Proc. Estonian Acad. Sci. Eng., 2000, **6**, 2, 135–143
https://doi.org/10.3176/eng.2000.2.05

# BIASING ERROR CORRECTION IN AVERAGING CURRENT-MODE RECTIFIERS

Vello MÄNNAMA[a] and Brett WILSON[b]

[a] Department of Electronics, Tallinn Technical University, Ehitajate tee 5, 19086 Tallinn, Estonia; vellom@va.ttu.ee
[b] Department of Electrical Engineering and Electronics, University of Manchester Institute of Science and Technology, PO Box 88, Manchester, M60 1QD, UK; wilson@fs5.ee.umist.ac.uk

Received 14 October 1999, in revised form 26 January 2000

**Abstract.** A current-mode approach to the design of precision rectifiers and absolute value circuits has been shown to extend high-speed signal capability and reduce distortion around the zero-crossing region. However, addition of bias to the bridge diodes to improve high-speed performance restricts linearity in the transition region. This paper develops an error analysis for current-mode rectifiers over various input signal waveforms and presents a bias error cancellation technique whereby the offset effects of bridge bias can be eliminated.

**Key words:** current-mode design, pre-biased rectifier, error analysis, error cancellation.

## 1. INTRODUCTION

Recent developments in high-speed signal rectification have been based on a current steering and summation technique involving pre-biased bridge diodes for improved switching speed and output waveform fidelity [1–3]. Performance in respect of temperature and supply sensitivity has been further improved by the present authors by adopting a transferred bias scheme and an all-conveyor implementation [2,3].

However, the use of a bridge bias current of typically 30–50 μA for improved high-speed performance influences linearity of the absolute-value circuit in the zero-crossing input transition region where the input current becomes comparable to the bias current [2,3]. Although at low bias current the effect is generally negligible, in very low signal applications it may contribute more significantly to the measurement error. In this paper we analyse the influence of the bridge bias current in greater detail and demonstrate that the error depends strongly on the form of the input signal. We also examine a number of possible compensation schemes and report on their respective effectiveness.

## 2. ERROR ANALYSIS

The summed output current $I_{out}$ from a pre-biased current-mode rectifier bridge (Fig. 1) can be expressed as follows [2,4]:

$$I_{out} = \sqrt{I_{in}^2 + I_b^2}, \quad (1)$$

where $I_{in}$ is the instantaneous value of the input current and $I_b$ is the constant bridge bias current. For the average value measurements, the rectifier error $D$ for the dc component of $I_{out}$ can be defined as

$$D = \frac{I_{in(dc)} - I_{out(dc)}}{I_{in(dc)}}, \quad (2)$$

where

$$I_{in(dc)} = \frac{2}{T}\int_0^{T/2} | I_{in}(t) | \,dt,$$
$$I_{out(dc)} = \frac{2}{T}\int_0^{T/2} | I_{out}(t) | \,dt. \quad (3)$$

The rectifier error depends on the ratio of the bias to signal current and also on the shape of the input signal. Below we consider three common input waveforms: a rectangular wave with variable duty cycle, a triangular wave, and a sine wave.

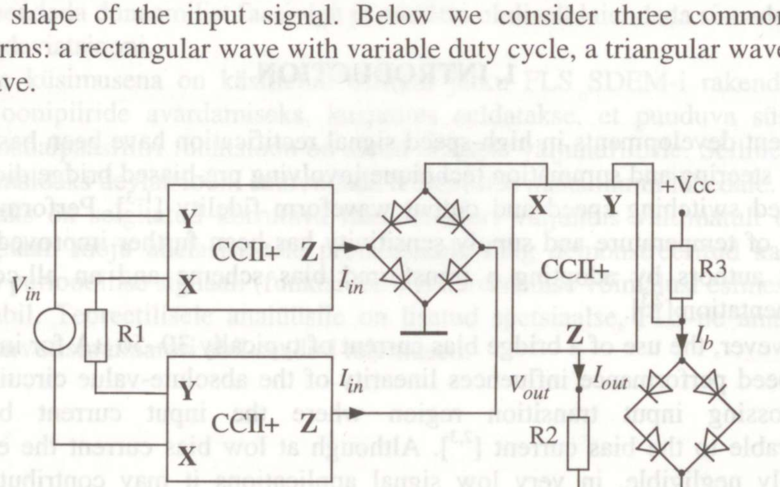


**Fig. 1.** All-conveyor wideband rectifier.

An input current with a rectangular waveform can be described by

$$I_{in}(t)=\begin{cases} I_M, \text{ if } nT<t\le \dfrac{2n+1}{2}T, \\ -I_M, \text{ if } \dfrac{2n+1}{2}T<t\le (n+1)T, \\ n=0,1,2,..., \end{cases} \quad (4)$$

where $I_M$ is the amplitude of the signal and $T$ its period. Since in this case the dc component of the rectified signal is equal to its amplitude, the rectifier error $D_r$ can be expressed as

$$D_r=\left(\sqrt{I_{br}^2+1}\right)-1, \quad (5)$$

where $I_{br}=I_b/I_M$ is the relative bias current.

For the general case of rectangular pulses with duty cycle $k$, the error is

$$D_r(k)=\left(\sqrt{I_{br}^2+1}\right)-1+\left(\frac{1-k}{k}\right)I_{br}, \quad (6)$$

and Eq. (5) can be considered as a particular case for $k=1$. The variation of the rectifier error as a function of the bias current for rectangular signals with various values of $k$ is shown in Fig. 2, according to which the error reduces with decreasing relative bias current, as expected.

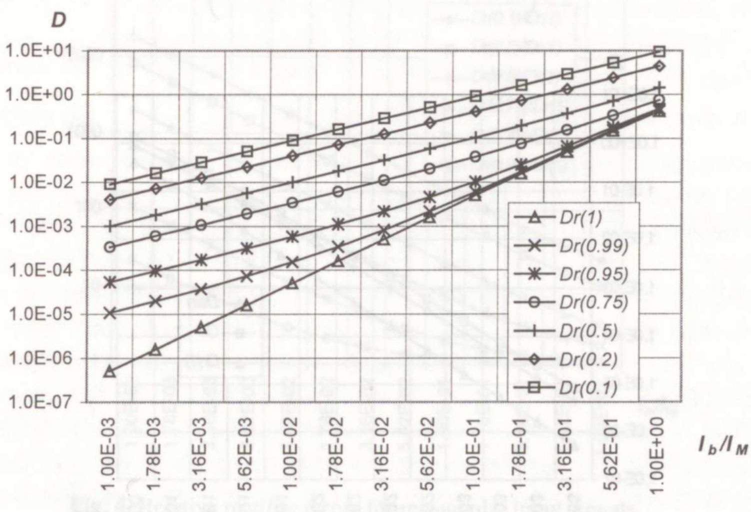


**Fig. 2.** Rectifier error *Dr*(*k*) as a function of the relative bias current for a rectangular input signal with varying duty cycle *k*.

However, the rate of error reduction depends on the duty cycle $k$ of the input waveform. As $k$ decreases, the level of error increases for fixed values of the relative bias current. Thus for very low duty cycles, a relatively large error can result even at low bias current.

If the input current has a triangular form with peak value $I_M$, then

$$I_{in}(t)=\begin{cases} 4\left(\dfrac{t}{T}-n\right)I_M, & \text{if } \dfrac{4n-1}{4}T<t\le\dfrac{4n+1}{4}T, \\ 4\left(n+\dfrac{1}{2}-\dfrac{t}{T}\right)I_M, & \text{if } \dfrac{4n+1}{4}T<t\le\dfrac{4n+3}{4}T, \\ n=0,\,1,\,2,\,..., & \end{cases} \tag{7}$$

in which case the associated rectifier error $D_{tri}$ can be expressed as

$$D_{tri}=\left(\sqrt{I_{br}^2+1}\right)-1+I_{br}^2\ln\left(\left(1+\sqrt{I_{br}^2+1}\right)\Big/I_{br}\right). \tag{8}$$

The behavior of $D_{tri}$ as a function of the relative bias current follows a pattern similar to the square wave case, as shown in Fig. 3.

For a sine wave input waveform with peak current $I_M$, we can evaluate the associated rectifier error $D_{\sin}$ from

$$D_{\sin}=\left(\int_0^{T/2}\left(\sin^2\left(\frac{2\pi t}{T}\right)+I_{br}^2\right)^{1/2}\mathrm{d}t\right)-1. \tag{9}$$

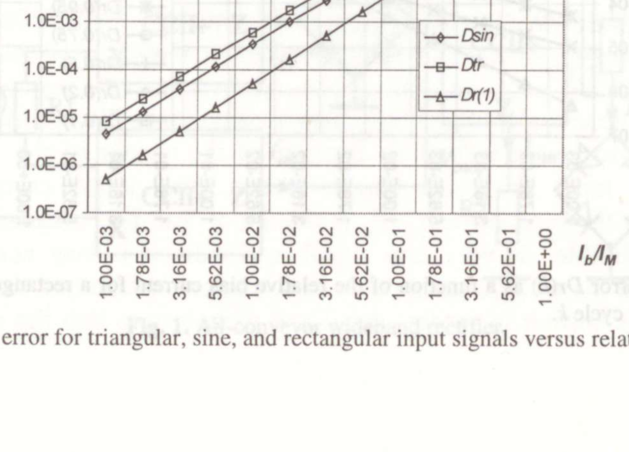


**Fig. 3.** Rectifier error for triangular, sine, and rectangular input signals versus relative bias current.

The resulting error for the sine wave case exceeds the error for a square wave, but is less then the error for a triangular wave input signal.

Comparing the rectifier error for various waveforms, it is evident from Eqs. (5)–(9) and Figs. 2–4 that the influence of the bias current is more significant for the signals having relatively low amplitudes, as expected. In the case of small values of $I_{br}$, the rectifier error for rectangular signals with $k << 1$ is proportional to $I_{br}$, while for square, triangular, and sine waves it is proportional to the square of the bias current, resulting in a twofold difference in the slope of the relationship between the error and the relative bridge bias.

The rectifier error may also be cast in the form of a relative error for rectangular input signals, compared to a square wave, as shown in Fig. 4. Errors for different input signal waveforms are compared in Fig. 5.

According to Figs. 4 and 5, the relative error of the rectangular signal with $k < 1$ increases if the relative bias current decreases, which differs from the behaviour of the sine wave and triangular wave errors as a function of relative bias current. The curves in Figs. 2 to 5 can be interpreted both for fixed $I_M$ and variable $I_b$, as well as for variable $I_M$ and fixed $I_b$. Since the X-terminal resistance of the conveyor at the bridge output has a finite value, the influence of the bias current under conditions of higher peak input current is marginally less than suggested by Eq. (1).

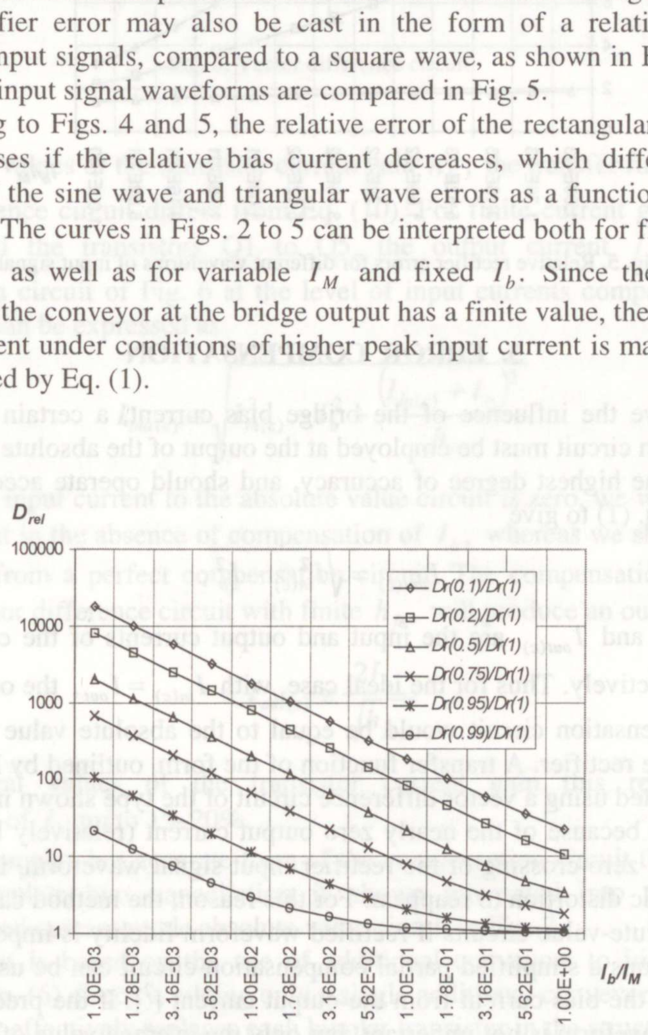


**Fig. 4.** Relative rectifier errors for rectangular input signals.

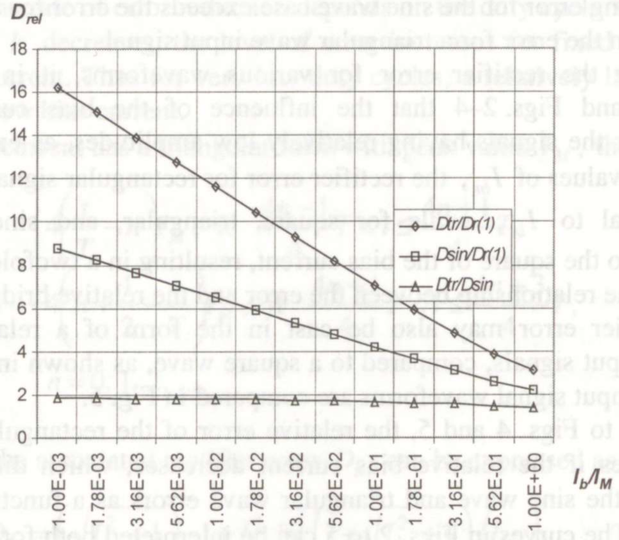


**Fig. 5.** Relative rectifier errors for different waveforms of input signals.

## 3. ERROR COMPENSATION

To remove the influence of the bridge bias current, a certain form of the compensation circuit must be employed at the output of the absolute value circuit to achieve the highest degree of accuracy, and should operate according to the inverse of Eq. (1) to give

$$I_{out(c)} = \sqrt{I_{in(c)}^2 - I_b^2}\,, \tag{10}$$

where $I_{in(c)}$ and $I_{out(c)}$ are the input and output currents of the compensation circuit, respectively. Thus for the ideal case, with $I_{in(c)} = I_{out}$, the output current of the compensation circuit would be equal to the absolute value of the input current of the rectifier. A transfer function of the form, outlined by Eq. (10), can be implemented using a vector difference circuit of the type shown in Fig. 6 [5].

However, because of the nearly zero output current (relatively large voltage excursion) at zero-crossing of the rectifier input signal waveform, its use would cause dynamic distortion to reappear. For this reason, the method cannot be used for fast absolute-value circuits if rectified waveform fidelity is important. Under these conditions a simplified partial compensation circuit can be used simply to subtract half the bias current from the output current [2]. If the precise shape of the output waveform is not important, but only the average value of the rectified current is desired using time integration of the output current, an inexact dynamic restoration of the rectified waveform has only a small influence on the averaged signal magnitude. Then, the vector difference circuit can be employed to provide effective compensation.

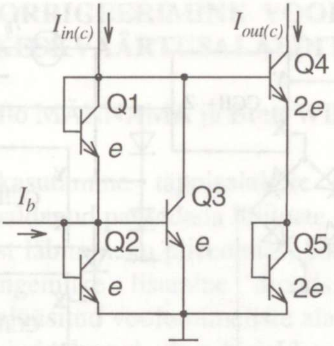

**Fig. 6.** Vector difference circuit.

For finite values of the transistor current gain $h_{fe}$, the transfer function of the vector difference circuit differs from Eq. (10). For finite current gains that are equal for all the transistors Q1 to Q5, the output current $I_{out(c)}$ of the compensation circuit of Fig. 6 at the level of input currents comparable to the bias current can be expressed as

$$I_{out(c)} \cong \sqrt{I_{in(c)}^2 - I_b^2 + \frac{\left(I_{in(c)} + I_b\right)^2}{h_{fe}}}. \tag{11}$$

When the input current to the absolute value circuit is zero, we will obtain an output current in the absence of compensation of $I_b$, whereas we should ideally obtain zero from a perfect compensation circuit. The compensation, available from the vector difference circuit with finite $h_{fe}$, will produce an output current

$$I_{out(c)} \cong \frac{2I_b}{\sqrt{h_{fe}}}. \tag{12}$$

For typical values of the transistor current gain this represents an improvement of $I_b$ up to 15–20%.

A more complex but accurate form of the compensation circuit that produces virtually complete bias cancellation is shown integrated into the previous conveyor-based current-mode absolute value circuit in Fig. 7.

The circuit is based on the use of additional conveyors to implement the function of Eq. (6) directly, adding only a single additional conveyor to the direct signal path. It effectively replaces each bipolar transistor in the structure of Fig. 6 with a "diamond" transistor formulation and using an additional CCII+ module to give the necessary current inversion [6]. This all-conveyor bias-cancellation structure can therefore be fabricated from a unified component base (diodes and "diamond" transistors) to give significant technological advantages.

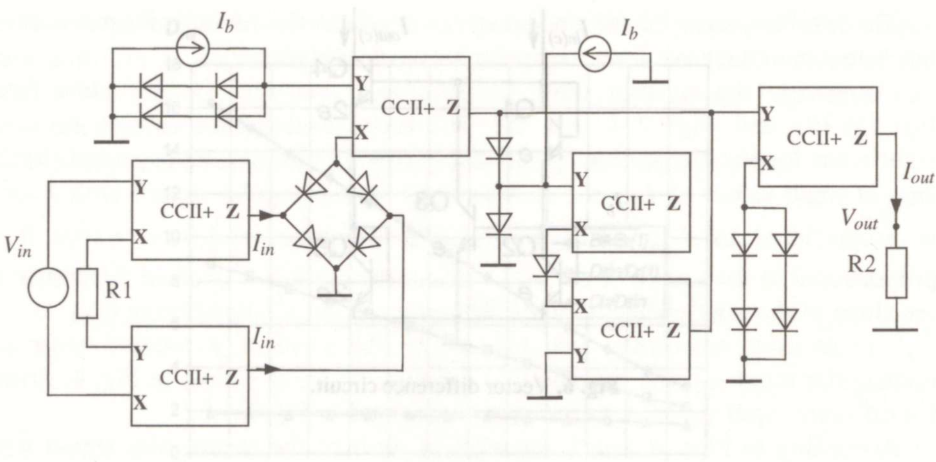


Fig. 7. All-conveyor rectifier with complete bias current cancellation.

## 4. CONCLUSION

It is shown that current-mode absolute-value circuits display a number of advantages compared to traditional operational amplifier/rectifier circuits, but still retain a residual error in the waveform crossover region because of the bridge pre-bias current. In principle, compensation of the resulting error is possible using a vector difference circuit, but in practice it reintroduces again distortion at high speeds, making it unsuitable for use in fast absolute-value circuits and restricting its use to time-averaged application measurements. An all-conveyor bias cancellation scheme is described that overcomes the previous objections and can be used in all high-speed applications.

## REFERENCES


1. Lidgey, F. J., Hayatleh, K., and Toumazou, C. New current-mode precision rectifiers. In *Proc. IEEE International Symposium on Circuits and Systems*. Chicago, 1993, 1322-1325.
2. Wilson, B. and Männama, V. Current-mode rectifier with improved precision. *Electron. Lett.*, 1995, **31**, 247–248.
3. Wilson, B., Dodd, A. J., and Männama, V. Very high-speed signal rectification using current conveyors. In *Proc. Baltic Electronics Conference BEC'96*. Tallinn, 1996, 421–424.
4. Männama, V. Current-mode signal processing circuits. *Proc. Estonian Acad. Sci. Eng.*, 1997, **3**, 4, 237–249.
5. Gilbert, B. Current-mode circuits from a translinear vievpoint: A tutorial. In *Analogue IC Design: The Current-mode Approach*. Peter Peregrinus, London, 1990.
6. Wide bandwidth operational transconductance amplifier OPA660. In *Burr-Brown IC Data Book. Linear Products*. Burr-Brown Corp., Tuscon, 1994, 2296–2313.

# NIHKEVEA KORRIGEERIMINE VOOLUTOIMELISTES KESKVÄÄRTUSALALDITES

Vello MÄNNAMA ja Brett WILSON

Voolutoimetehnika kasutamine täppisalaldite ja absoluutväärtuslülituste projekteerimisel on võimaldanud parandada lülituste kiirusomadusi ja vähendada signaali moonutusi nullist läbimineku piirkonnas. Samas piirab aga toimekiiruse tõstmiseks vajaliku pingenihke lisamine dioodsillale lülituste lineaarsust siirdealal. Artiklis on analüüsitud voolutoimeliste alaldite mõõtevigade iseloomu mitmesuguste signaalikujude korral ning kirjeldatud tehnikat, mis võimaldab kompenseerida silla nihkepingest põhjustatud vigu.