Design and Implementation of Tow-Thomas Second Order Bandpass Filter for Extremely Low Frequency (ELF) Applications

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Abstract: *In recent time where electronics and telecommunications play a vital and integral part in the technological advancements of the society in areas like Biomedical applications, defence communication systems, Aeronautical field, wireless communications systems, Space Systems etc. filters are utilized in all the fields mentioned above, therefore this paper proposed a second-order Tow-Thomas Biquad filter to be used in the Extremely Low Frequency (ELF) wave region and in doing so, the different parameters that define the characteristics of a filter like; frequency range, cut-off frequency, gain, bandwidth and roll-off rate were considered. Results showed that the cut-off frequency for the different quality factors Q=2.5, 5.0, 7.5 and 10 were slightly shifted to 1.51kHz but were found to be in good agreement with the EPC Glous 1 generation 2 protocol for RFID systems. However the midBand gain and bandwidths were not in agreement with theory where they decreased and increased respectively with increasing quality factor. Moreso, the filter's roll-off rate conformed to theory where it approached -40dB/decade at Q=5.0 and overshot thereafter. It was concluded that, the Tow-Thomas Second-order filter could be suitable for use in the Extremely low frequency (ELF) range if further adjustments are done to meet-up the required specification.*

Keywords: Tow-Thomas, Bandpass, Second-order, ELF Applications, Filter

INTRODUCTION

In the present time, electronics field is playing a vital role in advanced development of research areas like; Biomedical Field, Defence area, Aeronautical field, space system, etc. These above areas have major challenges urge to the system with very low cost, low power consumption, very high gain, wide spread band etc. (Raj, & Shiksha, 2020). Mostly systems mentioned above have pre-processing blocks such as low noise pre-amplifier and filters for the possession of low frequency signals are employed.

Extremely low frequency (ELF) refers to radio waves, like the amplitude modulated (AM) / Frequency Modulated (FM) signals which ranges from 300Hz to 30 kHz. ELF are useful scientifically because they largely reflect the D region of the Earth's ionosphere (60-90 kM altitude), and they are efficiently guided in the earth ionosphere wave guide to global distances. For instance, if you set-up a radio receiver just about anywhere on earth, you can pick up short bits of radiation from lightning strikes literally half way around the world. These are called radio atmospherics, or Sferics. ELF waves penetrate into seawater, which has led to their use over the past several decades for communication with submerged submarines at long distances (stanford VLF Group, 2022). Extremely low frequency waves can be applied in the area of Global Communication, lightning, geolocation, Ground-to-satellite communications, satellites protection subterranean mapping, lightning – ionosphere impacts, etc. This goes to show how important these ranges of frequencies are, in our modern society. The history of ELF research started mostly in the audio recordings, since the study of Extremely low frequency (ELF) and very low frequency (VLF) fall in the same range of 300Hz to 30kHz or (0-3kHz) in other climes, are the frequency range the human ear can recognise. Early ELF/VLF researchers would simply play the signal received by an antenna straight through a speaker. Hence we can listen to the data stream as if it were audio. That is why a bandpass filter is required both in the antenna to select and pass the required frequency range while rejecting the frequency outside the range. This filter is also needed in the receiver for the same purpose. Hence the choice of Tow-Thomas biquadratic circuit, this circuit is included in almost all textbooks in active filters (Ahmed, M.S. 2008) and is introduced in most universities to the undergraduate or graduate students. Although the Circuit was introduced since 38 years, it is still receiving interest of researchers in modifying it to fit the new CMOS technology, due to the great importance of this circuit and the progress in its realization. The introduction of low-order, low-sensitivity and stable filter circuits has provided network and system designers with the necessary building blocks. The Tow-Thomas Biquard circuit provides filters designers with a valuable building block for building higher order active filters. It is a very flexible circuit structure in which the transfer function properties are easily manipulated by modifying the passive RC elements that connect the operational amplifier. It has low sensitivity realization in which the general properties of the circuit remain stable even if the passive RC elements are modified (William, & Felma, 2001). Other advantages of the Tow-Thomas circuit performance as presented thoroughly by Thomas (1971) in his series of papers are Qp enhancement caused by finite gain-bandwidth, Noise distortion and signal level adjustment and temperature dependent only on the passive elements of the circuit. These advantages make this circuit suitable for use in this paper. An example of this circuit is that realized by Tow (1969) and Thomas (1971).

DESIGN CONSIDERATION

In this paper the second-order feed forward Tow-Thomas circuit was designed and simulated as shown in Figure 1.

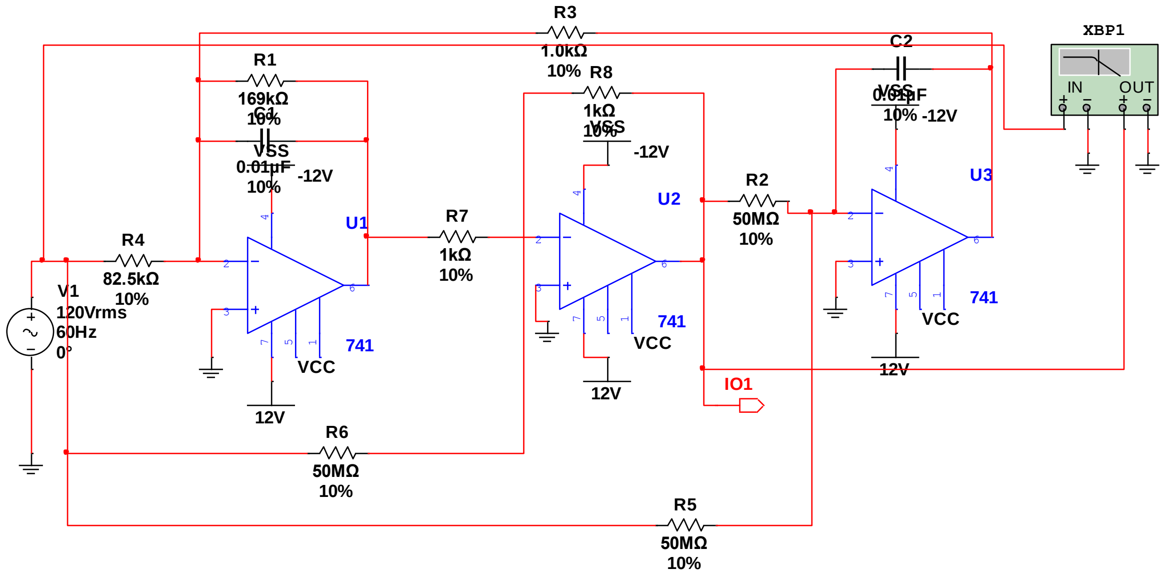

Fig 1 second-order feed forward Tow – Thomas filter circuit.

The filter specification was chosen as; centre – frequency (W_o) of 1.5kHz considering ELF of (0-3kHz) (Edward, & Johan, 2007) Variable Quality factors (Qp=2.5, 5.0, 7.5 and 10) and Bandpass gain $(HB_p = 2)$

The transfer functions of the circuit in Figure 1 is written as;

$$T_S = S\frac{\frac{R_8}{R_4R_7C_1}}{S^2 + S\frac{1}{R_1C_1} + \frac{R_8}{R_2R_3R_7C_1C_2}} -------------(1)$$

From equation 1, we can deduce the following parameters of the circuit as:

$$W_O = \sqrt{\frac{R_8}{R_2R_3R_7C_1C_2}} --------(2)$$

$$Quality\ factor\ Q = R_1\sqrt{\frac{R_8}{R_2R_3R_7C_2}} ---------------(3)$$

And $R_5 = R_6 = \infty$ ---------- (4)

If the voltage gain at the centre frequency ω_O is $H_{BP} = \frac{R_1R_8}{R_4R_7}$ ----- (5) then the equations 2, 3, and 5 can be scaled down to $\omega_O = \frac{1}{\propto RC}$ ----- (6)

$$Q = \frac{R_1}{\propto R} ------- (7)\ and\ HB_P = \frac{R_1}{R_4} ----- (8)$$

Where $\propto$ is a positive constant, R is the resistance of the filter circuit and C is the capacitance of the filter circuit. $R_{1,}R_2, \dots \dots \dots .., R_6$ Are resistors, C_1 & $C_2$are capacitors.

MATERIALS AND METHODS

The materials required for the design and simulation of the second-order feed forward Tow-Thomas filter circuit are: eight (8) resistors, two (2) capacitors, three (3) operational amplifiers (op. amps) of (µA741) type, One (1) AC power source, one (1) output connector, 4 earthlings and NI Multisim version 14.2 software.

The circuit diagram in Figure 1 was arranged on the Multisim work bench. The resistance and capacitance values R and C were chosen such that $R_3 = R_7 = R_8 = R = 1K\Omega$ and $C_1 = C_2 = C = 0.01\mu F$. Next the positive constant $\propto$ was determined using the equation $\propto = \frac{1}{\omega oRC} - - - -(9)$ and a value of 66.67 was found.

The value of R_1 was then determined using the equation 7. Where $R_1 = Q \propto R$ which gave $R_1 = 166.67K\Omega$.

Again the resistor R_2 was determined using the equation. $R_2 = \propto^2 R$ Giving a value of $R_2 = 4.4M\Omega$. finally, the value of R_4 was determined using equation 8. Where $R_4 = \frac{R_1}{HB_p} = 83.33k\Omega$ where $HB_p = 2$.

The process was then repeated for different quality factor (Q) values of 5.0, 7.5 and 10 respectively and the resistor values tabulated and presented in Table 1.

Table 1: Calculated and preferred Resistor values.

S/N	Quality factor Q	$R_1(k\Omega)$	Resistor values calculated							Preferred resistor values		
			R_2(kΩ)	R_3(MΩ)	R_4(kΩ)	R_5(kΩ)	R_6(MΩ)	R_7(MΩ)	R_8(kΩ)	R1((kΩ)	R2(MΩ)	R4(KΩ)
1	2.50	166.67	4.40	1.00	83.33	50.00	50.00	1.00	1.00	169.00	50.00	82.50
2	5.00	333.35	4.40	1.00	166.68	50.00	50.00	1.00	1.00	340.00	50.00	169.00
3	7.50	500.00	4.40	1.00	250.00	50.00	50.00	1.00	1.00	500.00	50.00	250.00
4	10.00	666.70	4.40	1.00	333.35	50.00	50.00	1.00	1.00	680.00	50.00	340.00

RESULTS AND DISCUSSION

The resistor values presented in table 1 was simulated for a centre frequency $\omega o = 1.5kHz$ and different values of quality factor $Q = 2.5, 5.0, 7.5, and$ 10 and results of plots generated are shown in Figure 2.

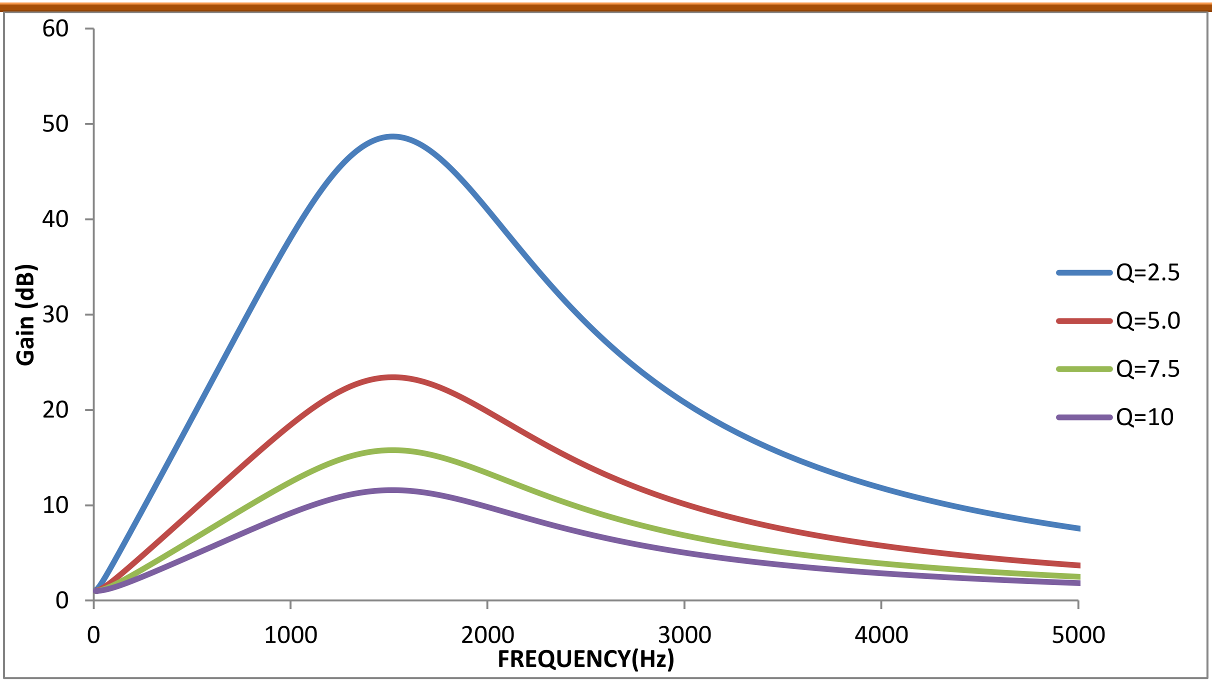

Figure 2. Response Curves at variable Quality Factor Values

From the result simulated, as the quality factor (Q) increase in value from 2.5 to 10, the mid band gain of the filter decreases in value from 48.69db to 11.59db Which does not support filter theory that states, ‘the quality factor increases with increasing midband gain’ indicating the selectivity of the filter (Amah, et al. 2014; Igwue, et al. 2014; Franco, 1988).The result is presented in Table 2.

Table 2: Results of Filter Parameters for $\omega o = 1.5kHz$

S/N	Freq. (KHz)	Quality factor Q	Mid-Band Gain (dB)	-3dB Gain	Higher cut-off Freq. (F4) KHz	Lower cut-off Freq. (FL) Hz	Bandwidth Bw (Hz)	ROLL OFF RATE (dB/decade)
1	1.51	2.50	48.69	45.69	1.82	1.26k	560.00	-34.33
2	1.51	5.00	23.44	20.44	1.95	1.12k	830.00	-40.56
3	1.51	7.50	15.78	12.78	2.09	1.02k	1.07k	-43.96
4	1.51	10.00	11.59	8.59	2.19	933.25	1.26k	-46.63

The circuit performance was studied with different values of Q (Q=2.5, 5.0, 7.5, and 10) Table 1 shows resistance values of resistance for different quality factors which was studied for a constant centre frequency (W_o) of 1.50kHz. The observed frequency response shows good agreement with theoretical results. The band pass response for different values of Q is shown in Figure 2. Where the mid band gain decreases as quality factor increases. Again Table 2 shows that the centre frequency at all the values of the quality factor Q is slightly shifted to a value of 1.51 kHz which represents $\pm 0.67\%$ shift. According to the EPC class 1 generation 2 protocols, a shift of $\pm 22\%$ for frequencies are acceptable. Also from the result, the bandwidth is observed to be increasing from a value of 560Hz at Q=2.5 to a value of 1.26 kHz at Q=10. This does not support the theoretical fact that bandwidth of a filter decreases as the quality factor Q increases. Furthermore, the roll off rate of the filter is observed to approach -40.56 dB/decade at Q=5.0 while an over shoot is observed at Q=7.5 and Q=10. This result shows that the filter is a second order double-pole filter with a little overshoot at quality factor of Q=7.5 and 10.

CONCLUSION

The result shows good agreement of the Tow-Thomas second-order filter with theory in terms of the centre frequency (ωo) which is slightly shifted to $\pm 0.67\%$ and is well within the frequency range of extremely low frequency of 300Hz to 30kHz. In terms of midBand gain, the filter has a high midBand gain of 48.69dB that decreases as the quality factor increases; this does not agree with filter theory and may be due to parasitic effect.

Furthermore the bandwidth is also not in agreement with filter theory but the filter gives a roll off rate that approaches a second order double pole filter at Q=5.0 and overshoots at Q=7.5 and 10. The result confirms the stability of the second-order Tow-Thomas filter to be used in the extremely low frequency range of radio receivers, even though some adjustments could be done in order to realize the required midband gain and bandwidth of the filter.

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