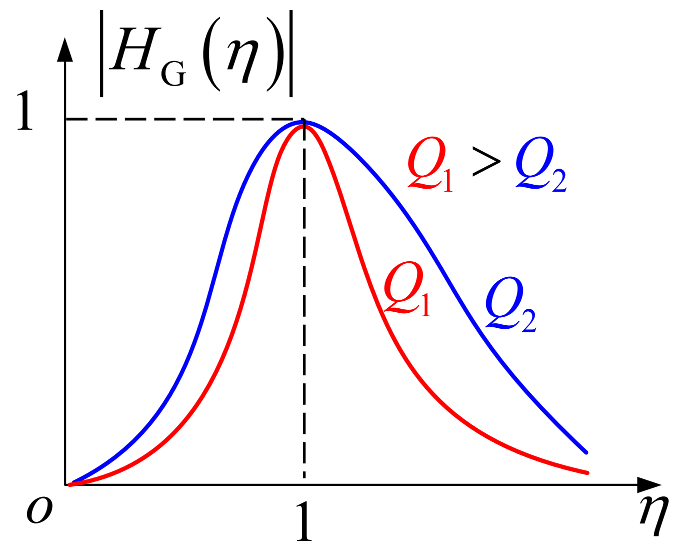
Q：品质因数

$$\left|H_G(\omega)\right| = \left|\frac{\dot{I}_G(\omega)}{\dot{I}_S(\omega)}\right| = \frac{G}{\left|G + \mathrm{j}(\omega C - \dfrac{1}{\omega L})\right|}$$



$$= \frac{1}{\sqrt{1+\left(\dfrac{\omega C}{G} - \dfrac{1}{G\omega L}\right)^2}}$$

$$= \frac{1}{\sqrt{1+Q^2\left(\dfrac{\omega}{\omega_0} - \dfrac{\omega_0}{\omega}\right)^2}}$$

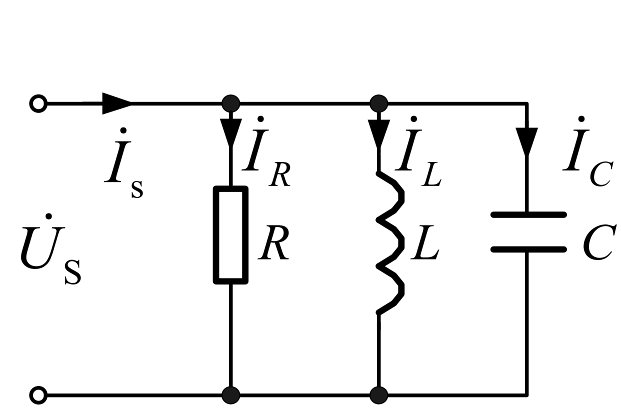


$$\frac{\omega}{\omega_0} = \eta \qquad \left|H_G(\eta)\right| = \frac{1}{\sqrt{1+Q^2\left(\eta - \dfrac{1}{\eta}\right)^2}}$$

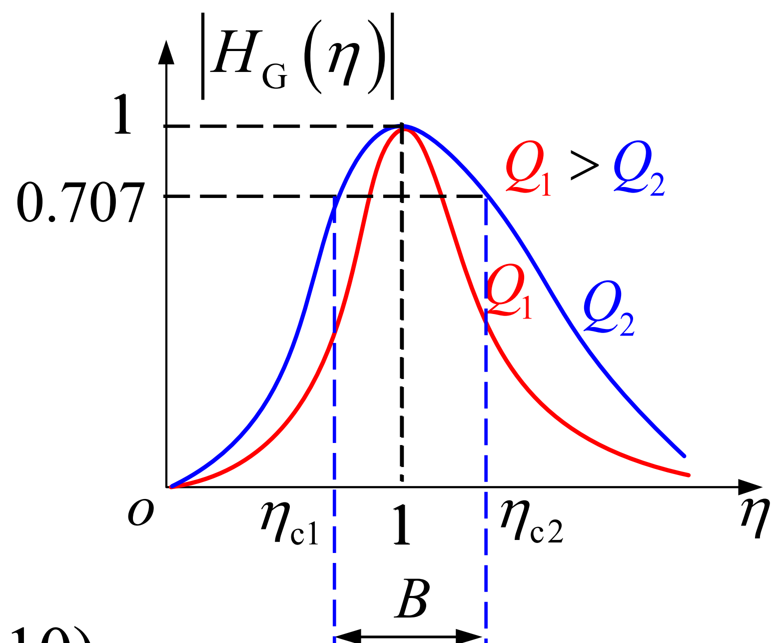
$\left|H_G(0)\right| = 0 \quad \left|H_G(\infty)\right| = 0 \quad \left|H_G(1)\right| = 1$

Q值越大，频率选择性越好

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



$$\begin{cases} \eta_{c1} = -\frac{1}{2Q} + \sqrt{\left(\frac{1}{2Q}\right)^2 + 1} \\ \eta_{c2} = \frac{1}{2Q} + \sqrt{\left(\frac{1}{2Q}\right)^2 + 1} \end{cases}$$



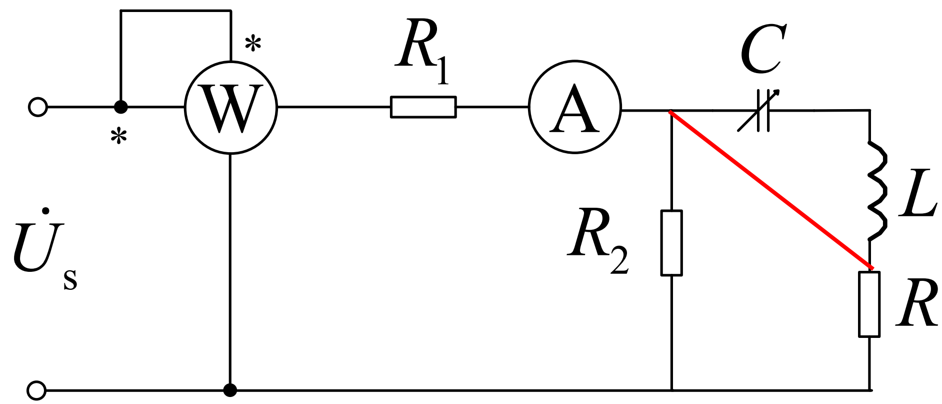
带宽 $B = (\eta_{c2} - \eta_{c1})\omega_0 = \frac{\omega_0}{Q}$

截止频率 $\omega_{c1,c2} \approx \omega_0 \mp \frac{1}{2}B \quad (Q \geq 10)$

	RLC串联谐振	GCL并联谐振
谐振频率	$\omega_0=\dfrac{1}{\sqrt{LC}}=\sqrt{\omega_{c1}\omega_{c2}}$	
品质因数	$Q=\dfrac{\omega_0 L}{R}=\dfrac{1}{\omega_0 CR}=\dfrac{\omega_0}{B}$	$Q=\dfrac{1}{\omega_0 LG}=\dfrac{\omega_0 C}{G}=\dfrac{\omega_0}{B}$
截止频率	$\omega_{c1,c2}=\mp\dfrac{\omega_0}{2Q}+\omega_0\sqrt{1+(\dfrac{1}{2Q})^2}$ $\omega_{c1,c2}\approx\omega_0\mp\dfrac{B}{2}\ (Q\geq 10)$	
带宽	$B=\omega_{c2}-\omega_{c1}=\dfrac{\omega_0}{Q}$	

例 电源频率f=100/π Hz，R_1=6 Ω，R_2=20 Ω，当改变电容C=1000 μF时，电流表读数I最大为1 A，功率表读数为10 W，试计算电阻R和电感L。

解 电流最大→总阻抗最小→LC串联谐振



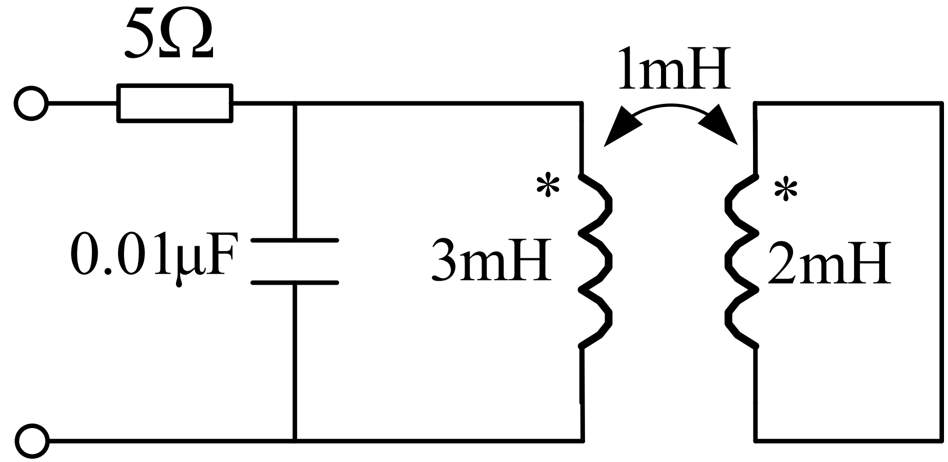
$$\omega_0 = 2\pi f = \frac{1}{\sqrt{LC}}$$

$$\Rightarrow \quad L = 25\ \mathrm{mH}$$

当LC发生串联谐振时，对外相当于短路。

$$P = U_s I = I^2 R_{eq} = I^2 \left(R_1 + R_2 \mathbin{//} R \right) \quad \Rightarrow \quad R = 5\ \Omega$$

例 求如图所示电路发生谐振时的谐振角频率ω_0



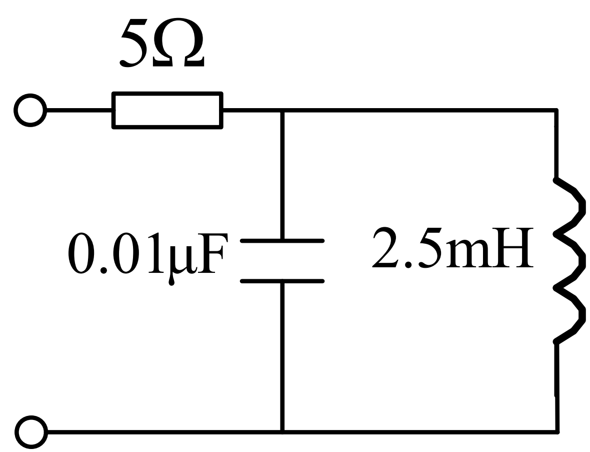
解 映射阻抗法

$$Z_{eq} = j\omega L_1 + Z_{ref}$$

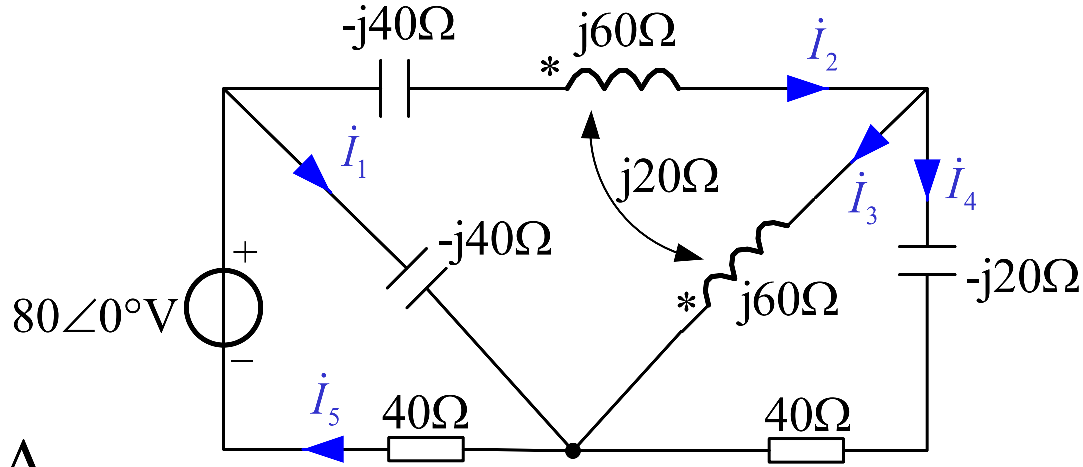
$$= j\omega L_1 + \frac{(\omega M)^2}{j\omega L_2}$$

$$L_{eq} = L_1 - \frac{M^2}{L_2} = 2.5\ \text{mH}$$

$$\omega_0 = \frac{1}{\sqrt{L_{eq}C}} = 200\ \text{kHz}$$



例 求图示电路中各支路电流。



解 先去耦。

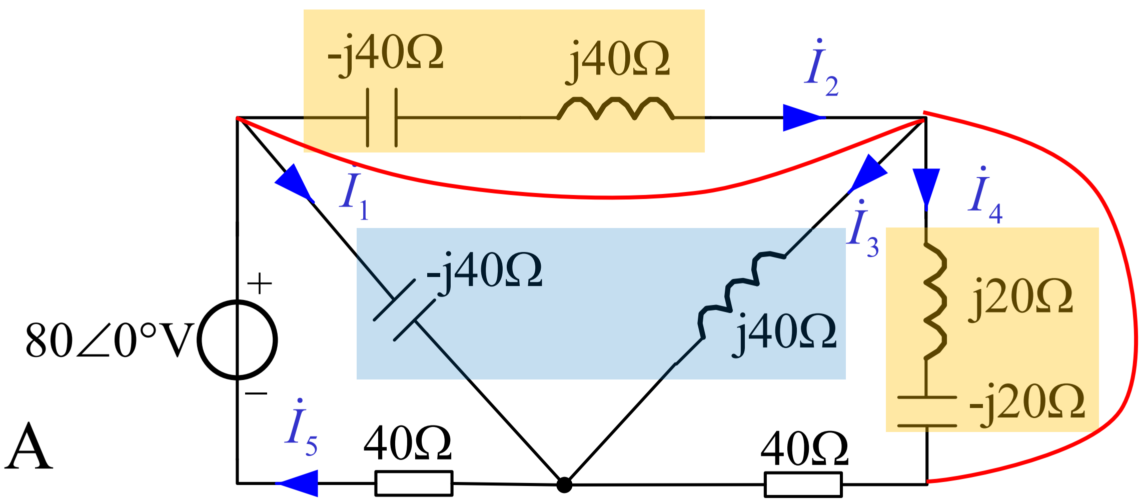
$$\dot{I}_1 + \dot{I}_3 = 0$$

$$\dot{I}_4 = \dot{I}_5 = \frac{80\angle 0^\circ}{40+40} = 1\angle 0^\circ \text{A}$$

$$\dot{I}_3 = \frac{40\dot{I}_4}{\text{j}40} = 1\angle -90^\circ \text{A}$$

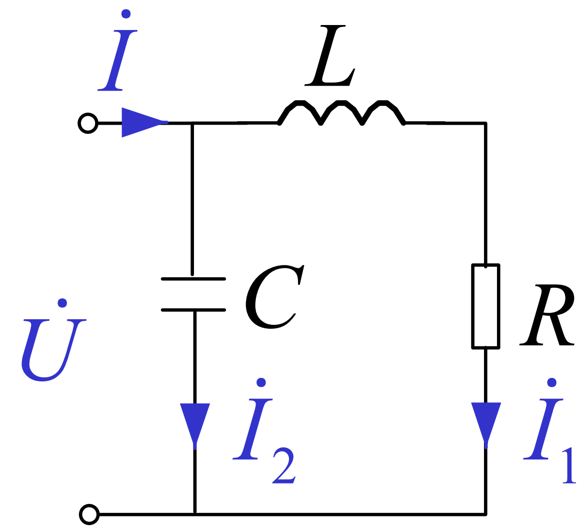
$$\dot{I}_1 = -\dot{I}_3 = 1\angle 90^\circ \text{A}$$

$$\dot{I}_2 = \dot{I}_3 + \dot{I}_4 = \sqrt{2}\angle -45^\circ \text{A}$$



例 图示电路的谐振角频率ω_0=1krad/s，谐振时端口等效阻抗Z_0=1kΩ，品质因数Q=10。（1）求参数R、L、C。（2）若在端口接频率为ω_0、R_p=2kΩ、I_s=1A的电流源，求品质因数及I、I_1、I_2。

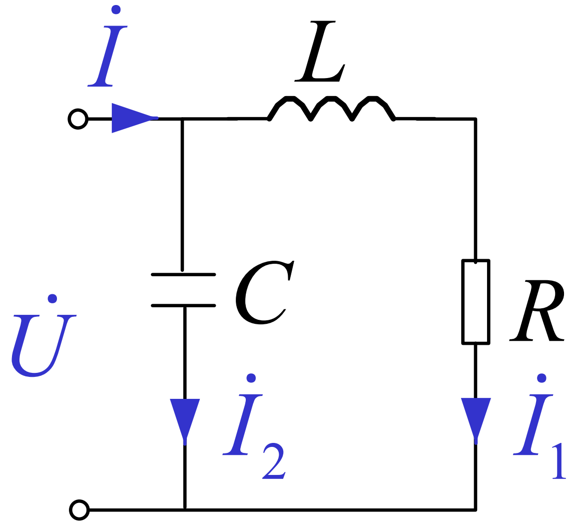
解 （1）等效为RLC并联形式



$$\frac{1}{Z_0}=\mathrm{j}\omega_0 C+\frac{1}{R+\mathrm{j}\omega_0 L}$$

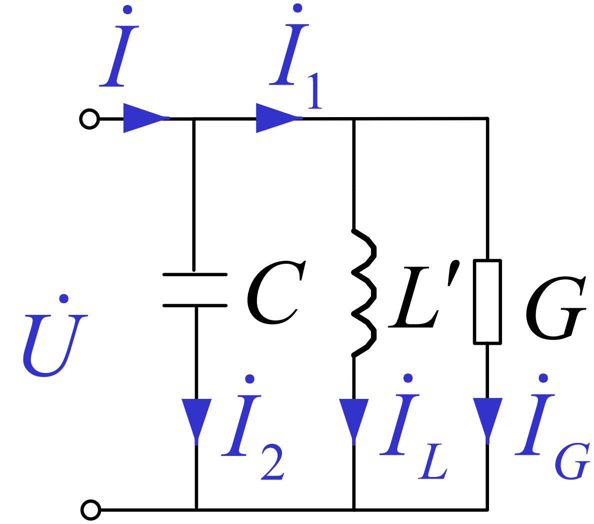
$$=\frac{R}{R^2+(\omega_0 L)^2}+\mathrm{j}\left[\omega_0 C-\frac{\omega_0 L}{R^2+(\omega_0 L)^2}\right]$$

$$=G'+\mathrm{j}(B_C-B_{L'})$$



$Q=10$

$Z_0=1\text{k}\Omega$



$$\frac{1}{Z_0}=\frac{R}{R^2+(\omega_0 L)^2}+\mathrm{j}\left[\omega_0 C-\frac{\omega_0 L}{R^2+(\omega_0 L)^2}\right]=G'+\mathrm{j}\left(B_C-B_{L'}\right)$$

$$\frac{1}{Z_0}=G'=\frac{R}{R^2+(\omega_0 L)^2}=\frac{1}{1000}$$

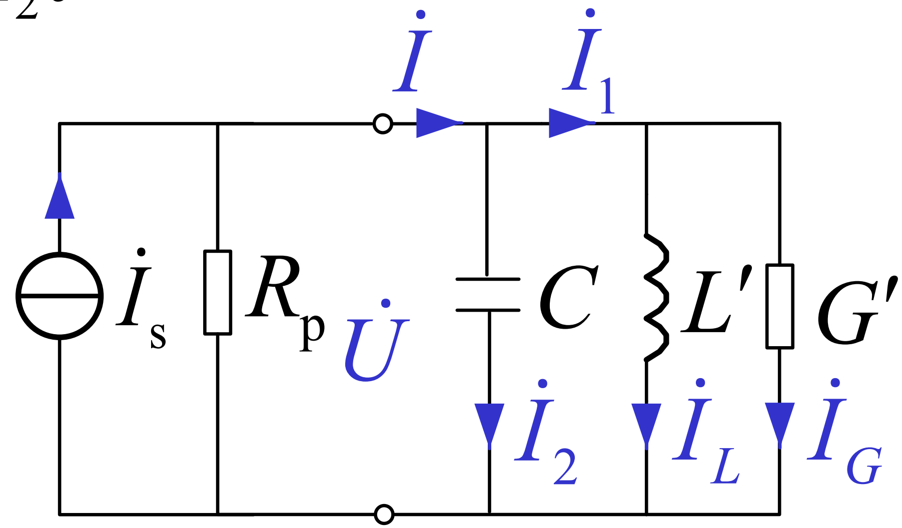
$$\rightarrow R=\frac{1000}{101}\Omega \qquad L=\frac{10}{101}\text{H}$$

$$Q=\frac{B_{L'}}{G'}=\frac{\omega_0 L}{R} \quad \rightarrow \omega_0 L=10R$$

$$B_C=B_{L'} \quad \rightarrow \omega_0 C=\frac{\omega_0 L}{R^2+(\omega_0 L)^2} \qquad \rightarrow C=10\mu\text{F}$$

（2）若在端口接频率为ω_0、R_p=2kΩ、I_s=1A的电流源，求品质因数及I、I_1、I_2。

$$Q' = \frac{B_C}{G' + G_\mathrm{p}} = \frac{\omega_0 C}{G' + G_\mathrm{p}} = \frac{20}{3}$$

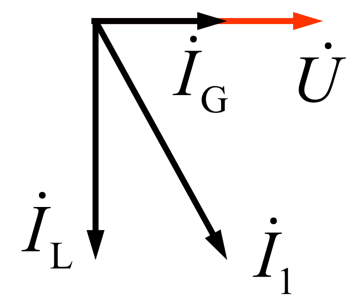


信号源内阻会影响性能指标

$$I = \frac{G'}{G' + G_\mathrm{p}} I_\mathrm{s} = \frac{2}{3}\ \mathrm{A}$$

$$I_2 = Q' I_\mathrm{s} = \frac{20}{3}\ \mathrm{A}\ \left(或\ I_2 = QI = 10 \times \frac{2}{3} = \frac{20}{3}\ \mathrm{A}\right)$$

$$\dot{I}_1 = \dot{I}_L + \dot{I}_G \rightarrow I_1 = QI + I = \frac{22}{3}\ \mathrm{A}$$



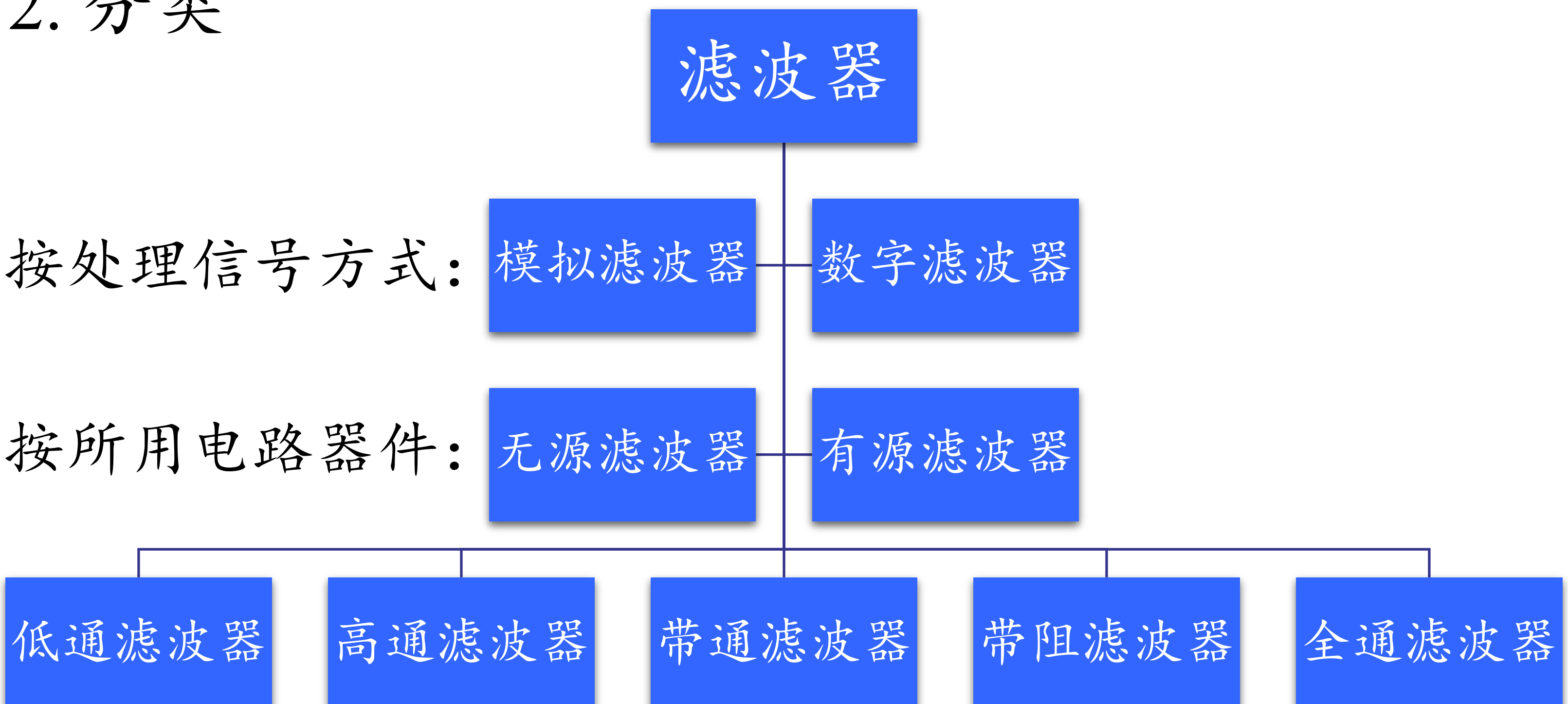
$$\dot{I}_1 = \dot{I}_L + \dot{I}_G \rightarrow I_1 = \sqrt{(QI)^2 + I^2} = 6.7\ \mathrm{A}$$

14.4 滤波器

1. 定义

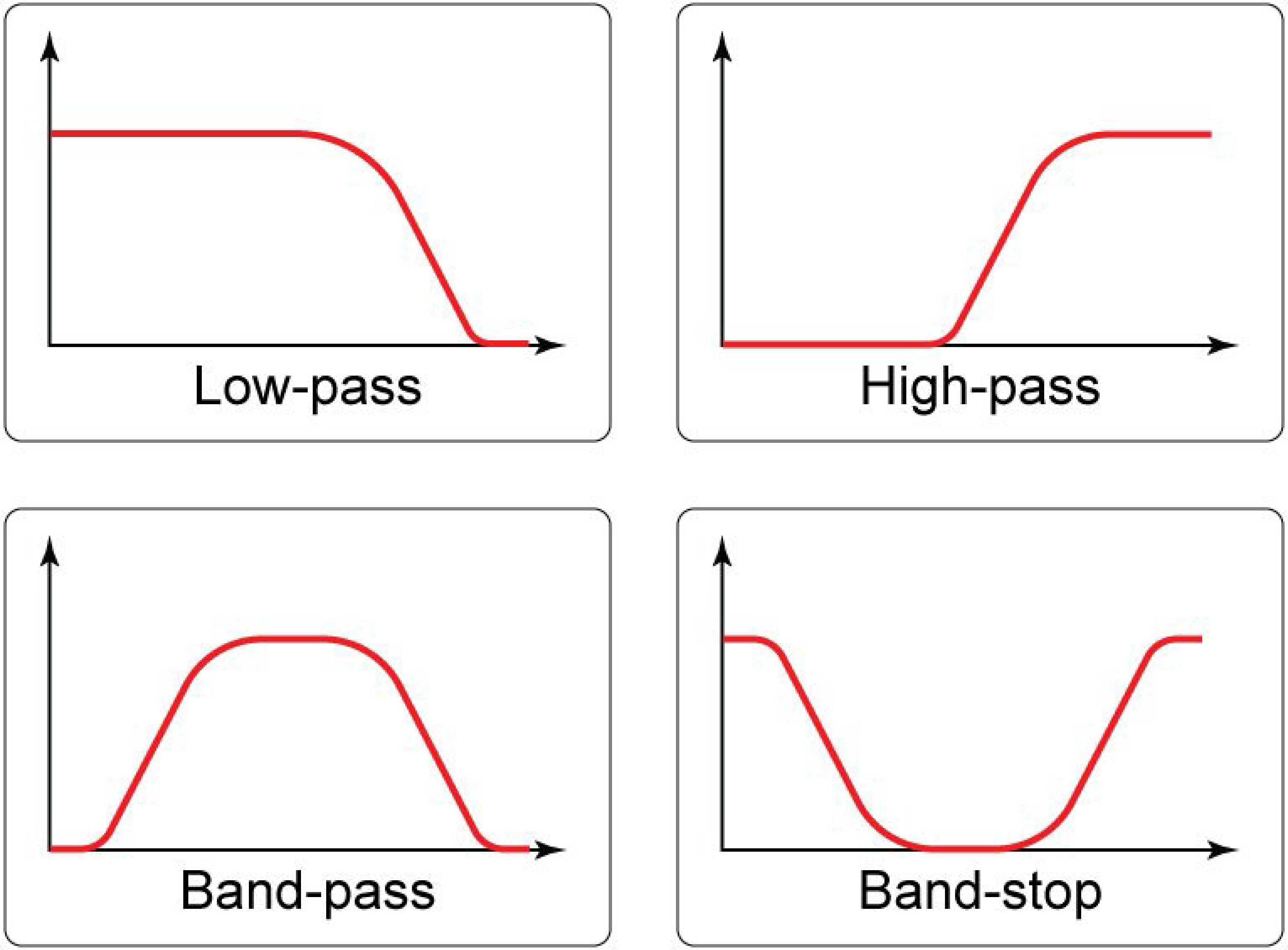
滤波器是对输入信号频率具有选择功能的电路，广泛应用于通信领域。

2. 分类

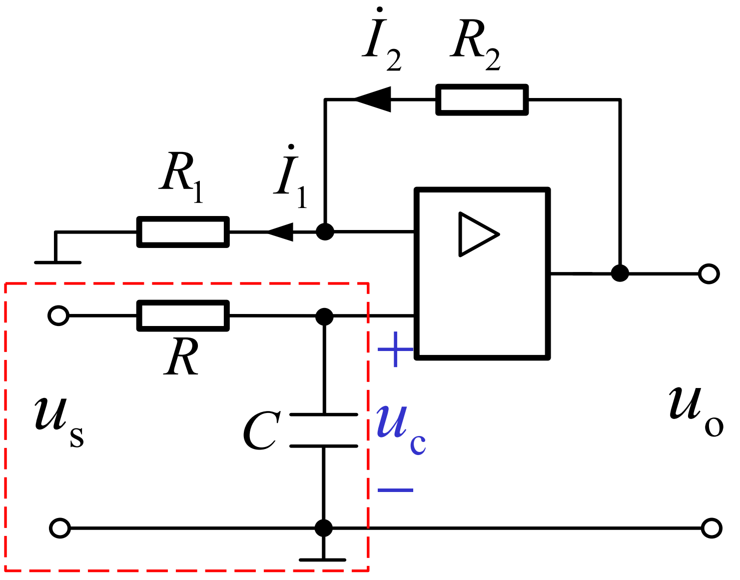


滤波器

- 低通滤波器：它允许信号中的低频或直流分量通过，抑制高频分量或干扰和噪声；
- 高通滤波器：它允许信号中的高频分量通过，抑制低频或直流分量；
- 带通滤波器：它允许一定频段的信号通过，抑制低于或高于该频段的信号、干扰和噪声；
- 带阻滤波器：它抑制一定频段内的信号，允许该频段以外的信号通过，又称为陷波滤波器。
- 全通滤波器：指在全频带范围内，信号的幅值不会改变，也就是全频带内幅值增益恒等于1。全通滤波器常用于移相。


Low-pass
High-pass
Band-pass
Band-stop

例 求图示电路中输出电压$\dot{U}_{\mathrm{O}}$



一阶有源低通滤波器

解 红框内为低通滤波器

$$\dot{U}_{\mathrm{C}}=\frac{\frac{1}{\mathrm{j}\omega C}}{R+\frac{1}{\mathrm{j}\omega C}}\dot{U}_{\mathrm{S}}=\frac{1}{1+\mathrm{j}\omega RC}\dot{U}_{\mathrm{S}}$$

应用运算放大器“虚短、虚断”特性：

$$\dot{I}_1=\dot{U}_{\mathrm{C}}/R_1 \qquad \dot{I}_1=\dot{I}_2$$

则输出电压：

$$\dot{U}_{\mathrm{O}}=R_2\dot{I}_2+R_1\dot{I}_1=\frac{R_1+R_2}{R_1}\dot{U}_{\mathrm{C}}=\left(1+\frac{R_2}{R_1}\right)\frac{1}{1+\mathrm{j}\omega RC}\dot{U}_{\mathrm{S}}$$

作业

- 14.3节：14-9，14-10
- 14.4节：14-14