# Fractional Order High Pass Filter Based on Operational Transresistance Amplifier with Three Fractional Capacitors of Different Order

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***Abstract.*** *Design, realization and performance evaluation of fractional order high pass filter based on Operational Transresistance Amplifier (OTRA) using three fractional elements of different order $\alpha$, $\beta$, $\gamma$ are presented in this paper. The projected circuit uses a single active current mode device i.e. OTRA and utilizes fractional capacitors of varying orders to boost the design flexibility. The design equations for fractional order high pass filter are computed from the transfer function. The paper elaborates the impact of fractional order elements of varying order on the frequency response of the filter. Subsequently, the sensitivity and stability of the transfer function of the proposed filter are also analyzed. The potential usefulness of the proposed filter is additionally incontestable through the Total Harmonic Distortion (THD), Power Supply Rejection Ratio (PSRR), Temperature sweep, Corner, Supply Voltage variation and Noise Analysis. It has been observed that the proposed pass filter in fractional domain supported OTRA provides greater flexibility in controlling the magnitude characteristics.*

## Keywords

***Fractional High Pass Filter (FHPF), Fractional Order Element (FOE), Fractional Order Signal Processing (FOSP), Operational Transresistance Amplifier (OTRA).***

## 1. Introduction

Signal processing applications supported by fractional order calculus are termed as Fractional Order Signal Processing (FOSP). Many applications supported by FOSP are mentioned within the literature which includes FO Oscillators [1] and [2], Filters [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17] and [18], Multivibrators [19], Differentiators and Integrators [20] and [21], etc. Active and passive integer order filters are realized by using components, such as resistor, capacitor and inductor in the time domain. Similarly, an inductor or capacitor whose impedance is given as $Z(s) = as^{\alpha} \Rightarrow Z(j\omega) = a\omega^{\alpha}e^{j(\pi\alpha/2)}$ are the kinds of fractance device which are the essential components in the realization of Fractional Order (FO) filters where $\alpha = 1, 0, -1$ represents an inductor, a resistor and a capacitor respectively in complex frequency domain [22], [23], [24] and [25]. The corresponding phase angle is $\pi/2$ and $-\pi/2$ for the impedance of the inductor and capacitor respectively. The passive elements can be therefore termed as Fractional Order Elements (FOEs) that have a constant phase angle with frequency. The impedance of this FOE is given as $Z_C^{\alpha}(s) = 1/s^{\alpha}C$ where $\alpha$ is the order of FO capacitance, $C$ is the capacitance with units $F/s^{1-\alpha}$ and $s$ is the unit of time [10].

In the design of FO systems, the realization of FO capacitors (FCs) and FO inductors (FIs) is a vital purpose of concern. Antecedently the realization of FOE approximation of type $Z = 1/Cs^{1/n}$ was reported [26], [27], [28] and [29] and these embrace realization either by RC trees [25], nested ladder [30] or domino ladder [31]. Subsequently, fabrication of two terminal fractance devices is reported in [22], [32] and [45] and these consist of metal insulator-liquid interface. Recently the fabrication of FOEs [33] and [34] using copper electrode and platinised silicon electrode is reported which has the advantage of better reproducibility and is smaller in dimensions. However, it has obstacles of a short lifetime, high cost, and is nonetheless not mass producible.

In the most recent studies, the current mode technique has been preferred in integrated circuit design because of its inherent superiority of high slew rate, wide bandwidth, low power consumption, and high speed over the voltage mode approach [35]. OTRA is a high gain current input voltage output device that acquires all the advantages of current mode techniques. OTRA is used as an active element for realizing signal processing and generation circuits resembling filters [35], [36] and [37], oscillators [38], multivibrators [39], and immitance simulators [40]. Due to varied applications of filters in instrumentation, communication and signal processing, numerous reported designs aim to generalize the design schemes of integer order filters to the fractional domain [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [41] and [42]. It can be identified from the literature that active FO filters based on FOEs are designed using Op-Amps [3], [4], [5], [7], [8], [10], [11], [16] and [42] however there are very few design reports of FO filters using current mode active elements [9], [12], [13], [14], [15] and [41]. There are reports of some integer order filters based on OTRA using one or more active components [35], [36] and [37], but high pass filter using single OTRA in the fractional domain has not nevertheless been reported.

In this paper, therefore, design procedure, realization and performance evaluation fractional of third order high pass filter using single OTRA is reported. The proposed circuit has the following characteristics:

- The proposed circuit uses single active current mode device i.e. OTRA, and utilizes fractional capacitors of different orders to enhance the design flexibility.
- The proposed circuit has a low RMS value of noise voltage and THD at the output.
- The proposed circuit has high PSRR.

The next section presents the proposed design of the fractional high pass filter for various values of order $\alpha$, $\beta$, and $\gamma$. The stability and sensitivity analysis of the presented filter is additionally delineated in Sec. 2. The evaluation of the proposed design is mentioned in Sec. 3. while Sec. 4. concludes the paper.

# 2. Proposed Design Procedure of High Pass Filter of Order $(\alpha+\beta+\gamma)$ Using OTRA

## 2.1. Circuit Description

The voltage and current relationship of the OTRA, shown symbolically in Fig. 1, is characterised by Eq. (1) where $R_m$ is the transresistance gain of OTRA. The Current Feedback Amplifier (CFA) primarily based OTRA given in Fig. 2 is employed to realize high pass fractional filter of order $(\alpha+\beta+\gamma)$ shown in Fig. 3 [37]. It is apparent that it uses single OTRA, four resistances, and five FOC's.

$$\begin{bmatrix} V_p \\ V_n \\ V_0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ R_m & -R_m & 0 \end{bmatrix} \begin{pmatrix} I_p \\ I_n \\ I_0 \end{pmatrix}. \quad (1)$$

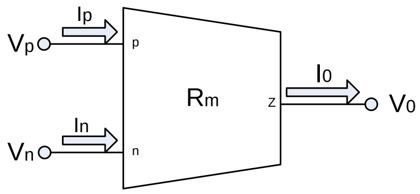



**Fig. 1:** Symbol of OTRA.

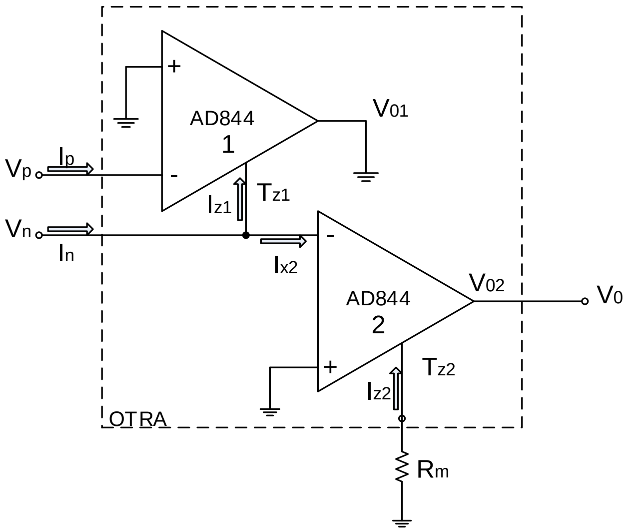



**Fig. 2:** CFA based OTRA.

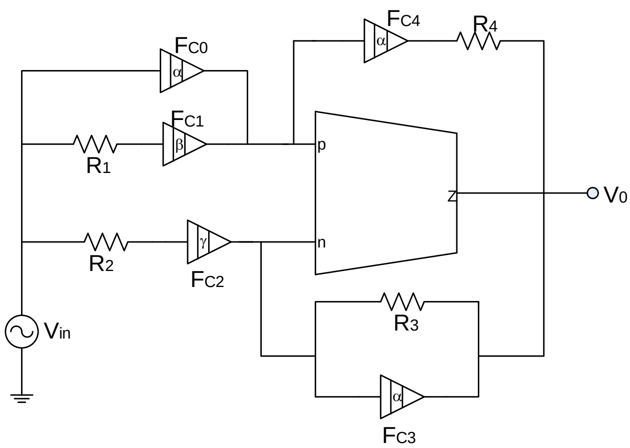



**Fig. 3:** Fractional order high pass filter based on OTRA.

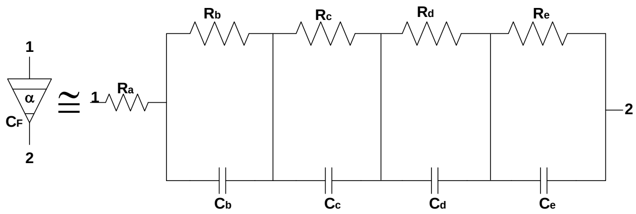



**Fig. 4:** Fourth order approximated representation of fractional capacitor.

The transfer function, given in Eq. (2), of the filter in Fig. 3 can be derived using KCL and nodal method. The simplification of the transfer function has been carried out under the following assumption:

- $F_{C0} = F_{C3}$,
- $F_{C1}F_{C2}R_2R_3 + F_{C0}F_{C2}R_2R_3 + F_{C0}F_{C1}R_1R_3 = F_{C1}F_{C2}R_1R_3$,
- $F_{C2}R_2 = F_{C4}R_4$,
- $F_{C0} + F_{C1} = F_{C2}$.

$$H(s) = \frac{ks^{\alpha+\beta+\gamma}}{s^{\alpha+\beta+\gamma} + d_2 s^{\alpha+\beta} + d_1 s^{\alpha} + d_0}, \qquad (2)$$

where $d_2 = \left(\frac{1}{F_{C2}R_3} + \frac{1}{F_{C2}R_2} + \frac{1}{F_{C1}R_1} - \frac{1}{F_{C3}R_2}\right)$, $d_1 = \left(\frac{1}{F_{C2}F_{C3}R_2R_3} + \frac{1}{F_{C1}F_{C2}R_1R_2} + \frac{1}{F_{C1}F_{C2}R_3R_1} + -\frac{1}{F_{C1}F_{C3}R_1R_2}\right)$, $d_0 = \frac{1}{F_{C1}F_{C2}F_{C3}R_1R_2R_3}$ and $k = 1$.

The magnitude and phase responses of the presented filter are given in Eq. (3) and Eq. (4):

$$|H(j\omega)| = \frac{k\omega^{\alpha+\beta+\gamma}}{\left[\begin{array}{c} \omega^{\alpha+\beta+\gamma} + 2d_2\cos\left(\frac{\gamma\pi}{2}\right)\omega^{2(\alpha+\beta)+\gamma} \\ +2d_1\cos\left(\frac{(\beta+\gamma)\pi}{2}\right)\omega^{2\alpha+\beta+\gamma} + \\ d_2^2\omega^{2(\alpha+\beta)} + 2d_2d_1\cos\left(\frac{\beta\pi}{2}\right)\omega^{2\alpha+\beta} \\ +2d_0\cos\left(\frac{(\alpha+\beta+\gamma)\pi}{2}\right)\omega^{\alpha+\beta+\gamma} \\ +2d_2d_0\cos\left(\frac{(\alpha+\beta)\pi}{2}\right)\omega^{\alpha+\beta} \\ +d_1^2\omega^{2\alpha} + 2d_1d_0\cos\left(\frac{\alpha\pi}{2}\right)\omega^{\alpha} + d_0^2 \end{array}\right]^{\frac{1}{2}}}, \qquad (3)$$

$$\arg\{H(j\omega)\} = \arg\{k\} + \frac{(\alpha+\beta+\gamma)\pi}{2} + -\tan^{-1}\left(\frac{\begin{array}{c} \omega^{\alpha+\beta+\gamma}\sin\left(\frac{(\alpha+\beta+\gamma)\pi}{2}\right) + \\ d_2\omega^{\alpha+\beta}\sin\left(\frac{(\alpha+\beta)\pi}{2}\right) + \\ d_1\omega^{\alpha}\sin\left(\frac{\alpha\pi}{2}\right) \end{array}}{\begin{array}{c} \omega^{\alpha+\beta+\gamma}\cos\left(\frac{(\alpha+\beta+\gamma)\pi}{2}\right) + \\ d_2\omega^{\alpha+\beta}\cos\left(\frac{(\alpha+\beta)\pi}{2}\right) + \\ d_1\omega^{\alpha}\cos\left(\frac{\alpha\pi}{2}\right) + d_0 \end{array}}\right). \qquad (4)$$

The phase of FHP filter is equal to $\left(\arg\{k\} + \frac{(\alpha+\beta+\gamma)\pi}{2}\right)$ for $\omega \to 0$ where the phase is equal to $(\arg\{k\})$ for $\omega \to \infty$. The critical frequencies, the peak value frequency $\omega_p$ (the maximum and minimum of magnitude occurs at this frequency), cut-off frequency $\omega_c$ (the power falls to $1/\sqrt{2}$ of passband at this frequency) [3], [4], [5] and [9] and right phase frequency $\omega_r$ are the important parameters of a filter. The peak value frequency $\omega_p$ of the high pass filter can be computed by solving the condition $\frac{\mathrm{d}}{\mathrm{d}\omega}|H(j\omega)|_{\omega=\omega_p} = 0$ and is given in Eq. (5):

$$\begin{array}{c} d_2\gamma\cos\frac{\gamma\pi}{2}\omega_p^{2\alpha+2\beta+\gamma} + d_1(\beta+\gamma)\cos\frac{(\beta+\gamma)\pi}{2}\omega_p^{2\alpha+\beta+\gamma} \\ +d_2^2\gamma\omega_p^{2\alpha+2\beta} + d_1d_2(\beta+2\gamma)\cos\frac{\beta\pi}{2}\omega_p^{2\alpha+\beta} \\ +d_0(\alpha+\beta+\gamma)\cos\frac{(\alpha+\beta+\gamma)\pi}{2}\omega_p^{\alpha+\beta+\gamma} \\ +d_1^2(\beta+\gamma)\omega_p^{2\alpha} \\ +d_0d_2(\alpha+\beta+2\gamma)\cos\frac{((\alpha+\beta)\pi}{2}\omega_p^{\alpha+\beta} \\ +d_0d_1(\alpha+2\beta+2\gamma)\cos\frac{\alpha\pi}{2}\omega_p^{\alpha} \\ +d_0^2(\alpha+\beta+\gamma) = 0. \end{array} \qquad (5)$$

The cut-off frequency $\omega_c$ of the presented high pass filter can be calculated through the condition $|H(j\omega)|\omega = \omega_c = 0.707 \cdot |H(j\omega)|_{\max}$ and is given in Eq. (6):

$$\begin{array}{c} \omega_c^{2(\alpha+\beta+\gamma)} - 2d_1d_2\cos\frac{\gamma\pi}{2}\omega_c^{2(\alpha+\beta)+\gamma} - \\ 2d_1\cos\frac{(\gamma+\beta)\pi}{2}\omega_c^{2\alpha+(\beta+\gamma)} - d_2^2\omega_c^{2(\alpha+\beta)} - \\ 2d_1d_2\cos\frac{\beta\pi}{2}\omega_c^{2\alpha+\beta} - 2d_0\cos\frac{(\alpha+\beta+\gamma)\pi}{2}\omega_c^{\alpha+\beta+\gamma} \\ -2d_0d_2\cos\frac{(\alpha+\beta)\pi}{2}\omega_c^{\alpha+\beta} - d_1^2\omega_c^{2\alpha} \\ -2d_0d_1\cos\frac{\alpha\pi}{2}\omega^{\alpha} - d_0^2 = 0. \end{array} \qquad (6)$$

The right phase frequency $\omega_r$ at which the phase $\angle H(j\omega_r) = \pm\frac{\pi}{2}$ for high pass filter can be acquired from the following Eq. (7):

$$\omega_r^{\alpha+\beta+\gamma} + d_2\omega_r^{\alpha+\beta}\cos\frac{\gamma\pi}{2} + d_1\omega_r^{\alpha}\cos\frac{(\beta+\gamma)\pi}{2} + +d_0\cos\frac{(\alpha+\beta+\gamma)\pi}{2} = 0. \quad (7)$$

The theoretical results obtained from Eq. (3) and Eq. (4) at $d_2 = 2$, $d_1 = 2$, and $d_0 = 1$ for different values of $\alpha, \beta, \gamma$ are plotted in Fig. 5. The value of $d_2$, $d_1$, and $d_0$ are taken from the Butterworth filter coefficient table for the third order filter. It is observed from the simulations that the magnitude and phase response of the proposed filter are not only controlled with the coefficients $(d_2, d_1, d_0)$ but can also be controlled with fractional order $(\alpha, \beta, \gamma)$ which increases the design flexibility of the proposed filter.

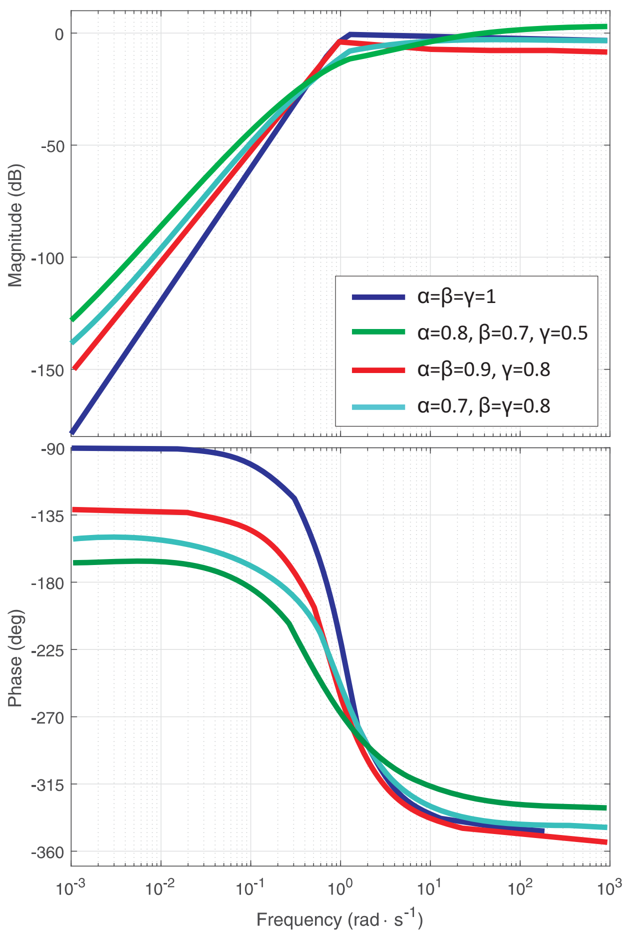



**Fig. 5:** MATLAB simulations of magnitude and phase response of proposed filter for different values of $\alpha$, $\beta$ and $\gamma$.

## 2.2. Non-Ideal Analysis

The performance of the FHPF may deviate because of non-idealities of OTRA in practice. Ideally OTRA is an infinite gain ($R_m \to \infty$), differential Current Controlled Voltage Source (CCVS) device. However, practically the value of $R_m$ is a frequency dependent.

Considering a single pole model of an OTRA, $R_m$ can be expressed as:

$$R_m(s) = \left[\frac{R_d}{1+\frac{s}{\omega_0}}\right], \quad (8)$$

where $R_d$ represents the dc transresistance gain. For high frequency applications, $R_m(s)$ reduces to:

$$R_m(s) \approx \frac{1}{sC_p}, \text{ where } C_p = \frac{1}{R_d\omega_0}.$$

Taking this consequence into account the transfer function given in Eq. (2) transforms to Eq. (9).

Where the uncompensated error term $sC_p$ appearing in parallel to $F_{C3}$ can lead to the introduction of another pole. The value of $F_{C3}$ may be decreased by $C_p$ to absorb the nonideality effect and thus achieving self-compensation. Another nonideality present in it is because of parasitic resistances and capacitances at higher frequencies shown in Fig. 6(a).

## 2.3. Stability

It is an important property of a fractional filter that can be investigated by converting the fractional domain into various domains [43]. The stability of the proposed fractional filter is studied by converting the s-domain into a W-domain that transforms the fractional order transfer function into integer order. The following steps are performed for the stability analysis of this filter:

- Convert the fractional domain into W-domain by using $W = s^{1/m}$ and $\alpha = k_1/m$ and $\beta = k_2/m$ and by selecting the values of $k_1$, $k_2$, and $m$ for the desired value of $\alpha$ and $\beta$.
- Solve the converted transfer function to compute minimum root angle$|\theta_w|$. If the minimum root angle$|\theta_w|$ is less than $\pi/2m$ then the filter is unstable otherwise it is stable.

This procedure is then applied to the denominator of Eq. (2) that gives the characteristic equation in the W-plan.

$$H(s)=\frac{s^{\alpha+\beta+\gamma}}{s^{\alpha+\beta+\gamma}+\left(\frac{1}{F_{C2}R_3}+\frac{1}{F_{C2}R_2}+\frac{1}{F_{C1}R_1}-\frac{1}{(F_{C3}+sC_p)R_2}\right)s^{\alpha+\beta}+\ldots}$$
$$\overline{\ldots+\left(\frac{1}{F_{C2}(F_{C3}+sC_p)R_2R_3}+\frac{1}{F_{C1}F_{C2}R_1R_2}+\frac{1}{F_{C1}F_{C2}R_3R_1}-\frac{1}{F_{C1}(F_{C3}+sC_p)R_1R_2}\right)s^{\alpha}\ldots} \quad (9)$$
$$\overline{\ldots+\frac{1}{F_{C1}F_{C2}(F_{C3}+sC_p)R_1R_2R_3}}.$$

$$W^{k_1+k_2+k_3}+d_2W^{k_1+k_2}+d_1W^{k_1}+d_0. \quad (10)$$

The roots of the Eq. (10) were calculated for various values of $\alpha$, $\beta$, and $\gamma$ with $d_2=2$, $d_1=2$, and $d_0=1$. It was observed that the minimum root angle $|\theta_w|_{\min}>\pi/2q=9^\circ$ where $q=10$ for various values of $\alpha$, $\beta$ and $\gamma$. The stability of the filter for various values of $\alpha$ and $\beta$ with coefficients $d_2$, $d_1$, and $d_0$ is given in Tab. 1 which confirms that the filter using these coefficients is stable when $\alpha\leq 1$, $\beta\leq 1$ and $\gamma\leq 1$.

**Tab. 1:** Minimum root angle for the third order filter in fractional domain for different values of $\alpha$, $\beta$, and $\gamma$ with coefficients, $d_2=2$, $d_1=2$, and $d_0=1$.

| $\alpha$ | $\beta$ | $\gamma$ | $\lvert\theta_w\rvert_{\min}$ | **Stability** |
|---|---|---|---|---|
| 0.9 | 0.6 | 0.5 | 15.45° | Stable |
| 0.7 | 0.8 | 0.8 | 14.94° | Stable |
| 0.9 | 0.9 | 0.8 | 13.29° | Stable |
| 0.5 | 0.6 | 0.9 | 14.11° | Stable |
| 0.8 | 0.7 | 0.6 | 16.26° | Stable |
| 1 | 1 | 1 | 12.00° | Stable |
| 1.2 | 0.8 | 0.7 | 11.61° | Stable |
| 1.4 | 1.4 | 0.8 | 8.53° | Unstable |
| 1.2 | 1.6 | 1.3 | 7.76° | Unstable |

## 2.4. Sensitivity Analysis

Sensitivity analysis is one of the most important parameters in computing the performance of active filters and is defined as:

$$S_x^y=\left(\frac{x}{y}\right)\left(\frac{\delta x}{\delta y}\right). \quad (11)$$

It means that the fractional change in the parameter (y) i.e. transfer function is normalised by the fractional change in component (x) value. Change in the sensitivity of transfer function relative to component variation is complex and difficult to compute [9]. The transfer function sensitivity relative to fractional orders, i.e. sensitivity toward $\alpha$, $\beta$, $\gamma$ can be derived by applying Eq. (11) to the transfer function of the proposed high pass filter, the sensitivities are given as:

$$S_\alpha^{T_{FHP}}=\frac{\alpha\ln s}{(s^{\alpha+\beta+\gamma}+d_2s^{\alpha+\beta}+d_1s^\alpha+d_0)}. \quad (12)$$

$$S_\beta^{T_{FHP}}=\frac{\beta(d_1s^\alpha+d_0)ln(s)}{(s^{\alpha+\beta+\gamma}+d_2s^{\alpha+\beta}+d_1s^\alpha+d_0)}. \quad (13)$$

$$S_\gamma^{T_{FHP}}=\frac{\gamma(d_2s^{\alpha+\beta}+d_1s^\alpha+d_0)ln(s)}{(s^{\alpha+\beta+\gamma}+d_2s^{\alpha+\beta}+d_1s^\alpha+d_0)}. \quad (14)$$

For the special case of $\alpha=\beta=\gamma=1$, the natural frequency $\omega_0$ and quality factor $Q_0$ of the proposed filter can be obtained by using normal capacitors is given as:

$$\omega_0=\frac{1}{\sqrt[3]{C_1C_2C_3R_1R_2R_3}}. \quad (15)$$

$$Q_0=\frac{\sqrt[3]{C_1C_2C_3R_1R_2R_3}}{C_1R_1+C_2R_2+C_3R_3-C_2R_3-\sqrt[3]{C_1C_2C_3R_1R_2R_3}}. \quad (16)$$

The sensitivities of $\omega_0$ w.r.t. various passive components are given as:

$$S_{C_1}^{\omega_0}=S_{C_2}^{\omega_0}=S_{C_3}^{\omega_0}=S_{R_1}^{\omega_0}=S_{R_2}^{\omega_0}=S_{R_3}^{\omega_0}=-\frac{1}{3}. \quad (17)$$

The sensitivities of $Q_0$ w.r.t. various passive components are given as:

$$S_{C_1}^{Q_0}=-\frac{1}{3},S_{C_2}^{Q_0}=\frac{2}{3},S_{C_3}^{Q_0}=-\frac{1}{3},$$
$$S_{R_1}^{Q_0}=-\frac{1}{3},S_{R_2}^{Q_0}=-\frac{1}{3},S_{R_3}^{Q_0}=-\frac{2}{3}. \quad (18)$$

It shows that the proposed circuit offers low passive sensitivity.

# 3. Circuit Simulation

The practicality of the proposed circuit in Fig. 3 is verified on the PSpice platform for four cases i.e.

- $\alpha\neq\beta\neq\gamma$ using factional capacitors of different order where $\alpha=0.8$, $\beta=0.7$ and $\gamma=0.5$.
- $\alpha\neq\beta=\gamma$ using two fractional capacitors of same order where $\alpha=0.7$ and $\beta=\gamma=0.8$.

**Tab. 2:** Component values used to realize fractional capacitor at a centre frequency of 1000 Hz.

| Passive Components | Fractional Capacitor | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $F_{c_0}=F_{c_3}=10\cdot10^{-9}[F/s^{1-\alpha}]$ | | | $F_{c_1}=10\cdot10^{-9}[F/s^{1-\beta}]$ | | | $F_{c_2}=20\cdot10^{-9}[F/s^{1-\gamma}]$ | | | $F_{c_4}=5\cdot10^{-9}[F/s^{1-\alpha}]$ | | |
| | $\alpha$=0.8 | $\alpha$=0.7 | $\alpha$=0.9 | $\beta$=0.7 | $\beta$=0.8 | $\beta$=0.9 | $\gamma$=0.5 | $\gamma$=0.8 | $\gamma$=0.7 | $\alpha$=0.8 | $\alpha$=0.7 | $\alpha$=0.9 |
| $R_a$ ($\Omega$) | 1681.73 | 8135.32 | 259.58 | 8135.32 | 1681.73 | 259.58 | 70082.47 | 840 | 4067.66 | 3363.47 | 16270.64 | 519.16 |
| $R_b$ (k$\Omega$) | 8.601 | 31.93 | 1.77 | 31.93 | 8.601 | 1.77 | 158.73 | 4.30 | 15.973 | 17.20 | 63.85 | 3.55 |
| $R_c$ (k$\Omega$) | 19.55 | 66.31 | 3.57 | 66.31 | 19.55 | 3.57 | 238.85 | 9.77 | 33.155 | 39.10 | 132.62 | 7.14 |
| $R_d$ (k$\Omega$) | 95.02 | 241.83 | 29.06 | 241.83 | 95.02 | 29.06 | 560.65 | 47.51 | 120.91 | 190.04 | 483.66 | 58.11 |
| $R_e$ (k$\Omega$) | 4853.26 | 5568.70 | 5574.59 | 5568.70 | 4853.26 | 5574.59 | 4648.35 | 2426.63 | 2784.35 | 9706.53 | 11137.4 | 11491.83 |
| $C_b$ (nF) | 2.98 | 0.79 | 16.9 | 0.79 | 2.98 | 16.9 | 0.132 | 5.97 | 1.59 | 1.49 | 0.4 | 2.72 |
| $C_c$ (nF) | 3.21 | 1.66 | 23.57 | 1.66 | 3.21 | 23.57 | 0.469 | 6.42 | 3.29 | 1.60 | 0.83 | 8.45 |
| $C_d$ (nF) | 6.54 | 1.96 | 42.44 | 1.96 | 6.54 | 42.44 | 0.851 | 13.08 | 4.70 | 3.27 | 0.98 | 11.78 |
| $C_e$ (nF) | 7.18 | 2.35 | 54.4 | 2.35 | 7.18 | 54.4 | 1.10 | 14.36 | 3.31 | 3.59 | 1.17 | 21.22 |

**Tab. 3:** Relative study of proposed filter with other fractional filters available in the literature.

| Ref. | Type of Fractional filter | Circuit simulations/ Experimental work of fractional filter | Type and number of active components used | Number of components used | | | Performance Parameter | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | R | C | FOC | Critical Frequencies | Sensitivity Analysis | Stability Analysis | Noise Analysis | THD | PSRR |
| [7] | KHN | FLPF of order $(\alpha+\beta)$, at $\alpha=0.7$, $\beta=1.2$ and $\alpha=0.7$, $\beta=0.7$ | Op-amp,3 | 6 | - | 2 | Yes | No | Yes | No | No | No |
| | Sallen-key | FLPF of order $(\alpha+\beta)$, at $\alpha=1.2$, $\beta=1.5$ and $\alpha=1.2$, $\beta=0.7$ | Op-amp,1 | 4 | - | 2 | | | | | | |
| [8] | KHN | FLPF, FHPF and FBPF of order $(\alpha+\beta)$ at $\alpha=0.86$, $\beta=0.46$ | Op-amp,3 | 6 | - | 2 | Yes | Yes | Yes | No | No | No |
| [9] | KHN | FLPF of order $(\alpha+\beta)$ at $\alpha=1.2$, $\beta=0.4$; $\alpha=0.8$, $\beta=0.7$ and $\alpha=1.2$, $\beta=1.7$ | CCII,4 | 6 | - | 2 | Yes | No | Yes | No | No | No |
| | Tow-Tomas | FLPF of order $(\alpha+\beta)$ at $\alpha=1.2$, $\beta=0.4$; $\alpha=1.7$, $\beta=1.2$ and $\alpha=0.8$, $\beta=0.7$ | CCII,3 | 4 | - | 2 | | | | | | |
| [10] | FO Chebyshev LPF | FLPF of order $(1+\alpha)$ at $\alpha=0.2$, 0.5 and 0.8 | Op-amp,3 | 6 | 1 | 1 | No | No | Yes | No | No | No |
| [11] | FO inverse Chebyshev LPF | FLPF of order $(1+\alpha)$ at $\alpha=0.2$, 0.5 and 0.8 | Op-amp,3 | 6 | 1 | 1 | No | No | Yes | No | No | No |
| [12] | FHPF with electronically controllable parameter | FHPF of order $(1+\alpha)$ at $\alpha=0.25$, 0.5 and 0.75 | OTA,3 ACA,2 DO-CF,1 | - | 3 | - | Yes | No | No | No | No | No |
| [13] | FLPF | FLPF of order $2\alpha$ at $\alpha=0.8$ | CCII,1 | 2 | - | 2 | Yes | Yes | Yes | No | No | No |
| [14] | FLPF with electronic tunability | FLPF of order $(1+\alpha)$ at $\alpha=0.1$, 0.3, 0.5, 0.7 and 0.9 | OTA,2 ACA,2 and MO-CF,1 | - | 3 | - | Yes | No | No | No | Yes | No |
| [15] | CDBA based fractional order Multi function filter | FLPF, FHPF, FBPF at $\alpha=\beta=\gamma=1$ $\alpha=0.5$,$\beta=0.9$,$\gamma=0.7$ $\alpha=\beta=\gamma=0.9$ | CDBA,1 | 5 | - | 5 | Yes | Yes | Yes | Yes | Yes | No |
| Proposed | FHPF | FHPF of order $(\alpha+\beta+\gamma)$ at $\alpha=\beta=\gamma=1$ $\alpha=\beta=0.9$, $\gamma=0.8$ $\alpha=0.7$, $\beta=\gamma=0.8$ $\alpha=0.8$, $\beta=0.7$, $\gamma=0.5$ | OTRA,1 | 4 | - | 5 | Yes | Yes | Yes | Yes | Yes | Yes |

- $\alpha=\beta\neq\gamma$ using two fractional capacitors of same order where $\alpha=\beta=0.9$ and $\gamma=0.8$.
- $\alpha=\beta=\gamma=1$ using a normal capacitor.

In all the cases the circuit remains in the stable region given in Tab. 3. The component values to obtain the frequency response of the proposed filter are:

- $F_{c_0}=10\cdot10^{-9}[F/s^{\alpha}]$,
- $F_{c_1}=10\cdot10^{-9}[F/s^{\beta}]$,
- $F_{c_2}=20\cdot10^{-9}[F/s^{\gamma}]$,
- $F_{c_3}=10\cdot10^{-9}[F/s^{\alpha}]$,
- $F_{c_4}=5\cdot10^{-9}[F/s^{\alpha}]$,
- $R_1$ = 10 k$\Omega$, $R_2$ = 2.5 k$\Omega$, $R_3$ = 20 k$\Omega$, $R_4$ = 10 k$\Omega$.

The fractional capacitors used for the Pspice simulations are realized as shown in Fig. 4 by fourth order rational approximation for $s^{\alpha}$ [44] using Continued Fraction Expansions (CFEs). By using this rational approximation, the fractional Laplacian operator can be realised physically with the RC ladder network. The impedance ($Z$) of this RC network is:

$$Z = R_a + \frac{\frac{1}{C_b}}{s + \frac{1}{R_b C_b}} + \frac{\frac{1}{C_c}}{s + \frac{1}{R_c C_c}} + \frac{\frac{1}{C_d}}{s + \frac{1}{R_d C_d}} + \frac{\frac{1}{C_e}}{s + \frac{1}{R_e C_e}}. \tag{19}$$

The values of resistances and capacitors are obtained by equating terms of fourth order rational approximation with the terms of the Eq. (19) and are given in Tab. 2 designed at a centre frequency of 1000 Hz. The PSpice simulations of Fig. 3 are shown in Fig. 6(a). It is observed that the simulation results are in accordance with theoretical results. Table 3 shows the relative study of the proposed filter with the fractional filters available in the literature. Noise analysis is also performed on the proposed fractional order high pass filter based on OTRA with three degrees of freedom using PSpice AC Sweep/Noise simulation program. Figure 6(b) shows the noise voltage and the Root Mean Square (RMS) value of the noise voltage at the output. The RMS value of noise voltage at the output of the proposed filter for all the four cases are $1.4 \cdot 10^{-7}$ V for order 2, $1.62 \cdot 10^{-7}$ V for order 2.3, $1.97 \cdot 10^{-7}$ V for order 2.6 and $3.89 \cdot 10^{-7}$ V for order 3. It is observed that the RMS value of noise voltage at the output of the fractional filter is less than that of the integer order filter. THD values are derived for input voltage amplitude values from 0 mV to 4000 mV from PSPICE Transient and Fourier analysis and are given in Fig. 6(c). The THD analysis results show that when the input voltage is below 2000 mV, the THD is less than 1 %: THD is less than 5 % of input voltage is below 4000 mV for all the four cases.

For PSRR measurement of the projected fractional order high pass filter, DC bias is connected to the input and AC signal is connected at VDD terminal. The PSRR analysis shows that the proposed circuit provides a 69.643 dB for order 2, +66.640 dB for order 2.3, 64.681 dB for order 2.6 and 59.760 dB for order 3 at 10 kHz. The simulation results for PSRR given in Fig. 6(d) show that the fractional order circuits have higher PSRR when compared to the integer order ones under similar conditions. Temperature sweep analysis is also performed on the proposed fractional order high pass filter based on OTRA with three degrees of freedom using PSPICE Temperature Sweep/transient analysis. Figure 6(e) shows the output voltage variation with change in temperature ranging from −50 °C to +50 °C. It is observed from the simulations that as the temperature increases the output of the circuit decreases. Figure 6(f) shows the change in output voltage with respect to supply voltage variation from 0 to 10 V at different values of $\alpha$, $\beta$ and $\gamma$. The simulation shows that the output voltage varies linearly with the supply voltage.

Corner analysis of the proposed circuit is given in Fig. 7(a) at $\alpha = 0.8$, $\beta = 0.7$, $\gamma = 0.5$, Fig. 7(b) at $\alpha = 0.7$, $\beta = \gamma = 0.8$ Fig. 7(c) at $\alpha = \beta = 0.9$, $\gamma = 0.8$ and Fig. 7(d) at $\alpha = \beta = \gamma = 1$. Three corners typical-typical (tt), slow-slow (ss) and fast-fast (ff) are considered. DC gain indicates approximately 3 % (ff) and 7.1 % (ss) change from the (tt) value for all the cases, therefore (ss) corner can be considered a worst case for this circuit. The performance parameters of the planned filter at different values of $\alpha$, $\beta$ and $\gamma$ are tabulated in Tab. 4.

**Tab. 4:** Performance parameters of proposed fractional order High Pass Filter.

| Order of fractional order HPF | Values of $\alpha$ $\beta$ and $\gamma$ | RMS value of Noise Voltage (V) | THD (%) @4 mV | PSRR (dB) @ 10 kHz |
|---|---|---|---|---|
| 2.0 | $\alpha = 0.8$ $\beta = 0.7$ $\gamma = 0.5$ | $1.4 \cdot 10^{-7}$ | 3.51 | 69.643 |
| 2.3 | $\alpha = 0.7$ $\beta = 0.8$ $\gamma = 0.8$ | $1.62 \cdot 10^{-7}$ | 3.60 | 66.640 |
| 2.6 | $\alpha = 0.9$ $\beta = 0.9$ $\gamma = 0.8$ | $1.97 \cdot 10^{-7}$ | 3.95 | 64.681 |
| 3.0 | $\alpha = 1$ $\beta = 1$ $\gamma = 1$ | $3.89 \cdot 10^{-7}$ | 4.50 | 59.760 |

## 4. Conclusion

In this work, a fractional high pass filter based on OTRA with three fractional capacitors of different order has been realized. Mathematical equations have been considered to develop the design procedure for high pass fractional filter. The stability and sensitivity analysis in the fractional domain has been conferred as well. The Noise Analysis shows that the RMS value of noise voltage at the output of the proposed filter for all the four cases is $1.4 \cdot 10^{-7}$ V for order 2, $1.62 \cdot 10^{-7}$ V for order 2.3, $1.97 \cdot 10^{-7}$ V for order 2.6 and $3.89 \cdot 10^{-7}$ V for order 3 and these are relatively low in comparison to the other reported designs. It is conjointly identified that the RMS value of noise voltage and THD at the output is low, whereas PSRR is at higher level for fractional order circuits as compared to the corresponding integer order circuit. Supply voltage variation analysis shows that the output voltage varies linearly with supply voltage. The simulated results validate the working principle of the OTRA based high pass filter in the fractional domain.

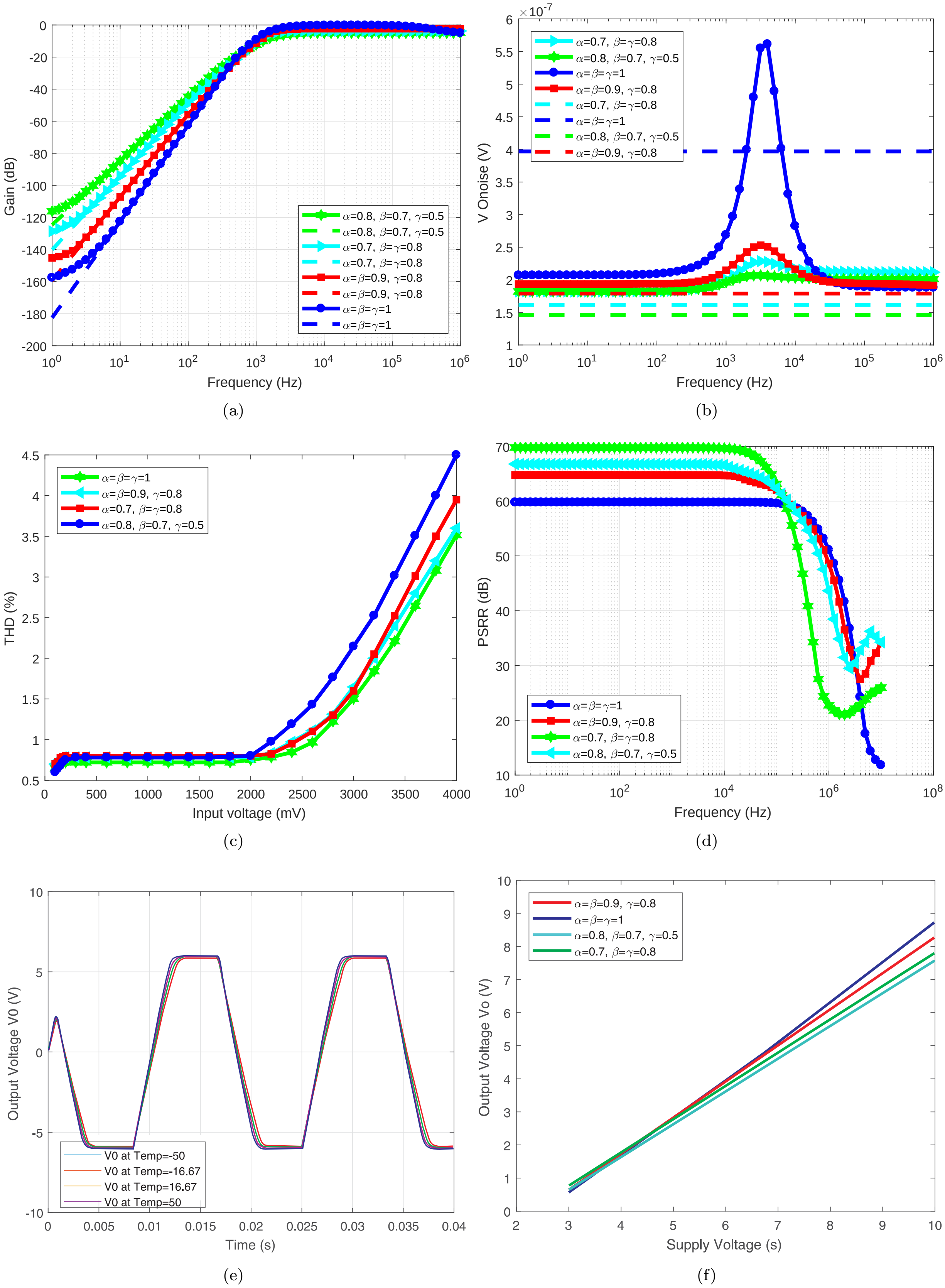
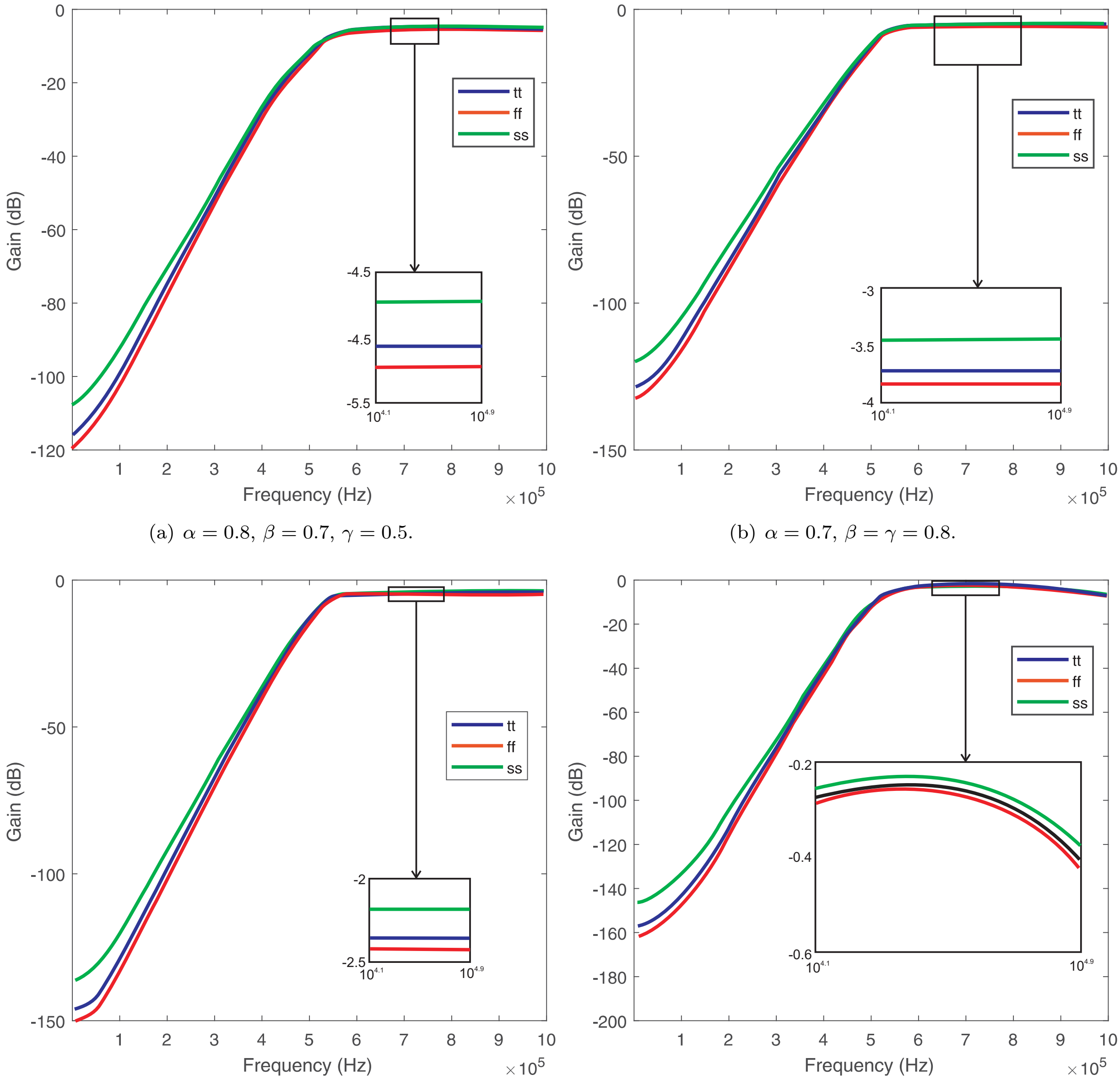



**Fig. 6:** (a) PSPICE simulation results of FHPF at different values of $\alpha$, $\beta$ and $\gamma$ (dotted lines represent the theoretical response and simulated response is represented by solid lines). (b) Output noise analysis of FHPF at different values of $\alpha$, $\beta$ and $\gamma$ (dotted lines represent the RMS value of the output noise voltage and the maximum value of output noise voltage is represented by solid lines) and (c) change of percentage THD with respect to the input voltage of FHPF at different values of $\alpha$, $\beta$ and $\gamma$. (d) PSRR of FHPF at different values of $\alpha$, $\beta$ and $\gamma$. (e) The temperature sweep of FHPF at $\alpha = \beta = 0.9$ and $\gamma = 0.8$. (f) Supply voltage variation analysis of FHPF at different values of $\alpha$, $\beta$ and $\gamma$.




(a) $\alpha = 0.8$, $\beta = 0.7$, $\gamma = 0.5$.

(b) $\alpha = 0.7$, $\beta = \gamma = 0.8$.

(c) $\alpha = \beta = 0.9$, $\gamma = 0.8$.

(d) $\alpha = \beta = 0.7\gamma = 1$.

**Fig. 7:** Corner analysis results of the FHPF.

# References

[1] RADWAN, A. G., A. S. ELWAKIL and A. M. SOLIMAN. Fractional-order sinusoidal oscillators: design procedure and practical examples. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 2008, vol. 55, iss. 7, pp. 2051–2063. ISSN 1549-8328. DOI: 10.1109/TCSI.2008.918196.

[2] SAID, L. A., A. G. RADWAN, A. H. MADIAN and A. M. SOLIMAN. Fractional order oscillators based on operational transresistance amplifiers. *AEU-International Journal of Electronics and Communications*. 2015, vol. 69, no. 7, pp. 988–1003. ISSN 1434-8411. DOI: 10.1016/j.aeue.2015.03.003.

[3] SOLTAN, A., A. G. RADWAN and A. M. SOLIMAN. Fractional order filter with two fractional elements of dependant orders. *Microelectronics Journal*. 2012, vol. 43, no. 11, pp. 818–827. ISSN 1879-2391. ODI: 10.1016/j.mejo.2012.06.009.

[4] RADWAN, A. G., A. M. SOLIMAN and A. S. ELWAKIL. First-order filters generalized to the fractional domain. *Journal of Circuits, Systems, and Computers*. 2008, vol. 17, no. 1, pp. 55–66. ISSN 1793-6454. DOI: 10.1142/S0218126608004162.

[5] RADWAN, A. G., A. S. ELWAKIL and A. M. SOLIMAN. On the generalization of second-order filters to the fractional-order domain. *Journal of Circuits, Systems, and Computers*. 2009, vol. 18, no. 2, pp. 361–386. ISSN 1793-6454. DOI: 10.1142/S0218126609005125.

[6] KHATEB, F., D. KUBANEK, G. TSIRIMOKOU and C. PSYCHALINOS. Fractional-order filters based on low-voltage DDCCs. *Microelectronics Journal*. 2016, vol. 50, iss. 1, pp. 50–59. ISSN 1879-2391. DOI: 10.1016/j.mejo.2016.02.002.

[7] ALI, A. S., A. G. RADWAN and A. M. SOLIMAN. Fractional order Butterworth filter: active and passive realizations. *IEEE Journal on emerging and selected topics in circuits and systems*. 2013, vol. 3, no. 3, pp. 346–354. ISSN 2156-3365. DOI: 10.1109/JETCAS.2013.2266753.

[8] TRIPATHY, M. C., K. BISWAS and S. SEN. A design example of a fractional-order Kerwin-Huelsman-Newcomb biquad filter with two fractional capacitors of different order. *Circuits, Systems, and Signal Processing*. 2013, vol. 32, no. 4, pp. 1523–1536. ISSN 1531-5878. DOI: 10.1007/s00034-012-9539-2.

[9] SOLTAN, A., A. G. RADWAN and A. M. SOLIMAN. CCII based fractional filters of different orders. *Journal of advanced research*. 2014, vol. 5, no. 2, pp. 157–164. ISSN 2090-1232. DOI: 10.1016/j.jare.2013.01.007.

[10] FREEBORN, T., B. MAUNDY and A. S. ELWAKIL. Approximated Fractional Order Chebyshev Lowpass Filters. *Mathematical Problems in Engineering*. 2015, vol. 2015, no. 832468, pp. 1–7. ISSN 1024-123X. DOI: 10.1155/2015/832468.

[11] FREEBORN, T. J., A. S. ELWAKIL and B. MAUNDY. Approximated fractional-order inverse Chebyshev lowpass filters. *Circuits, Systems, and Signal Processing*. 2016, vol. 35, no. 6, pp. 1973–1982. ISSN 0278-081X. DOI: 10.1007/s00034-015-0222-2.

[12] JERABEK, J., R. SOTNER, J. DVORAK, L. LANGHAMMER and J. KOTON. Fractional-order high-pass filter with electronically adjustable parameters. In: *2016 International Conference on Applied Electronics (AE)*. Pilsen: IEEE, 2016, pp. 111–116. ISBN 978-80-261-0602-9. DOI: 10.1109/AE.2016.7577253.

[13] SAID, L. A., S. M. ISMAIL, A. G. RADWAN, A. H. MADIAN, M. F. ABU EL-YAZEED and A. M. SOLIMAN. On the optimization of fractional order low-pass filters. *Circuits, Systems, and Signal Processing*. 2016, vol. 35, no. 6, pp. 2017–2039. ISSN 0278-081X. DOI: 10.1007/s00034-016-0258-y.

[14] LANGHAMMER, L., J. DVORAK, J. JERABEK, J. KOTON and R. SOTNER. Fractional-order low-pass filter with electronic tunability of its order and pole frequency. *Journal of Electrical Engineering*. 2018, vol. 69, no. 1, pp. 3–13. ISSN 1339-309X. DOI: 10.1515/jee-2018-0001.

[15] KAUR, G., A. Q. ANSARI and M. S. HASHMI. Fractional order multifunction filter with 3 degrees of freedom. *AEU-International Journal of Electronics and Communications*. 2017, vol. 82, iss. 1, pp. 127–135. ISSN 1434-8411. DOI: 10.1016/j.aeue.2017.08.010.

[16] ADHIKARY, A., S. SEN and K. BISWAS. Practical realization of tunable fractional order parallel resonator and fractional order filters. *IEEE Transactions on Circuits and Systems I: Regular Papers*. 2016, vol. 63, no. 8, pp. 1142–1151. ISSN 1549-8328. DOI: 10.1109/TCSI.2016.2568262.

[17] BERTSIAS, P., F. KHATEB, D. KUBANEK, F. A. KHANDAY and C. PSYCHALINOS. Capacitorless digitally programmable fractional-order filters. *AEU-International Journal of Electronics and Communications*. 2017, vol. 78, iss. 4, pp. 228–237. ISSN 1434-8411. DOI: 10.1016/j.aeue.2017.04.030.

[18] TSIRIMOKOU, G., C. PSYCHALINOS and A. S. ELWAKIL. Fractional-order electronically controlled generalized filters. *International Journal of Circuit Theory and Applications*. 2017, vol. 45, no. 5, pp. 595–612. ISSN 1097-007X. DOI: 10.1002/cta.2250.

[19] MAUNDY, B., A. ELWAKIL and S. GIFT. On a multivibrator that employs a fractional capacitor. *Analog Integrated Circuits and Signal Processing*. 2010, vol. 62, no. 1, pp. 99–103. ISSN 0925-1030. DOI: 10.1007/s10470-009-9329-3.

[20] TSENG, C.-C. Design of FIR and IIR fractional order Simpson digital integrators. *Signal Processing*. 2007, vol. 87, no. 5, pp. 1045–1057. ISSN 0165-1684. DOI: 10.1016/j.sigpro.2006.09.006.

[21] KRISHNA, B. T. Studies on fractional order differentiators and integrators: A survey. *Signal Processing*. 2011, vol. 91, no. 3, pp. 386–426. ISSN 0165-1684. DOI: 10.1016/j.sigpro.2010.06.022.

[22] AGAMBAYEV, A., S. PATOLE, H. BAGCI and K. N. SALAMA. Tunable fractional-order capacitor using layered ferroelectric polymers. *AIP Advances*. 2017, vol. 7, no. 9, pp. 1–8. ISSN 2158-3226. DOI: 10.1063/1.4991659.

[23] KRISHNA, B. T. and K. V. V. S. REDDY. Active and passive realization of fractance device of order 1/2. *Active and passive electronic components*. 2008, vol. 2008, no. 369421, pp. 1–6. ISSN 1563-5031. DOI: 10.1155/2008/369421.

[24] OLDHAM, K. and J. SPANIER. *The fractional calculus theory and applications of differentiation and integration to arbitrary order*. New York: Elsevier, 1974. ISBN 0-12-525550-0.

[25] NAKAGAWA, M. and K. SORIMACHI. Basic characteristics of a fractance device. *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*. 1992, vol. 75, no. 12, pp. 1814–1819. ISSN 0916-8508.

[26] SUGI, M., Y. HIRANO, Y. F. MIURA and K. SAITO. Simulation of fractal immittance by analog circuits: an approach to the optimized circuits. *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*. 1999, vol. 82, no. 8, pp. 1627–1635. ISSN 0916-8508.

[27] ROY, S. D. On the realization of a constant-argument immittance or fractional operator. *IEEE Transactions on Circuit Theory*. 1967, vol. 14, no. 3, pp. 264–274. ISSN 0018-9324. DOI: 10.1109/TCT.1967.1082706.

[28] CARLSON, G. and C. HALIJAK. Approximation of fractional capacitors (1/s)^(1/n) by a regular Newton process. *IEEE Transactions on Circuit Theory*. 1964, vol. 11, no. 2, pp. 210–213. ISSN 0018-9324. DOI: 10.1109/TCT.1964.1082270.

[29] STEIGLITZ, K. An RC Impedance Approximant to s^{-1/2}. *IEEE Transactions on Circuit Theory*. 1964, vol. 11, no. 1, pp. 160–161. ISSN 0018-9324. DOI: 10.1109/TCT.1964.1082252.

[30] SIEROCIUK, D., I. PODLUBNY and I. PETRAS. Experimental evidence of variable-order behavior of ladders and nested ladders. *IEEE Transactions on Control Systems Technology*. 2013, vol. 21, no. 2, pp. 459–466. ISSN 1063-6536. DOI: 10.1109/TCST.2012.2185932.

[31] SUGI, M., Y. HIRANO, Y. F. MIURA and K. SAITO. Frequency behavior of self-similar ladder circuits. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2002, vol. 198, iss. 1, pp. 683–688. ISSN 0927-7757. DOI: 10.1016/S0927-7757(01)00988-8.

[32] OLDHAM, K. B. and C. G. ZOSKI. Analogue instrumentation for processing polarographic data. *Journal of electroanalytical chemistry and interfacial electrochemistry*. 1983, vol. 157, no. 1, pp. 27–51. ISSN 1572-6657. DOI: 10.1016/S0022-0728(83)80374-X.

[33] MONDAL, D. and K. BISWAS. Packaging of single-component fractional order element. *IEEE Transactions on Device and Materials Reliability*. 2013, vol. 13, no. 1, pp. 73–80. ISSN 1530-4388. DOI: 10.1109/TDMR.2012.2212020.

[34] ADHIKARY, A., M. KHANRA, S. SEN and K. BISWAS. Realization of a carbon nanotube based electrochemical fractor. In: *2015 IEEE International Symposium on Circuits and Systems (ISCAS)*. Lisbon: IEEE, 2015, pp. 2329–2332. ISBN 978-1-4799-8391-9. DOI: 10.1109/ISCAS.2015.7169150.

[35] SALAMA, K. N. and A. M. SOLIMAN. CMOS operational transresistance amplifier for analog signal processing. *Microelectronics Journal*. 1999, vol. 30, no. 3, pp. 235–245. ISSN 0026-2692. DOI: 10.1016/S0026-2692(98)00112-8.

[36] KAFRAWY, A. K. and A. M. SOLIMAN. A modified CMOS differential operational transresistance amplifier (OTRA). *AEU-International Journal of Electronics and Communications*. 2009, vol. 63, iss. 12, pp. 1067–1071. ISSN 1434-8411. DOI: 10.1016/j.aeue.2008.08.003.

[37] GHOSH, M., S. K. PAUL, R. K. RANJAN and A. RANJAN. Third order universal filter using single operational transresistance amplifier. *Journal of Engineering*. 2013, vol. 2013, no. 317296, pp. 1–6. ISSN 2314-4904. DOI: 10.1155/2013/317296.

[38] PANDEY, R., N. PANDEY, G. KOMANAPALLI and R. ANURAG. OTRA based voltage mode third order quadrature oscillator. *ISRN Electronics*. 2014, vol. 2014, no. 126471, pp. 1–5. ISSN 2090-8679. DOI: 10.1155/2014/126471.

[39] LO, Y.-K., H.-C. CHIEN and H.-J. CHIU. Switch-controllable OTRA-based bistable multivibrators. *IET circuits, devices & systems*. 2008, vol. 2, no. 4, pp. 373–382. ISSN 1751-858X. DOI: 10.1049/ietcds:20080011.

[40] PANDEY, R., N. PANDEY, S. K. PAUL, A. SINGH, B. SRIRAM and K. TRIVEDI. Novel grounded inductance simulator using single OTRA. *International Journal of Circuit Theory and Applications*. 2014, vol. 42, no. 10, pp. 1069–1079. ISSN 1097-007X. DOI: 10.1002/cta.1905.

[41] ANSARI, A. Q., G. KAUR and M. S. HASHMI. Current Differencing Buffered Amplifier (CDBA) based Current Mode Universal Fractional Order Filter. In: *National Conference on Advances in*

*Microelectronics, Instrumentation and Communication (MICOM 2015)*. Pilani: BITS, 2015, pp. 1–4. ISBN 978-93-86256-11-9.

[42] SOLTAN, A., A. G. RADWAN and A. M. SOLIMAN. Fractional order Sallen-Key and KHN filters: stability and poles allocation. *Circuits, Systems, and Signal Processing*. 2015, vol. 34, no. 5, pp. 1461–1480. ISSN 0278-081X. DOI: 10.1007/s00034-014-9925-z.

[43] RADWAN, A. G., A. M. SOLIMAN, A. S. ELWAKIL and A. SEDEEK. On the stability of linear systems with fractional-order elements. *Chaos, Solitons & Fractals*. 2009, vol. 40, no. 5, pp. 2317–2328. ISSN 0960-0779. DOI: 10.1016/j.chaos.2007.10.033.

[44] TANWAR, R. and S. KUMAR. Analysis & design of fractance based fractional order filter. *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*. 2013, vol. 1, no. 3, pp. 113–122. ISSN 2321-2004.

[45] SHAH, Z. M., M. Y. KATHJOO, F. A. KHANDAY, K. BISWAS and C. PSYCHALINOS. A survey of single and multi-component Fractional-Order Elements (FOEs) and their applications. *Microelectronics Journal*. 2019, vol. 84, iss. 1, pp. 9–25. ISSN 0026-2692. DOI: 10.1016/j.mejo.2018.12.010.

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