ISSN 2278-3091
Volume 9, No.1.5, 2020
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse1091.52020.pdf
https://doi.org/10.30534/ijatcse/2020/1091.52020

Sizing of 4th order Active Band-Pass Filter based on Multiple Feed-Back Topology by using the Genetic Algorithm

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ABSTRACT

In this paper, we deal with the design of an active fourth order Butterworth bandpass filter for Radio Frequency IDentification (RFID) system reader to reject all signals outside the band (10-20) kHz and to amplify the low antenna signal with a center frequency of 15 kHz. The Multiple Feed-Back (MFB) topology is used to implement this filter. The values of the passive components, forming the studied filter, are selected from manufactured series, this selection is one of the most crucial design steps in analog active filter design problems. Thus, intelligent search methods must be performed for a fast and optimum selection. In this study, we focus on the use of the Genetic Algorithm (GA) for the optimal design of the 4th order Band Pass Filter, accompanied with a sensitivity analysis to determine the most influential components in the considered filter. SPICE simulations supported by Monte Carlo analysis are used to validate the obtained results/performance.

Key words: Genetic Algorithm, Metaheuristic, Multiple Feed-Back Topology, Optimization, Sensitivity Analysis, 4th order Band-Pass Filter.

1. INTRODUCTION

Analog filters are used in a wide variety of applications. In the field of wireless communication system such as RFID system, active band-pass filter is used to identify tagged objects, people or animals by rejecting all signals outside the (10-20) kHz and amplifying the low antenna signal.

Active 4th order band-pass filter is made up of many discrete components (Resistors and Capacitors), in the conventional design process, the values of those components are calculated by fixing the values of some components and finding the others in order to satisfy the design specifications [1], [2], but the use of this method limits the freedom of the design. However, in reality, components such as capacitors and resistors are collected from some standard values defined by the Electronic Industries Association (EIA). The “E” series specifies the preferred component values for various tolerances. Some industrial series are E12, E24, E48, E96 and E192 for which the components obtain 12, 24, 48, 96 and 192 values within each decade. In order to select the discrete components from those industrial series, the use of an exhaustive search on all possible combinations of preferred values to obtain an optimized design is infeasible. Thus, intelligent methods are required.

In the literature, the analog designers are used some Meta-heuristics to select the optimum components of analog active filters. In the studies [3]–[7], the Ant Colony Optimization (ACO), the Immune Algorithm (IA) and Parallel Tabu Search algorithm (PTS) are used to find the optimum component values of the state variable filter topology. In [8], [9], the Clonal Selection Algorithm (CSA) and Particle Swarm Optimization (PSO) are used to find the component values of the fourth-order Butterworth analog low-pass topology.

The genetic algorithm has already been successfully applied by the authors for the optimization of the design of an analog circuit namely a three-stage amplifier [10], [11]. In this study, the GA method is utilized to design a fourth order active band-pass filter, and the selection of the discrete components (capacitors and resistors) must be among industrial series to reach the defined specifications, this approach significantly reduces the design error when compared to the conventional method as the study [12] shows. In order to check the obtained results SPICE software was used for performing simulations.

The rest of this paper is organized as follows. Section 2, briefly discusses about the Genetic Algorithms (GA). Section 3 describes the application of this algorithm for the optimal design of the analog active band-pass filter. Section 4 puts the spot on the use of Richardson extrapolation technique in the sensitivity analysis. Section 5 covers the experimental results and discussions. Finally, Conclusion is given in section 6.

2. GENETIC ALGORITHM

Genetic algorithm (GA) is a stochastic numerical search method, inspired by evolutionary processes, which was first conceived by Holland [13]. A comprehensive discussion about GA can be found in [12]–[16].

In GA terminology, a solution vector x∈X is called an individual or a chromosome, a collection of chromosomes called population, and a collection of genes made a chromosome. Each gene represents the variables of the chromosome [17].

The initial population is usually randomly generated. After that, parents are selected based on their fitness values for the reproduction, in this step, two chromosomes (parents), combine together and form new chromosomes, called offspring. A new population is generated after reproduction, has more qualified genes and a higher fitness. In the next step, we find two operators, crossover and mutation operators, by using crossover iteratively we lead the population to converge to a general good solution by making the chromosomes in the population alike. The mutation operator causes random changes in characteristics of chromosomes in order to ensure diversity in the population and assists the search to escape from local optima [17].

The flowchart in Figure 1 provides an overview of a GA procedure.

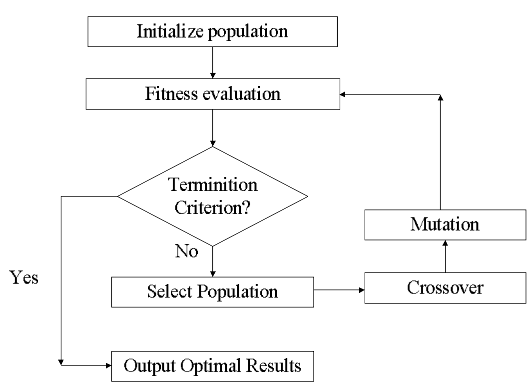

Figure 1: Flowchart of a GA

The genetic algorithm has been the subject of several studies and its fields of application are the widest and the most varied. These include for example: Robotics [18], Mathematics [19], Electric distribution systems [20], Traffic Light Signal Parameters Optimization [21], etc. In the next section, we present an application of the GA to the optimal design of the 4th order band-pass filter.

3. APPLICATION: OPTIMAL DESIGN OF THE 4TH ORDER BAND-PASS FILTER

We propose in this section, an application example as a direct application of the proposed approach.
The architecture that has been used to implement the 4th order band-pass filter is the Multiple Feedback (MFB) topology, this topology allows adjusting the quality factor (Q), the gain at the mid frequency (A_m), and the mid frequency (f_m) independently. The schematic of the MFB circuit is given in figure 2.

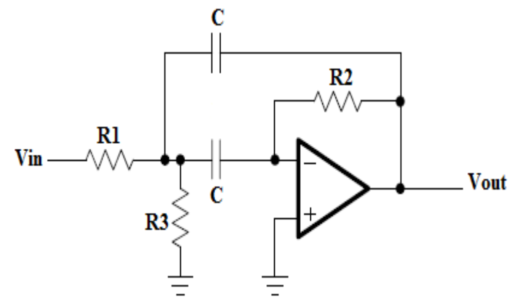

Figure 2: MFB Band-Pass

The general transfer function for a second-order band-pass filter is:

$$A(s)=\frac{\frac{A_m}{Q}s}{1+\frac{1}{Q}s+s^2} \tag{1}$$

The MFB band-pass circuit in figure 2 has the following transfer function:

$$A(s)=\frac{\frac{R_2R_3}{R_1+R_3}C\omega_m s}{1+\left[\left\{\frac{2R_1R_3}{R_1+R_3}C\omega_m\right\}s\right]+\left[\left\{\frac{R_1R_2R_3}{R_1+R_3}C^2\omega_m^2\right\}s^2\right]} \tag{2}$$

The coefficient comparison of equation (2) with equation (1) yields the following equations:

The mid-frequency of the filter (f_m) is:

$$f_m=\frac{1}{2\pi C}\sqrt{\frac{R_1+R_3}{R_1R_2R_3}} \tag{3}$$

The quality factor (Q) of the filter is:

$$Q=\pi f_m R_2 C \tag{4}$$

A fourth order Butterworth band-pass can be designed by cascading two second order blocks as the figure below shows, the general transfer function of this filter is expressed in (5) [22]:

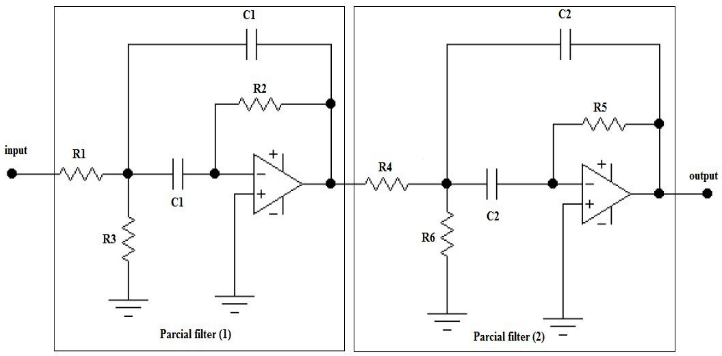

Figure 3: Schematic diagram of 4th order Butterworth active Band-pass filter circuit using MFB topology

$$A(s)=\frac{\left(\frac{A_{mi}}{Q_i}\alpha s\right)}{1+\frac{\alpha s}{Q_i}+(\alpha s)^2}\times\frac{\left(\frac{A_{mi}}{Q_i}\frac{s}{\alpha}\right)}{1+\frac{1}{Q_i}\times\left(\frac{s}{\alpha}\right)+\left(\frac{s}{\alpha}\right)^2} \tag{5}$$

This equation represents the connection of two second-order band-pass filters in series, Where:

- A_{mi} is the gain at the mid frequency, (f_{mi}), of each partial filter.
- Q_i is the pole quality of each partial filter.
- (α) and ($1/\alpha$) are the factors by which the mid frequencies of the individual filters,(f_{m1}) and (f_{m2}), derive from the mid frequency (f_m) of the overall band pass filter. Factor (α) is determined by using equation (6), [17].

$$\alpha^2+\left[\frac{\alpha\Delta\Omega a_1}{b_1\left(1+\alpha^2\right)}\right]+\left(\frac{1}{\alpha^2}\right)-\left[\frac{(\Delta\Omega)^2}{b_1}\right]=0 \tag{6}$$

Where, the normalized bandwidth $\Delta\Omega=(1/Q_{BP})$, (Q_{BP}) is the overall quality factor of the filter with (a_1) and (b_1) being the second-order low-pass coefficients of the desired filter type.

The mid frequency (f_{m1}) of partial filter (1) is [22]:

$$f_{m1}=\frac{f_m}{\alpha} \tag{7}$$

The mid frequency (f_{m2}) of partial filter (2) is [22]:

$$f_{m2}=f_m\ .\ \alpha \tag{8}$$

With (f_m) is the mid frequency of the overall fourth-order band-pass filter.

The individual pole quality (Q_i) is the same for both filters and by using (10), we calculated the quality factor of the overall filter [22]:

$$Q_i=Q_{BP}\left(\frac{\left(1+\alpha^2\right)b_1}{\alpha\ .a_1}\right) \tag{9}$$

$$Q_{BP}=\frac{f_m}{BW}=\frac{f_m}{f_H-f_L} \tag{10}$$

The design specifications of the active band-pass filter are:

- Mid-frequence of the overall filter, f_m =15 KHz (ω_m= 94.2 K rad/s). Q_i is the pole quality of each partial filter.
- Bandwidth of 10 KHz.
- Pass band frequencies: f_L = 10KHz ; f_H =20 kHz.

For Butterworth filter type, we have a_1=1.4142 and b_1=1, and by using equation (6), α is calculated and it's equal to 1.2711.

After the determination of α, all quantities of the partial filters can be computed as follows:

f_{m1} =11.8 KHz (ω_{m1}=74.14 K rad/s) by using equation (7).

f_{m2} = 19.067 KHz (ω_{m2}=119.80 K rad/s) by using equation (8).

The individual pole quality, Q_i, is the same for both filters, by using (9) we found Q_i equal to 2.1827.

In order to generate ω_{m1}, ω_{m2} and Q_i approaching the specified values; the values of the resistors and capacitors should be carefully selected. For this, we define the Total Error (TE) which is the summation of mid frequency deviation ($\Delta\omega_m$) and quality factor deviation (ΔQ), by:

$$TE=\alpha\Delta\omega_m+\beta\Delta Q \tag{11}$$

Where:

$$\Delta\omega_m=\frac{|\omega_1-\omega_{m1}|}{\omega_{m1}}+\frac{|\omega_2-\omega_{m2}|}{\omega_{m2}} \tag{12}$$

$$\Delta Q=\frac{|Q_1-Q_i|+|Q_2-Q_i|}{Q_i} \tag{13}$$

In terms of the components of the filter the mid frequency deviation parameter and the quality factor deviation can be written as:

$$\Delta\omega_m = \frac{\left|\frac{1}{C_1}\sqrt{\frac{R_1+R_3}{R_1R_2R_3}}-\omega_{m1}\right|}{\omega_{m1}} + \frac{\left|\frac{1}{C_2}\sqrt{\frac{R_4+R_6}{R_4R_5R_6}}-\omega_{m2}\right|}{\omega_{m2}} \quad (14)$$

$$\Delta Q = \frac{\left|\omega_1\frac{R_2C_1}{2}-Q_i\right|+\left|\omega_2\frac{R_5C_2}{2}-Q_i\right|}{Q_i} \quad (15)$$

The objective function considered is the Total Error which is calculated for the different values of α and β and the decision variables are the resistors and capacitors forming the circuit. Each component must have a value of the standard series (E192) and the varying ranges of these components are respectively, 100Ω–1MΩ for the resistors, and 1pF–1μF for the capacitors.

In order to identify the most influential components that can affect our filter's behavior, a sensitivity analysis is performed. This analysis is detailed in the next section.

4. SENSITIVITY ANALYSIS BY APPLYING RICHARDSON EXTRAPOLATION

In electric circuits, the sensitivity means the ability of that circuit to react with changes in certain parameters [23].
Equation 16 is the mathematical definition of circuit sensitivity:

$$S_{x_j}^{f_i} = \frac{\delta f_i}{\delta x_j}\frac{x_j}{f_i} \quad (16)$$

Where $f_i(x)$ is a performance response and $x=\left[x_1,...,x_n\right]^T$ are the design variables.

In order to evaluate the performances of an analog circuit, designers use an electrical simulator to evaluate these performances like: objective functions, problem constraints, etc. but by using this simulator, it is rarely possible to derive an explicit equation for each performance or objective function. Therefore, in order to compute the partial derivative required by (16), the Richardson extrapolation described by (17), is used herein:

$$\frac{\delta f_i}{\delta x_j} \cong \frac{f_i(x_1,...,x_j+h,...,x_n)-f_i(x_1,...,x_j-h,...,x_n)}{2h} \quad (17)$$

Where h is a step parameter that is updated in each iteration. For this case $h_u=2^{-u}h_{u-1}$, u is the current iteration and h_0 is assigned to an initial value [24]. Our proposed sensitivity analysis approach is based on the Richardson extrapolation, where its pseudo code is as follows [24]:

$h=h_0$
for u=0; u < MaxLoops; u++ **do**
  for v=0; v < MaxLoops; v++ **do**
    if v==0 **then**
    f^+ = Function evaluation with the parameter x_j+h
    f^- = Function evaluation with the parameter x_j-h
    $f'_{u,v} = (f^+ - f^-)/(2h)$
    else
      $f'_{u,v} = f'_{u,v-1} - (f'_{u,v-1} - f'_{u-1,v-1})/(4^v - 1)$
      if $\left|f'_{u,v} - f'_{u,v-1}\right| < \delta$ **then**
      break
      $d \leftarrow d/2;$
return $f'_{u,v}$

Algorithm.1. Pseudo code of Richardson extrapolation

5. RESULT AND DISCUSSION

In this section we applied GA to perform optimization of the 4th order Band-Pass filter. The optimization technique works on MATLAB codes with the following parameters given in table 1.

Table 1: GA Parameters

Population size	900
Generation	1000
Crossover	Two Point Crossover
Mutation rate	0.0001
Selection probability	50%

The optimal values of resistors and capacitors forming the active 4th order band-pass Butterworth filter are selected from the E192 series, the use of those series lie to the fact of having a tolerance less than 1% and as a consequence a good accuracy of results is obtained. The optimal values of components and the performance associated with these values for the different values of α and β are shown in table 2 for linear values and in table 3 for E192 series.
From tables 2 and 3 it is observed that the smallest design error is obtained for α = 0.6 β=0.4 for linear values, and α = 0.5 β=0.5 for E192 series.

4.2 Sensitivity analysis:

After performing the Richardson analysis technique, we notice that the quality factor Q_i is very sensitive to all the resistors except R6, as it is depicted in table 5.

Table 2: Optimal values of R and C and related performances for the different values of α and β

α	β	R1 (KΩ)	R2 (KΩ)	R3 (KΩ)	R4 (KΩ)	R5 (KΩ)	R6 (KΩ)	C1 (nF)	C2 (nF)	Δ ωm	ΔQ	TE
1	0	16.23	9.09	2.52	28.29	0.44	4.52	3.02	6.37	0.00364	1.4554	0.00364
0.9	0.1	1.88	24.29	4.11	0.95	17.84	12.81	2.41	2.09	0.00565	0.03479	0.00856
0.8	0.2	1.31	15.43	2.16	22.53	13.15	0.71	3.79	2.77	0.00489	0.00479	0.00487
0.7	0.3	1.21	21.28	13.91	3.50	16.10	1.11	2.76	2.26	0.0068	0.0028	0.0056
0.6	0.4	14.43	25.57	1.48	7.91	13.69	0.79	2.30	2.66	0.00168	0.00028	**0.00111**
0.5	0.5	1.00	16.74	7.15	8.38	9.21	0.51	3.52	3.96	0.00190	0.00330	0.00258
0.4	0.6	2.28	18.57	1.7	0.65	11.31	6.44	3.17	3.22	0.00368	0.00291	0.00322
0.3	0.7	1.54	22.96	5.53	0.78	13.59	8.71	2.56	2.68	0.00329	0.00204	0.00241
0.2	0.8	0.77	14.12	17.79	0.64	11.85	22.28	4.17	3.07	0.00332	0.00220	0.00242
0.1	0.9	2.18	13.93	1.1	2.35	11.24	0.79	4.22	3.24	0.00216	0.00129	0.00137
0	1	1.42	20.34	4.33	8.75	16.85	0.98	4.74	6.53	1.0581	0.00257	0.00257

Table 3: Values of components following E192 series and related performances for the different values of α and β

α	β	R1 (KΩ)	R2 (KΩ)	R3 (KΩ)	R4 (KΩ)	R5 (KΩ)	R6 (KΩ)	C1 (nF)	C2 (nF)	$\Delta\omega_m$	ΔQ	TE
1	0	16.20	9.09	2.52	28.4	0.442	4.53	3.01	6.34	0.00830	1.4553	0.0083
0.9	0.1	1.89	24.30	4.12	0.953	17.80	12.90	2.40	2.08	0.0113	0.0339	0.0135
0.8	0.2	1.32	15.40	2.15	22.60	13.20	0.706	3.79	2.77	0.0052	0.0118	0.0065
0.7	0.3	1.21	21.30	14.00	3.48	16.20	1.11	2.77	2.26	5.77e-4	0.0068	0.0025
0.6	0.4	14.50	25.50	1.47	7.87	13.70	0.787	2.29	2.67	0.0110	0.0037	0.0081
0.5	0.5	1.00	16.70	7.15	8.35	9.19	0.511	3.52	3.97	0.0016	0.0013	**0.0014**
0.4	0.6	2.29	18.70	1.69	0.649	11.30	6.42	3.16	3.20	0.0117	0.0076	0.0092
0.3	0.7	1.54	22.90	5.56	0.777	13.50	8.66	2.55	2.67	0.0141	0.0050	0.0078
0.2	0.8	0.768	14.20	17.80	0.642	11.80	22.3	4.17	3.05	0.0089	0.0099	0.0097
0.1	0.9	2.18	14.00	1.1	2.34	11.30	0.787	4.22	3.24	0.0023	0.0058	0.0055
0	1	1.42	20.30	4.32	8.76	16.90	0.976	4.75	6.49	1.0565	0.0065	0.0065

Table 4: Sensitivity analysis results for ω_i

$S^{\omega_1}_{R_1}$	$S^{\omega_1}_{R_2}$	$S^{\omega_1}_{R_3}$	$S^{\omega_1}_{C_1}$
-0.44	-0.50	-0.06	$1.05e^{-15}$
$S^{\omega_2}_{R_4}$	$S^{\omega_2}_{R_5}$	$S^{\omega_2}_{R_6}$	$S^{\omega_2}_{C_2}$
-0.029	-0.50	-0.005	$1.34e^{-15}$

Table 5: Sensitivity analysis results for Q_i

$S^{Q_1}_{R_1}$	$S^{Q_1}_{R_2}$	$S^{Q_1}_{R_3}$	$S^{Q_1}_{C_1}$
458	5000	-613	0
$S^{Q_2}_{R_4}$	$S^{Q_2}_{R_5}$	$S^{Q_2}_{R_6}$	$S^{Q_2}_{C_2}$
-2880	499	-0.47	0

In order to minimize this sensitivity, the GA routine is once again executed, but this time we restrict the varying ranges of the sensitive components, 1Ω–100 Ω for the resistors R1, R3, R4 and R6, 100 Ω –1K Ω for the resistors R2 and R5. 50 runs of the GA were performed; the new smallest Total Error obtained is equal to 0.0010, Figure 4 shows the corresponding boxplot diagram. The new optimal component values and the new related Q sensitivities are given respectively in table 4 and 5.

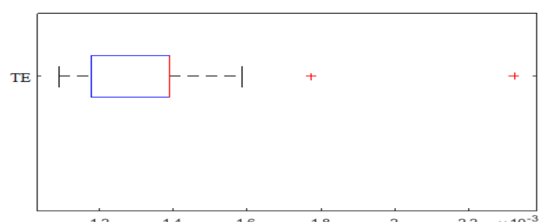

Figure 4: The 50-run boxplot for TE

Table 4: The new optimal components values

R_1 (Ω)	R_2 (Ω)	R_3 (Ω)	R_4 (Ω)	R_5 (Ω)	R_6 (Ω)	C_1 (nF)	C_2 (nF)
78.7	835	98.8	64.2	649	72.3	70.6	56.2

Table 5: Sensitivity analysis results for the new Q_i

$S^{Q_1}_{R_1}$	$S^{Q_1}_{R_2}$	$S^{Q_1}_{R_3}$	$S^{Q_2}_{R_4}$	$S^{Q_2}_{R_5}$	$S^{Q_2}_{R_6}$
-0.28	0.5	-0.22	-0.26	0.49	-0.23

In order to check and highlight the effectiveness of the results, SPICE simulation and Monte Carlo analyses were performed. figure 5 shows the SPICE simulation of the filter gain for the new optimal values, the practical mid frequency is equal to 15.47 KHz and the pass band frequencies: f_L = 11.18 KHz and f_H =21.9 KHz. We notice a slight difference between the specifications and the simulation results, this difference is mainly due to the imperfections of the op-amp which are considered perfect in the theoretical calculations.

Figure 6 shows Monte Carlo analysis with 100 runs, where we used 5% capacitors and 1% resistors. The obtained simulation results are as follow: ω_m value belongs to the interval [90.32krd/sec; 99.84krd/sec], and Q_{BP} value belongs to the interval [1.45; 1.73], therefore, we notice a low sensitivity of this filter design to component variances.

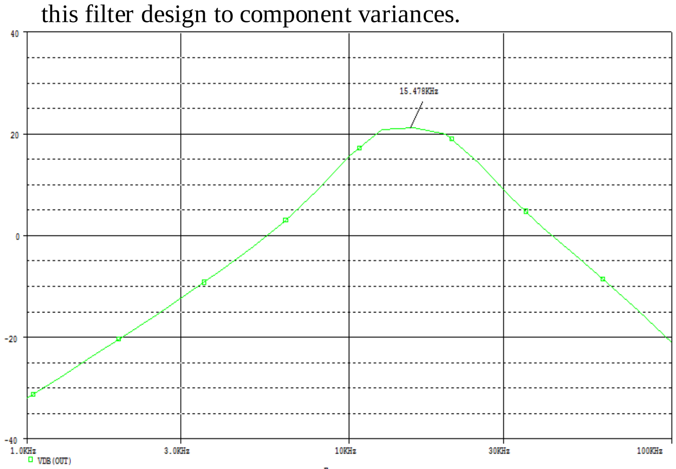

Figure 5: Frequency responses of 4th order band-pass Butterworth filter by using GA

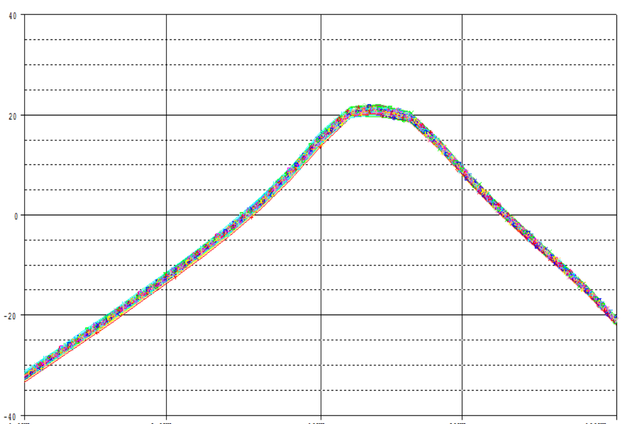

Figure 6: Monte Carlo Simulation Result

6. CONCLUSION

In this paper, we have presented an application of the Genetic Algorithm for the optimal design of 4th order band-pass Butterworth filter, in order to make it suitable for RFID application. We selected the optimal values of discrete components from E192 series known as a high precision manufacturing series. The GA method proves itself as an efficient tool for the optimal design of the analog filter. The results were checked via SPICE simulations and Monte Carlo analyses.

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