CIRCUITS SYSTEMS SIGNAL PROCESSING
VOL. 21, NO. 5, 2002, PP. 473–483

A NOVEL EXPONENTIAL VOLTAGE-TO-CURRENT CONVERTER*

Khaled M. Abdelfattah[1] *and Ahmed M. Soliman*[1]

Abstract. In this paper, a novel method to build a complementary metal oxide semiconductor (CMOS) exponential voltage-to-current converter has been developed. The method is based on a modular design approach in which increasing the dynamic range of the system—to any required value—is done by simply adding more cells. The method is based on a pulse width modulation technique to generate a pulse signal that is used to activate a number of cascaded integrators. Based on the presented method, a novel exponential voltage-to-current converter is introduced with an achieved dynamic range of 42 dB. The circuit operates from a single supply of 3 V. Simulation results are based on Mietec 0.5 μm CMOS technology.
Key words: Variable gain amplifiers.

1. Introduction

A variable gain amplifier (VGA) is employed in many applications to maximize the dynamic range of the overall system [6], [8], [12]. The primary usage of a VGA is to build an automatic gain control (AGC) system, which is used in wireless receivers to maintain a constant level of the delivered power to the subsequent stages irrespective of the unpredictable received power [9]. VGAs are also used in hearing aids [3] and disk drives [7]. Because there is a requirement to maintain constant settling time of the AGC circuit, the VGA should have an exponential gain control [10], i.e.,

$$V_{\text{out}} = GV_{\text{in}} = \exp(\alpha V_{\text{c}})V_{\text{in}}, \tag{1}$$

where, G is the gain, V_{c} is the control voltage, and α is a constant.

Because of the required exponential behavior, early implementations of the

* Received July 17, 2001.
[1] Electronics and Communications Engineering Department, Faculty of Engineering, Cairo University, Giza, Egypt. E-mail for Abdelfattah: kmahmoud@icsl.ucla.edu E-mail for Soliman: asoliman@idsc.net.eg

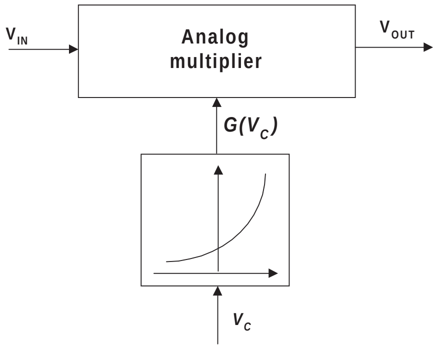

Figure 1. Block diagram of VGA with exponential gain control and an analog multiplier.

VGA made use of bipolar junction transistors that have an inherent exponential characteristic. However, as the world now is switching to digital complementary metal oxide semiconductor (CMOS) technology, the design of VGA is no longer that simple, and several approximations have been used to mimic the exponential characteristic. One of the approximations used in the literature [1], [2], [11], [13] is shown here.

The approximation stems from the well-known Taylor expansion of the exponential function

$$G = \exp(X) = 1 + X + \frac{X^2}{2!} + \frac{X^3}{3!} + \cdots, \tag{2}$$

where the last equation is truncated according to the required accuracy and the tolerated complexity of the hardware. Clearly, that taking more terms into account will make the approximation more accurate over a wider range of X and thus increase the dynamic range of the system. However, the relation is always truncated up to the second-order term for implementation feasibility [1], [2], [11], [13].

This paper presents a universal method to realize a CMOS exponential gain converter to be used with a multiplier to constitute a complete VGA, as shown in Figure 1. The method can make use of any number of terms of equation (2) as required. Based on the presented method, a novel exponential voltage-to-current converter is introduced in which all the terms up to the third-order term are taken into account. Section 2 describes the operation of the entire circuit as well as individual blocks. Section 3 gives the mathematical analysis of the circuit, Section 4 illustrates the simulation results, and the conclusions are given in Section 5.

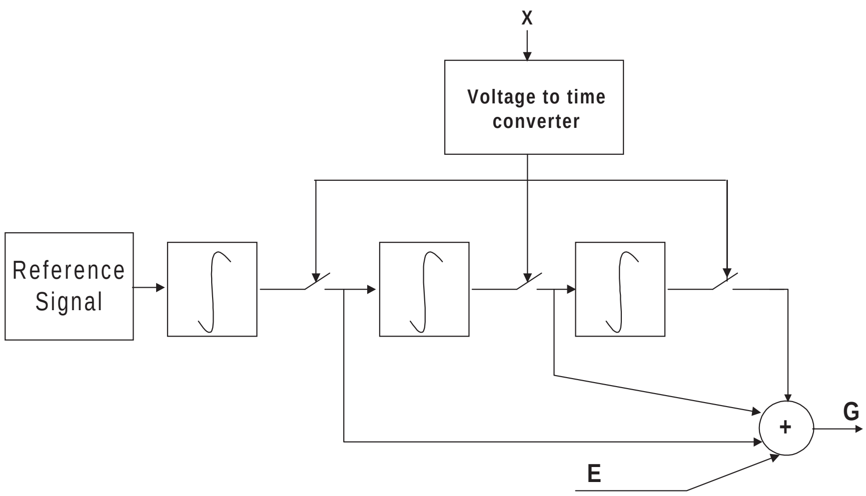

Figure 2. Overall block diagram.

2. Circuit description

2.1. Mathematical idea

The basic idea is based on the observation that each term of the expansion can be obtained by integrating the previous term with respect to the control signal X, and the first term has to be a constant value, i.e.,

$$G = 1 + \int 1\,dX + \int\int 1\,dX + \int\int\int 1\,dX + \cdots \tag{3}$$

However, the available integrators are only capable of integrating varying signals with respect to time, which means that one should find a transformation method to represent the input control signal by a corresponding time pulse. A proposed block diagram is shown in Figure 2, where equation (3) is truncated up to the third-order term.

2.2. Overall circuit operation

Figure 3 gives a more detailed insight into the details of the design (temporarily excluding the voltage-to-time converter) where the voltage integrators are realized by using a G_m-C network. Three cascaded integrators are used, where the integration time and thus the integrator outputs are controlled by three switches that are turned on for an interval T and then turned off again. It will be shown that the gain G depends exponentially on the period T.

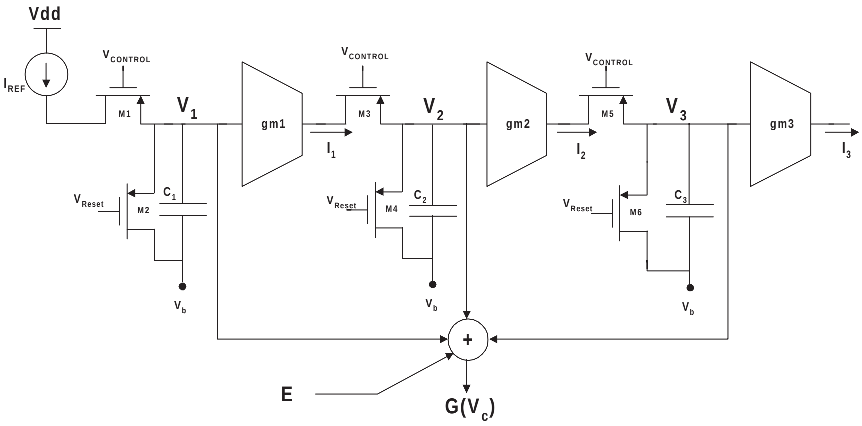

Figure 3. Detailed block diagram of the converter, excluding the voltage-to-time converter.

The operation of the circuit is as follows: given a certain control voltage which is necessary to obtain a specific gain value, the voltage-to-time converter subcircuit will convert the voltage to a pulse, called V_{control}, of duration T, where the duration is linearly proportional to the control voltage. This pulse will be used to activate the three switches (M1, M3, and M5), and thus the three integrators will begin working.

The input to the first integrator is a reference current that is constant; thus, integrating a constant will give the waveforms at nodes V_1, V_2, and V_3 that represent the second, third, and fourth terms of equation (3). When the duration T is over, V_{control} returns back to 3 V to deactivate the switches again, and the three output voltages V_1, V_2, and V_3 will hold their final values and then be summed up with a constant term to give the required gain value.

If another gain value is required, the capacitors will be discharged via the reset transistors (M2, M4, and M6) for a certain period that is sufficient to discharge all of them, and then another pulse will be applied to activate the switches for another interval.

2.3. Integrator design

The transconductor used should have good linearity in the operating region and also a small area because it will be used three times in the overall design. A good transconductor presented in [4] is shown in Figure 4. This transconductor depends on the principle of the nonlinear cancellation of matched MOS transistors operating in the ohmic region. All the transistors shown in Figure 4 are assumed to be in the saturation region except for M5 and M9, which operate in the ohmic region.

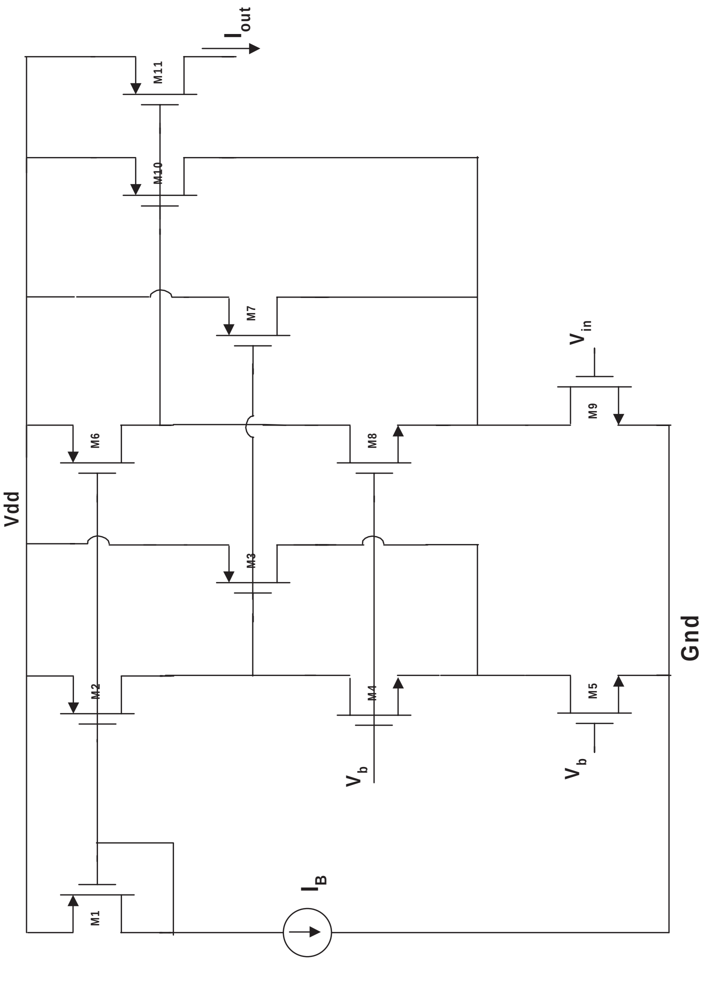

Figure 4. Transconductor used in realizing the integrators.

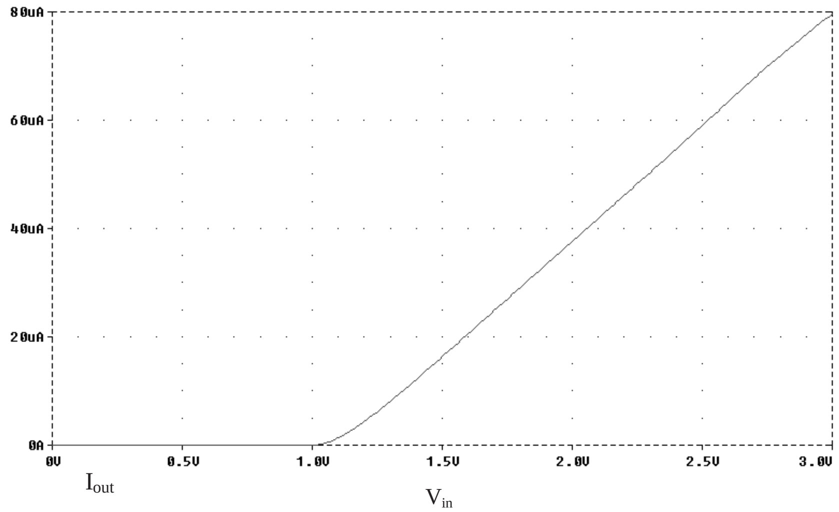

Figure 5. DC simulation of the circuit of the transconductor.

However, the output current is proportional to $V_{\text{in}} - V_{\text{b}}$ as shown in Figure 5 where V_{b} is taken to be 1 V. This calls for connecting the other side of the used capacitors to V_b, as shown in Figure 3.

2.4. Voltage-to-time converter

The control signal (V_{control}) of duration T can be generated in either one of two ways. It can be generated via a digital signal processor (DSP) that is found in the current state-of-the-art AGC systems [5]. The DSP takes the VGA output voltage, compares it with a prestored reference value, and then adapts the gain of the VGA to adjust its output voltage. Hence, one of the ways through which the DSP can change the gain G is to generate a control signal (V_{control}) with time duration proportional to the difference between the VGA output and the prestored reference voltage.

Another way to generate V_{control} is to use a voltage-controlled monostable circuit. The idea is very similar to pulse width modulation techniques, where the width of a time pulse is controlled by another signal. A simple circuit is shown in Figure 6. The circuit consists of a differential amplifier stage followed by digital inverters. The differential amplifier works as a comparator that compares the control signal V_{c} as defined in equation (1), with a periodic triangular waveform.

A simulation result of the circuit is given in Figure 7, where a triangular waveform of frequency l.6 MHz is assumed.

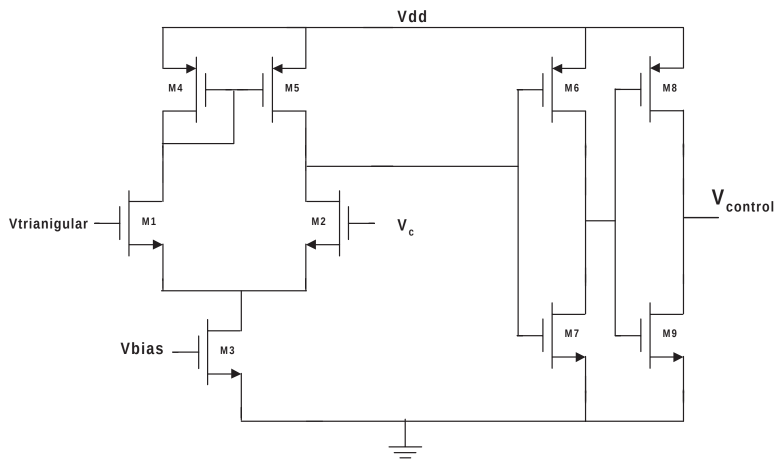

Figure 6. The proposed time-to-voltage converter.

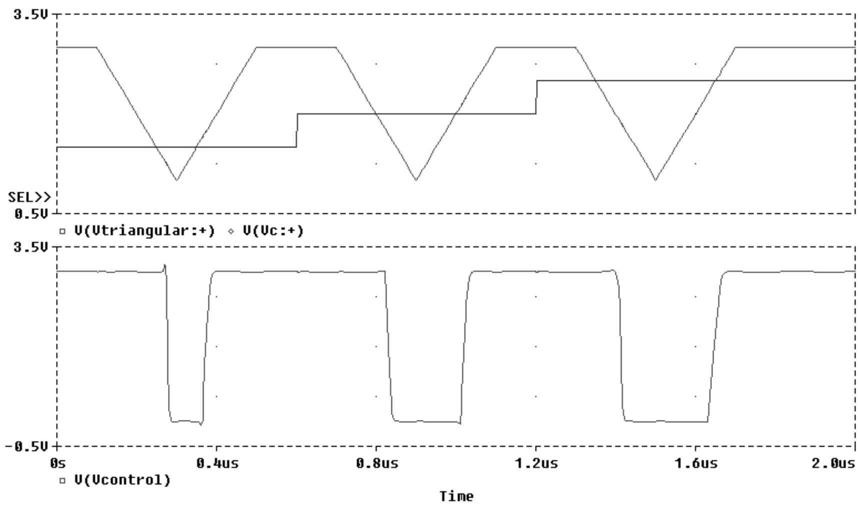

Figure 7. Simulation result of the voltage-to-time converter circuit.

3. Analysis of the circuit

Tracing the voltages of Figure 3 gives

$$V_1 = \frac{1}{C_1} \int I_{\mathrm{REF}}\, dt, \tag{4}$$

and because I_{REF} is constant,

$$V_1 = \frac{I_{\text{REF}}}{C_1} t. \tag{5}$$

Similarly,

$$V_2 = \frac{I_{\text{REF}}}{C_1} \frac{gm_1}{C_2} \frac{t^2}{2}, \tag{6}$$

and,

$$V_3 = \frac{I_{\text{REF}}}{C_1} \frac{gm_1}{C_2} \frac{gm_2}{C_3} \frac{t^3}{6}. \tag{7}$$

Because the output voltage is simply the addition of V_1, V_2, V_3, and a constant term E, then

$$V_{\text{out}} = E + V_1 + V_2 + V_3, \tag{8}$$

where E is a constant, and V_1, V_2, and V_3 are the integrator outputs.

But the addition of the transconductor output currents is more straightforward than the addition of output voltages: thus the following equation will be used instead:

$$I_{\text{out}} = I_{\text{REF}} + I_1 + I_2 + I_3, \tag{9}$$

where I_1, I_2, and I_3 can be expressed as

$$I_1 = gm_1 V_1 \tag{10}$$

$$I_2 = gm_2 V_2 \tag{11}$$

$$I_3 = gm_3 V_3. \tag{12}$$

Thus equation (9) will be

$$I_{\text{out}} = I_{\text{REF}} + gm_1 V_1 + gm_2 V_2 + gm_3 V_3. \tag{13}$$

To make I_{out} satisfy the truncated exponential series, one may use the condition

$$\frac{gm_1 V_1}{I_{\text{REF}}} = 2\frac{gm_2 V_2}{gm_1 V_1} = 3\frac{gm_3 V_3}{gm_2 V_2}. \tag{14}$$

If all switches remain on for $t = T$, then equation (14) along with equations (5), (6), and (7) result in the following necessary condition:

$$\frac{gm_1}{C_1} = \frac{gm_2}{C_2} = \frac{gm_3}{C_3}. \tag{15}$$

A possible choice that satisfies the preceding conditions is

$$C_1 = C_2 = C_3 = C \tag{16}$$

$$gm_1 = gm_2 = gm_3 = gm. \tag{17}$$

So, equation (9) will be rewritten as

$$I_{\text{out}} = I_{\text{REF}} \left(1 + \frac{gm}{C}T + \frac{1}{2}\left(\frac{gm}{C}T\right)^2 + \frac{1}{6}\left(\frac{gm}{C}T\right)^3\right) \approx I_{\text{REF}} \exp\left(\frac{gm}{C}T\right). \tag{18}$$

Note that although the voltage signal E is used in the analysis, it is not used in the final implementation because the design used current variables instead of voltage variables. Also, the argument of exponential relation is independent of I_{REF} as shown in equation (18); it is only a scaling factor. Note also that the three transconductors used should be matched to avoid any distortion in the exponential characteristics. As a result, sharing the same bias subcircuit, shown in Figure 4, i.e., I_B and M1–M5, seems to be mandatory. Thus, any change in the reference voltage V_{b} or in the current source I_{B} would affect all the transconductors equally, hence keeping the relative relations between series terms unchanged. Such a sharing will also help reduce the total power consumption and the total area of the converter.

For a higher precision, the capacitor may be tuned to compensate any mismatch between the transconductors. This can be done by putting varactor diodes in parallel with $C_2$and $C_3$and tuning their values sequentially, i.e., first disabling the third integrator and tuning the varactor diode that is in parallel with C_2 and then enabling the last integrator and tuning C_3. This technique can be helpful if a larger number of terms is considered.

4. Simulation results

Figure 8 shows the simulation results of the overall circuit, where V_{control} has two pulses; the first one sets the gain to its maximum value of -70 dB, and then the gain remains constant for some time. Before changing the gain, the reset signal is activated to discharge the capacitors; then giving another pulse to V_{control} sets another value of the gain.

The gain, which is the sum of I_{REF}, I_1, I_2, and I_3 is shown on a decibel scale. Clearly the gain is increasing linearly on a decibel scale with the increase of the pulse duration, which is proportional to the control voltage that is applied to the voltage-to-time converter (as explained in Section 2.4). The gain can vary from a minimum value of -112 dB to a maximum value of -70 dB, giving a range of 42 dB.

While the dymanmic range of the circuit is 42 dB, it could be allocated starting from any artbitrary datum by either changing the reference current source or changing the gain of the final mirrors.

5. Conclusion

A novel method to generate the exponential characteristic required in VGA circuits is presented. This method has the advantage of its flexibility to increase the required dynamic range of the circuit. As a demonstration, an exponential voltage-to-current converter is presented that has an overall dynamic range of 42 dB.

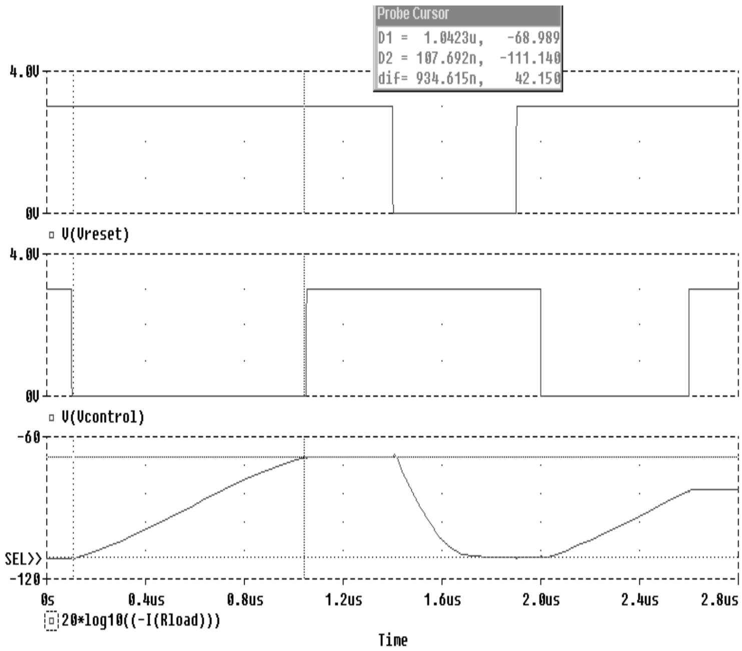

Figure 8. Output current on a decibel scale, V_{control} and V_{reset} versus time.

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