THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE

A Novel Sixth Order RC- Butterworth Low Pass Filter Implementation Using Folded Cascode OTA

Abhishek Saini
Assistant Professor, Instrumentation Engineering, School of Engineering and Technology
H.N.B. Garhwal University (A Central University), Uttarakhand, India
Deepa Saini
S.R.F., Department of Electronics and Communication Engineering
Indian Institute of Technology Roorkee, Uttarakhand, India

Abstract:
In this study, a novel continuous time 6th order Low Pass RC- Butterworth filter has been proposed by utilizing a FOLDED CASCODE OTA as an active component. The filter circuitry operates at a lower supply voltage of 0.75V in 0.18μm technology with a 3db bandwidth of 550 kHz. The basic building block i.e., FOLDED OTA is designed in 0.18μm CMOS process operated at 2.5V supply and having a bias current of 100 μA. The reported FOLDED CASCODE OTA based filter circuitry overcomes the bandwidth limitations of operational amplifier (Op-amps) based filters. Moreover, it provides comparatively higher speed of operation and low power consumption. TANNER TOOL 13.0 is used for all the performance analysis and simulative investigations.

Keywords: *OTA, FOLDED CASCODE OTA, RC-Butterworth filter*

1. Introduction

In the current research scenario, the designing of high performance signal processing circuits with reduced power consumption is getting more & more challenging. Filters are the electrical networks that process signals in a frequency-dependent approach. Hence, the basic concept of a filter can be explained by investigating the frequency dependent characteristics of the capacitors and inductor impedance. In the example of a voltage divider network, the shunt leg has reactive impedance. As the frequency is altered, the voltage divider ratio of the circuit changes and hence the reactive impedance changes accordingly. This method capitulates the frequency dependent transform on the input/output transfer function that is distinct as the frequency response [1].

Passive filters and active filters are the two types that categorize the filters. Passive filters are not employed in most of the signal processing circuits as they cannot provide gain to the signal and their input and output impedance is very far from desired values. Hence active filters are being employed in most of the signal processing and filtering circuits. An advantage of active filter studies is that the restraints of passive filter studies are totally eradicated. Subsequently, the low pass filters are most widely used filters in signal processing and communication system. The filters can be designed by means of Op-amps as the active element and capacitors and resistors as the passive elements [2] [11] (frequency discriminating part). Improved filter performance is obtained replacing Op-amps by operational trans-conductance amplifier (OTA) with superior slew rates and superior gain-bandwidths [10]. The filtering application of the circuit can be optimally represented by the frequency response parameters of the circuit. The frequency response parameters define the dissimilarity of the filter circuit gain with admiration to operating frequency [8]. Though in the design of active filters, voltage controlled Op-Amp and current controlled OTA are taken into consideration as basic active elements. The active filter design employing the use of Op-amp encompasses serious limitations over its applications in the high frequency regions. Hence, to surmount these limitations OTA based active filters are very popular owing to their salient features such as they have adjustable and linear transconductance g_m over a wide range of bias current, provide excellent matching between amplifiers, have controlled impedance buffers and provide high output signal to noise ratio [2].

Several filter approximations for the filter designing have been employed whereas one of the improved usage is the Butterworth approximation [3]. Butterworth filter is a category of electronic filter characterized by showing a maximally smooth magnitude response, *i.e.,* no ripple in amplitude of the pass-band. This circuit depends upon Butterworth transfer functions often called as Butterworth polynomials. In this paper folded cacode OTA based sixth order RC-Butterworth Low Pass Filter is implemented using linearity of transconductance of OTA with bias current.

2. Folded Cascode OTA

The OTA is basically a voltage controlled current source (VCCS) whose output current is produced by differential input voltage [4]. The Symbol and equivalent circuit of an OTA is dipicted in Fig. 1. The OTA's transconductance g_m makes it a voltage controlled current source, whereas the op-amps are the voltage controlled voltage source[9]. Its ability to tune analog devices such as filters, oscillators, *etc*. electronically makes it very much suitable for use in designing analog devices and it is the most attractive attribute of an OTA [5]. Its electronic tunability is achieved by varying its transconductance by controlling the bias current and hence by varying input voltage. Hence tunability is controlled by bandwidth of g_m, which depends on the bias current [6]. The term "cascade topology" refers to the cascade of a CS (common-source) stage and a CG (common-gate) stage which provides various valuable properties [13].
The expression for the output current of an OTA is given by

$$I_O = g_m (V_+ - V_-)$$

And the transconductance is given as

$$g_m = \frac{I_{bias}}{2V_t}$$

where V_t: Thermal voltage = 26 mV at room temperature.
I_{bias}:Bias current.
The transconductance g_m of the OTA is directly proportional to bias current I_{bias}. Characteristics of an ideal OTA are briefed as follows,
I/p impedance (*Zin*) = ∞
O/p Impedance (*Z0)* = ∞
Inverting i/p current *Io*-= Non-inverting i/p current I_{O+}
Bandwidth = ∞
The circuitry of a folded cascode OTA is shown in Fig. 2.In folded cascade OTA the differential input stage provides the gain of the operational amplifier. NMOS differential pair is taken as it has greater mobility as compared to PMOS and hence provides a larger value of transconductance and gain [6].The term folded cascode OTA is derived by folding down *p*-channel cascode active loads of a differential pair and changing the MOSFETs to *n*-channels.We have opted for folded cascade OTA for its large gain and high bandwidth performance and also has good PSRR compared to the two stage op-amp since the OTA is compensated with active loads. Fig. 3 shows the simulation setup of the Folded Cascode OTA. The Frequency vs. Gain and phase responses are shown in Fig. 4 and Fig. 5, respectively. The calculated values of the aspect ratios for the folded cascode OTA are encapsulated in Table 1.

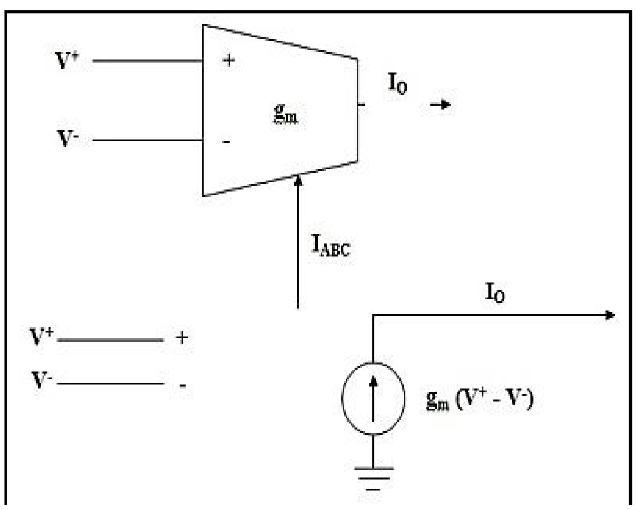

Figure 1: Symbol and equivalent circuit of an OTAFig.

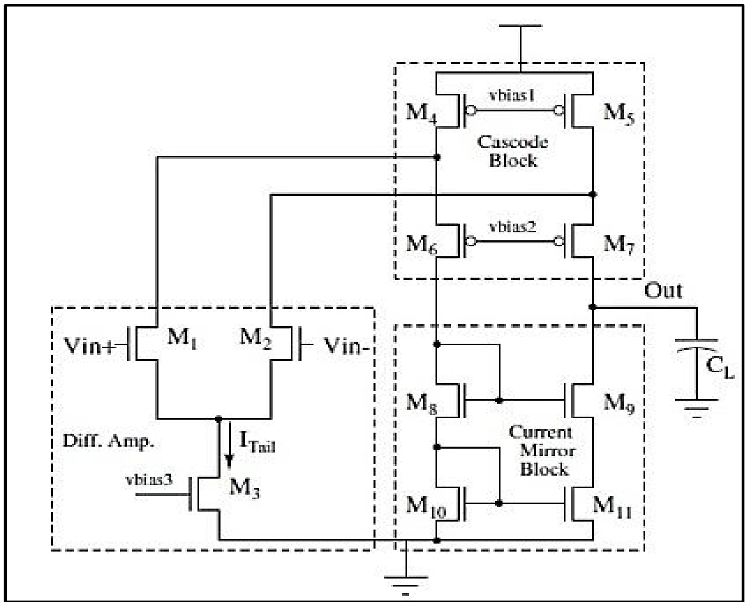

Figure 2: Circuit Diagram of a Typical Folded Cascode OTA

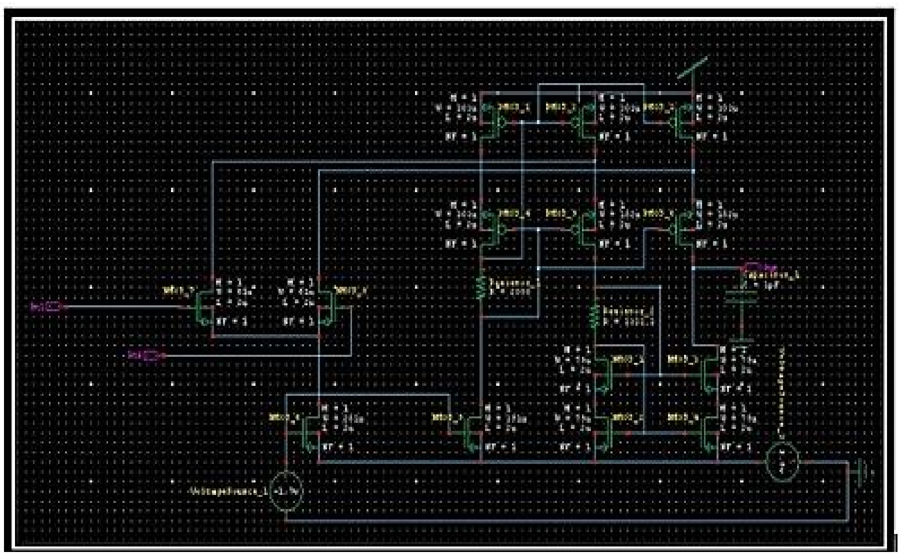

Figure 3: Circuit Implementation of Folded Cascode OTA

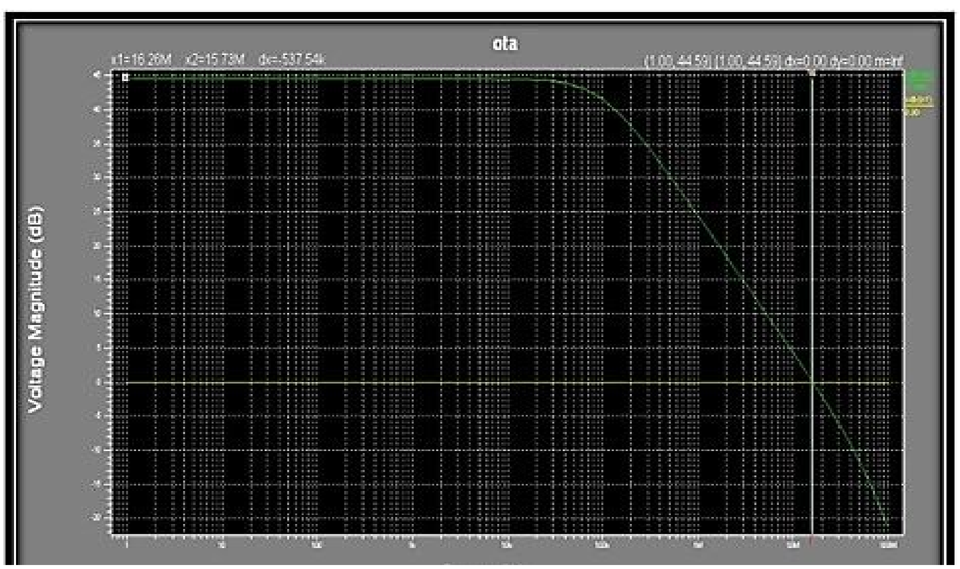

Figure 4: Frequency vs. Gain response of Folded Cascode OTA

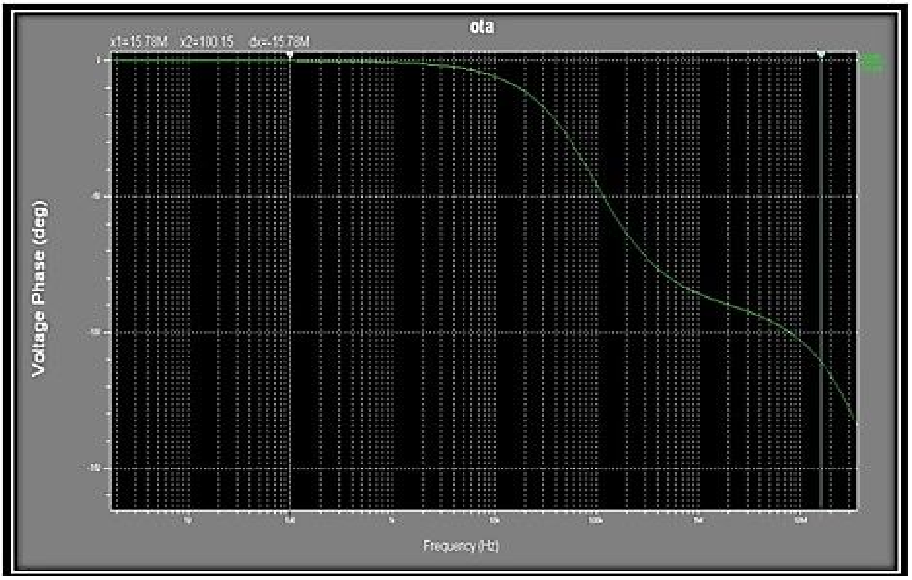

Figure 5: Frequency vs. Phase Response of Folded Cascode OTA

MOS	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
W/L(µm/µm)	61/2	61/2	281/2	303/2	303/2	182/2	182/2	75/2	75/2	75/2	75/2	351/2	303/2	303/2

Table 1: Calculated Values of Aspect Ratios for the Folded Cascode OTA

3. Proposed Design

The proposed sixth order RC- Butterworth is designed by cascading three blocks of second order RC-Butterworth filter; below we give the design of second order LPF section.

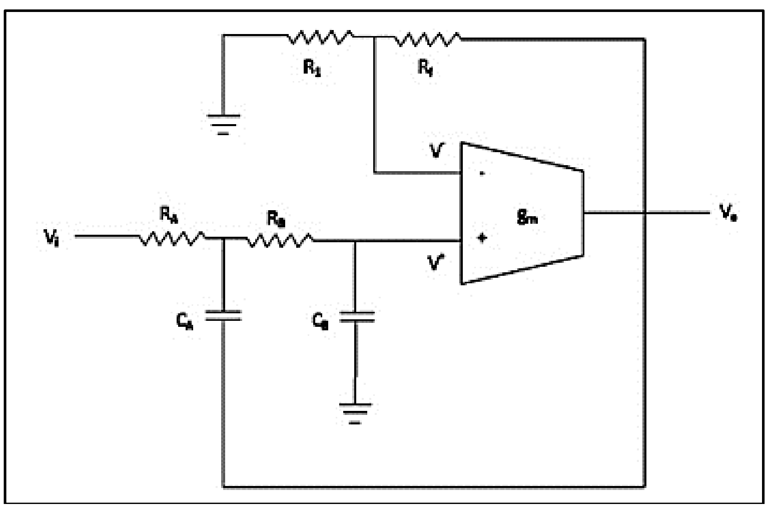

Figure 6: Second order OTA based LPF

3.1. Filter Specifications

The specifications of the filter are as follows:

a) The maximum approved variation in pass-band transmission A_{max}= 1 dB.
b) The pass-band edging ω_p= 550 KHz.
c) The stop-band edging ω_s = 5MHz.
d) The minimum necessary stop-band attenuation, A_{min} = 110 dB.
e) Gain = unity

For the Butterworth filter the order can be considered if the four parameters shown above are given. Transfer function of the Butterworth filter can be computed subsequently. The Butterworth low-pass filter exhibits a monotonically declining transmission zeros at $\omega = \infty$, building it an all pole filter. The magnitude function for an Nth order Butterworth filter [3] with a pass-band edge ω_p is specified by

$$|T(j\omega)| = \frac{1}{\sqrt{1+\varepsilon^2\left(\frac{\omega}{\omega_p}\right)^{2N}}}$$

At $\omega=\omega_p$

$$|T(j\omega)| = \frac{1}{\sqrt{1+\varepsilon^2}}$$

The parameter ε calculates the maximum deviation in pass-band transmission, A_{max}, according to the following equation:

$$A_{max} = 20\log\sqrt{1+\varepsilon^2}$$

As per the specifications and the transfer function, the determination of order can be in following steps:

3.2. Determination of ε.

$$\varepsilon = \sqrt{10^{A_{max}/10} - 1}$$

It can be shown that the first $2N-1$ derivatives of $|T|$ comparative to ω are zero at $\omega=0$. This property forms the Butterworth response very flat near $\omega=0$ and gives the response as name maximally flat response [3]. As the order N is increased the degree of pass-band flatness increases.

$A_{max} = 1$, hence

$$\varepsilon = \sqrt{10^{1/10} - 1}$$
$$\varepsilon = 0.5088$$

3.3. Determination of the filter order, N.

At the edge of the stop-band ($\omega=\omega_s$), the attenuation of the Butterworth filter will be

$$A(w_s) = -20\log\left[1/\sqrt{1+\varepsilon^2\left(w_s/w_p\right)^{2N}}\right] = 10\log\left[1+\varepsilon^2\left(w_s/w_p\right)^{2N}\right]$$

Above equation can be simplified as given below:

$$110 = 10\log\left[1+0.5088^2\,(5000/550)^{2N}\right]$$
$$(9.09)^{2N} = 3.863\times10^{11}$$

The above equation can be used in calculating the filter order required, which is the lowest integer value of N that gives, $A(\omega_s) \geq A_{min}$.
For $A(\omega_s) \geq A_{min}$, This gives $N = 6$

$$A(\omega_s) = 115\text{ dB (at } N = 6)$$

$N=6$ is the lowest integer value of N that gives $A(\omega_s) \geq A_{min}$. Therefore, filter order should be 6.

3.4. Calculation of transfer function, T(s)

The transfer function [2] can be calculated as

$$T(s) = \frac{K(\omega o)^N}{(S-P_1)(S-P_2).....(S-P_N)}$$

where K is constant which is equal to the required DC gain of the filter. For the calculation of the transfer function we have to calculate the values of 6 natural modes, *i.e.*, $p_1, p_2,....,p_6$.

The natural modes of 6th order Butterworth filter can be obtained from the graphical structure. The graphical modes lie down on a circle of radius $\omega_s(1/\varepsilon)^{1/N}$ and are parted by equal angles of $\pi/N = 30°$, with the initial mode at an angle $\pi/2N = 15°$ from the $+j\omega$ axis. As the natural modes all have identical radial distance from the origin they all have the similar frequency,

$$\omega_0 = \omega_s(1/\varepsilon)^{1/N} = 5.596\times10^6 \text{ rad/sec}$$

Now, the poles can be calculated as

$$p1 = (\cos105° + j\sin105°) \times 5.59\times10^6 = (-1.44 + j5.39)\times10^6$$
$$p2 = (\cos135° + j\sin135°) \times 5.59\times10^6 = (-3.95 + j3.95)\times10^6$$
$$p3 = (\cos165° + j\sin165°) \times 5.59\times10^6 = (-5.39 + j1.44)\times10^6$$
$$p4 = (\cos195° + j\sin195°) \times 5.59\times10^6 = (-5.39 - j1.44)\times10^6$$
$$p5 = (\cos225° + j\sin225°) \times 5.59\times10^6 = (-3.95 - j3.95)\times10^6$$
$$p6 = (\cos255° + j\sin255°) \times 5.59\times10^6 = (-1.44 - j5.39)\times10^6$$

Thus, the transfer function can now be found. The transfer function of the filter is as calculated as:

$$T(s)=3.07\times10^4\times\left(\frac{1}{S^2+S*2.88*10^6+31.12*10^{12}}\right)\times\left[\left(\frac{1}{S^2+S*7.9*10^6+31.20*10^{12}}\right)\times\left(\frac{1}{S^2-S*10.78*10^6+31.12*10^{12}}\right)\right]$$

3.5. Compute the values of feedback resistors in order to get the specific pass-band gain.

R_F/R_1 ratio is set for the required gain. For example, for the 1st order Butterworth filter shown in figure 4.1 R_F/R_1 is held as 1.

$$A_F = 1+\frac{R_F}{R_1}\text{(pass-band gain of the filter)}$$

All the stages of filter are designed with unity gain configuration.

3.6. Calculations of the RC components

We have analysed the values of RC components for obtaining the desired frequency response. We have fixed value of capacitors and taken the smallest feasible value of capacitors because high capacitances acquire more area in the layout. For the distinct pass-band frequency the value of resistance can then be intended as $R = 1/2\pi\omega_p C$.

Getting the value of capacitor as C = 10 pF and value for resistor is 10 kΩ. There is an insignificant difference occupied between the required pass-band frequencies and calculated. This is for the reason that of the active component reduces the pass-band frequency.

3.6.1. Simulation Circuit of the 6th order Butterworth filter

This section includes the responses obtained by the schematic level simulations. The schematic drawn in S-Edit unit of Tanner EDA Tool and the simulations are completed in T-Spice unit of Tanner EDA Tool. The 6th order Butterworth filter schematic is shown in fig. 7. Three stages of 2nd order filters are shown by the schematic. In fig. 8 the frequency response of the 6th order Butterworth filter is shown.

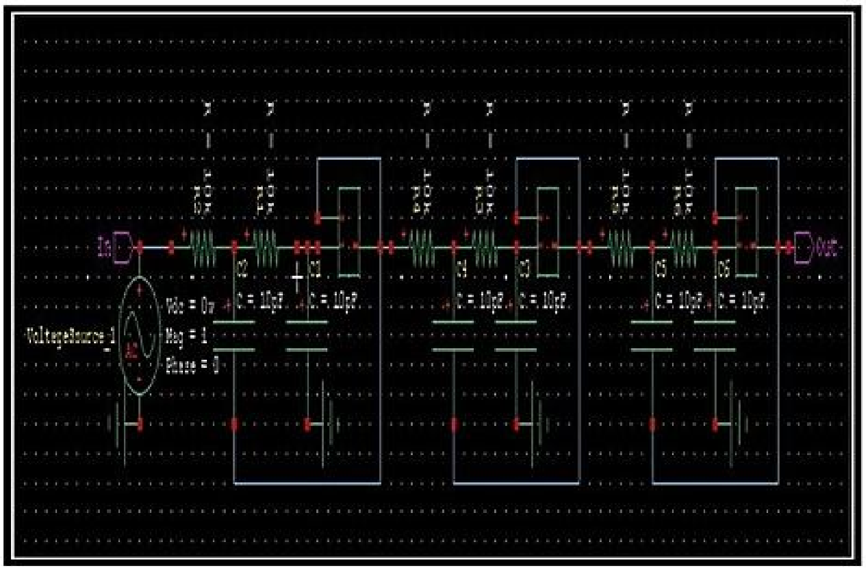

Figure 7: Schematic of 6th order Active-RC Butterworth filter

4. Simulation Results

The proposed model is simulated using TANNER TOOL 13.0.

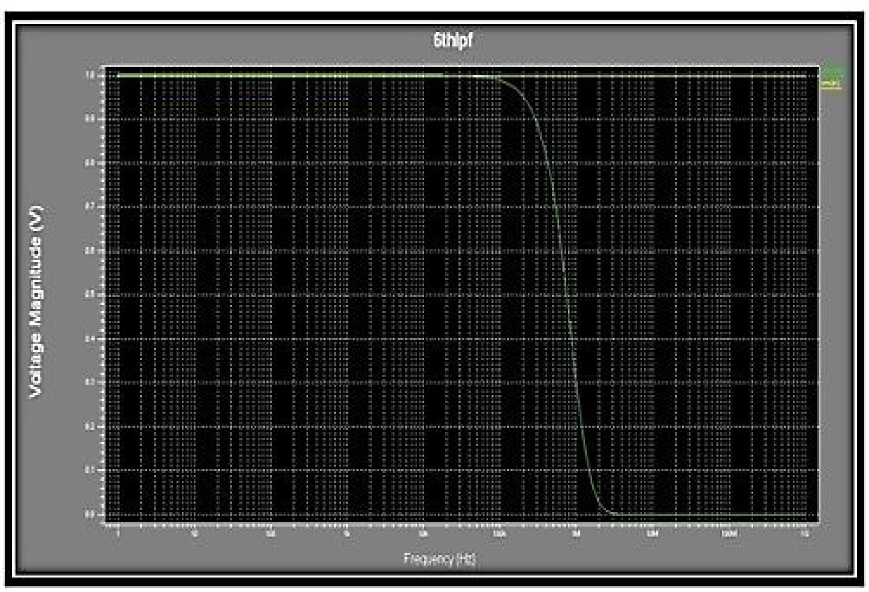

Figure 8: Frequency Response of 6th Order Low-Pass Active RC-Butterworth Filter

4.1. The Simulation Results Are as Follow

The DC Gain = Unity

The Pass-band frequency, ω_p = 531 KHz

4.2. Study and Analysis of the Simulation Results

Through simulations some components values were varied to see the effects on the frequency response.

1. The calculated values and the simulated results have significant difference.
2. There is no zero observed in the frequency response. Zero is at infinite frequency (in case of Butterworth filter). Thus, the response has been justified.
3. R_F/R_1 has been mentioned as a ratio. If the values of R_F and R_1 were changed in same ratio however with different values it affects the gain with slight variation (in our design we have used unity gain).
4. There is an increase in the pass-band frequency when decreasing the value of RC.
5. The DC gain does not affected by changing in the values of RC. RC decides the pass-band frequency and R_F/R_1 governs the pass-band gain.

5. Conclusion

Since the frequency determining resistors(10k) are all equal, and as are the frequency determining capacitors(10p), the cut-off or 3db frequency (f_c) for either a first, second or even a fourth-order or higher order filter must also be equivalent and is originate by using old familiar equation:

$$f_c = \frac{1}{2\pi RC} * \sqrt{2^{\frac{1}{N}} - 1}$$

Where N is the order of filter

For 6th order LPF shown in fig.7 the value of $N=6$ and the theoretical value of cut-off frequency from the above equation is 556 KHz and the simulated value of cut-off frequency from the fig.8 is 532 KHz, both simulated and calculated values of 3db cut-off frequency are approximately equal. Hence the design is verified.

6. References

1. C. Feng, "The design of OTA-C filter based on the prototype of ladder LC filter",Journal of Theoretical and Applied Information Technology, vol. 49 No. 1, pp. 144-148, March 2013.
2. R. S. Mathad, M. M. Mutsaddi and S. V. Halse, "Design of OTA-C low pass filter using multiple OTA's", IOSR Journal of Applies Physics, vol. 1, no. 4, pp. 08-12, Aug. 2012.
3. S.P.R Almazan andM.T.G de Leon, "A 3rd order butterworth Gm-C filter for WiMAX receivers in a 90nm CMOS process" 12th International Conference on Computer Modelling and Simulation (UK Sim), pp. 625-630, March 2010.
4. A. Saini, D. Saini and V. Ramola, "Telescopic OTA based KHN filter", International Journal of Advanced Research in Electronics and Communication Engineering, vol. 2, issue 8, pp. 728-731, Aug. 2013.
5. B. P. Das, N. Watson and Y. Liu, "Simulation of voltage controlled tunable all pass filter using LM13700 OTA", International Journal of Electrical and Computer Engineering, vol. 5, no. 6, pp. 322-326, 2010.
6. B. P. Das, N. Watson and Y. H. Liu, "Bipolar OTA based voltage controlled sinusoidal oscillator", In Proceedings of the International Conference on Circuits, Systems, Signals, pp. 101-105, 2010.
7. H. D. Dammak, S. Bensalem, S. Zouari, and M. Loulou, "Design of folded cascode OTA in different regions of operation through gm/ID methodology", World Academy of Science, Engineering and Technology, vol. 45, pp. 28-33, 2008.
8. Y.P. Tsividis and J. O. Voorman, "Integrated continuous-time filters", IEEE press, New York, 1992.
9. L.Bouzerara and M.T.Belaroussi, "Low voltage, low power and high gain CMOS operational tansconductance amplifier", IEEE International Symposium on Circuits and Systems, vol. 1, pp. 1325-1328, 2002.
10. J.Glinianowicz, J.Jakusz, S.Szczepanski and Y.Sun, "High-frequency two-input CMOS OTA for continuous-time filter applications" IEEE Proceedings on Circuits, Devices and Systems, vol. 147, issue 1, pp. 13-18, Feb. 2000.
11. M. Loulou, S. A. Ali, M. Fakhfakh, and N. Masmoudi, "An optimized methodology to design CMOS operational amplifier", IEEE journal, pp. 14-17, 2002
12. A.K.Mal and R.Todani, "A digitally programmable folded cascode OTA with variable load applications" IEEE Symposium on Industrial Electronics and Applications (ISIEA), pp. 295- 299, Sept. 2011.
13. Er. Rajni, "Design of high gain folded-cascode operational amplifier using 1.25 µm CMOS technology", International Journal of Scientific & Engineering Research, vol. 2, Issue 11, Nov. 2011.