Ways to Optimize Analogue Switched Circuits

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Abstract. *This paper describes how analogue switched circuits (switched-capacitor and switched-current circuits) can be optimized by means of a personal computer. The optimization of this kind of circuits is not so common and their analysis is more difficult in comparison with continuously working circuits. Firstly, the nonidealities occurring in these circuits whose effect on their characteristics should be optimized are discussed. Then a few ways to analyze analogue switched circuits are shown. From all optimization algorithms applicable for this kind of optimization, two ones that seem to be the most promising are proposed. The differential evolution (one of evolutionary algorithms) combined with the simplex method was found to be most appropriate from these two ones. Two types of programs are required for the optimization of these circuits: a program for implementing calculations of the used optimization algorithm and a program for the analysis of the optimized circuit. Several suitable computer programs from both of the groups together with their proper settings according to authors' experience are proposed. At the end of the paper, an example of a switched-current circuit optimization documenting the previous description is presented.*

Keywords

Optimization, switched-capacitor circuit, switched-current circuit, evolutionary algorithm.

1. Introduction

The goal of optimization is to achieve a required status having the most advantageous parameters, which are set in advance [1], [2]. In case of electrical circuits, optimization is usually carried out to eliminate or at least to suppress the effect of nonideal features of the components in the circuits on their characteristics (e.g., their frequency response).

Optimization can be accomplished either by an analytical method or by a numerical method. Nowadays numerical methods are applied rather than analytical ones because they have an advantage of the possibility of meeting more requirements – the ability to solve multi-objective (multi-criteria) tasks. In case of analytical methods, this would be either unfeasible or very complicated. Numerical methods are more time consuming but it is not such a big disadvantage because the performance of computer technology has increased during several recent years enough to enable their common use.

There are several numerical methods usable for optimization, e.g., gradient methods, evolutionary algorithms (EAs). The methods in the second group are particularly very powerful and robust. To acquire an additional improvement of these methods, they can be combined with another method.

In electronics, optimization by means of numerical methods has been applied as well. Then more aspects can be taken into account while the optimization, e.g., the parameters of used components: the tolerance and spread of their values, their nonideal features, circuit characteristic sensitivities to their values, and so on. The optimization of continuously working circuits has been utilized for a long time and is relatively well explored (from many publications, see, e.g., [3]) unlike discrete working circuits, whose optimization has not been widespread so far [4], [5].

Analogue switched circuits (ASCs) represent a group of discrete working circuits. Two basic techniques belong in this group: switched-capacitor (SC) circuits [6] and switched-current (SI) [7] circuits. They are applied commonly for the implementation of functional blocks nowadays. However, their analysis is more complicated than in case of classical (continuously working) circuits due to the discrete character of their operation. Consequently, the optimization of this kind of circuits is more difficult compared to continuously working ones (since their analysis is a necessary part of optimization).

In this paper, the nonideal features of ASCs are mentioned at first. Then the description of the way to analyze these circuits and the way to optimize them by applying numerical methods follows. Several programs for doing both an optimization algorithm and the analysis of these circuits are presented. Two methods that were supposed to be applicable for this optimization are described here. These are the differential evolution (one of EAs) combined with another algorithm and the branch-and-bound algorithm. The paper is ended by an example of the optimization of an SI circuit implementing a band-pass filter. This example shows the practical applicability of the theory in this article.

2. Nonidealities in Analogue Switched Circuits

In this section, nonideal features occurring in ASCs are listed. These features affect the characteristics of these circuits, e.g., their frequency response. It is necessary to know these nonidealities because the optimization is performed with respect to them, i.e., to eliminate or at least to suppress their effects.

- Switched-capacitor circuits

The main nonideal features in these circuits relate to the switches: nonzero on-state resistance, nonzero off-state conductance, and parasitic capacitances.

In SC circuits, operational amplifiers can be used too. Their nonidealities are well known, e.g., finite input resistance, nonzero output resistance, finite unity-gain bandwidth, and so on.

- Switched-current circuits

In SI circuits, the nonidealities concerning the switches are the same as in case of SC circuits (see the previous subsection). In addition to them, the current sources and the transistors (working as controlled current sources) have other nonidealities, the main ones are the following: finite output resistance, parasitic capacitances, and charge injection.

3. Ways of Analogue Switched Circuit Analysis

During carrying out the optimization of an ASC, its analysis has to be made so that the satisfying of the requirements on optimization results can be found out.

ASCs are analyzable with more difficulty than continuously working circuits. This is caused by the discrete character and multiphase mode of their operation. Hence, methods of the analysis different from the ones for continuously working circuits have to be applied.

Of course, for the purposes of optimization, only the analyzing methods that are capable to analyze ASCs including nonidealities are utilizable. Therefore, the methods able to analyze idealized ASCs only cannot be applied.

There are a few methods for the analysis of nonideal ASCs. Three of them, which are utilizable for obtaining the frequency response, are briefly described below. The first two ones are applicable for numerical analyzing (e.g., in Spice-compatible programs); the third one is applicable for symbolical analyzing, which can provide a symbolical or semisymbolical transfer function.

Other methods are explained in, e.g., [8] and [9].

- Analogue switched circuit excited by a set of harmonic signals

The frequency response of the analyzed ASC is acquired by the discrete Fourier transformation (DFT) of the output signal of the ASC after performing its transient analysis. This harmonic exciting is described in detail in [10].

- Analogue switched circuit excited by a rectangular pulse

The analyzed ASC is excited by one rectangular pulse, which takes half a clock signal period of the ASC (in case of a two-phase ASC with the same duration of both of the half-phases). The frequency response of the ASC is calculated as the ratio of the DFT of the output and input signal. Other details about this method can be found in [11].

- Symbolical analysis of analogue switched circuits

In this method, a technique that is able to provide a result in a symbolical form is applied. For instance, this technique can be the mixed s-z description [12] for ASCs. A practical example of the application of this technique is the PraSCAn package [13] (see subsection 6.2). Other techniques are described in, e.g., [14].

4. Suitable Optimization Methods

Optimization methods usually operate with an objective function, whose value expresses the quality of the obtained solution of the optimized task. The aim of the optimization method is to find the best solution of the task, which corresponds to the global extreme of the objective function. Therefore, the optimization tries to get either the maximum or the minimum value of the objective function – it depends on the task – by finding appropriate values of the variables of the objective function [1], [2]. In case of electrical circuit optimization, these variables are the circuit parameters whose values are changed during the optimization in order for the required result of the optimization to be obtained. The parameters are the values of components in the circuit.

When choosing a method for a given optimization task, it is necessary to know if the applied objective function is continuous and differentiable for all the values of its variables within its definition scope. Unless both of these features are valid, any gradient method (or, more generally, a method that requires the differentiation of the objective function) is inapplicable.

In case of the optimization of ASCs, the objective function is not usually differentiable for all the values of its variables within its definition scope. Therefore, an optimization method that does not need the differentiability of the objective function has to be applied.

EAs represent a group of methods that satisfy this requirement. From the objective function, they need only its value. Another method satisfying this requirement is the branch-and-bound algorithm (BBA). EAs and the BBA are quite powerful so they were expected to be suitable for the optimization of ASCs.

4.1 Evolutionary Algorithms

From all EAs (e.g., genetic algorithms, evolutionary strategy, differential evolution (DE), etc.), the DE achieves the best results as far as the speed of optimization is concerned [15]. Moreover, when it is combined with another algorithm, e.g., with the simplex method (SM) [16], its results can be even better. According to performed tests (see, e.g., [17]), the combination of the DE and SM achieves a very good convergence speed into the global extreme of the objective function. A detailed description of the DE and SM is available in the references mentioned above.

4.2 Branch-and-Bound Algorithm

The description of this algorithm is presented in [18]. It does not require the continuity and the differentiability of the objective function, such as in case of EAs.

The authors utilized and tested the BBA in the mathematical program Maple$^{\mathrm{TM}}$ [19], for which it is provided within the Global Optimization toolbox.

The BBA was tested by the authors on testing objective function, which are used on finding out the performance and robustness of optimization algorithms (they are listed in [2]). The results of this testing was very good; the BBA was able to find the global extreme of most of the testing objective functions, even when the number of their variables (i.e., the dimension of a searched space) was set to a higher number.

Based on these findings, the BBA was supposed to be sufficiently powerful for the optimization of ASCs. However, in case of the objective function for this optimization, the BBA was found not to be able to find its global extreme. Many tests with various circuits were made but the BBA was not successful in any one of them. Every time the BBA terminated its optimization process with a message "cycling or stall detected in solver."

5. Ways of Analogue Switched Circuit Analysis during Optimization

The analysis of ASCs has to be performed during their optimization (see section 3). Two ways of the analysis are possible: with and without using the symbolical transfer function of the optimized ASC.

5.1 With a Symbolical Transfer Function

In this case, the symbolical form of the transfer function of the analyzed ASC is available. The variables of this symbolical form have to be frequency and all the circuit parameters (denoting the values of components in the circuit) whose values can be changed so that the required result of the optimization is obtained.

In case of this possibility, only the substituting of values of objective function variables has to be done in order to analyze the ASC. Thus, a whole analysis of the ASC need not be done, so the optimization process can be faster.

This possibility can happen in case of simpler ASCs only because for ASCs that are more complex, the calculation of their symbolical transfer function is difficult or even impossible. Moreover, a program capable of providing the symbolical transfer function has to be available. From the programs mentioned here, this can be done only by PraSCAn, which is one of the few programs capable of doing it (see subsection 6.2).

When this possibility is used, the mathematic program implementing calculations of the applied optimization algorithm is required to be able to compute symbolically.

5.2 Without a Symbolical Transfer Function

In this case, the symbolical form of the transfer function of the analyzed ASC is unavailable (or it is very complicated, so its using is not suitable).

In case of this possibility, a whole analysis of the ASC has to be performed for every combination of values of objective function variables (i.e., repeatedly). Thus, the optimization process is slower. However, the optimization process with repeated analyzing can be faster than with a symbolical transfer function if the symbolical transfer function is very complicated. If so, a long time is necessary for substituting concrete values into it (see subsection 8.3).

The mathematic program implementing calculations of the applied optimization algorithm repetitively calls an analyzing program with calculated values of objective function variables, i.e., the circuit parameters (denoting the values of components in the circuit). This program analyzes the ASC whose values of circuit parameters are those given by the mathematic program. The analyzing program is either (added) part of the mathematic program (a case of PraSCAn for Maple) or an external one (e.g., WinSpice, Mentor Graphics, and Cadence), see subsection 6.2. In case of an external analyzing program, it has to be executable from a command line with specifying the circuit to be analyzed and it has to provide the results of the analysis in the form of a text file.

6. Programs Needed for Optimization

6.1 Programs for Optimization Algorithm Implementation

The first program required for performing the optimization of ASCs is a program for implementing the calculations of the applied optimization algorithm.

Because mathematical operations have to be made during performing the optimization algorithm, a program capable of doing it is necessary for this purpose. Another feature that the program should have is the possibility of symbolical calculation. Suitable programs are Maple™ [19] and MATLAB® [20] – one of the most widespread mathematical programs.

6.2 Programs for Analogue Switched Circuit Analysis

As stated in the previous section and in section 3, it is necessary to carry out the analysis of ASCs during their optimization. As a result, a program for the analysis of the optimized circuit is necessary besides a program for implementing calculations of the used optimization algorithm. Four programs are listed in this subsection: PraSCAn, WinSpice, Mentor Graphics, and Cadence. When analyzing ASCs by these programs, one of possible procedures is described in section 3.

- PraSCAn

PraSCAn [13] can analyze real ASCs – both SC and SI circuits. It can calculate their frequency as well as transient response in a symbolical form.

- WinSpice

WinSpice is a general-purpose well-known Spice-compatible program [21] for circuit simulation.

- Mentor Graphics and Cadence

These programs belong in a group of professional programs (not only) for numerical analyzing circuits [22], [23].

7. Switched-Current Circuit Optimization

The most often nonidealities considered in the optimizations of SI circuits are nonzero on-state resistance of the switches and finite output resistance of the current sources and the transistors (working as controlled current sources).

A usual aim of the optimization of an SI circuit is to remove the effect of chosen nonidealities on the magnitude frequency response of the circuit, i.e., to achieve the shapes of the magnitude frequency responses of the circuit with ideal components (denoted as M_{I}) and the circuit with the nonidealities (denoted as M_{N}) as similar as possible. This aim is to be met by finding appropriate transistor transconductance values – the main parameters in SI circuits.

For the purpose of this optimization, a magnitude filter specification has to be created. It consists of several intervals $\langle B_{\mathrm{LdB}}(f_i)$ and $B_{\mathrm{UdB}}(f_i)\rangle$ at a few frequencies f_i. Because of the aim of the optimization, the intervals are derived from the magnitude frequency response M_{I}. The value of the magnitude frequency response M_{N} at every frequency f_i should be within the corresponding range.

The following objective function F can be applied for the optimization:

$$F(g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})=\begin{cases}\displaystyle\sum_{i=1}^{L}F_{\mathrm{L}i}(g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})\\ \displaystyle+\sum_{i=1}^{U}F_{\mathrm{U}i}(g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})\\ \qquad\text{if the circuit is stable,}\\ 1000\quad\text{if the circuit is unstable,}\end{cases}\tag{1}$$

$$F_{\mathrm{L}i}(g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})=\begin{cases}\dfrac{B_{\mathrm{L}}(f_i)-M_{\mathrm{N}}(f_i,g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})}{B_{\mathrm{L}}(f_i)}\\ \quad\text{if } M_{\mathrm{N}}(f_i,g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})<B_{\mathrm{L}}(f_i),\\ 0\quad\text{else,}\end{cases}\tag{2}$$

$$F_{\mathrm{U}i}(g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})=\begin{cases}\dfrac{M_{\mathrm{N}}(f_i,g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})-B_{\mathrm{U}}(f_i)}{B_{\mathrm{U}}(f_i)}\\ \quad\text{if } M_{\mathrm{N}}(f_i,g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n})>B_{\mathrm{U}}(f_i),\\ 0\quad\text{else,}\end{cases}\tag{3}$$

the meaning of the symbols is as follows:

$g_{\mathrm{m}1},\ldots,g_{\mathrm{m}n}$	transconductance values,
L	the number of the lower bounds B_{LdB},
U	the number of the upper bounds B_{UdB}.

It is apparent that this objective function is not differentiable for all the values of its variables within its definition scope (and it is nonlinear).

To achieve the aim of the optimization, this objective function has to be minimized. A suitable powerful optimization algorithm for this minimization is the DE combined with the SM (see subsection 4.1). The global minimum of this objective function is 0 – this value means the satisfying of the aim of the optimization.

8. Example of Analogue Switched Circuit Optimization

This example presents an optimization of an SI circuit, which is used on the realization of a band-pass filter.

8.1 Optimized Circuit and Its Parameters

Fig. 1 shows the schematic diagram of the optimized circuit (a biquad). The required parameters of this filter are as follows:

- clock frequency: f_{C} = 10 MHz,
- center frequency: f_0 = 1 MHz,
- quality factor: Q = 10,

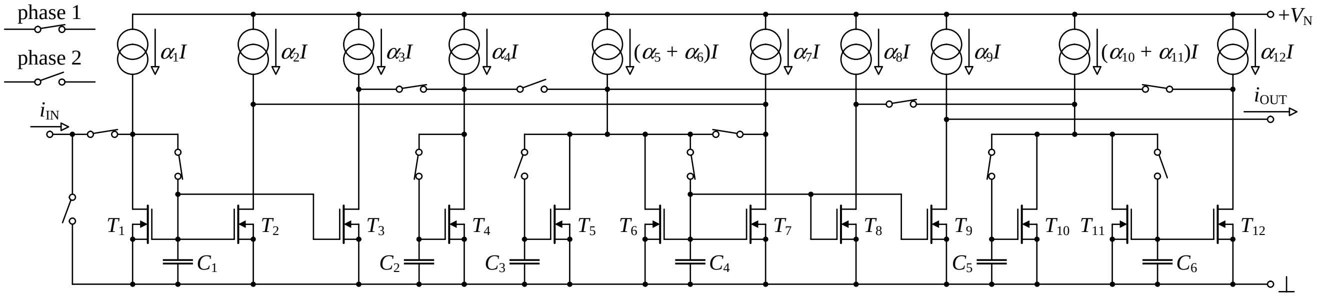

Fig. 1. Biquadratic section in the switched-circuit technique.

- gain at f_0: $G = 20$ dB.

A dominant characteristic of the used transistors T_1 to T_{12} is represented by their transconductances g_{m1} to g_{m12}. The ratio of the currents of any two current sources in the upper part of Fig. 1 (expressed by the numbers α_1 to α_{12}) is the same as the ratio of the transconductances of the transistors connected to these current sources.

The nonidealities taken into account in this optimization are as mentioned in section 7. Their used values were 1 kΩ and 20 kΩ, respectively. Their choice was based on values common in real SI circuits. Linearized models were applied for the transistors in the filter during its analyzing to express their transconductance and output resistance.

The magnitude frequency response of the filter from the input i_{IN} to the output i_{OUT} with ideal components is denoted M_I, a denotation M_N is used in case of nonideal components. Both of the frequency responses are considered from phase 1 on the input to phase 1 on the output.

If the nonidealities are considered in the filter designed according to a conventional procedure, its magnitude frequency response changes from the solid line to the dotted one in Fig. 2. It is apparent that the difference between the two magnitude frequency responses is high.

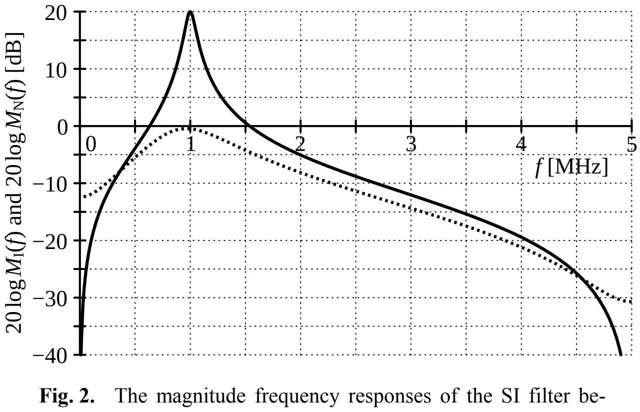

Fig. 2. The magnitude frequency responses of the SI filter before the optimization, dotted line: the magnitude M_N, solid line: the magnitude M_I.

8.2 Details about Optimization

The aim of the optimization was discussed in section 7. This aim was accomplished by finding appropriate transconductance values g_{m1} to g_{m12} (or current source values α_1 to α_{12}).

As presented in section 7, a magnitude filter specification was applied. It is shown in Fig. 3 and 4.

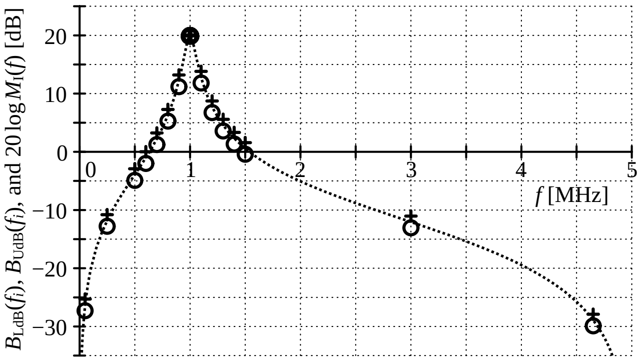

Fig. 3. The magnitude filter specification for the optimization, dotted line: the magnitude frequency response M_I, crosses: the upper bounds B_{UdB} of the magnitude ranges, circles: the lower bounds B_{LdB} of the magnitude ranges.

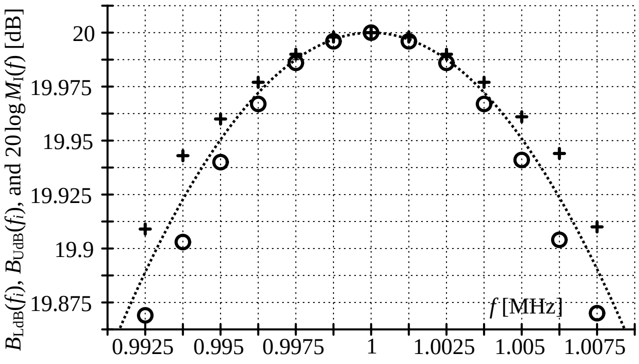

Fig. 4. Detail of Fig. 3 for a vicinity of the frequency f_0.

The objective function applied in this optimization was of form (1) to (3) with the values $L = H = 27$ (and $n = 12$).

The optimization process was carried out in the Maple program and PraSCAn was applied for the analysis of the filter. The reason of the use of PraSCAn was a shorter time of the analysis (see the next subsection).

One generation of the optimization process consisted of 104 members (i.e., combinations of objective function values). The values of transconductances were chosen from a range of 50 μS to 20 mS. The values of the parameters of the DE was the following: crossover constant $CR = 0.9$, mutation constant $F = 0.5$. For the SM, these values of its parameters were used: reflection parameter $\alpha = 3$, expansion parameter $\beta = 2$, contraction parameter $\gamma = 0.5$.

8.3 Results from Optimization

The optimization algorithm was required to achieve the value of the objective function lower or equal to 10^{-10}. This was accomplished after 116 generations, when the objective function had a value of 7.995^{-11}.

In this optimization, repeated (semisymbolical) analyzing (see subsection 5.2) was applied in spite of the possibility of obtaining the symbolical transfer function of the filter (by PraSCAn). This was done because this symbolical transfer function is very complicated (it has more than 10^6 nodes), so the optimization took a longer time than with repeated analyzing. PraSCAn was utilized for this repeated analyzing because it was able to achieve a shorter analyzing time than the other programs listed in subsection 6.2. Tab. 1 shows the times required by the programs to analyze the filter. When the symbolical transfer function was used, one substituting took 2 s. However, the times for WinSpice, Mentor Graphics, and Cadence are only for the transient analysis, they do not include a time for DFT computing. (PraSCAn provides as its result a (semi)symbolical transfer function, so any DFT is not necessary.) The analysis and optimization was performed by a personal computer with a 3 GHz Pentium processor and 1 GB memory.

Analyzing program	Required time
PraSCAn	**1.1 s**
WinSpice	**20 s**
Mentor Graphics	**9 s**
Cadence	**10 s**

Tab. 1. Required times for the analysis of the filter by the analyzing programs listed in subsection 6.2.

The settings used for the analysis by WinSpice, Mentor Graphics, and Cadence were according to [10] and [11].

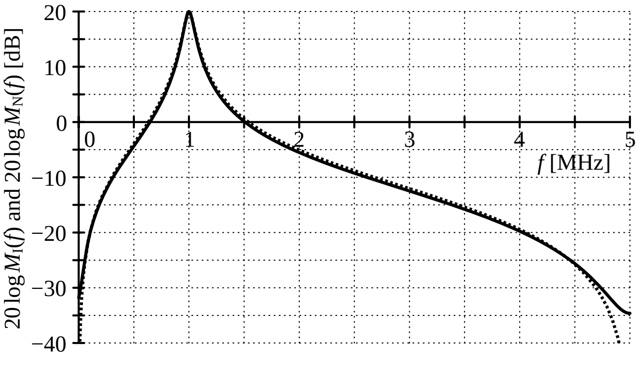

Fig. 5. The magnitude frequency responses of the SI filter after the optimization, dotted line: the magnitude M_I, solid line: the magnitude M_N.

The resulting magnitude frequency response M_N obtained from the optimization is plotted in Fig. 5 and 6. The magnitude frequency response M_I is also plotted there for comparing.

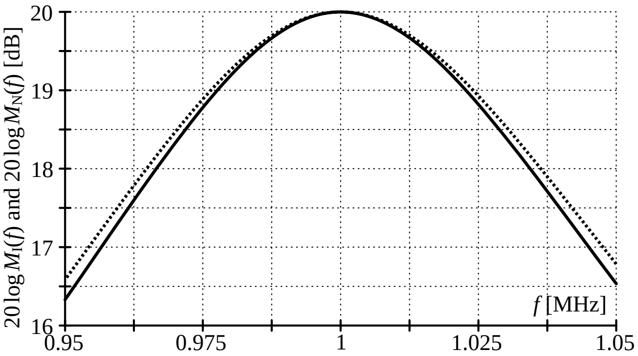

Fig. 6. Detail of Fig. 5 for a vicinity of the frequency f_0.

All the magnitude frequency responses in this example were obtained by PraSCAn and verified by WinSpice according to the procedure described in section 3.

9. Conclusion

This paper results from the authors' research in the area of the optimization of analogue switched circuits. It deals with the possibilities of this optimization. It presents the nonidealities in analogue switched circuits, how these circuits can be analyzed, and suitable methods for their optimization. Several programs able both to perform an optimization algorithm and to analyze analogue switched circuits are mentioned too. To explain the description better, an example of a switched-current circuit optimization is presented at the end of the paper.

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