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An Optimized Design Methodology &Synthesis for Stability of 3^{rd}-Pole Current-Mode Active-R Filter

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ABSTRACT: The study proposes an optimized design methodology & synthesis for stability of 3^{rd}-pole current-mode active-R filter for f_0=20 KHz and Q-factor =1. This paper illustrates a new configuration to realize the stability of 3^{rd}-pole current-mode active-R filter. The proposed circuit implements three transfer functions lowpass, bandpass, and highpass concurrently in single circuit with work at different nodes with gratified results. It observed that, all poles of transfer functions have negative real parts, and they are lying within the left-half of the s-plane. The return ratio of Nyquist diagram does not enclose the critical point (-1, 0) for all transfer functions. The gain (G_m) and phase (p_m) margins are both positive. Thus the closed-loop for all transfer functions of 3^{rd}-pole current-mode active-R filter at different nodes are asymptotically stable. This filter is stable for 1Hz ≤ f_0 ≥1449 KHz for Q-factor = 1. The output and input gains are identical at gain cross over frequency. The benefits of this filter are the reducing in weight and size, increasing of circuit quality with wide range for frequency, and it is easier and more economical for producing.

KEYWORDS: Stability, 3^{rd}-pole current-mode, active-R filter, Bode diagram, Pole/Zero Map, Step response, Nyquist diagram.

I. INTRODUCTION

In this paper, 3^{rd}-pole current-mode active-R filter one input and three outputs multifunction has been presented. This paper will discuss the stability of 3^{rd}-pole current-mode active-R filter. This active filter is designed with operational amplifier and resistors only. Analog filters are important building blocks and widely used for continuous-time signal processing [1]. In recent years, the current mode analogue signal processing circuit techniques have received wide attention due to the high accuracy, the wide signal bandwidth and the simplicity of implementing signal operations [2, 3]. In filter circuit designs, current-mode filters are becoming popular since they have many advantages compared with their voltage-mode counter parts, the current-mode filters have large dynamic range, higher bandwidth, greater linearity, simple circuitry, and low power consumption etc. [4-6].Current-mode filter theoretically should exhibit high output impedance (Ideally infinite) and low input impedance (Ideally Zero) [4-10].In this filter, we use at least ten passive components such as resistor and three active components such as operation amplifier to realize 3^{rd}-pole current-mode active-R filter.

II. PROPOSED CIRCUIT CONFIGURATION

The proposed circuit configuration for an optimized design methodology & synthesis for stability of 3^{rd}-pole current-mode active-R filter is as shown in Fig 1. The circuit consists of three Operational Amplifiers (OAs) (LF356N) with wide identical gain bandwidth product (GBP=6.392 MHz) and ten Resistors. Resistors (formed by g_{ia} and g_{ib}) assist voltage-divider arrangement. The input sinusoidal low current is applied to the inverting terminal of the first op-amp through first voltage-divider (formed by g_{1a} and g_{1b}). The non-inverting terminal is grounded. The output of the first op-amp is connected to non-inverting input of second op-amp through second voltage-divider (formed by g_{2a} and g_{2b}). The feed forward input signal is given to the inverting terminal of the second op-amp. The output of the second op-amp is connected to non-inverting input of third op-amp through third voltage-divider (formed by g_{3a} and g_{3b}). The inverting terminal is grounded. If voltage-dividers have high input impedances and low output impedances the circuit executes three transfer functions (lowpass, bandpass and highpass) at three different nodes. The lowpass, bandpass and highpass transfer functions are as shown in Fig 1.

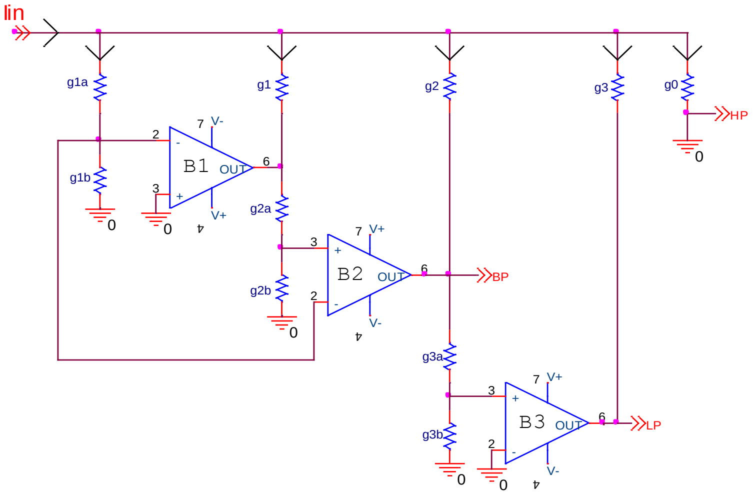

Fig 1: An Optimized Design Methodology & Synthesis for Stability of 3^{rd}-pole Current-Mode Active-R Filter.

III. CIRCUIT ANALYSIS AND DESIGN EQUATIONS

Op-amp (LF356N) is an internally compensated op-amp, which is represented by “a single-pole model”,

$$A(S) = \frac{A_0 w_0}{S} \qquad (1)$$

Where,

A_0 = open loop D.C. gain, w_0= open loop -3dB bandwidth, β =$A_0 w_0$= gain bandwidth product of op-amplifier.

$$A(S) = \frac{A_0 w_0}{S} = \frac{\beta}{S} \qquad (2)$$

Here $s \gg w_0$.
This shows that the op-amplifier is an “integrator”. Thus, the transfer functions at three different nodes are given below.

The current-mode transfer function for lowpass filter:

$$T_{Lp} = \frac{k_1 k_2 k_3 \beta_1 \beta_2 \beta_3 g_3}{y_1 S^3 + y_2 S^2 + y_3 S + y_4} \qquad (3)$$

The current-mode transfer function for bandpass filter:

$$T_{Bp} = \frac{k_1 k_2 \beta_1 \beta_2 g_2 S}{y_1 S^3 + y_2 S^2 + y_3 S + y_4} \qquad (4)$$

The current-mode transfer function for highpass filter:

$$T_{Hp} = \frac{g_0 S^3}{y_1 S^3 + y_2 S^2 + y_3 S + y_4} \qquad (5)$$

Where
$y_1 = g_0 + g_1 + g_2 + g_3$
$y_2 = k_1 \beta_1 g_1 + k_1 \beta_2 g_2$

$y_3 = k_1k_2\beta_1\beta_2g_2 + k_1k_3\beta_2\beta_3g_3$
$y_4 = k_1k_2k_3\beta_1\beta_2\beta_3g_3$, and
$k_1 = \{g_{1a} | (g_{1a} + g_{1b})\}$
$k_2 = \{g_{2a} | (g_{2a} + g_{2b})\}$
$k_3 = \{g_{3a} | (g_{3a} + g_{3b})\}$

The circuit was designed using coefficient matching technique viz by comparing these transfer functions with General 3^{rd}-order transfer function [8]. The general 3^{rd}-order transfer function is given by

$$T(s) = \frac{\alpha_3 s^3 + \alpha_2 s^2 + \alpha_1 s + \alpha_0}{s^3 + w_0\left(1+\frac{1}{Q}\right)s^2 + w_0^2\left(1+\frac{1}{Q}\right)S + w_0^3} \qquad (6)$$

By comparing (3), (4), and (5) with (6), we get the design equations as

$$g_0 + g_1 + g_2 + g_3 = 1 \qquad (7)$$

$$k_1\beta_1g_1 + k_1\beta_2g_2 = w_0\left(1 + \frac{1}{Q}\right) \qquad (8)$$

$$k_1k_2\beta_1\beta_2g_2 + k_1k_3\beta_2\beta_3g_3 = w_0^2\left(1 + \frac{1}{Q}\right) \qquad (9)$$

$$k_1k_2k_3\beta_1\beta_2\beta_3g_3 = w_0^3 \qquad (10)$$

So that values of, g_0, g_1,g_2 and g_3 can be calculated using these equations for the values of f_0=20 KHz, Q =1 and k_1=k_2=k_3=0.5 mS (table1).

Table 1: Resistance values for the values of $f_0 = 20$ KHz & Q =1.

f_0 (kHz)	g_0 (kΩ)	g_1 (kΩ)	g_2 (Ω)	g_3 (Ω)
20	**987.48**	**12.44**	**78.1**	**0.25**

IV. SENSITIVITY

The sensitivities of w_0 and Q in this 3^{rd}-pole current-mode active-R filter are as follows.

$$S_{g_0}^{w_0} = -\frac{1}{3}g_0 \qquad (11)$$

$$S_{g_1}^{w_0} = -\frac{1}{3}g_1 \qquad (12)$$

$$S_{g_2}^{w_0} = -\frac{1}{3}g_2 \qquad (13)$$

$$S_{g_3}^{w_0} = -\frac{1}{3}\{g_3 - 1\} \qquad (14)$$

$$S_{K_1}^{w_0} = S_{K_2}^{w_0} = S_{K_3}^{w_0} = \frac{1}{3} \qquad (15)$$

$$S_{\beta_1}^{w_0} = S_{\beta_2}^{w_0} = S_{\beta_3}^{w_0} = \frac{1}{3} \qquad (16)$$

$$S_{g_0}^{Q} = -\frac{1}{3}(1 + Q)g_0 \qquad (17)$$

$$S_{g_1}^{Q} = -\frac{1}{3}(1 + Q)g_1 \qquad (18)$$

$$S_{g_2}^{Q} = -\frac{1}{3}(1 + Q)g_2\left(\frac{3}{(g_2 + g_3)} - 1\right) \qquad (19)$$

$$S_{g_3}^{Q} = -\frac{1}{3}(1 + Q)\left(\frac{3g_3}{(g_2 + g_3)} - (g_3 + 2)\right) \qquad (20)$$

$$S_{K_1}^{Q} = -\frac{1}{3}(1 + Q) \qquad (21)$$

$$S_{K_2}^{Q} = -\frac{2}{3}(1 + Q)\left(\frac{3g_2}{2(g_2 + g_3)} - 1\right) \qquad (22)$$

$$S^{Q}_{K_3} = -\frac{2}{3}(1+Q)\left(\frac{3g_3}{2(g_2+g_3)}-1\right) \qquad (23)$$

$$S^{Q}_{\beta_1} = -\frac{2}{3}(1+Q)\left(\frac{3g_2}{2(g_2+g_3)}-1\right) \qquad (24)$$

$$S^{Q}_{\beta_2} = -\frac{1}{3}(1+Q) \qquad (25)$$

$$S^{Q}_{\beta_3} = -\frac{2}{3}(1+Q)\left(\frac{3g_3}{2(g_2+g_3)}-1\right) \qquad (26)$$

Passive and active sensitivities are smaller than unity. These values ensure the stability of the circuit.

V. EXPERIMENTAL SET UP

The circuit consists of three operational amplifiers (OAs) (LF356N) with wide identical gain bandwidth product (GBP=6.392 MHz) and ten Resistors. Resistors (formed by g_{ia} and g_{ib}) assist voltage-divider arrangement. The circuit performance is studied for values of f_0=20 KHz with the circuit Q-factor =1. The general operating range of this filter is 10 Hz to 10 MHz. The value of β (β_1=β_2=β_3) is ($2\pi \times 6.392 \times 10^6$rad/sec) and k ($k_1$=$k_2$=$k_3$) is 0.5 mS. The voltage-dividers have high input impedances and low output impedances. The input sinusoidal low current is applied to the inverting terminal of the first op-amp through first voltage-divider (formed by g_{1a} and g_{1b}).

VI. RESULT AND DISCUSSION

The following observations are noticed for the stability of lowpass, bandpass and highpass at corresponding nodes.

A.THE STABILITY OF LOWPASS RESPONSE:

(a) Bode diagram for lowpass response:

Fig 2 shown bode diagram for the lowpass response of 3^{rd}-pole current-mode active-R filter. The data obtained from the analysis bode diagram for the lowpass response curve is as shown in table 2.The phase cross over frequency f_{PCO} is at 28.3 KHz when the phase is at -180°, then gain is -9.54 dB at 28.3 KHz, so that the gain is less than zero dB, then the feedback system of 3^{rd}-pole current-mode active-R filter is stable. The gain cross over frequency f_{GCO} is at 0.173 KHz, when the gain is at 0 dB, then phase is -1° at 0.173 KHz. The gain margin is 9.54 dB at 28.3 KHz, while the phase margin is 179° at 0.173 KHz, then the gain (G_m) and phase (p_m) margins are both positive. Thus the lowpass response of 3^{rd}-pole current-mode active-R filter is asymptotically stable. The output and input gains are identical at 0.173 KHz. The phase (degrees) response of 3^{rd}-pole current-mode active-R filter is shown in Fig 2. It varies from 0° at low frequencies to −270° at high frequencies.

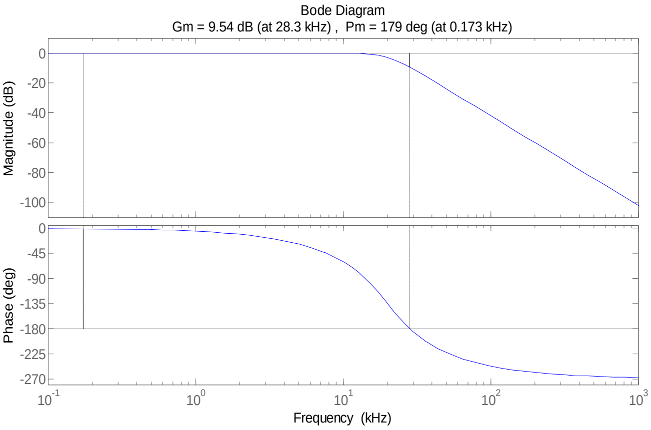

Fig 2: Bode diagram for lowpass response for values of f_0=20 KHz and Q =1.

Table 2: Graph analysis of Fig 2.

For Gain Margin						For Phase Margin					
Phase		Gain		Gain Margin		Gain		Phase		Phase Margin	
Ø (deg)	f_{PCO} (KHz)	dB	f_{PCO} (KHz)	G_M (dB)	f_{PCO} (KHz)	dB	f_{GCO} (KHz)	Ø (deg)	f_{GCO} (KHz)	P_M (deg)	f_{GCO} (KHz)
-180	28.3	-9.54	28.3	9.54	28.3	0	0.173	-1	0.173	179	0.173
f_{GCO}:- Gain Cross Over Frequency G_M:- Gain Margin						f_{PCO}:- Phase Cross Over Frequency P_M:- Phase Margin					

(b) Pole/Zero Map for lowpass response:

Fig 3 shown the pole/zero map for lowpass response for values of f_0=20 KHz and Q =1. The Zeros and Poles of lowpass response are given as Z =0, 0 and 0 where these three Zeros are at infinity, and Poles at-1.26×10^5, and -6.28×10^4±i1.09×10^5. It observed that, all poles have negative real parts, and they are lying within the left-half of the s-plane. Thus the lowpass response is asymptotically stable. The locations of the Poles of 3^{rd}-pole current-mode active-R filter are shown in Fig 3.The zero is marked by a circle (o) and the pole is marked by a cross (×).

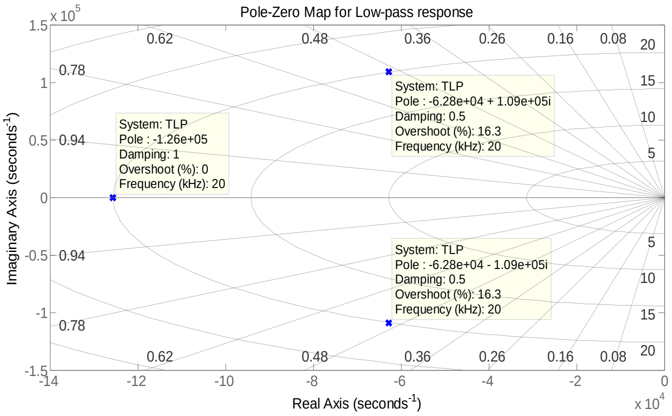

Fig 3: The pole/zero map for lowpass response for values of f_0=20 KHz and Q=1.

(c) Step response for lowpass response:

Fig 4 shown the step response for lowpass response of 3^{rd}-pole current-mode active-R filter. It is observed that, the poles are complex. Thus the system of lowpass response is under-damped with an overshoot, it is 0.08 dB and that is as shown in Fig 4. The characteristics response obtained from the analysis step response of lowpass response curve is as shown in table 3.

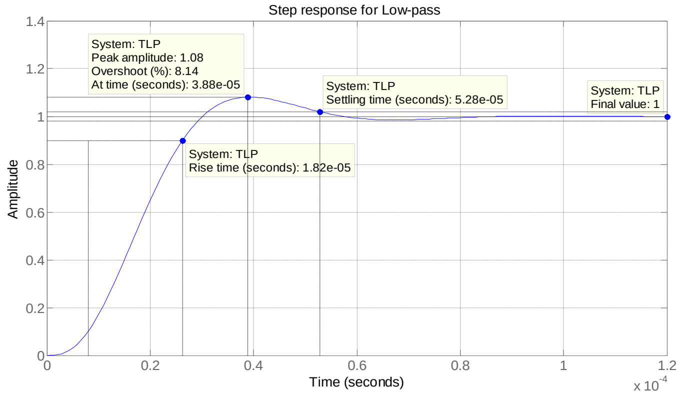

Fig 4: The step response for lowpass response for values of f_0=20 KHz &Q = 1.

Table 3: Graph analysis of Fig 4.

Peak amplitude		Rise time (sec)	Setting time (sec)	Final value at (dB)	Overshoot	
dB	**Time (sec)**				**dB**	**%**
1.08	**3.88×10^-5**	**1.82×10^-5**	**5.28×10^-5**	**1**	**0.08**	**8.14**

(d) Nyquist diagram for lowpass response:

The Nyquist diagram for lowpass response of 3^{rd}-pole current-mode active-R filter is as shown in Fig 5. It observed that, the return ratio of Nyquist diagram for lowpass response does not enclose the critical point (-1, 0). Thus the closed-loop for lowpass response of 3^{rd}-pole current-mode active-R filter is asymptotically stable. The Gain margin is 9.54 dB at 28.3 KHz, and the phase margin is 179° at 0.173 KHz.

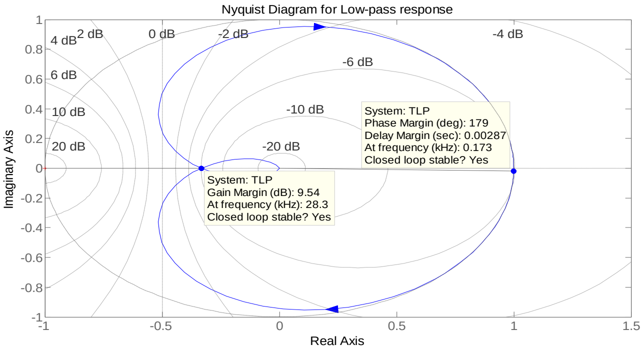

Fig 5: The Nyquist diagram for lowpass response for values of f_0 =20 KHz &Q = 1.

B.THE STABILITY OF BANDPASS RESPONSES:

(a) Bode diagram for band pass response:

Fig 6 shown bode diagram for bandpass response of 3^{rd}-pole current-mode active-R filter. The data obtained from the analysis bode diagram for the bandpass response curve is as shown in table 4.The phase cross over frequency f_{PCO} is at Infinity KHz when the phase is at -180°, then gain is Infinity dB at Infinity KHz. The gain cross over frequency f_{GCO} is at 27.2 KHz, when the gain is at 0 dB, then phase is -85.8° at 27.2 KHz. The gain margin is Infinity dB at Infinity KHz, while the phase margin is 94.2° at 27.2 KHz, then gain (G_m) and phase (p_m) margins are both positive. Thus the bandpass response of 3^{rd}-pole current-mode active-R filter is asymptotically stable. The output and input gains are identical at 27.2 KHz. The phase (degrees) response of 3^{rd}-pole current-mode active-R filter is shown in Fig 6. It varies from 90° at low frequencies to -180° at high frequencies.

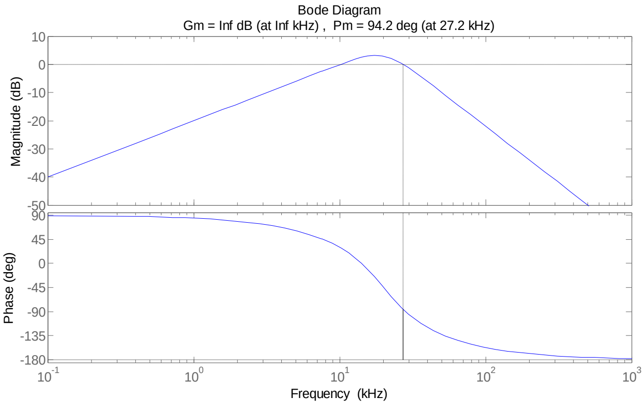

Fig 6: Bode diagram for bandpass response for values of f_0 =20 KHz &Q = 1.

Table 4: Graph analysis of Fig 6.

For Gain Margin						For Phase Margin					
Phase		Gain		Gain Margin		Gain		Phase		Phase Margin	
Ø (deg)	f_{PCO} (KHz)	dB	f_{PCO} (KHz)	G_M (dB)	f_{PCO} (KHz)	dB	f_{GCO} (KHz)	Ø (deg)	f_{GCO} (KHz)	P_M (deg)	f_{GCO} (KHz)
-180	Infinity	Infinity	Infinity	Infinity	Infinity	0	27.2	-85.8	27.2	94.2	27.2
f_{GCO}:- Gain Cross Over Frequency G_M:- Gain Margin						f_{PCO}:- Phase Cross Over Frequency P_M:- Phase Margin					

(b) Pole/Zero Map for bandpass response:

Fig 7 shown the pole/zero map for bandpass response for values of f_0=20 KHz and Q-factor =1. The Zeros and Poles of bandpass response are given as Z =0, 0 and 0, where two Zeros are at infinity while one Zero is at the origin, and Poles at -1.26×10^5, and -6.28×10^4±i1.09×10^5. It observed that, all poles have negative real parts, and they are lying within the left-half of the s-plane. Thus the bandpass response is asymptotically stable. The locations of the Poles of 3^{rd}-pole current-mode active-R filter are shown in Fig 7.

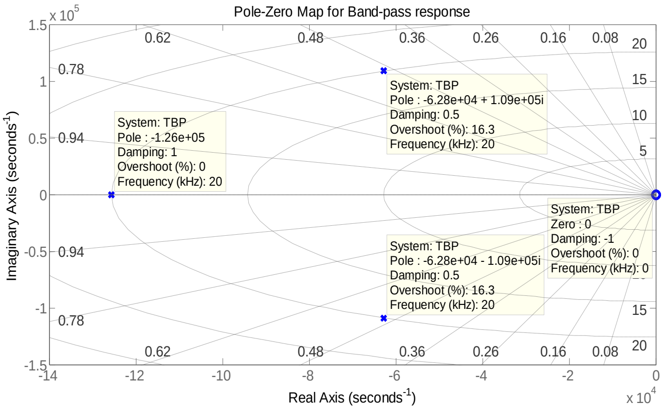

Fig 7: The pole/zero map for bandpass response for values of f_0=20 KHz &Q = 1.

(c) Step response for bandpass response:

Fig 8 shown the step response for bandpass response of 3^{rd}-pole current-mode active-R filter. It is observed that, the poles are complex. Thus the system of bandpass response is under-damped with an overshoot, it is 0.806 dB and that is as shown in Fig 8. The characteristics response obtained from the analysis step response of bandpass response curve is as shown in table 5.

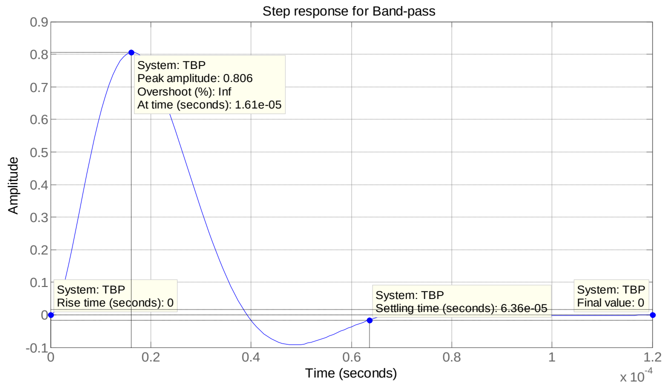

Fig 8: The step response for bandpass response for values of f_0=20 KHz &Q = 1.

Table 5: Graph analysis of Fig 8.

Peak amplitude		Rise time (sec)	Setting time (sec)	Final value at dB	Overshoot	
dB	Time (sec)				dB	%
0.806	1.61×10^-5	0	6.36×10^-5	0	0.806	Infinity

(d) Nyquist diagram for bandpass response:

The Nyquist diagram for bandpass response of 3^{rd}-pole current-mode active-R filter is as shown in Fig 9. It observed that, the return ratio of Nyquist diagram for bandpass response does not enclose the critical point (-1, 0). Thus the closed-loop for bandpass response of 3^{rd}-pole current-mode active-R filter is asymptotically stable. The Gain margin is Infinity dB at Infinity KHz, and the phase margin is 94.2° at 27.2 KHz.

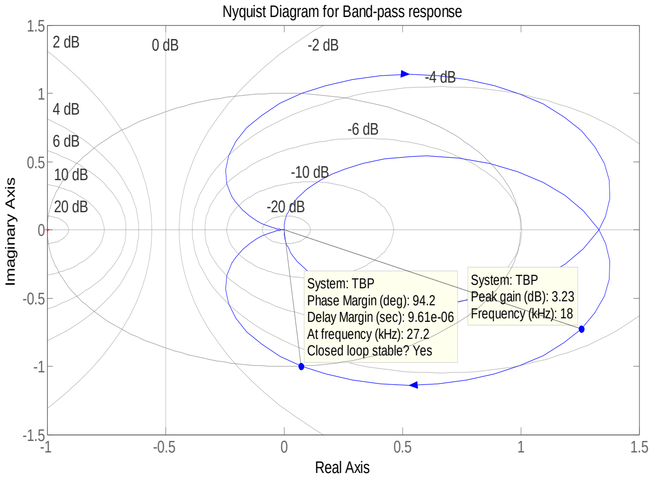

Fig 9: The Nyquist diagram for bandpass response for values of f_0 =20 KHz &Q = 1.

C. THE STABILITY OF HIGHPASS RESPONSE:

(a) Bode diagram for highpass response:

Fig 10 shown bode diagram for the highpass response of 3^{rd}-pole current-mode active-R filter. The data obtained from the analysis bode diagram for the highpass response curve is as shown in table 6.The phase cross over frequency $f_{PCO}$is at 14.1 KHz when the phase is at -180°, then gain is -9.65 dB at 14.1 KHz, so that the gain is less than zero dB, then the feedback system of 3^{rd}-pole current-mode active-R filter is stable. The gain cross over frequency $f_{GCO}$is at Infinity KHz, when the gain is at 0 dB, then phase is Infinity at Infinity KHz. The gain margin is 9.65 dB at 14.1 KHz, while the phase margin is Infinity at Infinity KHz, then the gain (G_m) and phase (p_m) margins are both positive. Thus the highpass response of 3^{rd}-pole current-mode active-R filter is asymptotically stable. The phase (degrees) response of 3^{rd}-pole current-mode active-R filteris shown in Fig 10. It varies from 270° at low frequencies to 0° at high frequencies.

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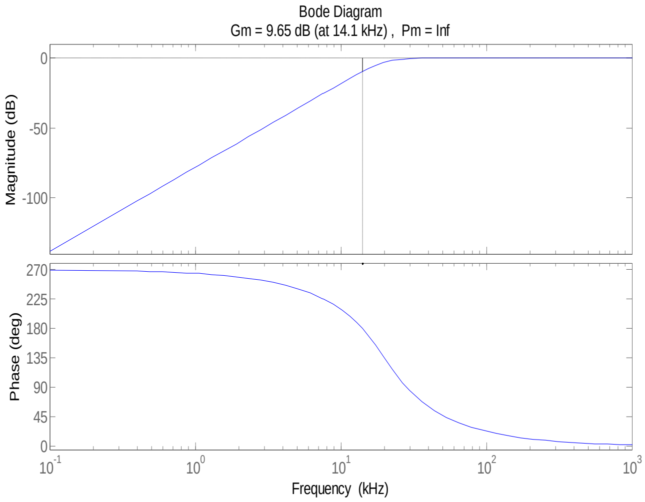

Fig 10: Bode diagram for highpass response for values of f_0 =20 KHz &Q = 1.

Table 6: Graph analysis of Fig 10.

For Gain Margin						**For Phase Margin**					
Phase		**Gain**		**Gain Margin**		**Gain**		**Phase**		**Phase Margin**	
Ø (deg)	**f_{PCO} (KHz)**	**dB**	**f_{PCO} (KHz)**	**G_M (dB)**	**f_{PCO} (KHz)**	**dB**	**f_{GCO} (KHz)**	**Ø (deg)**	**f_{GCO} (KHz)**	**P_M (deg)**	**f_{GCO} (KHz)**
-180	**14.1**	**-9.65**	**14.1**	**9.65**	**14.1**	**0**	**Infinity**	**Infinity**	**Infinity**	**Infinity**	**Infinity**
f_{GCO}:- Gain Cross Over Frequency **G_M:- Gain Margin**						**f_{PCO}:- Phase Cross Over Frequency** **P_M:- Phase Margin**					

(b) Pole/Zero Map for highpass response:

Fig 11 shown the pole/zero map for high pass response for values of f_0 =20 KHz and Q-factor = 1. The Zeros and Poles of highpass response are given as Z =0, 0 and 0, where three Zeros are at the origin, and Poles at -1.26×10^5, and -6.28×10^4±i1.09×10^5. It observed that, all poles have negative real parts, and they are lying within the left-half of the s-plane. Thus the highpass response is asymptotically stable. The locations of the Poles of 3^{rd}-pole current-mode active-R filter are shown in Fig 11.

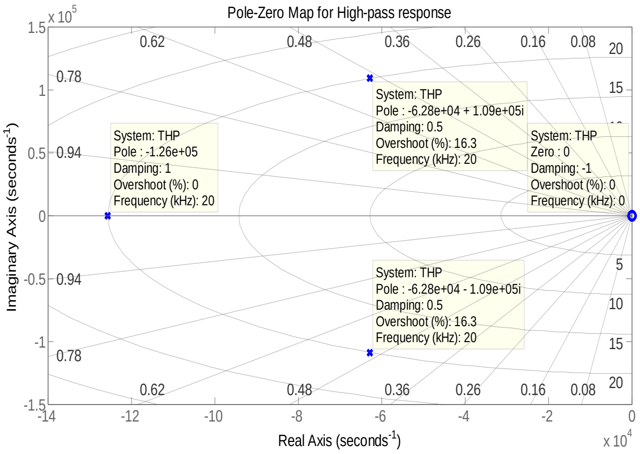

Fig 11: The pole/zero map for highpass response for values of f_0 =20 KHz & Q = 1.

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(c) Step response for highpass response:

Fig 12 shown the step response for highpass response of 3^{rd}-pole current-mode active-R filter.It is observed that, the poles are complex. Thus the system of highpass response is under-damped with an overshoot, it is 0.937 dB and that is as shown in Fig 12. The characteristics response obtained from the analysis step response of highpass response curve is as shown in table 7.

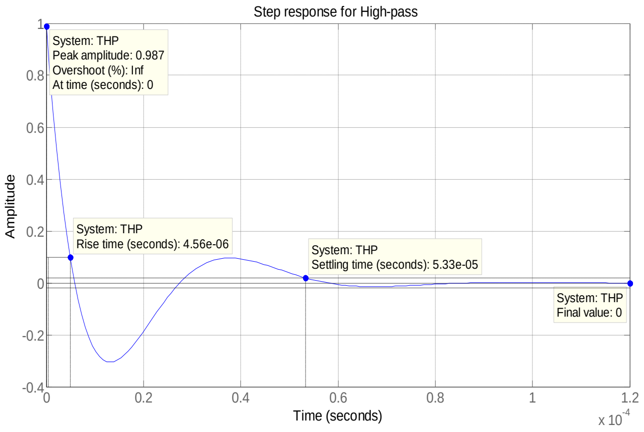

Fig 12: The step response for highpass response for values of f_0 =20 KHz & Q = 1.

Table 7: Graph analysis of Fig 12.						
Peak amplitude		Rise time (sec)	Setting time (sec)	Final value at (dB)	Overshoot	
dB	Time (sec)				dB	%
0.937	0	4.56×10^-6	5.33×10^-5	0	0.937	Infinity

(d) Nyquist diagram for highpass response:

The Nyquist diagram for highpass response of 3^{rd}-pole current-mode active-R filter is as shown in Fig 13. It observed that, the return ratio of Nyquist diagram for highpass response does not enclose the critical point (-1, 0). Thus the closed-loop for highpass response of 3^{rd}-pole current-mode active-R filter is asymptotically stable. The Gain margin is 9.55 dB at 14.1 KHz, and the phase margin is Infinity.

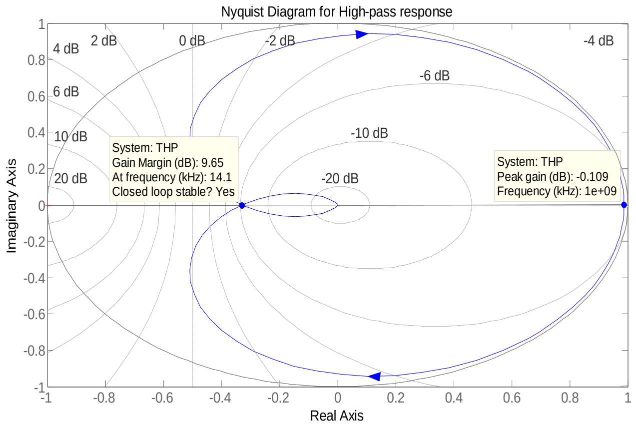

Fig 13: The Nyquist diagram for highpass response for values of f_0 =20 KHz &Q = 1.

VII. CONCLUSIONS

A realization of stability of 3^{rd}-pole current-mode active-R filter for values of f_0=20 KHz and Q-factor=1 has been proposed. The proposed circuit implements three filter functions lowpass, bandpass, and highpass concurrently in single circuit. The three filter functions lowpass, bandpass and highpass work at different nodes with gratified results. The gain (G_m) and phase (p_m) margins are both positive for all the transfer functions. It observed that, all poles of transfer functions have negative real parts, and they are lying within the left-half of the s-plane. The return ratio of Nyquist diagram does not enclose the critical point (-1, 0) for all transfer functions. The gain (G_m) and phase (p_m) margins are both positive. Thus the closed-loop for all transfer functions of 3^{rd}-pole current-mode active-R filter at different nodes are asymptotically stable. This filter is stable for 1Hz $\leq f_0 \geq$1449 KHz, for Q-factor =1. The output and input gains are identical at gain cross over frequency.

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