

Applying Fuzzy Sets Intersection in the Sizing of Voltage Followers

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Abstract. An automatic fuzzy–set–intersection–based approach is presented to compute the optimum sizes of Voltage Followers (VFs). Based on Monte Carlo simulations and two fuzzy sets to represent the gains closer to unity and higher bandwidths, the approach compute the optimum sizes through the application of fuzzy sets intersection, subject to a distance from the maximum gain defined by a threshold and a lower bound to gains, both defined by the circuit design expert.

Key words: Fuzzy Sets Intersection, Circuit Optimization, Analog Design Automation, Circuit Sizing

1 Introduction

Electronic systems, such as cellular telephones, magnetic disk drives and speech recognition systems [1], require an interface with the external world. Since the world is analog in nature all these kind of electronic systems require analog circuits. In the analog design automation (ADA) tools, new techniques need to be developed to improve the design of integrated circuits (ICs), in order to reduce the costs of the production, to shorten the time to market [2], and to enhance the quality and optimality of integrated circuits.

Different kinds of active elements that are used in analog signal processing applications, such as to design chaotic oscillators [3], to design current conveyors [4], to design filters [5] and to develop secure communication systems [6], are designed by using unity-gain cells (UGCs) such as Voltage Followers (VFs) [7]. In order to improve the performance of these applications, it is needed to compute optimal sizes of the VFs [8]. In [8][9][10][11][12] some ADA procedures to automate the sizing process are given, but an open problem remains related to the selection of an optimal sized topology whose parameters such as gain, bandwidth (BW), input and output impedances, among others, need to be classified.

The automatic selection of an optimum sized VF topology is addressed in this paper. Given a VF its gain is optimized to be closer to unity and with the large BW. In this problem there are two linguistic variables: "closer to unity" and "large", then the fuzzy sets are well suited to represent the behavior of the

VF under several values of its parameters, such as width (W) and length (L) of the transistors, and current bias, since the fuzzy sets allow formalizing linguistic sentences to express ideas that are subjective and which can be interpreted in different ways by various individuals [13]. Then, defining appropriate membership functions it is possible to construct two fuzzy sets: a fuzzy set to represent the higher BWs and a fuzzy set to represent the gains closer to unity.

In this manner, the proposed approach finds the optimum sizes of the VF where both conditions (higher BW and gain closer to unity) are satisfied: first selecting the parameters of the VF such that the gain is far from the maximum gain in certain distance, that is defined by a threshold, and such that the gain is greater than certain lower bound; second defining the fuzzy sets; then computing the intersection of both fuzzy sets that takes the minimum between both membership values; finally, taking the maximum of intersection result. The threshold and the lower bound, as well as the parameter values of the VF, are defined by the circuit design expert.

2 The Fuzzy Sets Intersection Method

Let X be the universe set of all sizes combinations of a VF and their performances. Since in this paper a VF is characterized by its length and width, and the current bias used, it is defined a conventional set on X as follows: Let P be a set of parameters defined by [14] [15]

$$P = \{x \mid x = \{L(\mu m), I(\mu A), W(\mu m)\}\}$$

where L is the length of all transistors, W is the width of each transistor, and I is the current bias. Each x associates sizes to perform a SPICE simulation, which results are introduced in two fuzzy sets defined on X as follows: The BWs are collected in \underline{A} , the fuzzy set of large bandwidths, defined as

$$\underline{A} = \left\{ \frac{\mu_{\underline{A}}(x)}{x} \mid x \text{ is a large bandwidth and } \mu_{\underline{A}}(x) = \frac{x}{max_bandwidth} \right\}, \quad (1)$$

where $max_bandwidth$ is the maximum BW of all P sizes and the membership value of each BW, $\mu_{\underline{A}}(x)$, depends on how much its value is large. The gains are collected in \underline{B} , the fuzzy set of gains close to unity, defined as

$$\underline{B} = \left\{ \frac{\mu_{\underline{B}}(x)}{x} \mid x \text{ is a gain close to unity and } \mu_{\underline{B}}(x) = x \right\}, \quad (2)$$

where the membership value of each gain, $\mu_{\underline{B}}(x)$, depends on how much its value is closer to unity. Then, there is a correspondence among elements in P , \underline{A} and \underline{B} .

The proposed method allows to the circuit design expert to define the P set through the definition of L , I and W values of a VF, and the expert can request

that the gain obtained from SPICE simulation is greater than a certain lower bound, low_bou , then if

$$gain \geq low_bou, \quad (3)$$

the gain, that is represented with an element of \underline{B} , along with the corresponding elements in P and \underline{A} are desired values, else they are eliminated. Also, the expert may request that the gain is far from maximum gain in certain desired distance given through a threshold, defined as $thr = max_gain - \frac{des_dis \times \Delta_{gain}}{100}$, where max_gain is the maximum gain of all P configurations, des_dis is the desired distance from maximum gain (measured in a percentage), and $\Delta_{gain} = max_gain - min_gain$, where min_gain is the minimum gain of all P configurations. Then if

$$gain \geq thr, \quad (4)$$

the gain (represented with an element of \underline{B}) along with the corresponding elements in P and \underline{A} are desired values, else they are eliminated.

Once the low_bou and thr are defined, and the gains (with the corresponding bandwidths and parameters) are selected under the two restrictions (3) and (4), the proposed method builds the fuzzy sets \underline{A} and \underline{B} in accordance with (1) and (2) and computes the intersection of these fuzzy sets as follows

$$\underline{C} = \underline{A} \cap \underline{B} = \left\{ \frac{\mu_{\underline{C}}(x)}{x} \mid \mu_{\underline{C}}(x) = \min\{\mu_{\underline{A}}(x), \mu_{\underline{B}}(x)\} \right\}.$$

In this case, as \underline{A} is the fuzzy set of large bandwidth and \underline{B} is the fuzzy set of gains close to unity, the intersection of \underline{A} and \underline{B} represents the set of P configurations where the gain is close to unity and the BW is large. Then the optimum sizes are computed by $OptVF = \max\{\mu_{\underline{C}}(x)\}$, where the correspondent P element of this maximum is the optimum size of the given VF. All these steps to compute the optimum sizes of a VF automatically are collected in the following algorithm.

ALGORITHM FuzzySetIntersecMethod

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IN: VF:file;Lvalues,Ivalues,Wvalues:Set;desDis:int;lowBou:real
OUT: optLvalue,optIvalue,optWvalue,optGain,optBandwidth:real
BEGIN
/* Define P set of the VF parameters */
  t = 1
  FOR i = 1, 2, ..., cardinality of Lvalues
    FOR j = 1, 2, ..., cardinality of Ivalues
      FOR k = 1, 2, ..., cardinality of Wvalues BEGIN
        P(t) = [Lvalues(i), Ivalues(j), Wvalues(k)]
        t = t+1
      END
    END
  END
/* Collect gains and bandwidths using Montecarlo simulation */
  FOR i = 1, 2, ..., cardinality of P BEGIN
    [GAINS(i), BANDWIDTH(i)] = SPICE(VF with P(i) parameters)
  END
END

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/* Compute the two fuzzy sets */
max_bandwidht = maximum(BANDWIDTHS)
[max_gain,min_gain] = [maximum(GAINS), minimum(GAINS)]
thres = max_gain - (desDis*(max_gain - min_gain))/100
t = 1
FOR i = 1, 2, ..., cardinality of GAINS BEGIN
    IF (GAINS(i)>=thres) AND (GAINS(i)>=lowBou) BEGIN
        Afuzzy(t) = BANDWIDTHS(i) / max_bandwidth
        Bfuzzy(t) = GAINS(i)
        Q(t) = P(i)
        t = t+1
    END
END
/* Compute intersection of the fuzzy sets */
FOR i = 1, 2, ..., cardinality of Afuzzy BEGIN
    Cfuzzy(i) = minimum(Afuzzy(i),Bfuzzy(i))
END
/* Compute VF optimum size (intersection maximum) */
optc = Cfuzzy(1)
j = 1
FOR i = 2, ..., cardinality of Cfuzzy BEGIN
    IF (optc < Cfuzzy(i)) THEN BEGIN
        optc = Cfuzzy(i)
        j = i
    END
END
END
[optLvalue, optIvalue, optWvalue] = [Q(j).Lvalue,
                                     Q(j).Ivalue, Q(j).Wvalue]
[optGain, optBandwidth] = [GAINS(j), BANDWIDTHS(j)]
END

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This algorithm allows to compute the optimum parameters of a VF such that its bandwidth is large and its gain is close to unity at the same time through a single operation (the fuzzy sets intersection), based on the proper definition of the fuzzy sets, meanwhile other methods compute the optimum using different stages. For example, the approach [8] takes a few VF parameters to simulate the VF, first computing the VF parameters where the gains are close to unity, then selecting from these computed gains the larger bandwidth.

3 Experimental Results

In Fig. 1 are shown the VFs used to compute their optimum sizes by using SPICE and under several P set, des_dis and low_bou values. These VFs are synthesized by P-MOSFETs and N-MOSFETs [9]. For each VF of Fig. 1 the circuit design expert has defined the following P set

$$P = \{L, I, \{W_A, W_B, W_C\}\}, \quad (5)$$

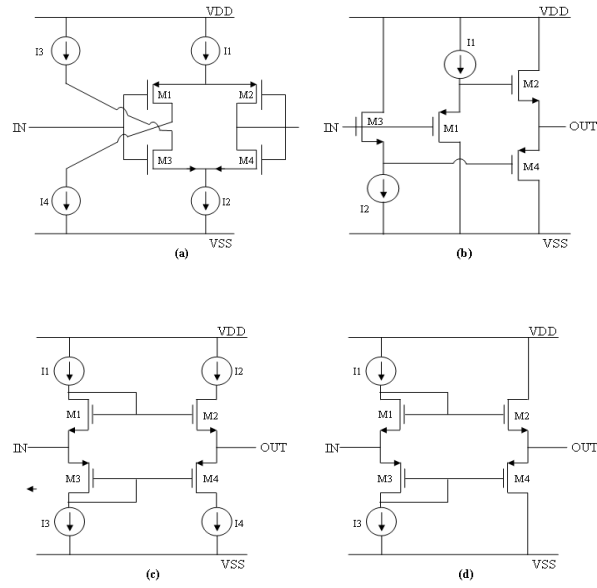


Fig. 1. Voltage Followers under test.

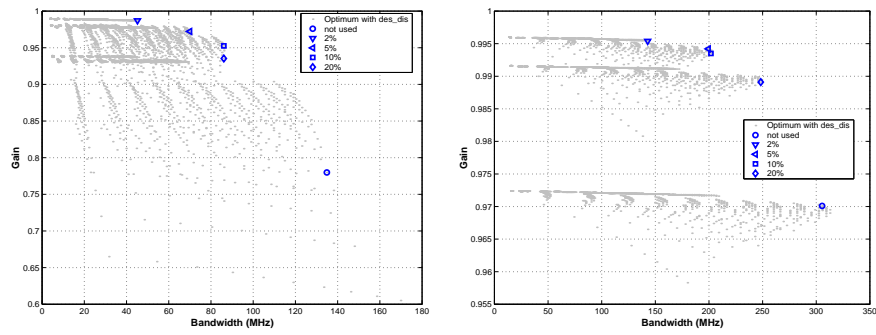


Fig. 2. Optimums computed by the proposed fuzzy set intersection method for the VF of Fig. 1(a)–(b).

where $L = \{0.4, 0.7, 1.0\} \mu m$, $I = \{10, 20, \dots, 100\} \mu A$, $W_A = \{10, 20, \dots, 100\} \mu m$, $W_B = \{300, 310, \dots, 400\} \mu m$, and $W_C = \{600, 610, \dots, 700\} \mu m$. Then, the VFs were sized using three different lengths (L), ten different currents for biasing (I) and thirty different VF widths (W_A, W_B, W_C). This leads us to 4950 combinations in sizing when the P-MOSFETs widths are greater than or equal to the N-MOSFETs widths, that means that $W_{M_1, M_2} \geq W_{M_3, M_4}$ for VF of Fig. 1(a), $W_{M_1, M_4} \geq W_{M_2, M_3}$ for VF of Fig. 1(b), and $W_{M_3, M_4} \geq W_{M_1, M_2}$ for VFs of Fig. 1(c) and Fig. 1(d).

The results obtained with the proposed method to size the VFs of Fig. 1, under (5) parameters, are given in Fig. 2-3. In all cases, the optimums computed by the proposed method are marked under several des_dis values, $des_dis = \{2\%, 5\%, 10\%, 20\%\}$, and $low_bou = 0.5$. It is easy to see that the proposed method gives good optimums applying the fuzzy sets intersection, since although there are some results where the BW is greater, the method has selected the sizes-combinations where the BW is greater but A_V is closer to unity.

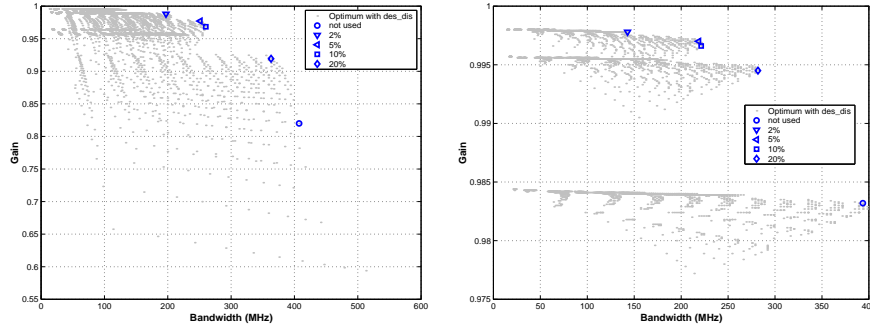


Fig. 3. Optimums computed by the proposed fuzzy set intersection method for the VF of Fig. 1(c)-(d).

Some details of the results obtained in each graphic of Fig. 2-3 are given in Table 1. For VF of Fig. 1(a), good results are given when $des_dis = \{5\%, 10\%\}$ ($A_v=0.9723$, $BW=69.98MHz$ and $A_v=0.9526$, $BW=86.1MHz$, respectively). Meanwhile a good result is obtained for VF of Fig. 1(b) with $des_dis = 20\%$, where the bandwidth is almost larger among all results ($BW=248.3MHz$) and the gain is good enough ($A_v=0.9891$). When $des_dis = \{5\%, 10\%\}$ good optimums are obtained ($BW=199.5 MHz$, $A_v=0.9942$ and $BW=201.8MHz$, $A_v=0.9935$, respectively).

A good behavior for VF of Fig. 1(c) in Table 1 is provided when $des_dis = 10\%$, where $A_v=0.9684$ and $BW=260MHz$. However, an acceptable result is given when $des_dis = 20\%$ ($A_v=0.9192$, $BW=363.1MHz$). Finally, a good result is obtained for VF of Fig. 1(d) when des_dis is not used, since the gain is good enough, $A_v=0.9831$, and $BW=393.6MHz$ is largest of all experiment results.

Table 1. VF optimum sizes of Fig. 1(a)–(d).

VF of	<i>des_dis</i>	<i>L</i>	<i>I</i> _{1,2}	<i>I</i> _{3,4}	<i>W</i> _{<i>M</i>₁,<i>M</i>₂}	<i>W</i> _{<i>M</i>₃,<i>M</i>₄}	<i>A</i> _{<i>v</i>}	<i>BW</i>
Fig. 1(a)	without	0.4	100	50	30	20	0.7789	134.9
	5%	1	100	50	70	70	0.9723	69.98
	10%	0.7	100	50	60	60	0.9526	86.1
	20%	0.7	100	50	40	40	0.9353	86.1
Fig. 1(b)	<i>des_dis</i>	<i>L</i>	<i>I</i> _{1,2}		<i>W</i> _{<i>M</i>₁,<i>M</i>₄}	<i>W</i> _{<i>M</i>₂,<i>M</i>₃}	<i>A</i> _{<i>v</i>}	<i>BW</i>
	without	0.4	100		90	90	0.9701	305.5
	5%	1	100		90	70	0.9942	199.5
	10%	1	100		60	60	0.9935	201.8
20%	0.7	100		60	60	0.9891	248.3	
Fig. 1(c)	<i>des_dis</i>	<i>L</i>	<i>I</i> _{1,2,3,4}		<i>W</i> _{<i>M</i>₃,<i>M</i>₄}	<i>W</i> _{<i>M</i>₁,<i>M</i>₂}	<i>A</i> _{<i>v</i>}	<i>BW</i>
	without	0.4	100		30	30	0.82	407.4
	5%	0.7	100		90	90	0.9771	251.2
	10%	0.7	100		60	60	0.9684	260
20%	0.4	100		90	90	0.9192	363.1	
Fig. 1(d)	<i>des_dis</i>	<i>L</i>	<i>I</i> _{1,2,3,4}		<i>W</i> _{<i>M</i>₃,<i>M</i>₄}	<i>W</i> _{<i>M</i>₁,<i>M</i>₂}	<i>A</i> _{<i>v</i>}	<i>BW</i>
	without	0.4	100		90	90	0.9832	393.6
	5%	1	100		80	70	0.997	218.8
	10%	1	100		50	50	0.9966	221.3
20%	0.7	100		60	60	0.9945	281.8	

4 Conclusions

An automatic method based on intersection of fuzzy sets has been introduced to solve the open problem of sizing Voltage Followers (VFs), unity-gain cells that are used to design active elements used in several analog signal processing applications. The proposed method formalize the representation of the behavior of VFs under several values of its parameters (width and length of the MOSFET, and current bias) using two fuzzy sets: a fuzzy set to represent the large bandwidths and a fuzzy set to represent the gains close to unity of a VF. The bandwidths and the gains are obtained of Monte Carlo simulations using several combinations and varying the current biases, the widths and the length of the MOSFETs, that are parameters defined by the circuit design expert. Through the fuzzy sets intersection the optimum sized of a given VF is computed, since the intersection is a natural manner to represent the VF configurations where the gain is close to unity and the bandwidth is large at the same time. The successful of the results obtained with the intersection, as has been seen in previous section, lies in the definition of the fuzzy sets and their appropriate membership functions, that are the key of the proposed method. The expert can select a desired distance from the maximum gain obtained from SPICE simulations to compute the optimum VF behavior. Also, in order to eliminate non-significant results obtained from Monte Carlo simulations, the proposed method allows to

expert to define a lower bound to gain. These additional restrictions help to compute several optimums that can be conveniently selected by the expert.

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