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EC160: Experiment 7
RC Frequency Response

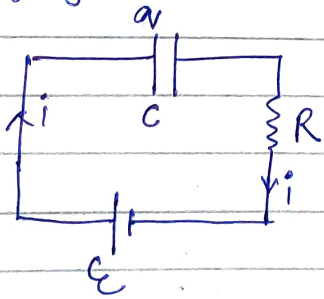
Objective: (i) Explain RC voltage dividers
(ii) to understand RC circuit as low pass filters
(iii) to understand RC circuit as high pass filters.

Theory :-

Charging of a Capacitor

When a capacitor is connected to a battery, positive charge appears on one plate and negative charge on other. The potential difference between the plates ultimately becomes equal to emf of the battery. The whole process takes some time and during this time there is an electric current through the connecting wires and the battery.

A charging circuit of a capacitor is shown



Suppose a capacitor of capacitance C, a resistor R and a battery of emf ε is connected as shown at $t=0$.

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Suppose the charge on the capacitor and the current in the circuit are q and i respectively at time t.

$\therefore$ the potential drop across the capacitor is $\frac{q}{C}$

and across the resistor is iR.

also, charge deposited on capacitor plate in time dt is

$$dq = i\,dt$$

Using Kirchoff's Loop law,

$$\frac{q}{C} + Ri - \mathcal{E} = 0$$

$$R\frac{dq}{dt} = \mathcal{E} - \frac{q}{C}$$

$$\frac{dq}{\mathcal{E}C - q} = \frac{1}{RC}dt$$

Integrating using proper limits

$$\int_0^q \frac{dq}{\mathcal{E}C - q} = \int_0^t \frac{1}{CR}dt$$

After solving,

$$q = \mathcal{E}C\left(1 - e^{-t/RC}\right)$$

This gives charge on the capacitor at time t.

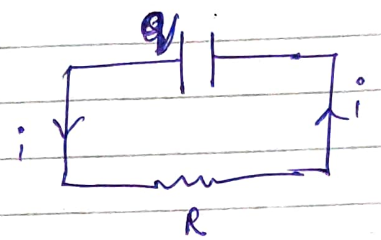
Also, the current i in the circuit at time t is,

$$i = \frac{dq}{dt} = \frac{\mathcal{E}}{R}e^{-t/RC}$$

Name: Archit Agrawal
Student ID: 202052307

Discharging of Capacitor

If the plates of a charged capacitor are connected through a conducting wire, the capacitor gets discharged. Again there is a flow of charge through the wires and hence there is a current. Suppose a capacitor of capacitance C has a charge Q. At $t=0$, the plates are connected through a resistance R as shown



Let the charge on capacitor be q and current in the circuit be i at a time t.

Using Kirchoff's Loop law

$$\frac{q}{C} - Ri = 0$$

Here $i = -\frac{dq}{dt}$ because the charge q decreases as time passes,

Thus,

$$R\frac{dq}{dt} = -\frac{q}{C}$$

$$\frac{dq}{q} = -\frac{1}{CR}dt$$

$$\int_{Q}^{q} \frac{dq}{q} = \int_{0}^{t} \frac{-1}{CR} dt$$

Name: Archit Agrawal
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$$\ln \frac{q}{Q} = \frac{-t}{CR}$$

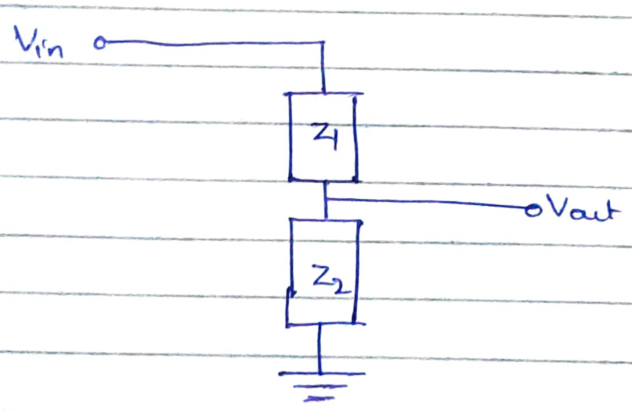
$$q = Q e^{-t/CR}$$

This gives charge on the capacitor at a time t.
In principle, discharging is complete only at $t = \infty$.

RC voltage dividers :- A voltage divider is a fundamental circuit which can produce a portion of its input voltage as an output. It is formed using two passive components (resistor, capacitor etc.) and a voltage source.

Voltage divider in Unloaded Condition

The simple voltage divider circuit with reference to the ground is shown below.



Z_1 and Z_2 are electrical impedances.

Under open-circuit output condition; there will be no current flow in the output side, then

$$V_{out} = \frac{Z_2}{Z_1 + Z_2} \times V_{in}$$

The capacitive divider circuits never allow DC to

Name: Archit Agrawal
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pass. They work on AC input.

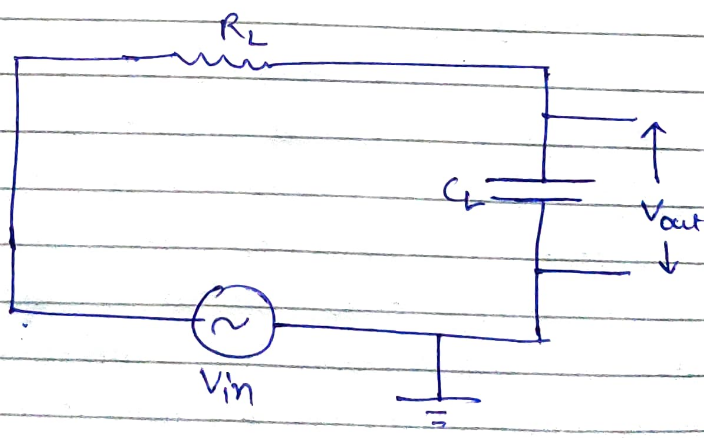
Capacitive Reactance :- The capacitive reactance indicates the amount of opposition to current flow, but unlike resistance, the amount of opposition depends on the frequency of the signal passing through the capacitor.

Capacitive Reactance $X_C = \frac{1}{2\pi f C}$

Impedance $Z = \sqrt{R_L^2 + X_C^2}$

RC Circuit as Low pass filter :-

A simple passive RC Low pass filter or LPF, can be easily made by connecting together in series a single resistor with a single capacitor as shown below.



In this arrangement, the input signal (V_{in}) is applied to the series combination but the output signal (V_{out}) is taken across the capacitor only.

Name: Archit Agrawal
Student ID: 202052307

The reactance of a capacitor varies inversely with frequency, while the value of resistor remains constant. At low frequencies, the capacitive reactance, X_C will be very large compared to the resistive value of resistor, R_L. Voltage across the capacitor will be much larger than the voltage across the resistor. At high frequencies the reverse is true with V_C being small and V_R being large due to change in capacitive reactance value. Thus, low frequencies are passed and high frequencies are blocked.

$$\text{Magnitude} = 20 \times \log\left(\frac{X_C}{Z}\right)$$

$$V_{out} = V_{in}\left(\frac{X_C}{Z}\right)$$

where $X_C = \dfrac{1}{2\pi f C_L}$

and $Z = \sqrt{R_L^2 + X_C^2}$

Low-pass filter phase shift

Each reactive element in a circuit introduces 90° of phase shift, but this phase shift do not happen at once. The phase of the output signal, just like the magnitude of output signal, changes gradually as the input frequency increases. In an RC-low pass filter, we have one reactive element i.e. capacitor, and consequently the circuit will eventually introduce 90° of phase shift.

$$\text{phase shift } \phi = -\arctan(2\pi f C_L R_L)$$

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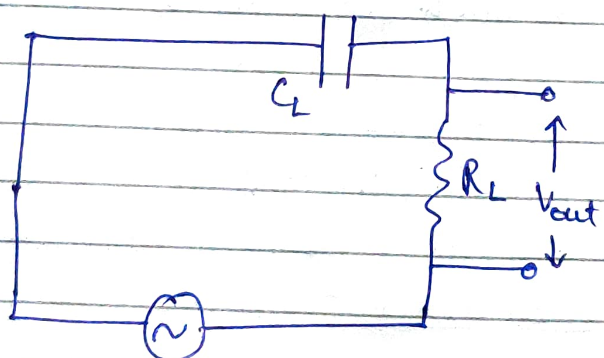
Low-pass filter Cut-off Frequency

The cutoff frequency of an RC low-pass filter is the frequency at which the amplitude of the input signal is reduced by 3 dB (3 dB reduction in amplitude is chosen as it corresponds to 50 % reduction in power). Thus, the cutoff frequency is also called −3dB frequency.

$$\text{Cutoff - frequency } (f_c) = \frac{1}{2\pi R_L C_L}$$

RC circuit as High-Pass filter :-

A simple passive RC high pass filter or HPF, can be easily made by connecting together in series a resistor and a capacitor as shown.



In this arrangement, the input signal (V_{in}) is applied to the series connection of capacitor and resistor but the output is taken across resistor only.
In this circuit, the reactance of capacitor is high at low frequencies so the capacitor acts like an open circuit and blocks any input signals at (V_{in}) until the cutoff frequency

Name : Archit Agrawal
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point (f_c) is reached. Above this cut-off frequency point the reactance of the capacitor has reduced sufficiently as to now act like a short circuit allowing all of the input signal to pass directly to the output.

$$\text{Magnitude} = 20 \times \log\left(\frac{R}{Z}\right)$$

$$V_{out} = V_{in}\left(\frac{R}{Z}\right)$$

Cut-off frequency and phase shift

cut-off frequency for high pass filter is given by

$$f_c = \frac{1}{2\pi R_L C_L}$$

and phase shift for high pass filter is given by

$$\phi = \arctan\left(\frac{1}{2\pi f R_L C_L}\right)$$

Procedure for the Experiment

Frequency Response of RC Low pass and RC High pass filter.

Step 1 : Set load resistance (R_L) = 10 kΩ
Step 2 : Set load capacitance (C_L) = 0.01 nF
Step 3 : Source voltage (Vin) is set to 10 V.
Step 4 : Keeping source voltage constant, vary the frequency from 50 Hz in regular steps.

Name : Archit Agrawal
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Step 5 : Click on "Add to Table" button to add the readings to the table.

Step 6 : Vary the frequency be keeping the load resistance and load capacitance fixed.

Step 7 : Select "plot" button to plot the frequency graph or phase graph of the RC frequency. frequency (Hz) along x-axis and magnitude (dB) along Y-axis.

Simulation Results

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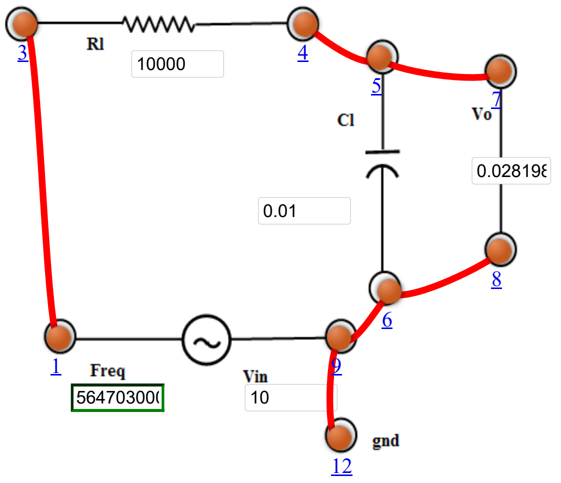
RC Frequency Response-LPF

INSTRUCTION



Frequency Response of 1st order low pass filter

CONTROLS

Load Resistance (R_L) : Ω
Load Capacitor(C_L) : nf
Input Voltage (V_{in}) : V
Frequency (Freq) : Hz

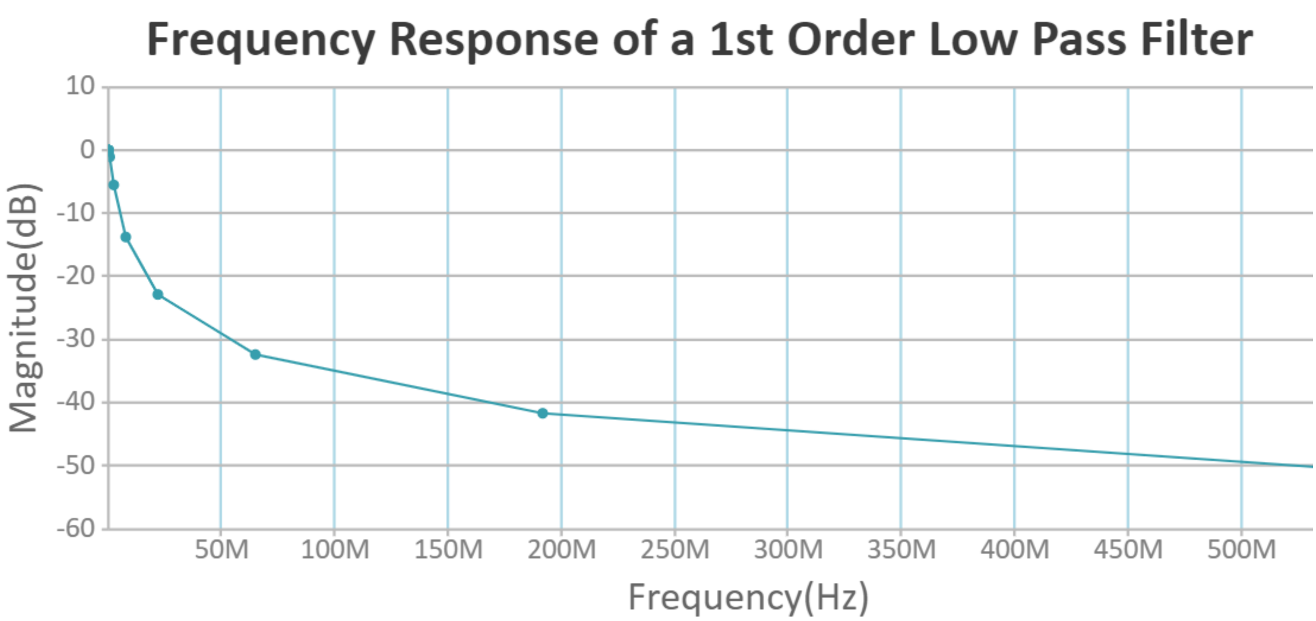
Add to Table | Frequency Resp | Clear

Check connection | Delete all connection

EXPERIMENTAL TABLE

5	3818	-0.0000249656	-0.13744
6	11267	-0.000217436	-0.40561
7	33252	-0.001893432	-1.19691
8	98134	-0.01646342	-3.52837
9	289614	-0.1413372	-10.3134
10	854713	-1.099534	-28.2394
11	2522440	-5.45226	-57.7660
12	7444240	-13.5899	-77.9657
13	21969500	-22.818399999999997	-85.8980
14	64836600	-32.1982	-88.6381
15	191346000	-41.5958	-89.5686
16	564703000	-50.9956	-89.8840

GRAPH PLOT



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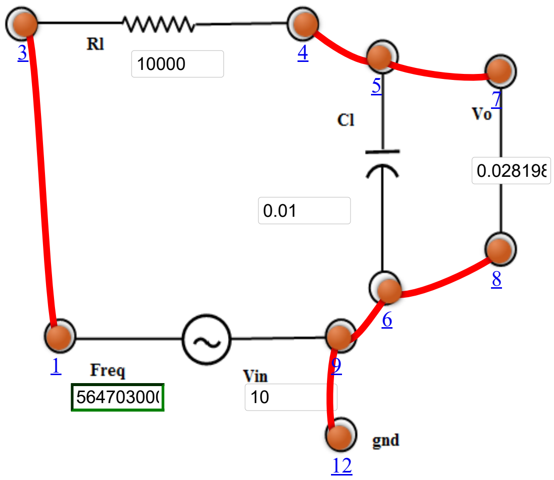
RC Frequency Response-LPF

INSTRUCTION



Phase of 1st order low pass filter

CONTROLS

Load Resistance (R_L) : Ω
Load Capacitor(C_L) : nf
Input Voltage (V_{in}) : V
Frequency (Freq) : Hz

Add to Table | Phase Response | Clear

Check connection | Delete all connection

EXPERIMENTAL TABLE

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6	11267	-0.000217436	-0.40561
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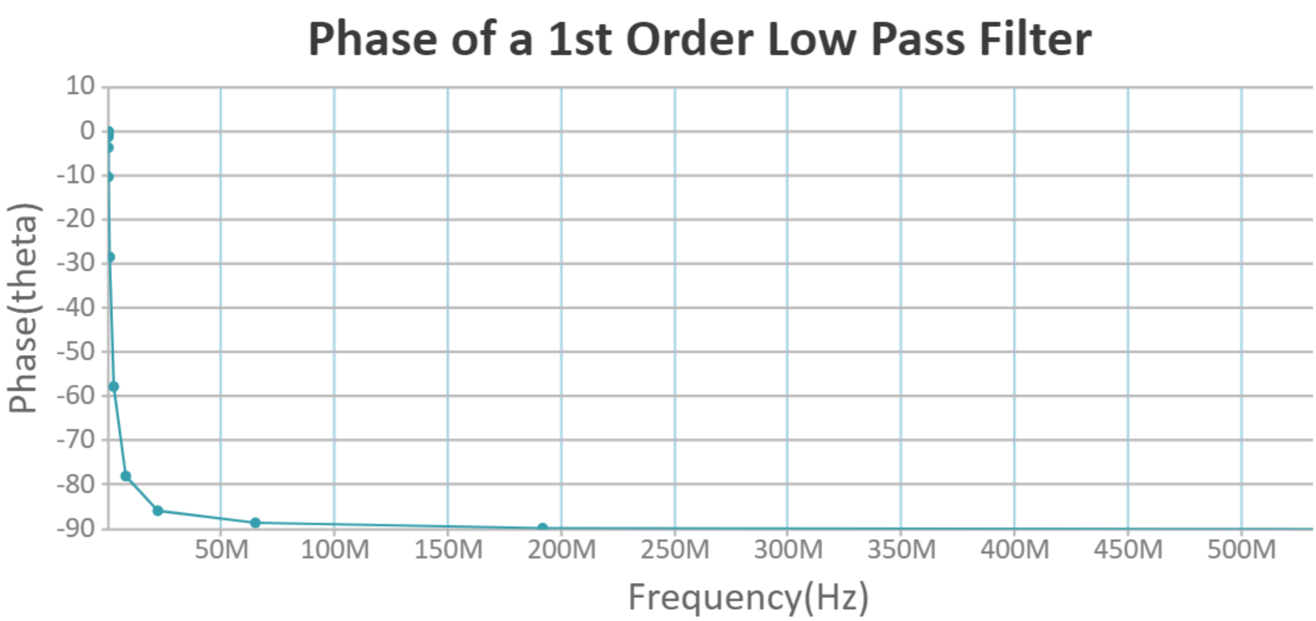

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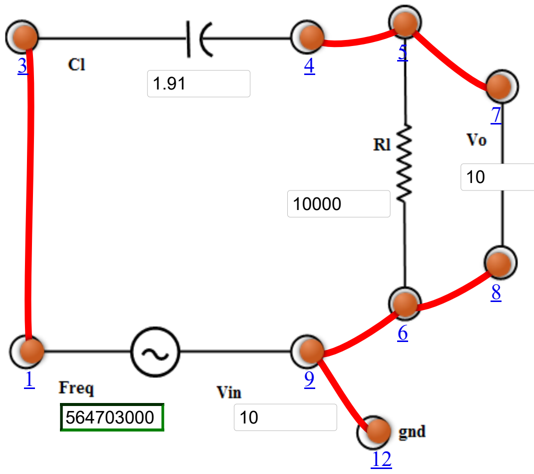
RC Frequency Response-HPF

INSTRUCTION



Frequency Response of 1st order low pass filter

CONTROLS

Load Resistance (R_L) : Ω
Load Capacitor(C_L) : nf
Input Voltage (V_{in}) : V
Frequency (Freq) : Hz

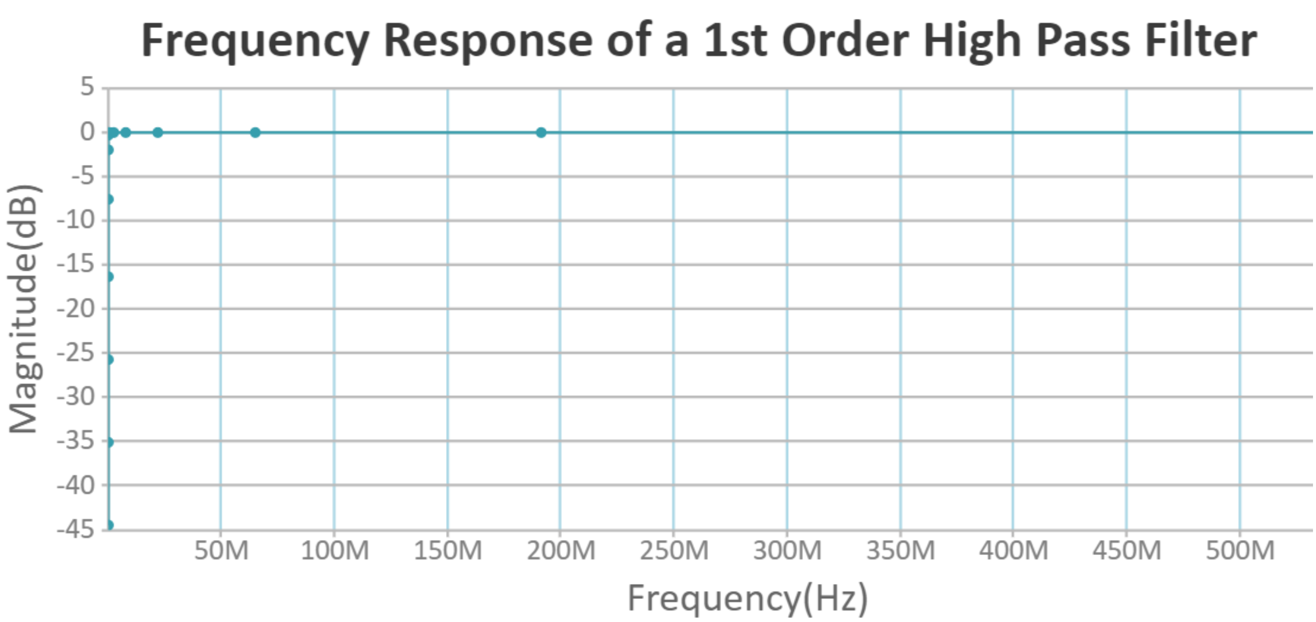
Add to Table | Frequency Resp | Clear

Check connection | Delete all connection

EXPERIMENTAL TABLE

5	3818	-7.6105599999999995	65.4280
6	11267	-1.896272	36.5171
7	33252	-0.26476	14.0821
8	98134	-0.0312318	4.85834
9	289614	-0.0035973199999999998	1.64972
10	854713	-0.000413178	0.559134
11	2522440	-0.000047441	0.189464
12	7444240	-0.000005447	0.0641992
13	21969500	-6.254e-7	0.0217535
14	64836600	-7.18056e-8	0.00737105
15	191346000	-8.2444e-9	0.00249764
16	564703000	-9.4658199999999999e-10	0.000846311

GRAPH PLOT



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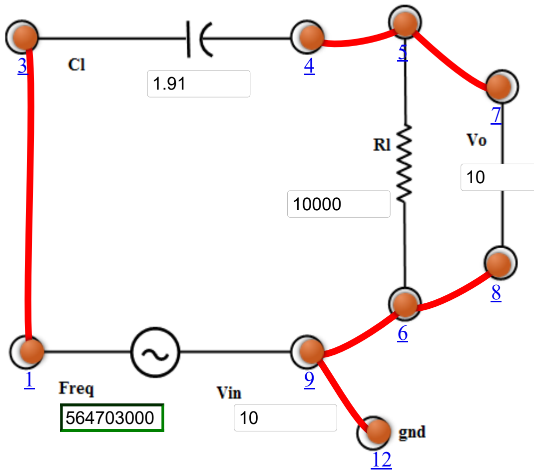
RC Frequency Response-HPF

INSTRUCTION



Phase of 1st order low pass filter

CONTROLS

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Load Capacitor(C_L) : nf

Input Voltage (V_{in}) : V

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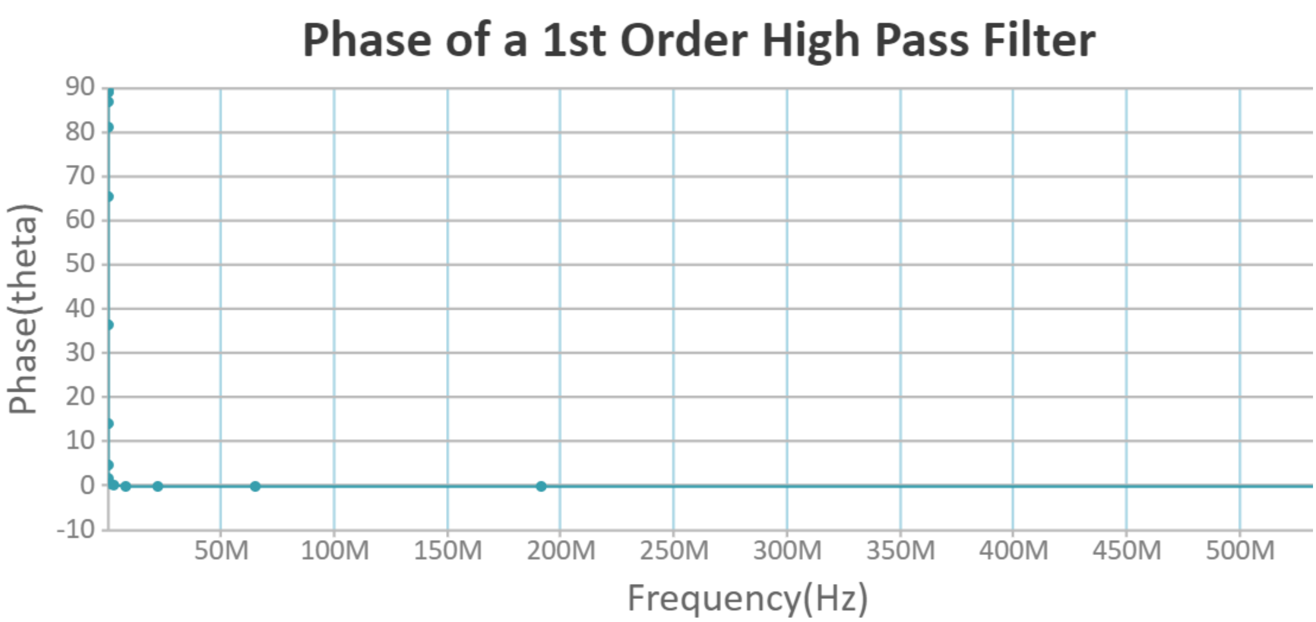

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Conclusion:- Performing the experiment we have come to draw the following conclusions:-

(i) A voltage divider produces a portion of Input voltage as output.

(ii) The capacitive reactance $X_c = \frac{1}{\omega C} = \frac{1}{2\pi f C}$

(iii) A RC low pass filter allows only low frequencies to pass through it.

(iv) A RC high pass filter allows only high frequencies to pass through it.

Quiz Performance

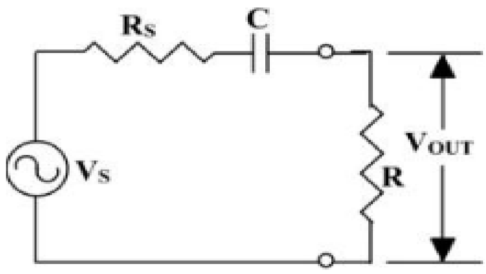
RC Frequency Response

THEORY (#) PROCEDURE (#) SIMULATION (#) QUIZ (#) REFERENCES (#)

Quiz

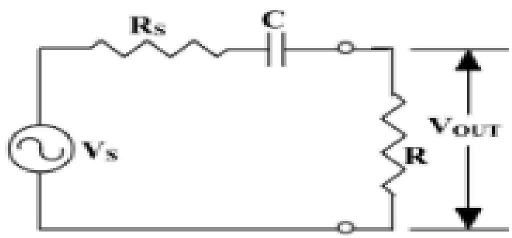
Test Your Knowledge!!

✓ 1. A signal generator with a negligible internal resistance R_S is connected to a resistor R=10kΩ through a coupling capacitor C=1μF . RC Combination acts as



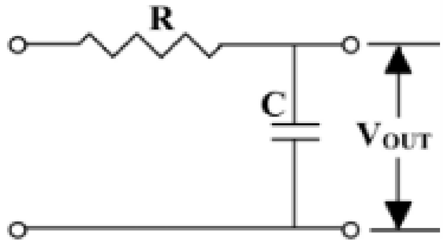
- Low Pass Filter
- High Pass Filter
- None of the above

✓ 2. A signal generator with a negligible internal resistance R_S is connected to a resistor R=10kΩ through a coupling capacitor C=1μF . The upper cut off frequency is f_H & lower cut off frequency is f_L



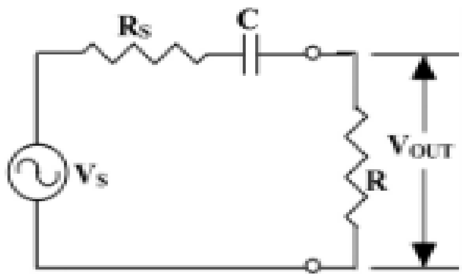
- f_H and f_L can not be determined from given data
- f_H = 6.28 kHz
- 15Hz ≤ f_L ≤ 20HZ

✓ 3. Given the approximate equivalent circuit of an amplifier. R=effective output impedance of the amplifier C=effective capacitance across the output of the amplifier. V_{out}=Signal output voltage when no load is connected. R=250Ω and C=200pF. RC Combination acts as



- [x] Low Pass Filter
- [ ] High Pass Filter
- [ ] None of the above

✓ 4. Given the approximate equivalent circuit of an amplifier. R=effective output impedance of the amplifier C=effective capacitance across the output of the amplifier. V_{out}=Signal output voltage when no load is connected. R=250Ω and C=200pF. f_H and f_L are upper and lower cut off frequency respectively



- [x] f_L and f_H can not be determined from the given data
- [ ] f_H = 6.28 kHz
- [ ] 15Hz ≤ f_L ≤ 20HZ

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