Chương 5: Mạch lọc

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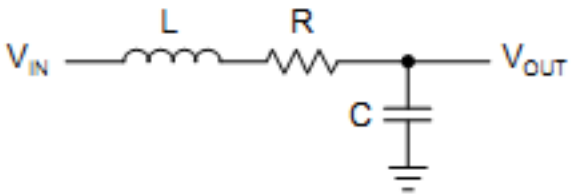
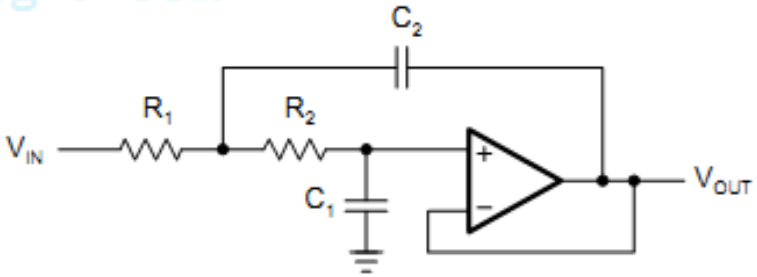
Nội dung

- Phân loại mạch lọc theo linh kiện.
  - Thụ động (RLC)
  - Tích cực (RC & OpAmp)



- Phân loại mạch lọc theo đáp ứng tần số
  - Mạch lọc thông thấp.
  - Mạch lọc thông cao.
  - Mạch lọc thông dải.
  - Mạch lọc chắn dải.
  - Mạch lọc toàn dải (dịch pha tuyến tính).



- Thiết kế mạch lọc Butterword.

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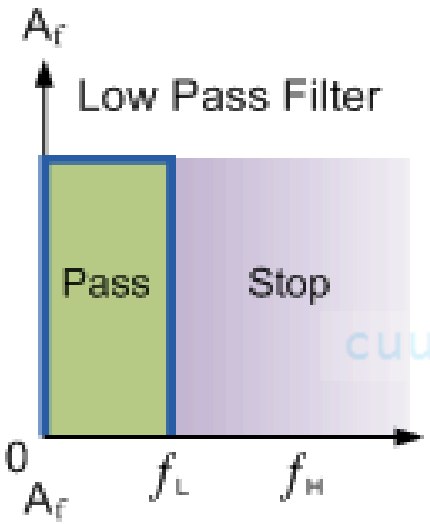
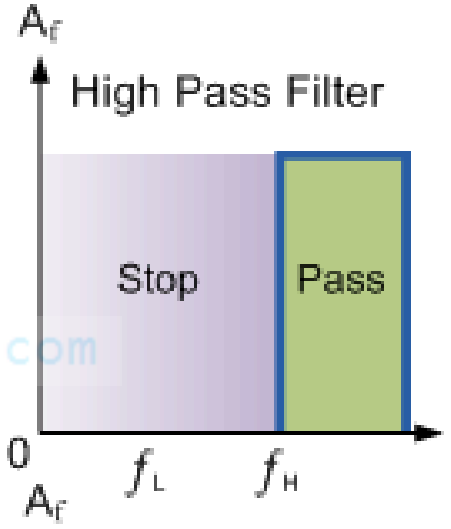
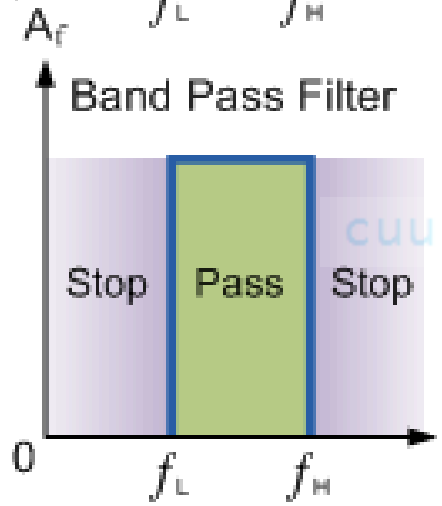
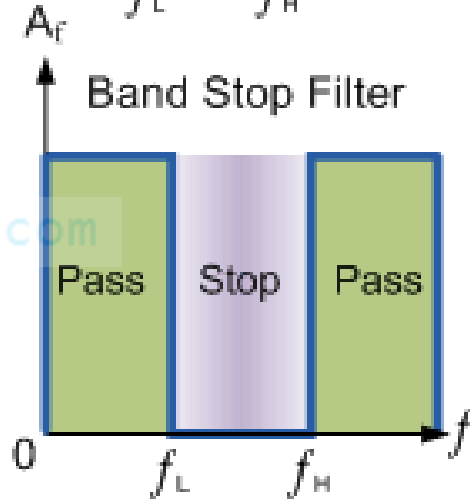
Phân loại mạch lọc (lý tưởng)









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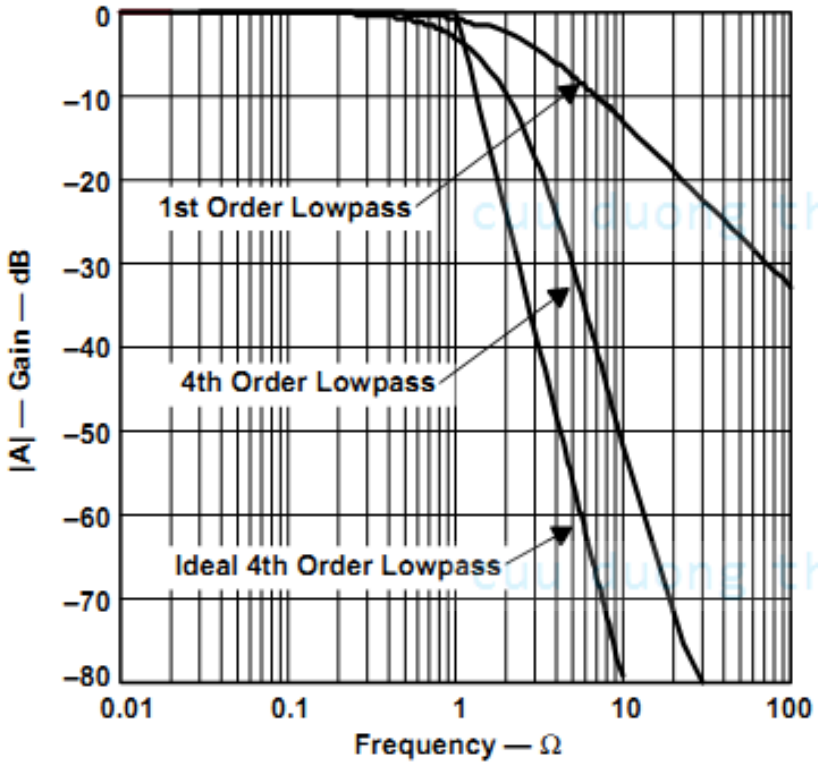
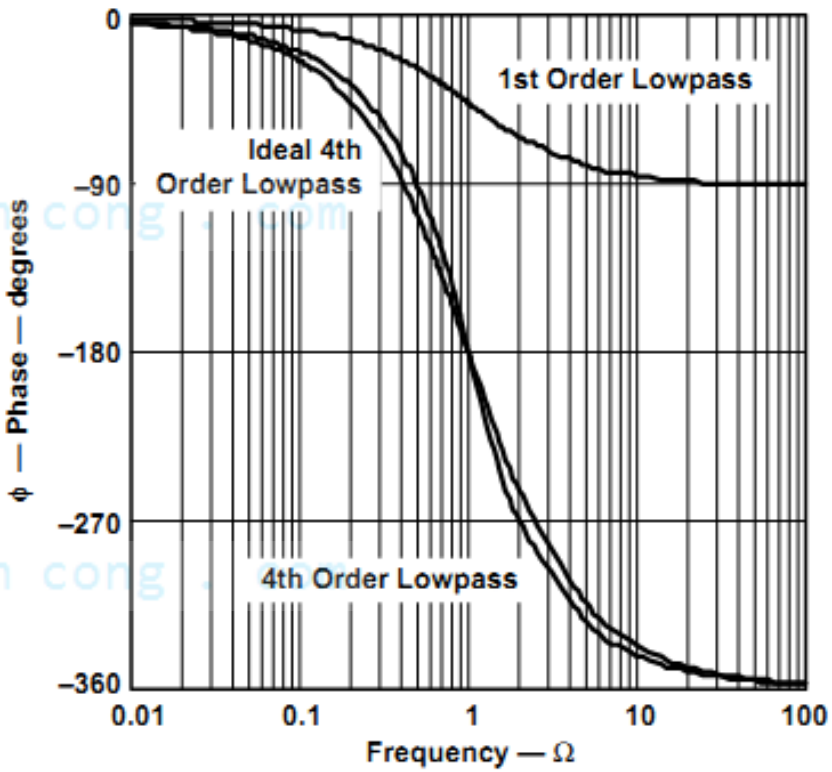
Đáp ứng bộ lọc thực tế





Tiêu chuẩn tối ưu

- Dải thông phẳng cực đại → Butterworth
- Khoảng dịch chuyển dải thông-dải chắn nhỏ → Tschebyscheff
- Pha tuyến tính → Bessel

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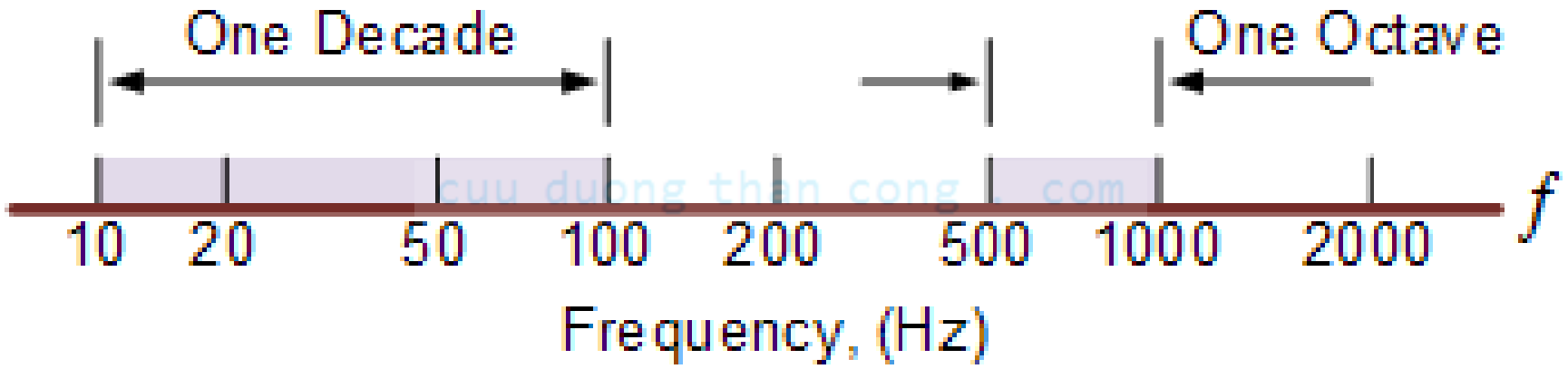
$$\frac{A_0}{\prod_i \left(1 + a_i s + b_i s^2\right)}$$

$$Q = \frac{f_m}{(f_2 - f_1)}$$

$$Q = \frac{\sqrt{b_i}}{a_i}$$

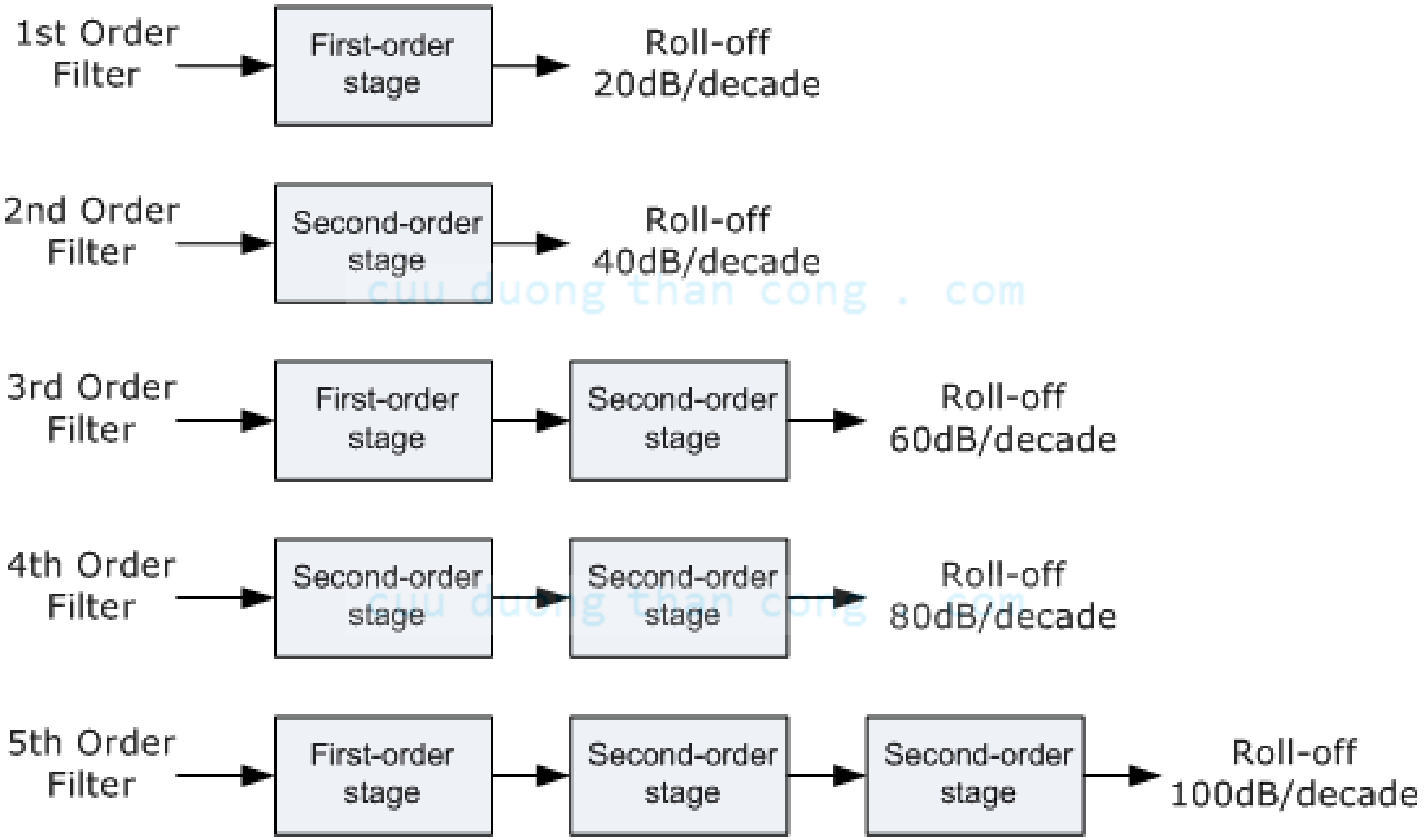
Thiết kế bộ lọc Butterworth



$$f_c = \frac{1}{2\pi RC} \; Hz$$

capacitor values should be on the order of magnitude of $(10/f_c)$ μF

Độ dốc bộ lọc ghép liên tầng



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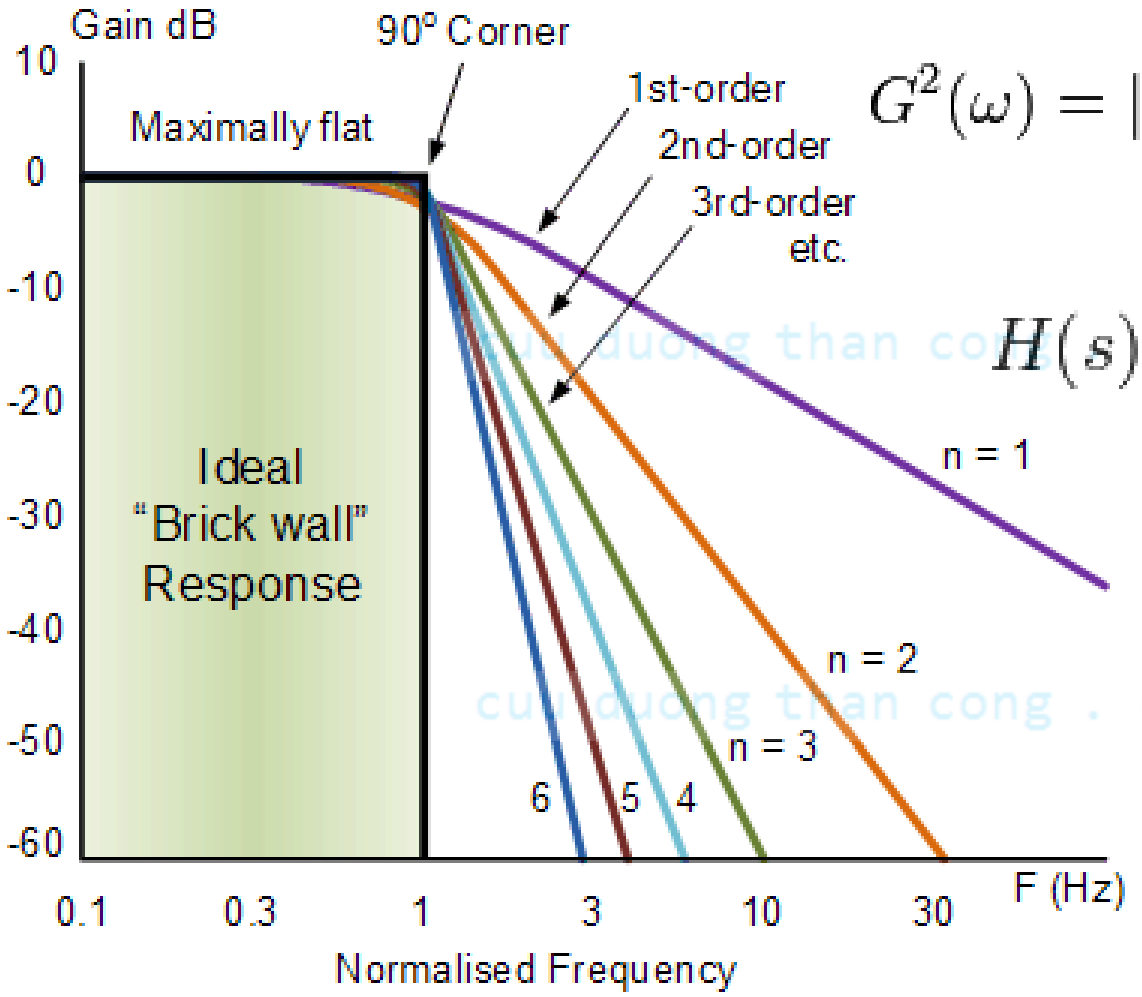
Thiết kế bộ lọc Butterworth (tt)



$$G^2(\omega) = |H(j\omega)|^2 = \frac{{G_0}^2}{1 + \left(\frac{\omega}{\omega_c}\right)^{2n}}$$

$$H(s) = \frac{G_0}{\prod_{k=1}^{n}(s - s_k)/\omega_c}$$

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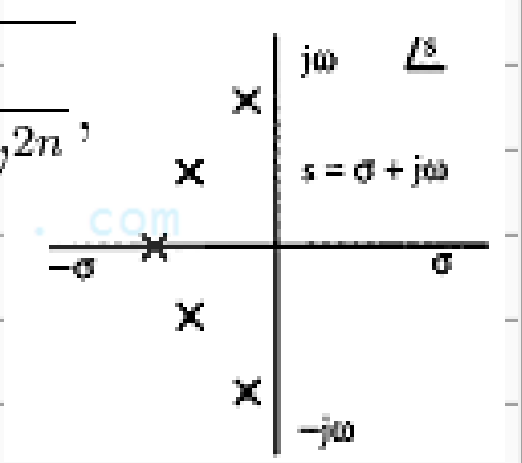
Thiết kế bộ lọc Butterworth (tt)

n	Normalised Denominator Polynomials in Factored Form
1	(1+s)
2	$(1+1.414s+s^2)$
3	$(1+s)(1+s+s^2)$
4	$(1+0.765s+s^2)(1+1.848s+s^2)$
5	$(1+s)(1+0.618s+s^2)(1+1.618s+s^2)$
6	$(1+0.518s+s^2)(1+1.414s+s^2)(1+1.932s+s^2)$
7	$(1+s)(1+0.445s+s^2)(1+1.247s+s^2)(1+1.802s+s^2)$
8	$(1+0.390s+s^2)(1+1.111s+s^2)(1+1.663s+s^2)(1+1.962s+s^2)$
9	$(1+s)(1+0.347s+s^2)(1+s+s^2)(1+1.532s+s^2)(1+1.879s+s^2)$
10	$(1+0.313s+s^2)(1+0.908s+s^2)(1+1.414s+s^2)(1+1.782s+s^2)(1+1.975s+s^2)$

$$G(\omega) = \sqrt{\frac{1}{1+\omega^{2n}}},$$



$$s_k = \omega_c e^{\frac{j(2k+n-1)\pi}{2n}} \qquad k = 1, 2, 3, \ldots, n$$

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$$H(s) = \frac{G_0}{B_n(a)} \qquad a = \frac{s}{\omega_c}$$

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- n chẵn $B_n(s) = \prod_{k=1}^{\frac{n}{2}} \left[s^2 - 2s\cos\left(\frac{2k+n-1}{2n}\pi\right) + 1 \right]$

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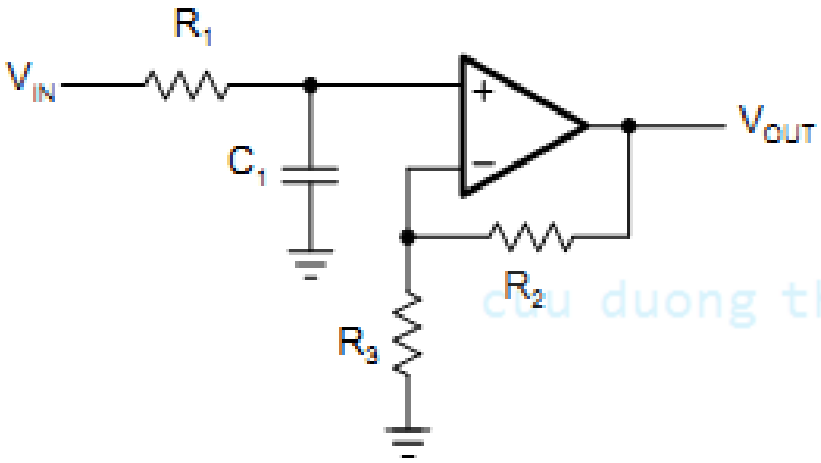
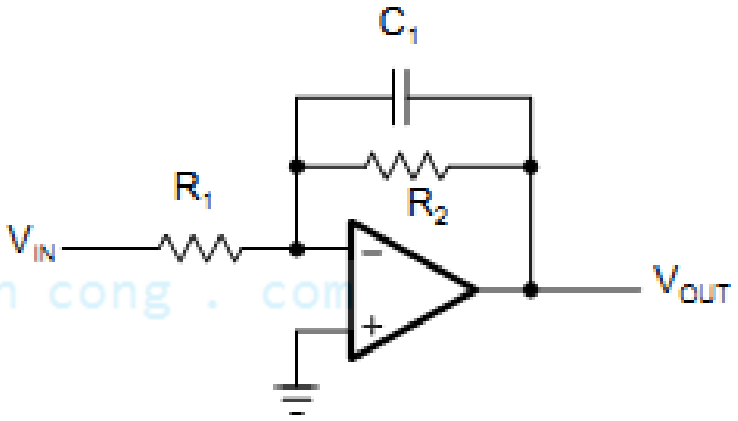
- n lẻ $B_n(s) = (s+1)\prod_{k=1}^{\frac{n-1}{2}} \left[s^2 - 2s\cos\left(\frac{2k+n-1}{2n}\pi\right) + 1 \right]$

Thông thấp bậc 1





$$\frac{1 + \frac{R_2}{R_3}}{1 + \omega_c R_1 C_1 s}$$

$$\frac{-\frac{R_2}{R_1}}{1 + \omega_c R_2 C_1 s}$$

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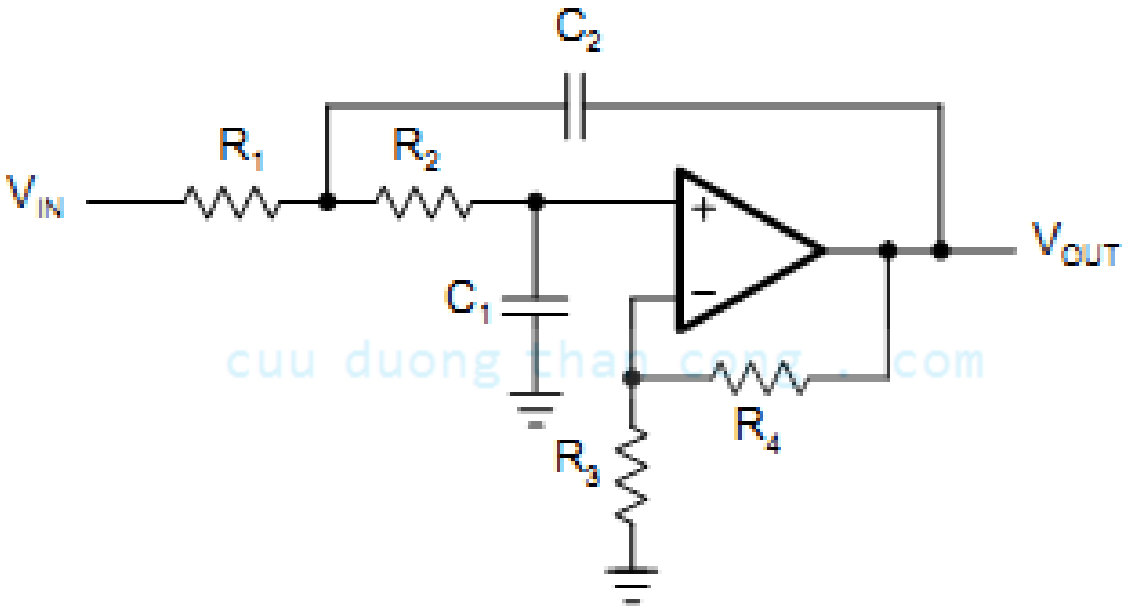
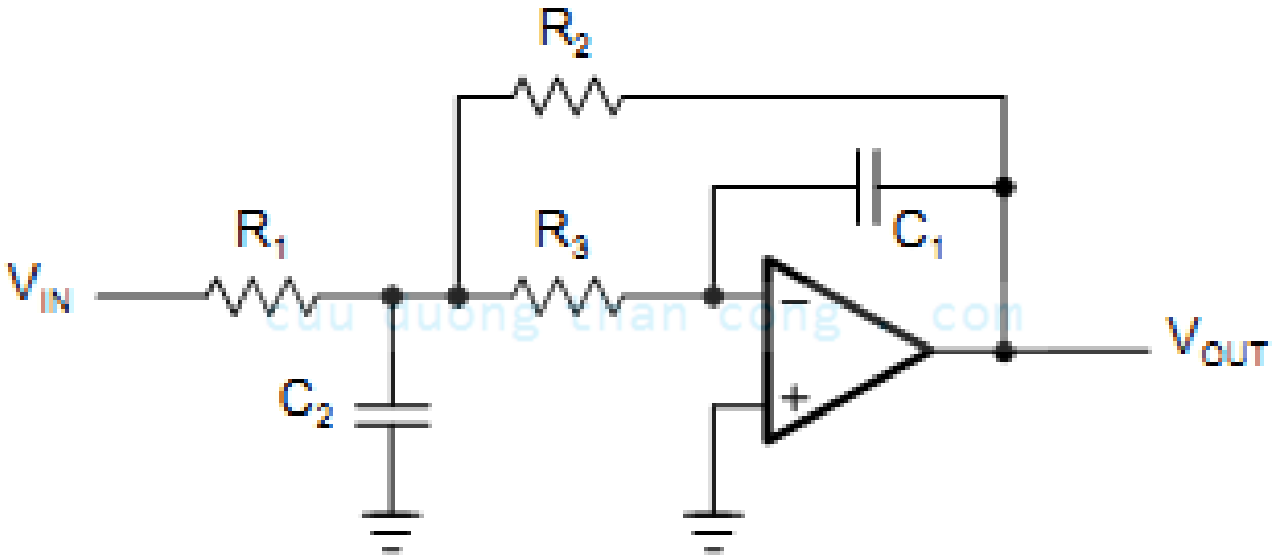
Thông thấp bậc 2



- Hàm truyền đưa về chuẩn hóa từ w_c

$$\frac{A_0}{1 + \omega_c\left[C_1(R_1 + R_2) + (1 - A_0)\,R_1C_2\right]s + \omega_c^2\,R_1R_2C_1C_2s^2}$$

Thông thấp bậc 2



- Hàm truyền đưa về chuẩn hóa từ w_c

$$-\frac{\frac{R_2}{R_1}}{1+\omega_c C_1\left(R_2+R_3+\frac{R_2R_3}{R_1}\right)s+\omega_c{}^2 C_1C_2R_2R_3s^2}$$

Lọc thông cao

- Thay s bởi 1/s
- Thay R bởi C và ngược lại

$$\frac{A_\infty}{\prod_i \left(1 + \frac{a_i}{s} + \frac{b_i}{s^2}\right)}$$

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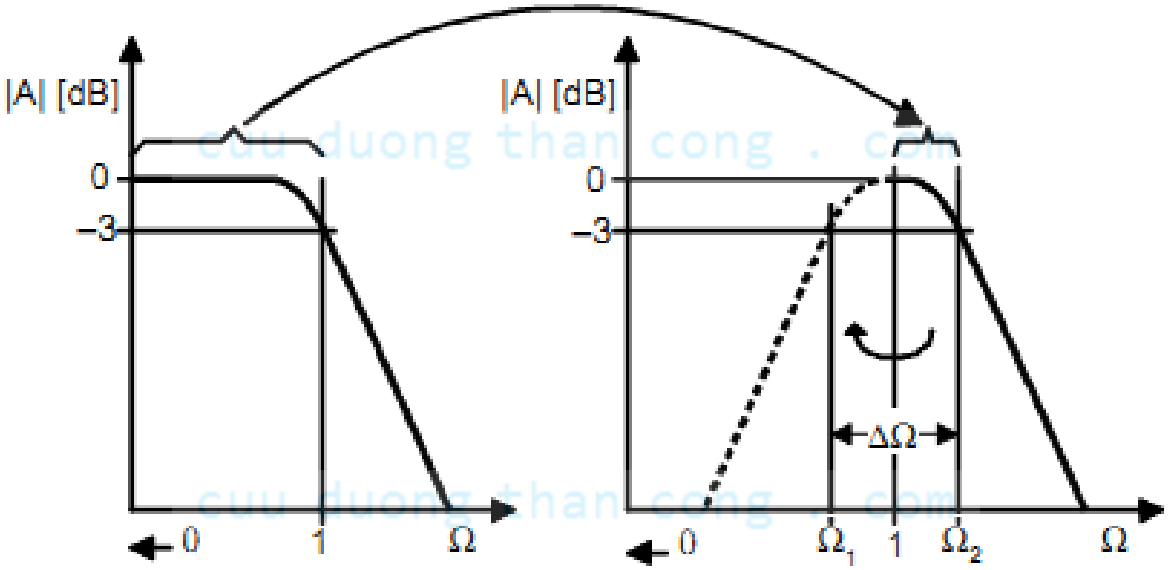
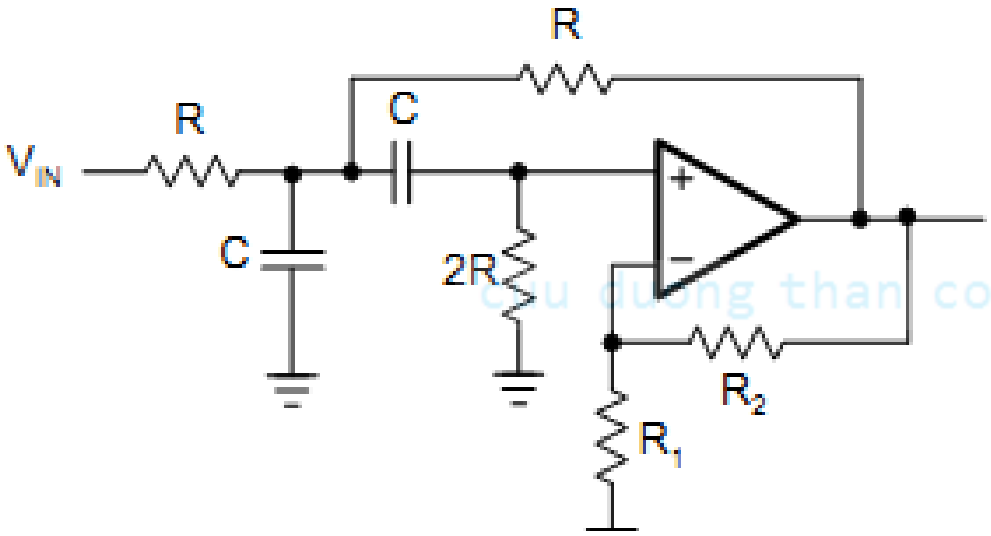
Lọc thông dải

- Thay s bởi $\frac{1}{\Delta\Omega}\left(s + \frac{1}{s}\right)$



- Nối tiếp lọc thông thấp với lọc thông cao

Lọc thông dải bậc 2



$$\frac{A_0 \cdot \Delta\Omega \cdot s}{1 + \Delta\Omega \cdot s + s^2}$$

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$$\frac{G \cdot RC\omega_m \cdot s}{1 + RC\omega_m(3 - G) \cdot s + R^2C^2\omega_m^2 \cdot s^2}$$

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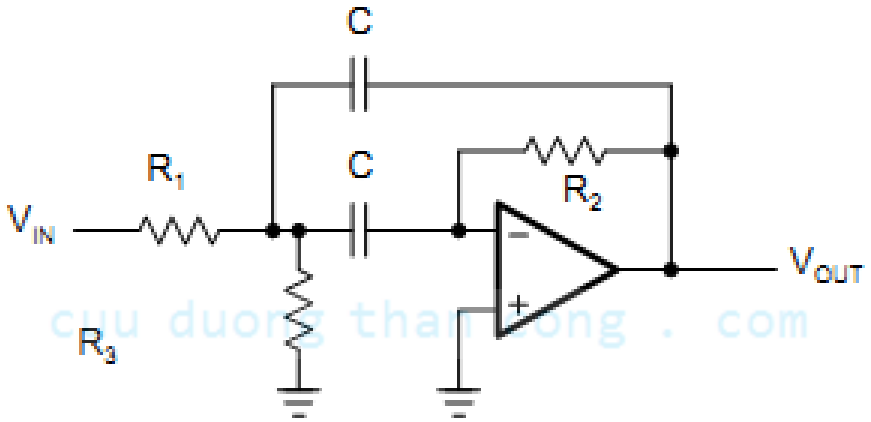
$$f_m = \frac{1}{2\pi RC} \qquad A_m = \frac{G}{3 - G} \qquad G = 1 + \frac{R_2}{R_1}$$

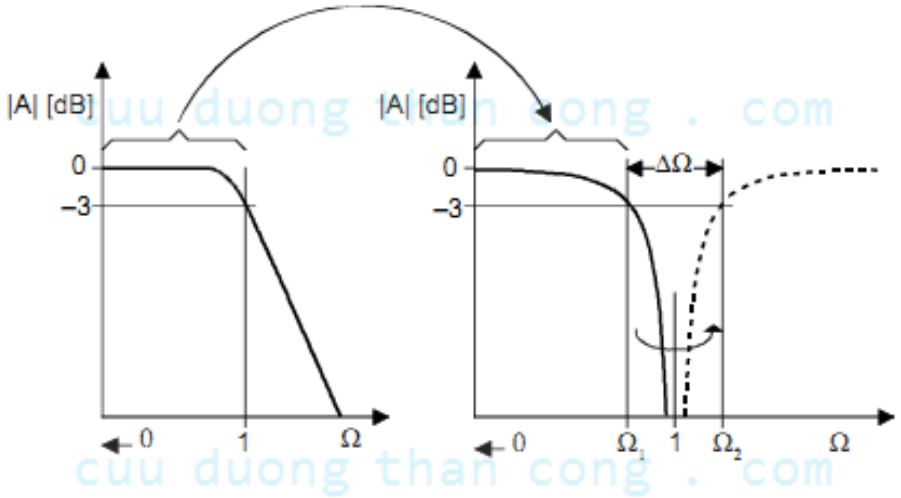


$$\frac{-\frac{R_2R_3}{R_1+R_3}C\omega_m\cdot s}{1+\frac{2R_1R_3}{R_1+R_3}C\omega_m\cdot s+\frac{R_1R_2R_3}{R_1+R_3}C^2\cdot\omega_m{}^2\cdot s^2}$$

$$f_m=\frac{1}{2\pi C}\sqrt{\frac{R_1+R_3}{R_1R_2R_3}} \qquad -A_m=\frac{R_2}{2R_1} \qquad B=\frac{1}{\pi R_2C}$$

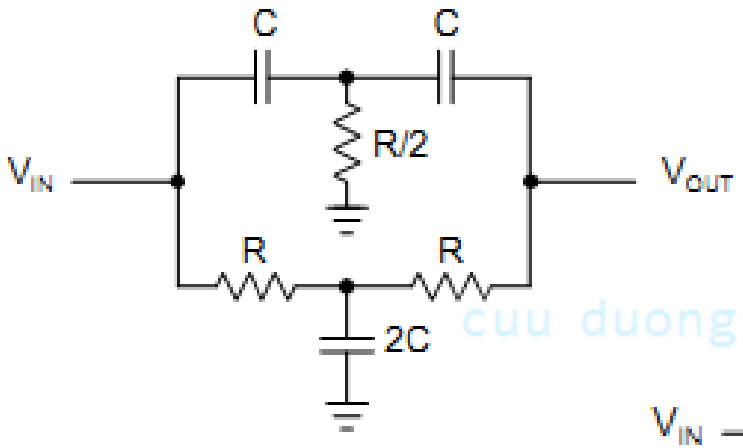
Bộ lọc chắn dải

- Thay s bởi $\dfrac{\Delta\Omega}{s + \frac{1}{s}}$

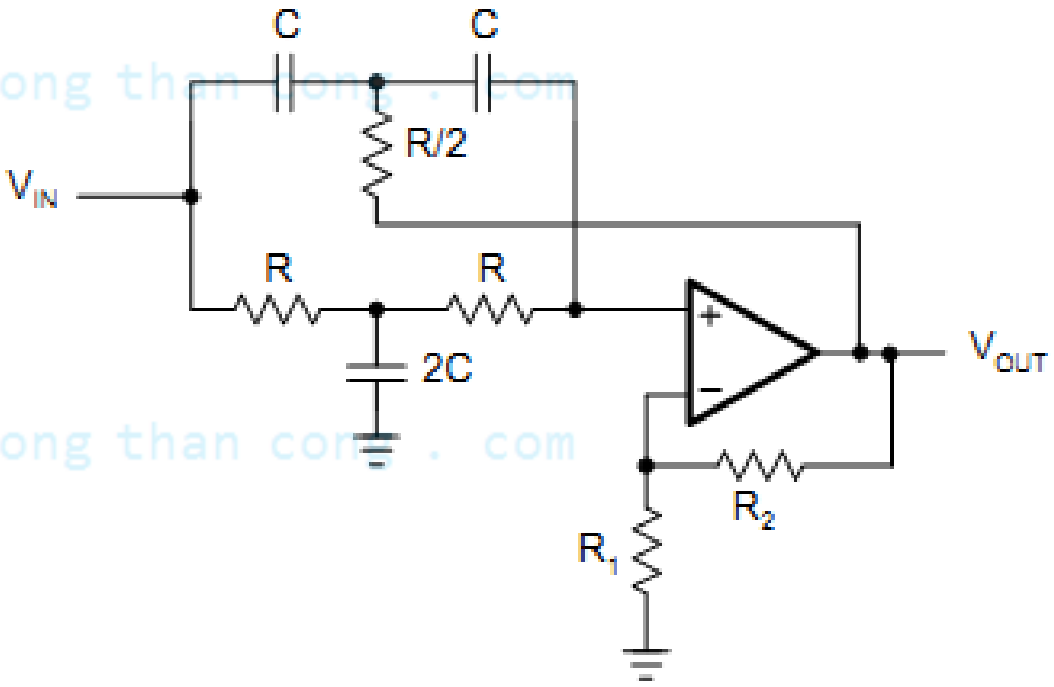


$$\frac{A_0(1 + s^2)}{1 + \Delta\Omega \cdot s + s^2}$$

Mạch lọc chắn dải cầu đôi T



$$\frac{k(1 + s^2)}{1 + 2(2 - k)\cdot s + s^2}$$



$$f_m = \frac{1}{2\pi RC}$$

$$G = 1 + \frac{R_2}{R_1}$$

$$A_0 = G$$

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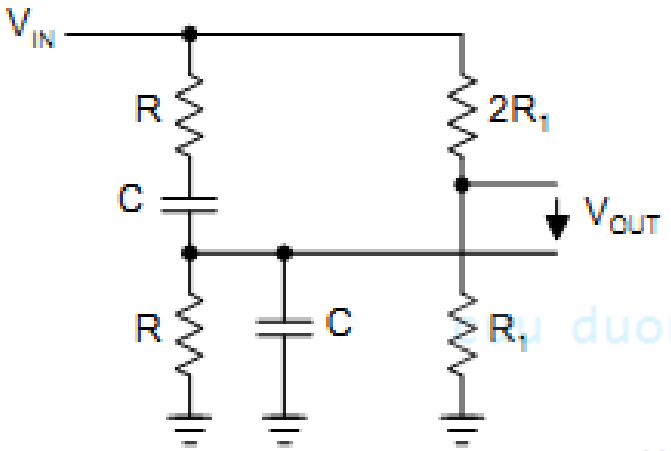
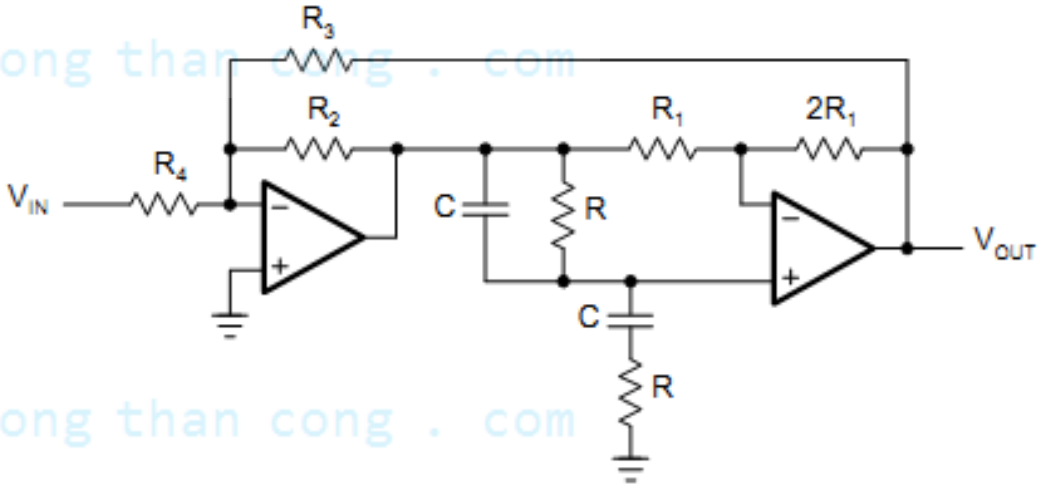
Mạch lọc chắn dải Wien-Robison



$$-\frac{\frac{\beta}{1+\alpha}\left(1+s^2\right)}{1+\frac{3}{1+\alpha}\cdot s+s^2}$$



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$$\alpha = \frac{R_2}{R_3}$$

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$$\beta = \frac{R_2}{R_4}$$

$$f_m = \frac{1}{2\pi RC}$$

$$A_0 = -\frac{\beta}{1+\alpha}$$

Mạch lọc toàn dải

$$\frac{\prod_i \left(1 - a_i s + b_i s^2\right)}{\prod_i \left(1 + a_i s + b_i s^2\right)}$$

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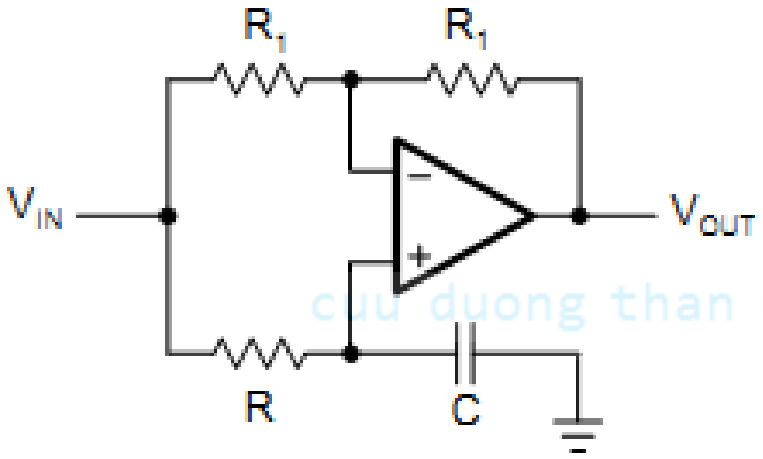

$$\frac{1 - RC\omega_c \cdot s}{1 + RC\omega_c \cdot s}$$

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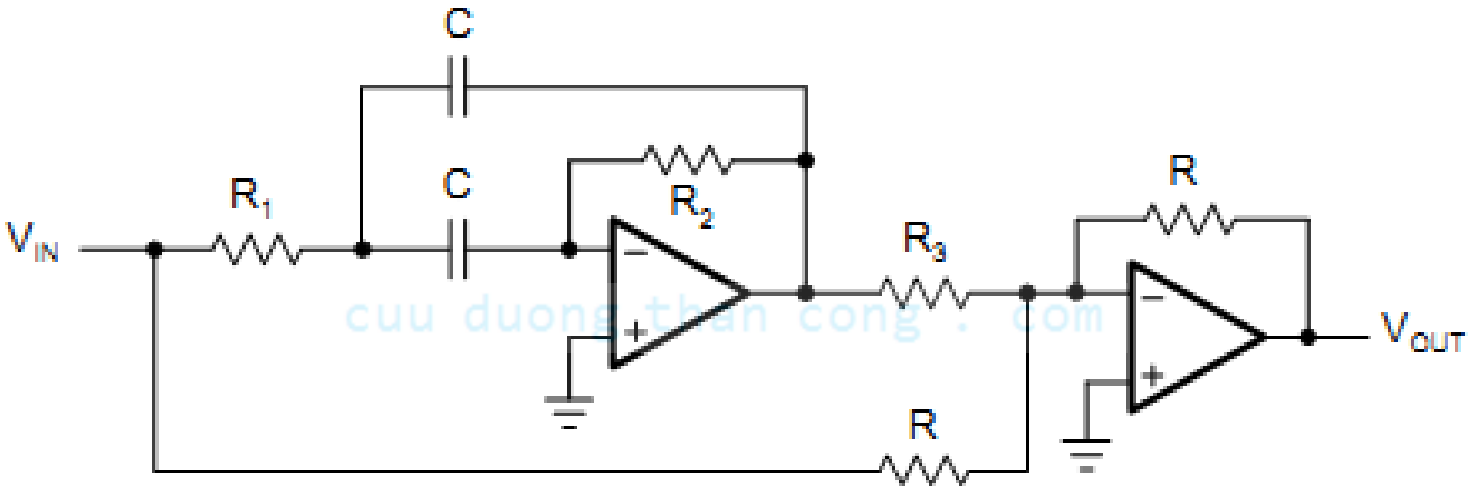

$$\frac{1 + (2R_1 - \alpha R_2)C\omega_c \cdot s + R_1R_2C^2\omega_c{}^2 \cdot s^2}{1 + 2R_1C\omega_c \cdot s + R_1R_2C^2\omega_c{}^2 \cdot s^2}$$

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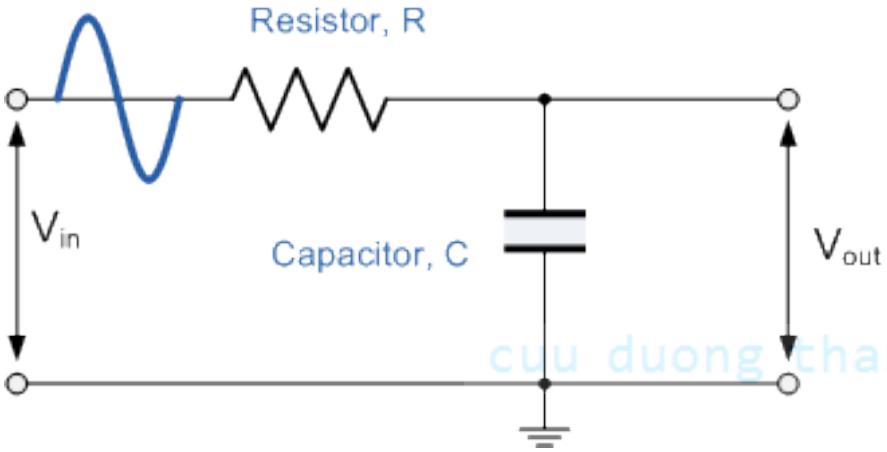
Mạch lọc thông thấp thụ động



$$\frac{1}{1 + sRC}$$

$$f_c = \frac{1}{2\pi RC}$$

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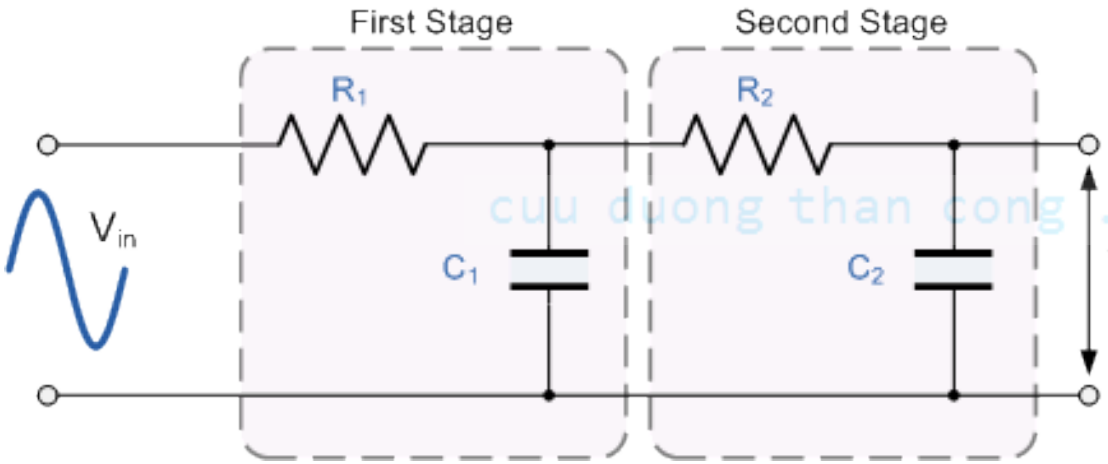
$$|A| = \frac{1}{\sqrt{1 + \Omega^2}}$$

$$\Omega = f/f_C$$



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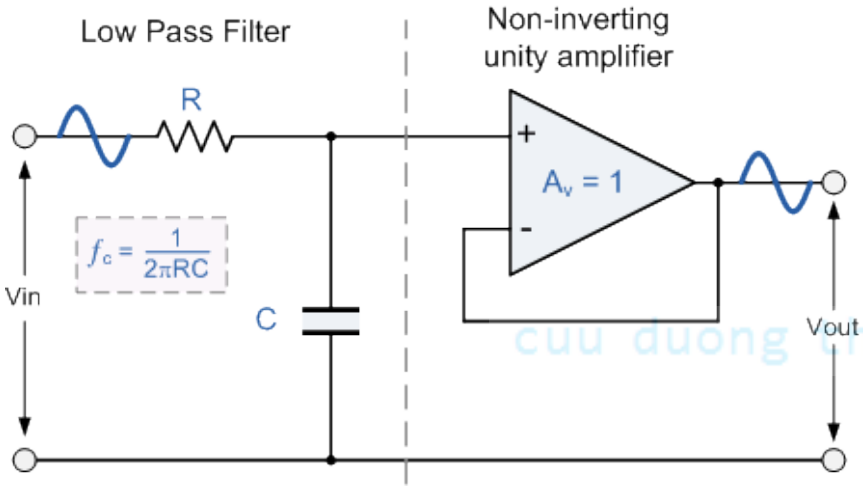
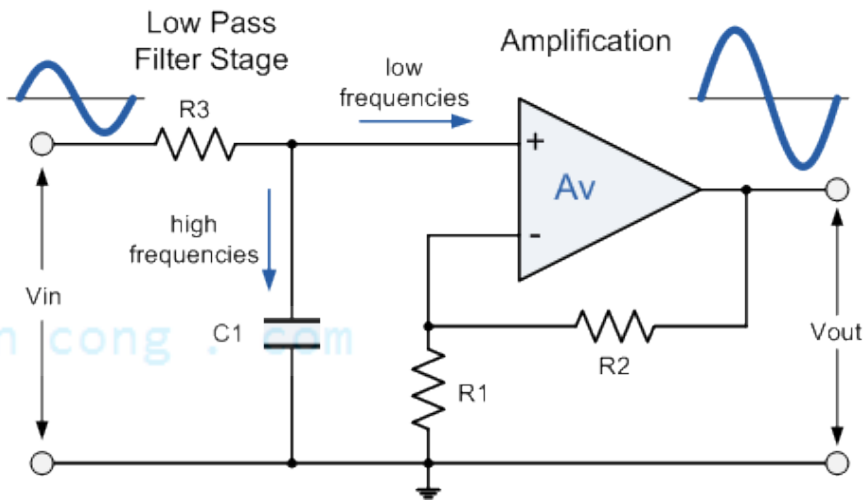
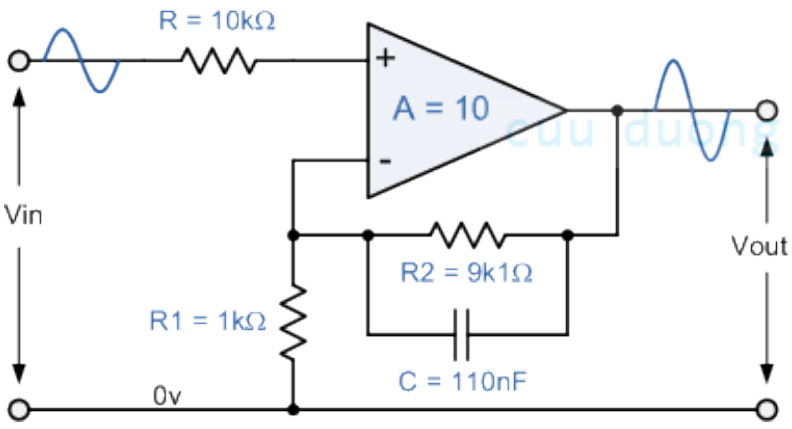
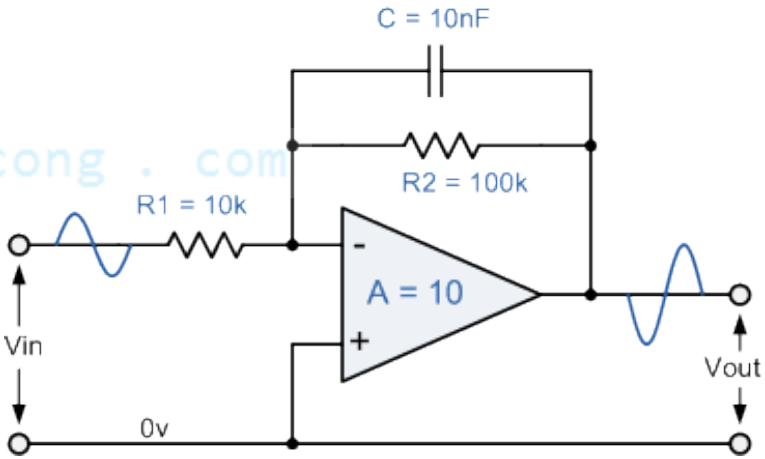
$$f_C = \frac{1}{4\pi\sqrt{R_1 C_1 R_2 C_2}} \text{ Hz}$$

Mạch lọc thông thấp tích cực









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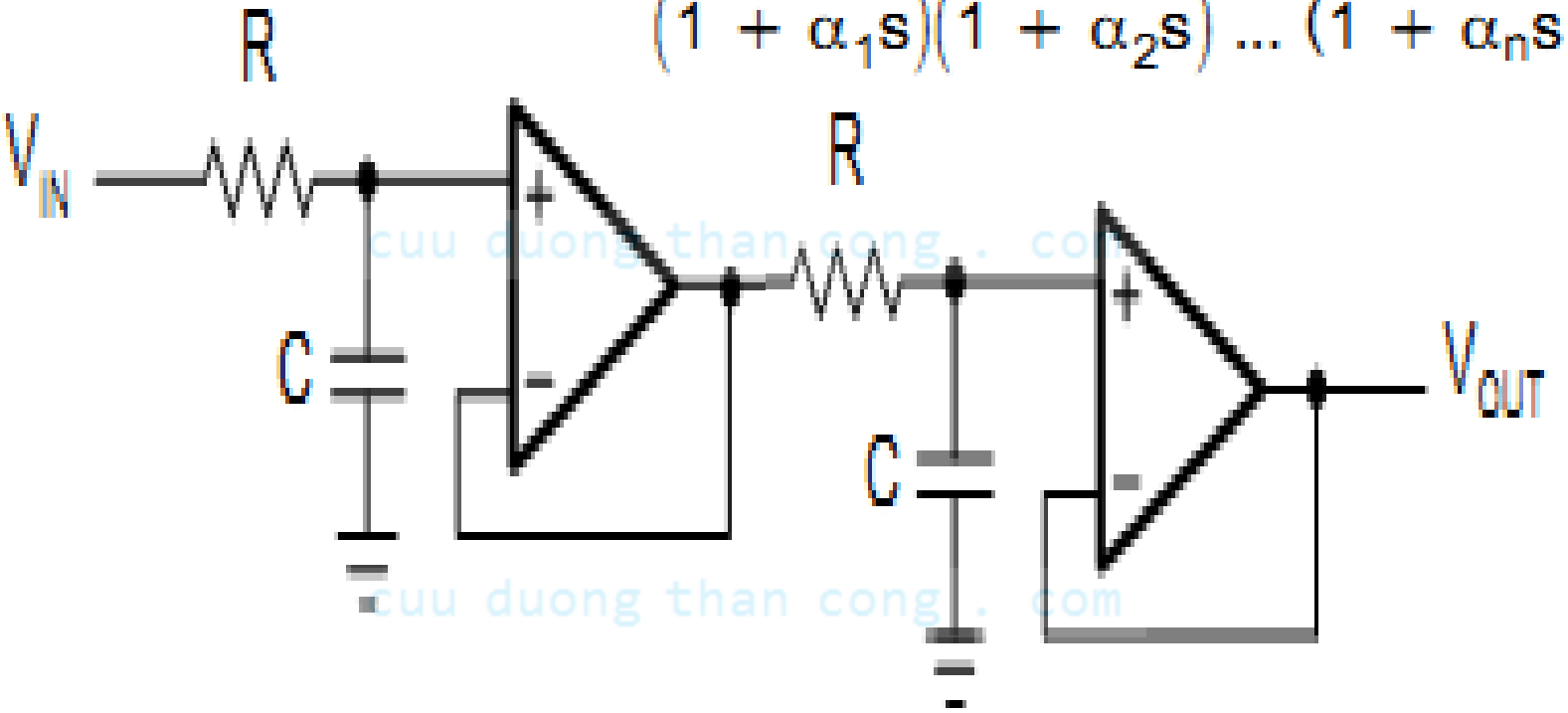
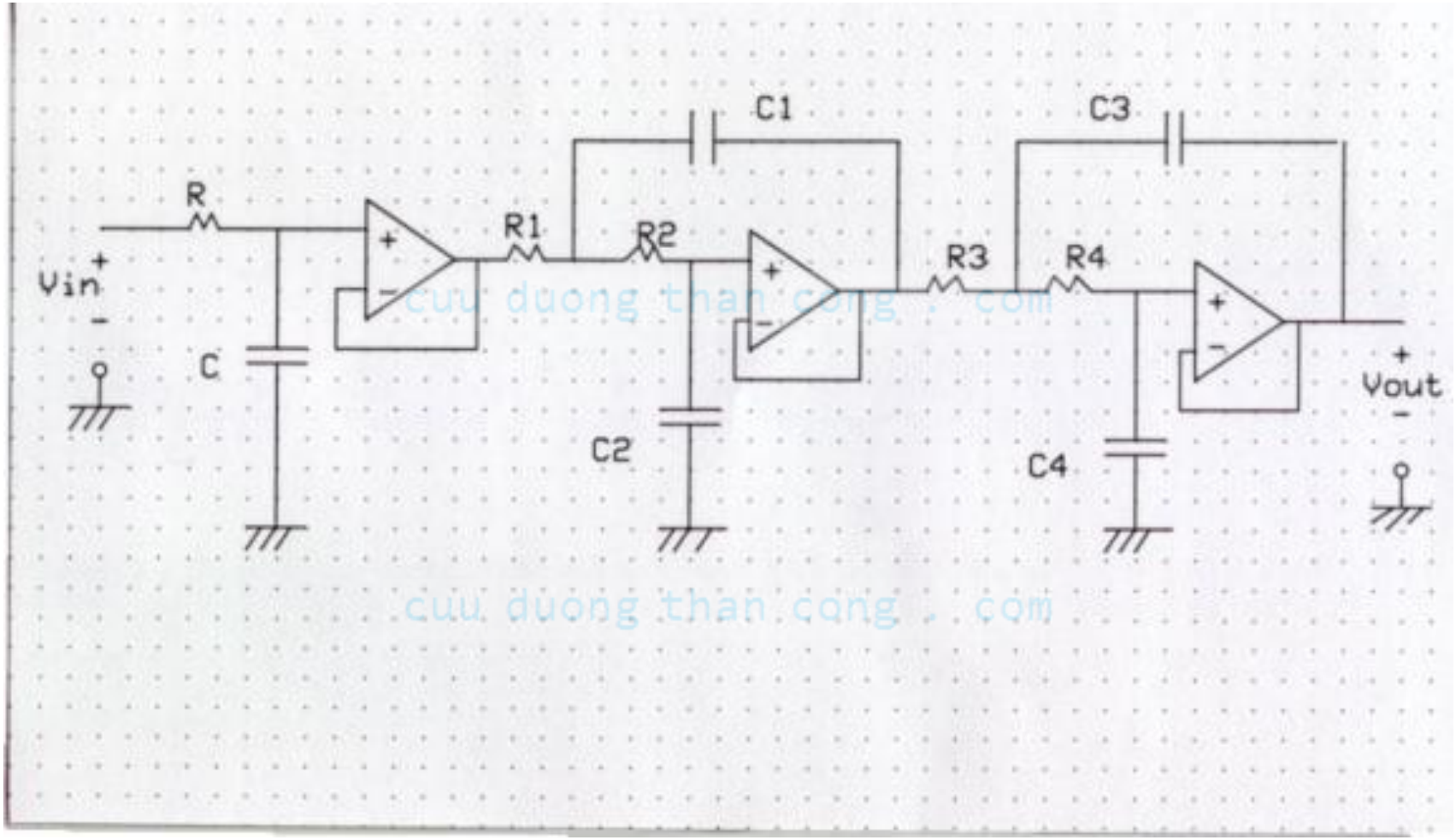
$$\frac{1}{(1+\alpha_1 s)(1+\alpha_2 s)\ldots(1+\alpha_n s)}$$



$$\alpha_1 = \alpha_2 = \ldots \alpha_n = \alpha = \sqrt{\sqrt[n]{2} - 1}$$



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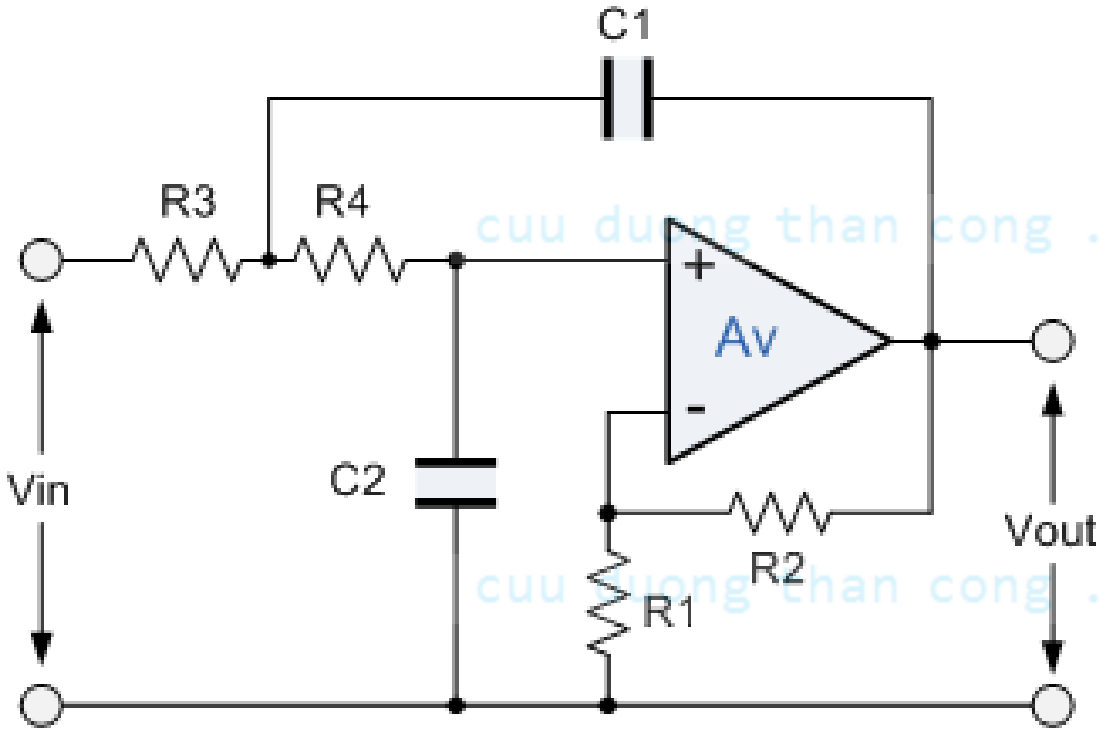
Mạch lọc thông thấp tích cực (tt)

- Sallen & Key 2



$$Av = 1 + \frac{R_2}{R_1}$$

$$f_C = \frac{1}{2\pi\sqrt{R_3R_4C_1C_2}}$$

$$H(s) = \frac{k\omega_0^2}{(s^2 + (\omega_0/Q)s + \omega_0^2)}$$

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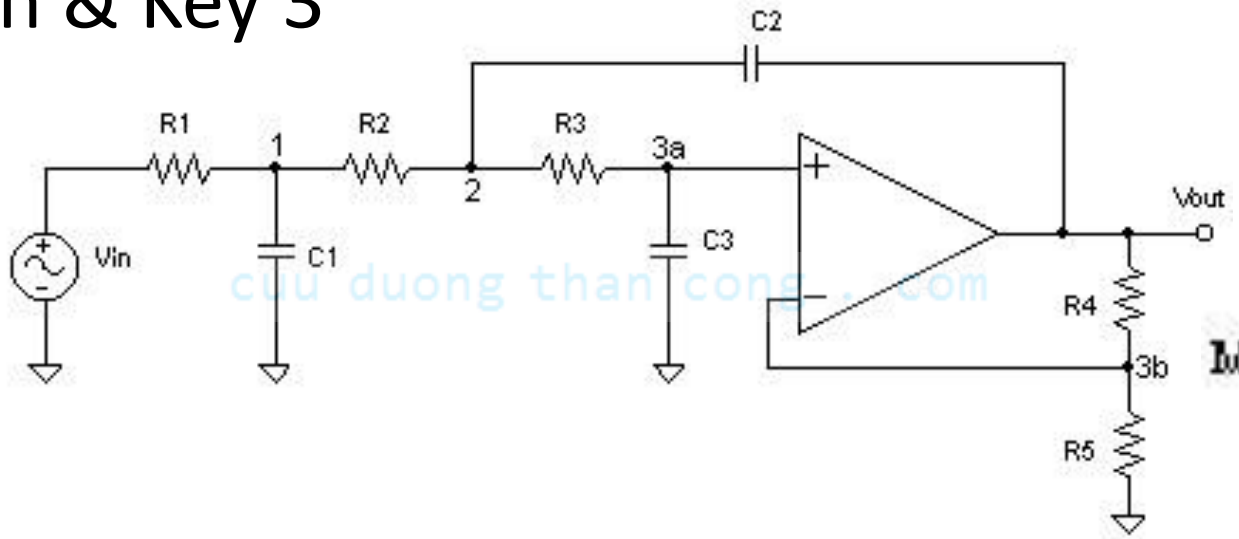
- Sallen & Key 3



$$M = 1 + \frac{R4}{R5}$$

$$\frac{\frac{M}{R_1 \cdot R_2 \cdot R_3 \cdot C_1 \cdot C_2 \cdot C_3}}{\left[s^3 + \left(\frac{1}{R_1 \cdot C_1} + \frac{1}{R_2 \cdot C_1} + \frac{1}{R_2 \cdot C_2} + \frac{1 - M}{R_3 \cdot C_3} + \frac{1}{R_3 \cdot C_2}\right) \cdot s^2 + \left[\frac{C_3 \cdot R_3 + R_1 \cdot C_3 + R_2 \cdot C_3 + C_1 \cdot R_1 + (1 - M) \cdot (R_1 + R_2) \cdot C_2}{R_1 \cdot R_2 \cdot R_3 \cdot C_1 \cdot C_2 \cdot C_3}\right] \cdot s + \frac{1}{(R_1 \cdot R_2 \cdot R_3 \cdot C_1 \cdot C_2 \cdot C_3)}\right]}$$

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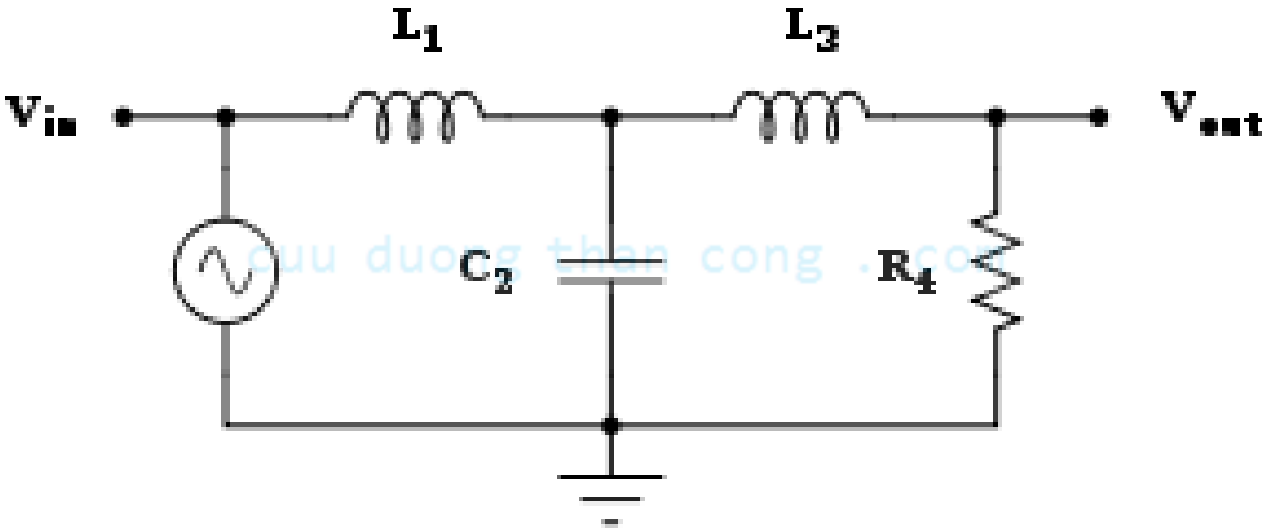
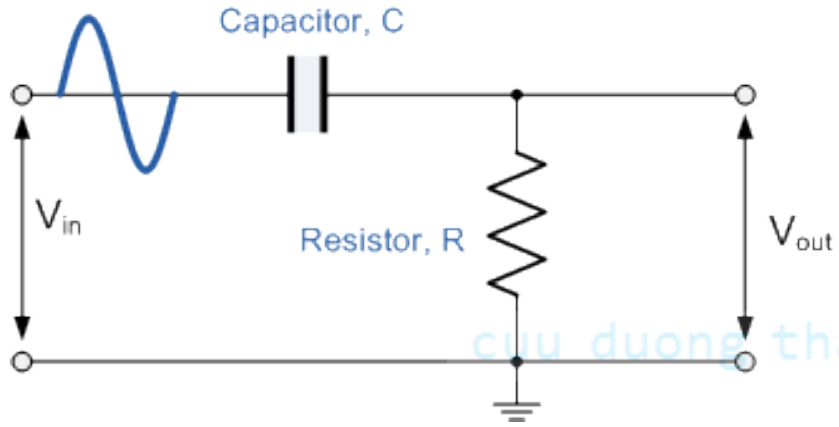
Bộ lọc thông thấp bậc 3

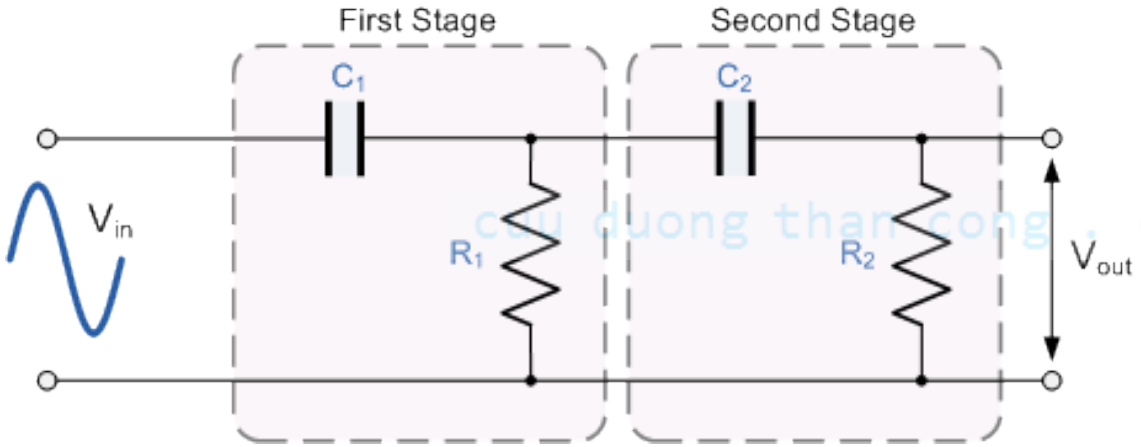
- Cauer



- The filter becomes a Butterworth filter with cutoff frequency ω_c=1 when (for example) C_2=4/3 farad, R_4=1 ohm, L_1=3/2 henry and L_3=1/2 henry.

Mạch lọc thông cao thụ động





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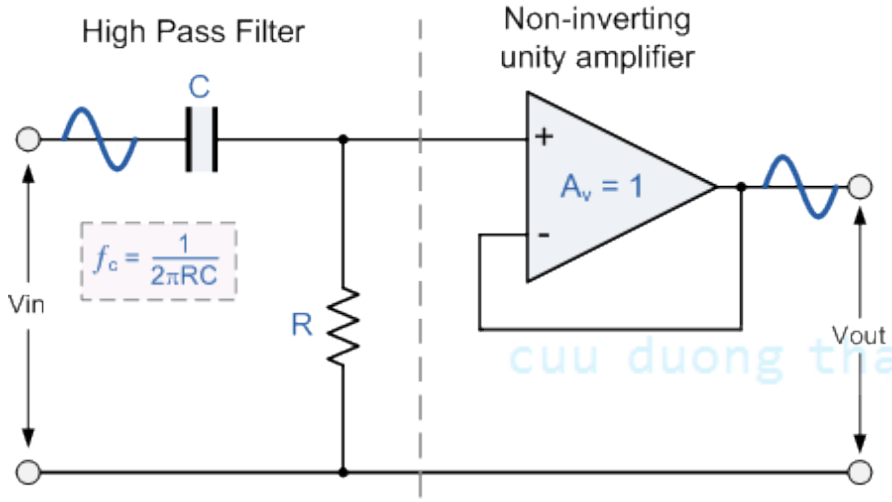
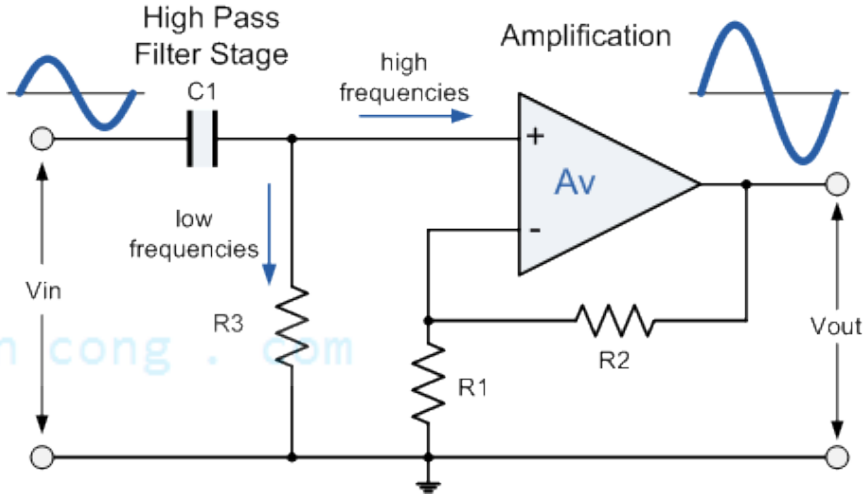
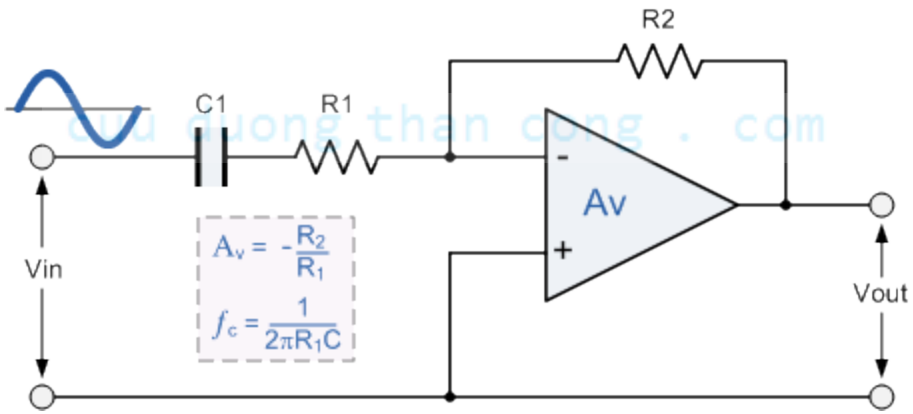
Mạch lọc thông cao tích cực







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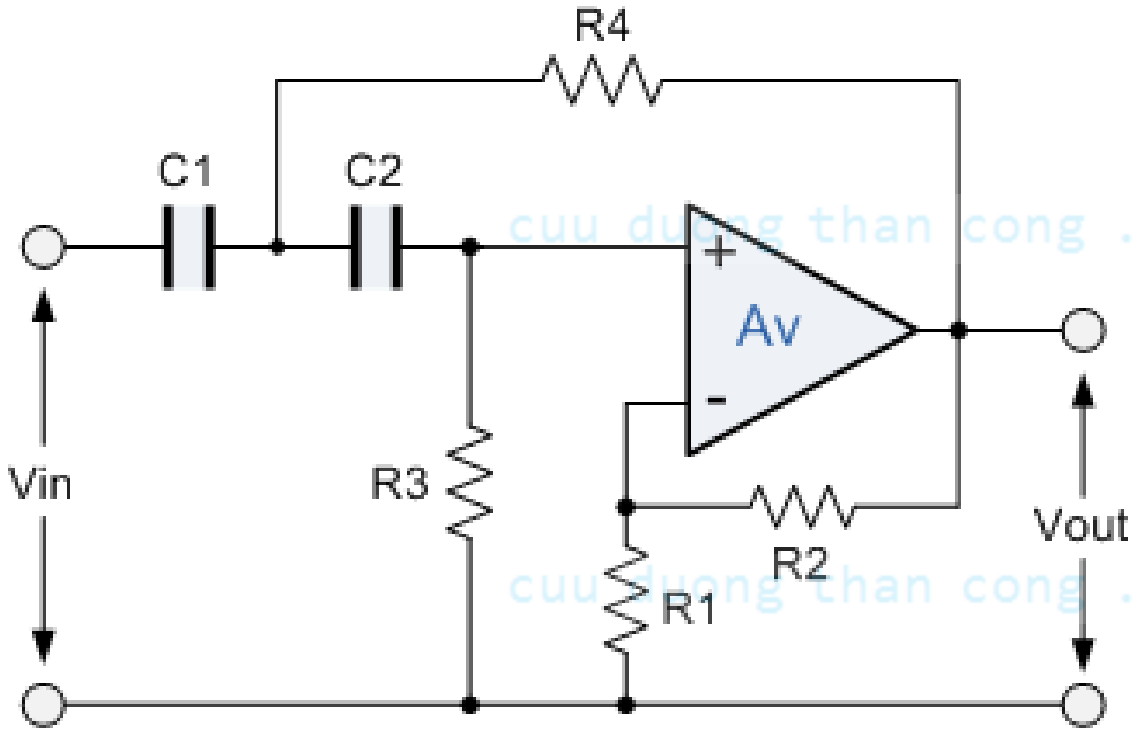
Mạch lọc thông cao tích cực (tt)



$$Av = 1 + \frac{R_2}{R_1}$$

$$f_C = \frac{1}{2\pi\sqrt{R_3R_4C_1C_2}}$$

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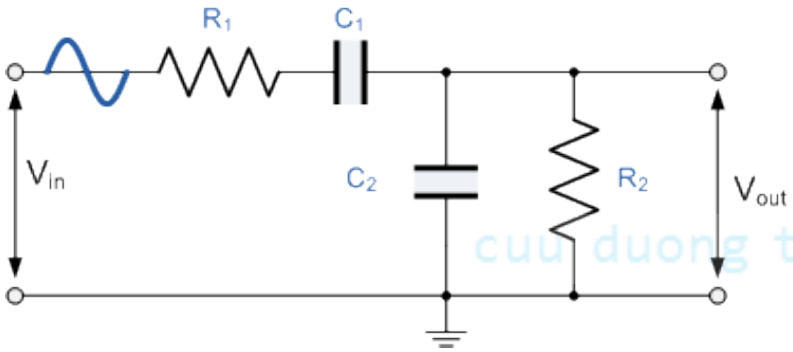
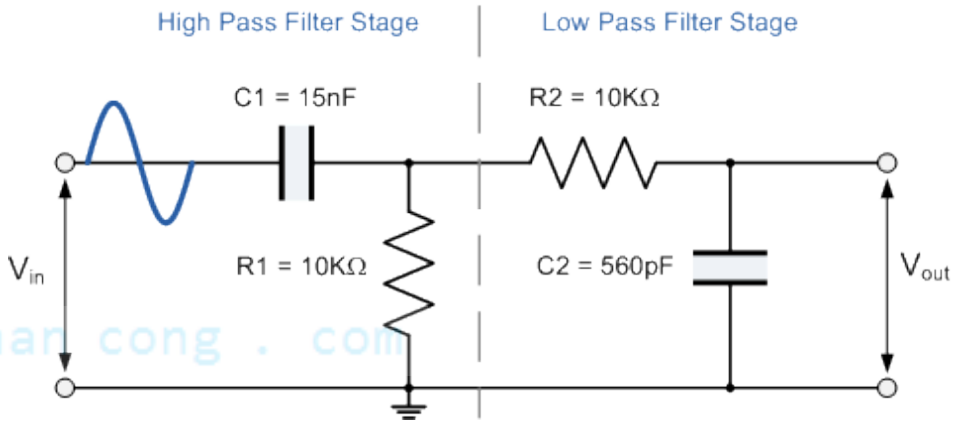
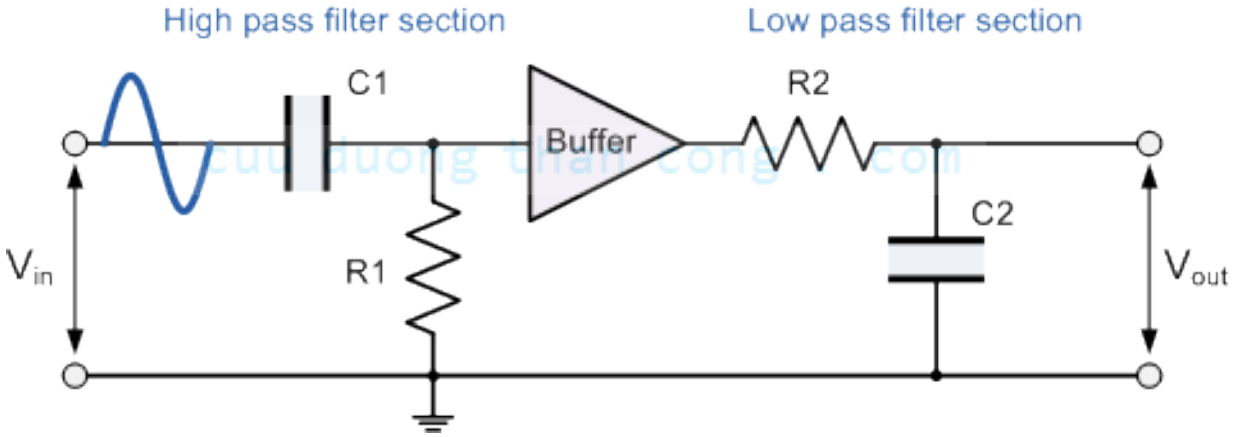
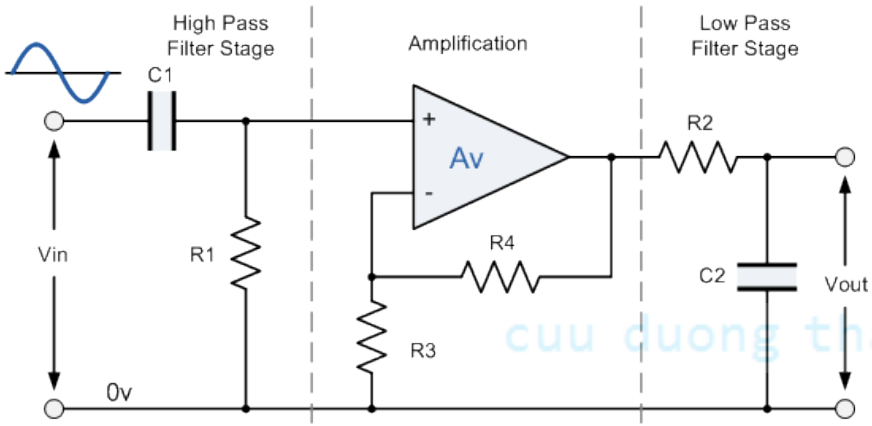
Mạch lọc thông dải thụ động

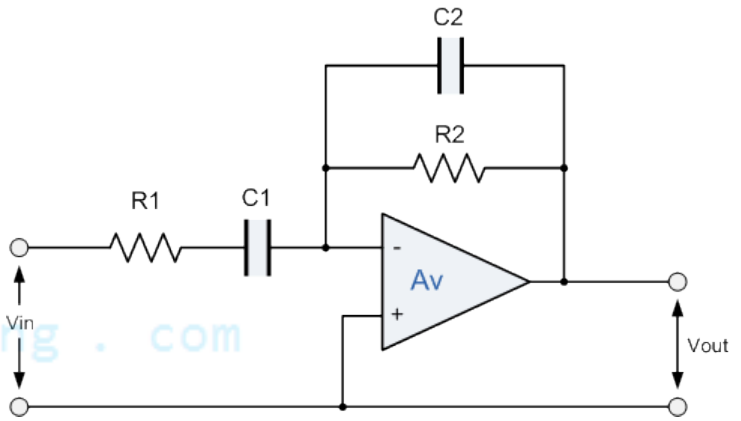


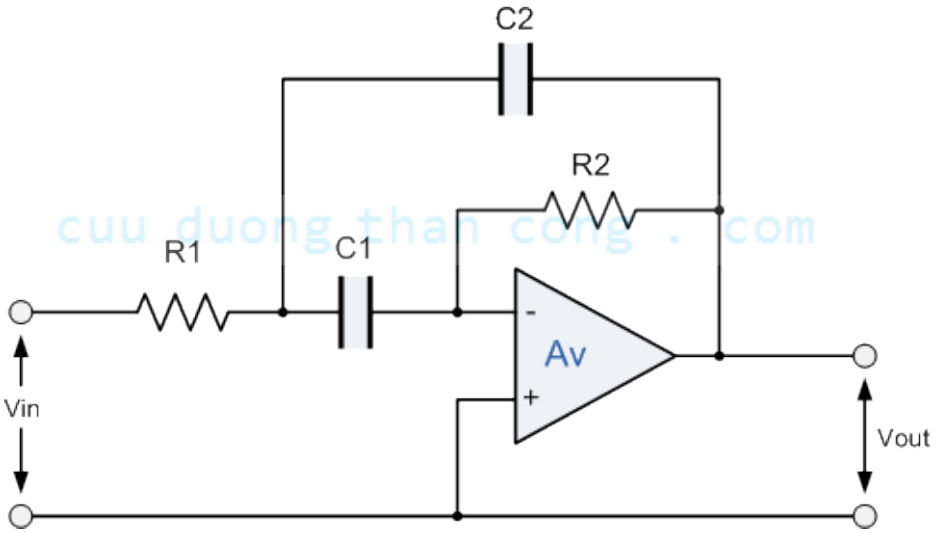




Mạch lọc thông dải tích cực







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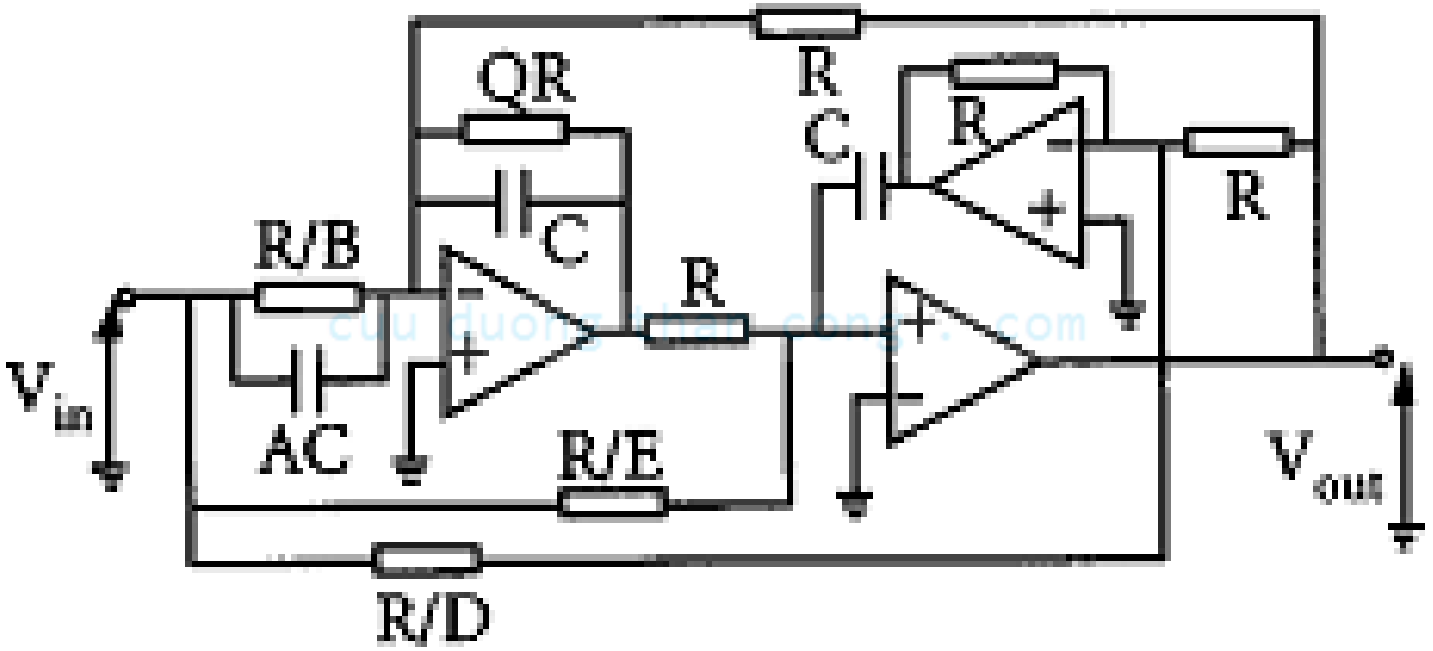
Bộ lọc biến trạng thái bậc 2



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$$-\frac{As^2 + \omega_0(B - D)s + E\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

$$\omega_0 \triangleq 1/RC$$

To transform a low-pass filter to high-pass, we first scale it to a cut-off frequency of 1 rad/s if it is not already at 1 rad/s. This allows a simple frequency rotation about 1 rad/s of $s \rightarrow 1/s$. All Ls become Cs, all Cs become Ls, and all values reciprocate. The cut-off frequency does not change.

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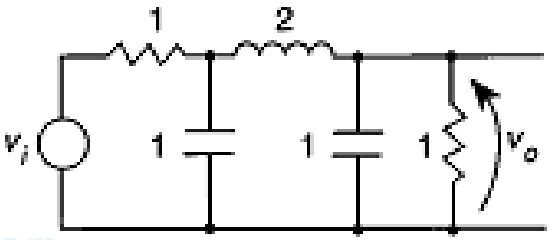
Example 4.7. Design a third-order, high-pass Butterworth filter to operate from a 600-Ω source to a 600-Ω load with a cut-off frequency of 500 Hz.



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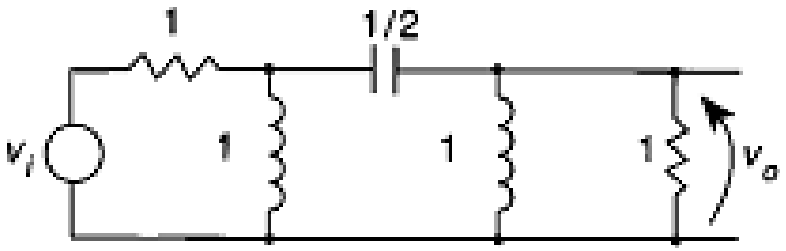

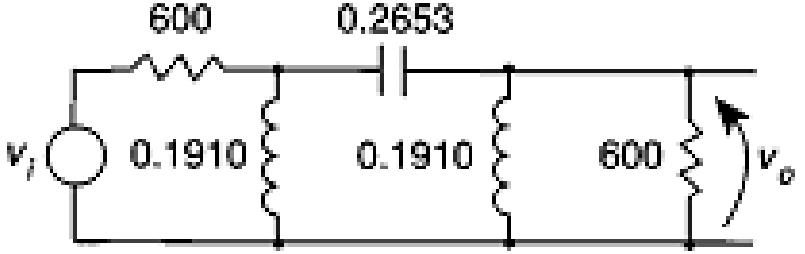

To transform a low-pass filter to a bandpass filter we must first scale the low-pass filter so that the cut-off frequency is equal to the bandwidth of the normalized bandpass filter. The normalized center frequency of the bandpass filter is $\omega_0 = 1$ rad/s. Then we apply the transformation $s \longrightarrow s + 1/s$. For an inductor

$$Z = Ls \text{ transforms to } Z = L\left(s + \frac{1}{s}\right)$$

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For a capacitor

$$Y = Cs \text{ transforms to } Y = C\left(s + \frac{1}{s}\right)$$

The first step is then to determine the Q of the bandpass filter where

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$$Q = \frac{f_0}{B} = \frac{\omega_0}{B_r}$$

(f_0 is the center frequency in Hz and B is the 3-dB bandwidth in Hz). Now we scale the low-pass filter to a cut-off frequency of $1/Q$ rad/s, then series tune every inductor, L, with a capacitor of value $1/L$ and parallel tune every capacitor, C, with an inductor of value $1/C$.

Example 4.8. Design a bandpass filter centered at 100 kHz having a 3-dB bandwidth of 10 kHz starting with a third-order Butterworth low-pass filter. The source and load resistors are each to be 600 Ω.

The Q required is

$$Q = \frac{100 \text{ kHz}}{10 \text{ kHz}} = 10, \text{ or } \frac{1}{Q} = 0.1$$

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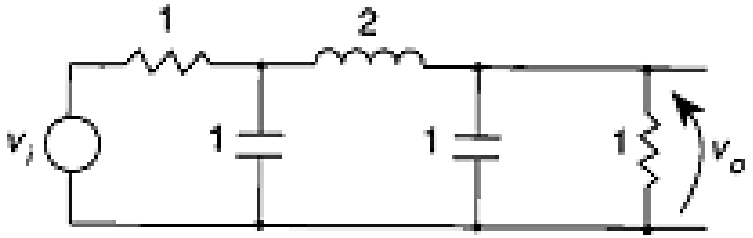

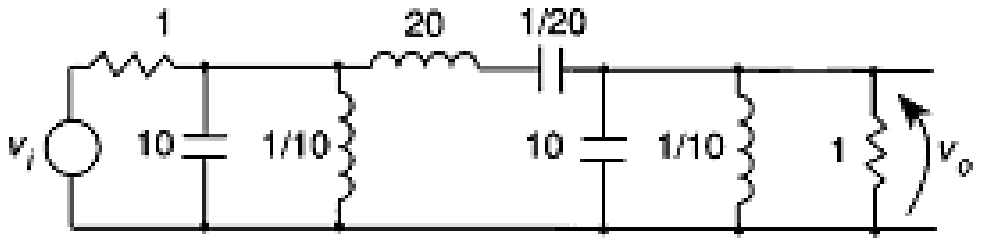

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