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Frequency Response of Low Pass Butterworth RC Filters Using Operational Amplifiers

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Abstract: This paper presents a detailed design of First Order and Second Order low pass Butterworth filters using operational amplifier. The frequency response of the filters is also studied.
Keywords: Filter, Butterworth, Frequency response, operational amplifier (OPAMP)

I. INTRODUCTION

A filter is a frequency- selective circuit that allows a specified band of frequencies and blocks or attenuates signal of frequencies outside this band. Thus a filter is an electrical or electronic network that alters the amplitude or phase characteristics of a signal with respect to the frequency. Filters are generally classified as (a) Analog or Digital (b) Passive or Active and (c) audio frequency (AF) or radio frequency (RF). In this paper design and fabrication of active filters are presented. Operational amplifiers along with resistors and capacitors are used for fabrication of filters. The frequency response of the filters was studied.

A. Theoretical Background and circuit diagrams of the filters

1) First order low pass Butterworth filter :

Figure-1 shows the circuit of first order low pass Butterworth filter using RC network and operational amplifier (OPAMP).

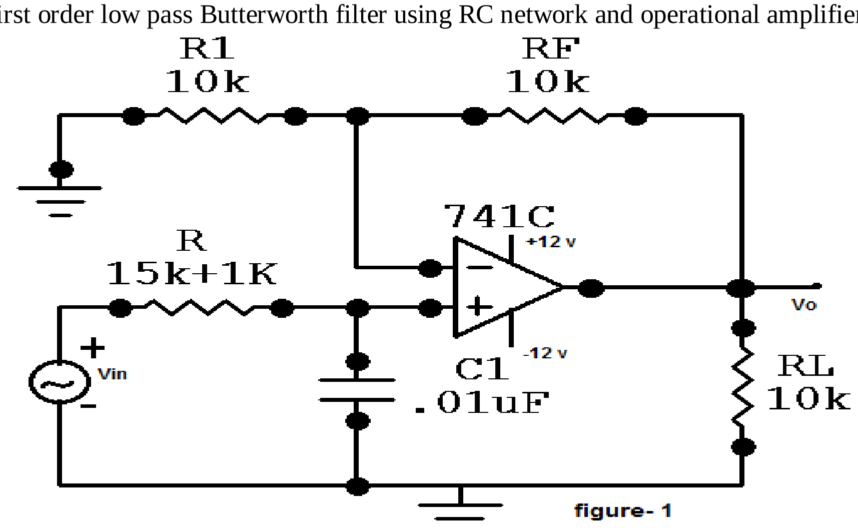

figure- 1

According to the voltage divider rule, the voltage at the non inverting terminal is

$$v_1 = \frac{-jX_C}{R - jX_c} v_{in}$$

$$j = \sqrt{-1} \quad and \quad -jX_C = \frac{1}{j2\pi f RC}$$

Taking into account the non inverting close loop gain of OP-AMP the overall gain is

$$\frac{v_o}{v_{in}} = \frac{A_F}{1+j(f/f_H)} \quad (1)$$

Where, $A_F = \left(1 + \frac{R_F}{R_1}\right)$ = Passband gain of the filter

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f = frequency of the input signal

$f_H = \frac{1}{2\pi RC}$ =higher cut off frequency of the filter.

The gain magnitude and phase angle equations of the low pass filter can be obtained by converting the equation (1) into equivalent polar form as follows.

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1+(\frac{f}{f_H})^2}} \quad (2)$$

$$\phi = -\tan^{-1}(f/f_H) \quad (3)$$

Where, ϕ is the phase angle in degree.

The operation of the low pass filter can be verified from the gain magnitude equation (2)

when $f < f_H$ then, $\left|\frac{v_o}{v_{in}}\right| \cong A_F$

When $f = f_H$ then, $\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{2}} = 0.707A_F$

when $f > f_H$ then, $\left|\frac{v_o}{v_{in}}\right| < A_F$

frequency decrease at a constant rate. The rate at which the gain rolls off after f_H is 20dB /decade.

2) Second order low-pass Butterworth filter

A stopband response having a 40dB/ decade roll off is obtained with the second order low pass filter. A first order low pass filter is converted into second order by using an additional RC network as shown in figure -2.

The gain of the second order filter is set by the R_1 and R_F, while the higher cut off frequency f_H is equal to: $f_H = \frac{1}{2\pi\sqrt{R_2R_3C_2C_3}}$

Furthermore, for a second order low pass Butterworth filter, the voltage gain magnitude equation is $\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1+(\frac{f}{f_H})^4}}$

Where, $A_F = \left(1 + \frac{R_F}{R_1}\right)$= Passband gain of the filter

f = frequency of the input signal

$f_H = \frac{1}{2\pi\sqrt{R_2R_3C_2C_3}}$ =Higher cut off frequency

3) Calculation of circuit components

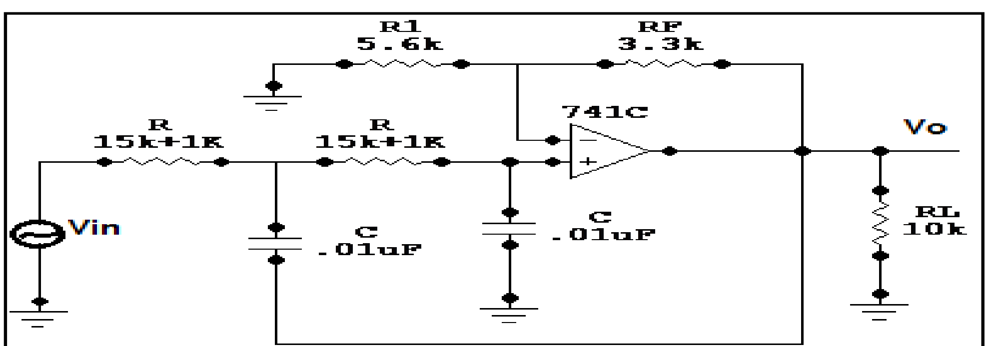

figure- 2

a) First order low pass Butterworth filter

For a low pass filter of cut off frequency 1KHz with a pass band gain equal to 2, f_H = 1KHz If C= 0.01$\mu F$is choosen, then $R = \frac{1}{2\pi(10^3)(10^{-8})} = 15.9$.

Since passband gain is 2 we can select, $R_F = R_1 = 10K\Omega$

b) Second order low-pass Butterworth filterhigher cut off frequency f_H = 1KHz:

Forsimplification the conditions $R_2 = R_3 = R$ and $C_2 = C_3 = C$ are satisfied. Taking C= 0.01 μF, $R = \frac{1}{2\pi(10^3)(10^{-8})} = 15.9\ K\Omega$

To guarantee Butterworth response gain must be =1.586. This is made by satisfying the condition, $R_F = 0.586R_1$. Inthis design, $R_F = 3.3K\Omega$ and $R_1 = 5.6\ K\Omega$ are choosen.

c)Frequency response Data

The data for studying frequency response of the filters are shown in Table-1 and Table-2.

First order low pass Butterworth filter

Table- 1

Input frequency (f) in (Hz)	Input voltage v_{in} in volt	Output voltage v_o in volt	Gain magnitude $\left\|\frac{v_o}{v_{in}}\right\|$	Magnitude (dB)=20 log $\left\|\frac{v_o}{v_{in}}\right\|$
10	1.00	1.80	1.80	5.10
100	1.00	1.80	1.80	5.10
200	1.00	1.80	1.80	5.10
500	1.00	1.70	1.70	4.61
700	1.00	1.50	1.50	3.52
800	1.00	1.45	1.45	3.23
1000	1.00	1.40	1.40	2.92
3000	1.00	0.56	0.56	-5.04
7000	1.00	0.24	0.24	-12.40
10000	1.00	0.18	0.18	-14.89
100000	2.00	0.07	0.07	-23.10

Second order low pass Butterworth filter

Table- 2

Input frequency (f) in (Hz)	Input voltage v_{in} in volt	Output voltage v_o in volt	Gain magnitude $\left\|\frac{v_o}{v_{in}}\right\|$	Magnitude (dB)=20 log $\left\|\frac{v_o}{v_{in}}\right\|$
30	1.00	1.650	1.650	04.35
100	1.00	1.550	1.550	03.80
200	1.00	1.600	1.600	04.08
500	1.00	1.550	1.550	03.80
600	1.00	1.450	1.450	03.22
800	1.00	1.300	1.300	02.27
900	1.00	1.200	1.200	01.58
1000	1.00	1.050	1.050	00.42
1200	1.00	0.850	0.850	-01.41
1500	1.00	0.600	0.600	-04.43
2000	1.00	0.360	0.360	-08.87
3000	1.00	0.160	0.160	-15.91
7000	1.00	0.030	0.030	-30.45
10000	1.00	0.020	0.020	-36.47
30000	1.00	0.004	0.004	-47.95
100000	1.00	0.002	0.002	-53.97

The frequency response curves for 1st order and 2nd order filters are shown in Figure-3 and Figure-4 respectively.

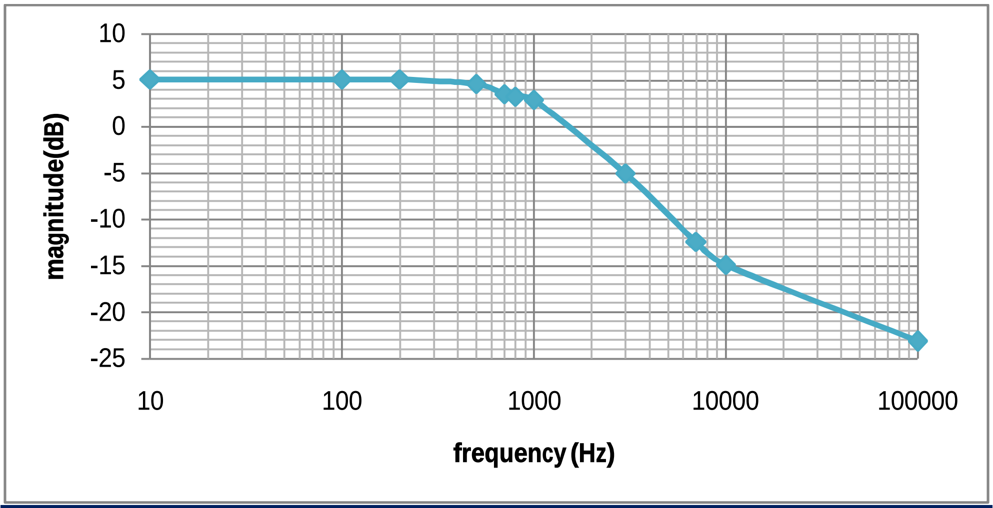

Figure-3: Frequency Response curve of 1st order Butterworth filter

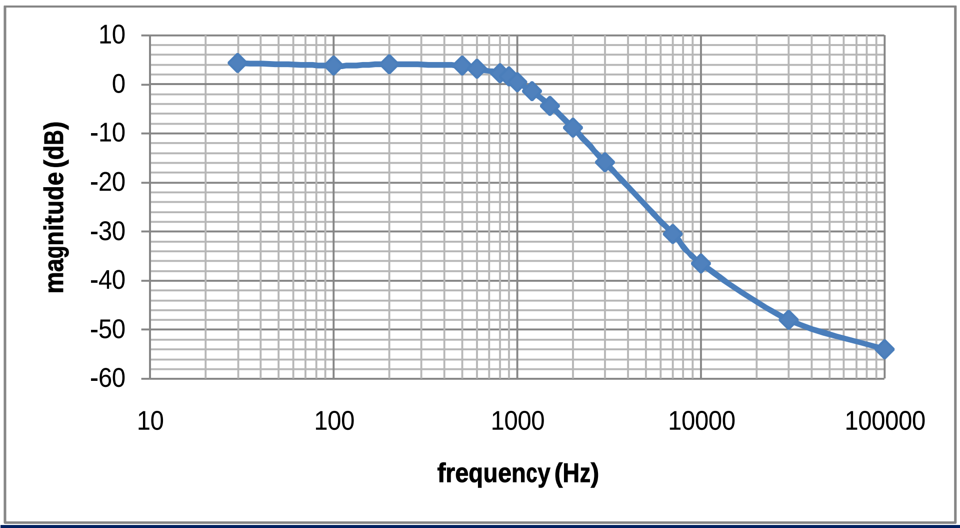

Figure-4: Frequency Response curve of 2nd order Butterworth filter

II. CONCLUSIONS

In this paper the low pass Butterworth filter of order 1 and 2 have been successfully implemented. The frequency response of the filter closed to the ideal one. Each of these filters uses an OP-AMP as the active element and resistors and capacitors as the passive elements. Since,the OP-AMP is capable of providing high gain; the input signal is not attenuated as it is in passive filters. Because of the high input resistance and low output resistance of the OP-AMP, the active filter does not cause loading of the source or load.

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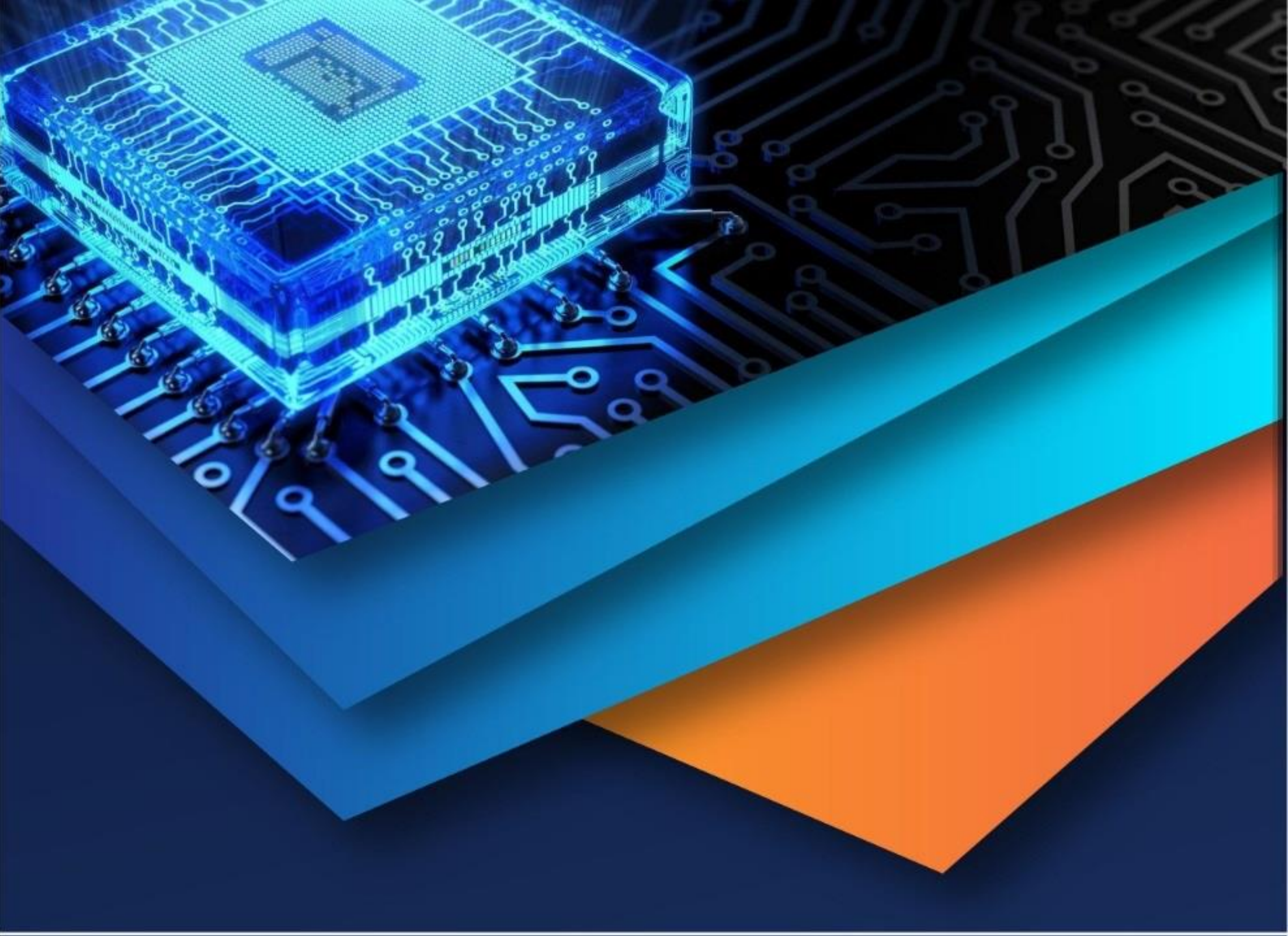

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