# New Current-Mode Full-Wave Precision Rectifier Based on Two CCII- and Two Diodes

Milan Vesković, Slobodan Djukić

***Abstract*—Precision full-wave rectifier with two current conveyors, two diodes and without any passive component is shown. The theory of the rectifier operation is described and analyzed. In the presented rectifier input signal can be only rectified, but at the same time it can also be rectified and amplified or rectified and attenuated. The current mode technique has been employed in order to provide the high-precision capability of the circuit. PSPICE program has been used to verify the proposed design of the current-mode precision full-wave rectifier. To evaluate the accuracy of the current-mode full-wave rectifier generalized frequency response concept is used.**

***Index Terms*—Signal processing, current mode circuits, current conveyor, precision rectifier, generalized frequency response.**

## I. Introduction

Precision rectifiers are important building blocks for signal processing, conditioning and instrumentation of low-level signals and they are extensively used in wattmeters, AC voltmeters, RF demodulators, linear function generators, and various nonlinear analogue signal-processing circuits. The operation of diode-only rectifiers is limited by the threshold voltages of diodes, approximately 0.3 V for germanium diodes and 0.6 V for silicon ones. Therefore diode-only rectifiers are used only in those applications in which the precision in the range of threshold voltage is insignificant, such as DC voltage supply rectifiers. Better implementation of precision full-wave rectifiers is based on using op-amps with diodes within the feedback path to provide the necessary non-inverting gain for positive input signals and inverting gain for negative input signals as shown by Toumazou and Lidgey [1]. However, the classical problem with rectifiers based on diodes and op-amps is that during the non-conduction/conductions transition of the diodes the op-amps must recover with a finite small-signal dV/dt resulting in significant distortion during the zero crossing of the input signal. The use of the high slew-rate op-amps does not solve this problem because it is small-signal transient problem. These rectifiers are limited to frequency performance well below the gain-bandwidth performance product $f_T$ of the amplifier as shown by Djukic [2]. This limitation is improved with designing the rectifiers by the use of current mode techniques.

The current-mode full-wave rectifiers using second type current conveyors (CCII) as the voltage to current converter have received much attention in scientific literature as shown by Khan et al. [3] and Gift and Monday [4]. Full-wave rectifier developed by Toumazou et al. [5], with addition of a DC source, tends to reduce the distortion due to small signal dV/dt limitation. Rectifier proposed by Hayatleh et al. tends to reduce the effect of temperature on the zero-crossing performance by using a current source and resistor instead the DC voltage source, as shown by Hayatleh et al. [6], and Djukic [7]. In both cases, the frequency response of the circuit was improved because the diodes were initially turned on thereby reducing the time to force them into full conduction. Monpapassor et al. have suggested a full-wave rectifier with second type current conveyor, four current mirrors, three DC current sources and two grounded resistors as shown by Monpapassorn et al. [8]. The proposed rectifier is temperature stable, has small rectifying error and is suitable for IC fabrication.

On the other hand, the proposed rectifier has several disadvantages. First, the current conveyor has an imprecise voltage transfer function because the value of the effective resistance $r_x$, seen at the inverting terminal of the conveyor is not zero, and its value cannot be known with a high degree of accuracy. Second, there is a severe distortion, particularly at the zero-crossing point of the input signal, arising from the on-off switching of the transistors positioned between the current conveyor and current mirrors. Third, this switching, as well as the large number of the current mirrors, limits the frequency performance of the circuit. Finally, the input sensitivity, i.e., the peak amplitude of the lowest input signal that can be rectified, is limited by the action of the mentioned transistors.

Kumngern and Dejhan propose realization with CCII, seven current mirrors, two diodes and five grounded resistors as shown by Kumngern and Dejhan [9]. The proposed configuration is very suitable for integrated circuit implementation both in bipolar and CMOS technologies. Sahu et al. [10] propose a precision full-wave rectifier using an all-pass filter that acts as a 90 degrees phase shifter, two squaring circuits, one summer, and one square rooter. Koton et al. [11] have suggested full-wave rectifier with current and voltage conveyors. Yuce et al. [12] have suggested full-wave rectifier

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with two second type current conveyors and three NMOS transistors without any passive components. Gift [13] proposed a new operational conveyor full-wave rectifier with current-mode absolute-value circuit. This circuit consists of complementary common base transistors biased by current sources and diode connected transistors. Unfortunately, this realization does not eliminate output offset voltage, which makes significant difficulties when we want to rectify small amplitude signal.

This paper presents a simple design with two current conveyors, two diodes, two DC voltage sources, one DC current source, and without any resistors. Proposed rectifier is suitable for small-amplitude signals rectifying. Current conveyor based on current steering output stage with good voltage and current transfer characteristic, without $r_x$ resistance, is used for rectifier design.

## II. Current Conveyor Implementation Employing Current-Steering Output Stage

In the case of current-mode processing circuits we always have a need to make copy of the current and we make it with different type of the current conveyor [14]. The second type of the current conveyor (negative) can be represented as a three terminal device in which voltage applied to high-impedance terminal Y is buffered with unity gain to the terminal X, and current from terminal X is mirrored to terminal Z. Symbol of the current conveyor is presented in Fig 1.

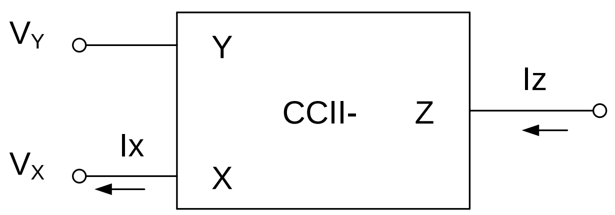



Fig. 1. Symbol of the second type current conveyor (negative)

Mathematically, the second type of the current conveyor (negative) can be described by the matrix equation:

$$\begin{bmatrix} I_Y \\ V_Y \\ I_Z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & r_x & 0 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} V_X \\ I_X \\ V_Z \end{bmatrix} \quad (1)$$

or by three linear equations:

$$V_Y = V_X + r_x I_X \quad (2)$$

$$I_Y = 0 \quad (3)$$

$$I_Z = -I_X \quad (4)$$

where $r_x$ is input resistance seen at the inverting terminal of the current conveyor.

In the case that the value of $r_x$ is approximately zero, we have an ideal current conveyor.

A new current-conveyor formulation based on current-steering output stage [15] which detailed explanation is done in the paper [16,17], will be used in this paper.

## III. Proposed Rectification Circuit

At the beginning real and approximate volt-ampere characteristic of a small-signal diode has to be shown. Volt-ampere characteristic for small-signal silicon diode in the direct polarization is presented in Fig. 2 (full line). Theoretical considerations result in the following relation for current and voltage in a junction diode:

$$i_D = I_s \left[ \exp\left( \frac{v_D}{V_T} \right) - 1 \right] \quad (5)$$

where Is represent reverse saturation current and has a value on the order of 0.01pA for small-signal junction diode (1N4148) at room temperature. $V_T$ is thermal voltage, at room temperature it amounting to $V_T$ =26 mV. Therefore, the current begins to flow at the voltage $V_\gamma = v_D = 0.5$ V, and within $V_\gamma < v_D < V_f$ functional dependence is not linear, and for $v_D > V_f$ ampere-volt characteristic is linear with the slope $1/R_f$ ($R_f$ is diode resistance in the direct polarization and $V_f$ is ca 0.6 V for Si-diode). Thus, diode characteristic for direct polarization can be approximated with voltage battery $V_f$ in series with resistance $R_f$ (dot line). Also, it can be noticed that small current I0 flows through diode at the voltage $V_f$. Therefore, in order to put the diode on the edge of conduction, battery $V_B$ for direct polarization has to be used, and the following relation has to be fulfilled

$$V_\gamma < V_B \leq V_f \quad (6)$$

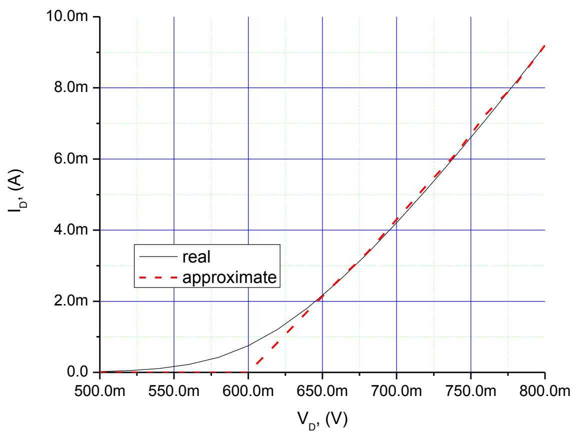



Fig. 2. Characteristic $I_d = f(V_d)$: a) real- full line, b) approximate - dash line.

Proposed full-wave rectifier circuit is presented in Fig. 3.

Functional explanation for the proposed full-wave rectifier is as follows:

$V_{in}$ = 0, DC currents $I_0$ flow through diodes D1 and D2, and these currents are provided by the DC current sources $2I_0$, $V_{x1} = 0$, $V_{x2} = V_B$, $V_{out} = 0$.

$V_{in}$ +, additional current $i_{x1}$ (thick arrow) flows through diode D1 and the following equation can be set:

$$V_{in} - V_f - R_f\, i_{X1} + V_B = 0 \Rightarrow i_{X1} = \frac{V_{in}}{R_f} \quad \left(V_B \cong V_f\right) \qquad (7)$$

and output voltage of the rectifier is

$$V_{out} = -R_L\, i_{X1} = -\frac{R_L}{R_f} V_{in} \qquad (8)$$

$V_{in}$ -, additional current $i_{x2}$ (thick arrow) flows through diode D2 and the following relation is reached:

$$V_{in} + V_f + R_f\, i_{X2} - V_B = 0 \Rightarrow i_{X2} = -\frac{V_{in}}{R_f} \quad \left(V_B \cong V_f\right) \qquad (9)$$

and output voltage of the rectifier is

$$V_{out} = -R_L\, i_{X2} = \frac{R_L}{R_f} V_{in} \qquad (10)$$

Generaly, the following equation for positive and negative input signal, is valid

$$V_{out} = -\frac{R_L}{R_f} \left|V_{in}\right| \qquad (11)$$

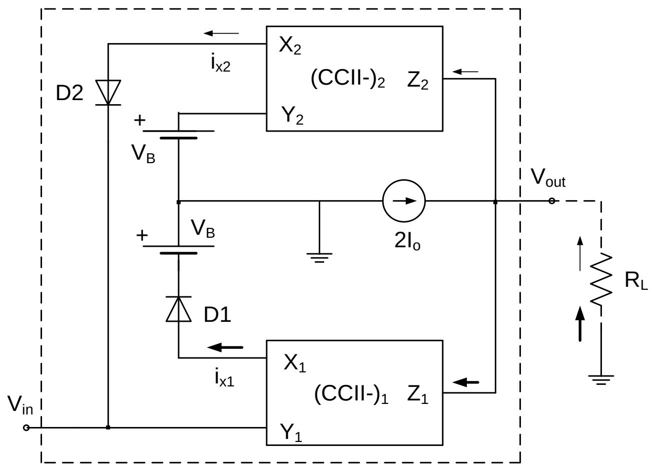



Fig. 3. Proposed precision full-wave rectifier.

Therefore, we have proved that the circuit in Fig. 3 is full-wave rectifier with amplification or rectifier with attenuation. The DC current source $2I_0$ is used for ellimination of the offset voltage at the rectifier output. It is important to note that an increasing of $V_{in}$ in positive direction causes the offset current $I_0$ through D2 goes down, and it becomes zero for $V_{in} > V\gamma$, causing an increase of the offset current of D1 to $2I_0$. In our case it is not important because the circuit rectifies small-amplitude input signal.

## IV. Simulation Results

The proposed full-wave rectifier is realised as shown in Fig. 3, with: I ($V_B$ = 0.58 V, $I_0$ = 1.4 mA, $R_L$=28 Ω), II ($V_B$ = 0.6 V, $I_0$ = 0.74 mA, $R_L$=26 Ω), III ($V_B$ = 0.62V, $I_0$ = 1.7 mA, $R_L$=25.4 Ω). Fast diode 1N4148, whose characteristic $i_D = f(v_D)$ is shown in Fig. 2, has been used in the circuit. From Fig. 2 we can conclude that $R_f$ changes the value within range 20 Ω ≤ $R_f$ ≤ 50 Ω, and value for $R_L$ must be variable for unity gain of the rectiffier. All npn transistors in the circuit are 2N3904 and all pnp transistors are 2N3906. Operational amplifier TL082 uses FET transistors at differential entry points and has small DC bias currents.

Transfer characteristic of the full-vave rectifier is shown in Fig. 4.

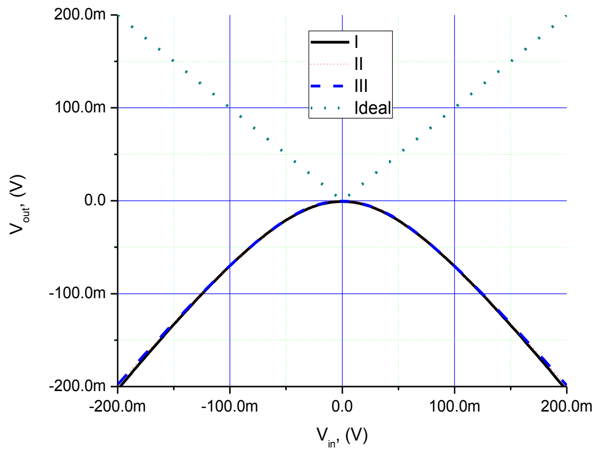
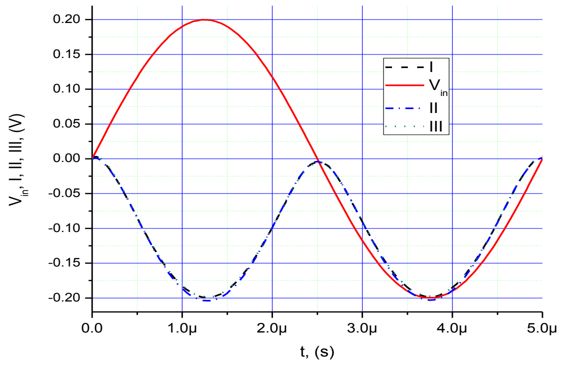


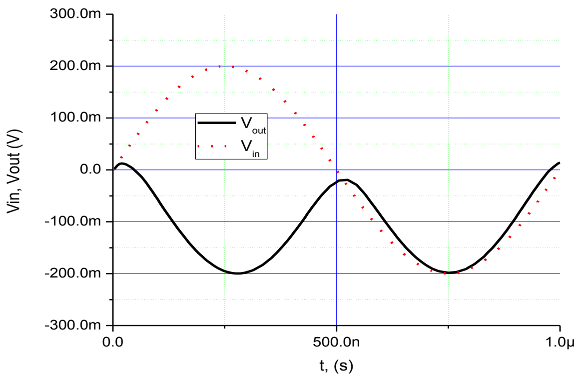

Fig. 4. Transfer characteristic of the proposed full-wave rectifier.

From transfer characteristic of the proposed full-wave rectifier it is clear that there is no dead zone at input signal zero crossing. Also, a significant deviation from ideality occurs (mathematically equation y = -|x|). The deviation from ideality is a consequence of $R_f$ variability.

Rectified output of the proposed rectifier for 200 $mV_{pk}$ input signal and frequency a) 200 kHz, I, II, III b) 1 MHz, II, is shown in Fig. 5.




a)




b)

Fig. 5. Rectified output for $V_{in}$= 200 mV: a) I, II,III, f = 200 kHz, b) II, f = 1 MHz.

Since the rectifier is a significantly nonlinear device, the conventional AC analysis cannot be used for evaluating the quality of its high-frequency operation, and the concept of the generalized frequency response (GFR) will be used [18-21]. Average Value Ratio (AVR) is the first characteristic of the rectifier, and can be calculated as

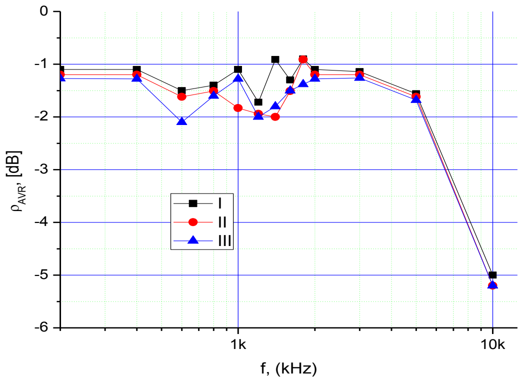
$$\rho_{AVR} = \frac{\frac{1}{T}\int_T v_{rect}(t)\,dt}{\frac{1}{T}\int_T v_{ideal}(t)\,dt} \quad (12)$$

Here, $v_{rect}(t)$ is signal at the output of the rectifier, $v_{ideal}(t)$ is absolute value of the input signal, and the T is signal repetition period. The ideal operation of the rectifier is characterized by the value, $\rho_{AVR} = 1$.

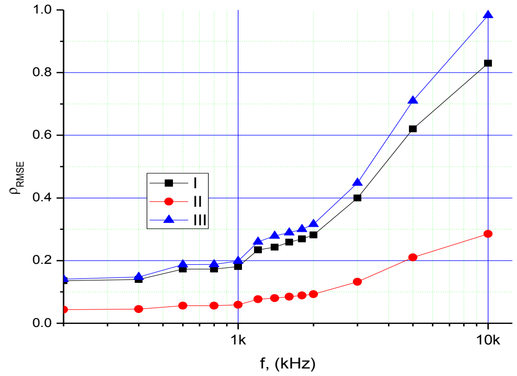
The second characteristic is ratio of the two RMS values, the RMS of the difference of the real and ideal output $v_{rect}$ and $v_{ideal}$, and the RMS value of the ideal signal, and can be calculated as

$$\rho_{RMSE} = \sqrt{\frac{\frac{1}{T}\int_T \left[v_{rect}(t) - v_{ideal}(t)\right]^2 dt}{\frac{1}{T}\int_T \left[v_{ideal}(t)\right]^2 dt}} \quad (13)$$

For ideal rectifier circuit we have $v_{rect}(t) = v_{ideal}(t)$, the result is $\rho_{RMSE} = 0$, while in the case of total attenuation of the input signal it is $\rho_{RMSE}=1$.




a)




b)

**Fig. 6.** Generalized frequency response of the rectifier for input signal of the $V_{in}$=200 mV and I ($V_B$ = 0.58 V, $I_0$ = 1.4 mA, $R_L$=28 Ω), II ($V_B$ = 0.6 V, $I_0$ =0.74 mA, $R_L$=26 Ω), III ($V_B$ = 0.62V, $I_0$ =1.7 mA, $R_L$=25.4 Ω) a) AVR versus frequency, b) RMS error versus frequency

The transient analysis of the rectifier was performed repeatedly over a time interval of 5μs for the input signal of 200 mV, and for frequencies from 200 kHz to 10 MHz. To eliminate transients at the beginning of the analysis runs, integral characteristics (12) and (13) of the rectified signal were computed from 2.5 μs to 5 μs.

As can be seen from Fig. 6(a), the rectified voltage has attenuation of ca 0.87 for the frequencies below 4 MHz, and the 3dB bandwidth of DC value transfer is ca 6 MHz. Voltage attenuation at the output of the proposed rectifier is consequence of the DC transfer characteristic (his deviation from ideality). Fig 6 (b) shows that the polarization of the diodes with VB=0.6V is with the smallest RMS error.

## V. CONCLUSION

A CCII- based full-wave rectifier has been presented in this paper. The circuit employs two CCII-, two diodes, two DC voltage sources and one DC current source. The circuit is realized for rectifying small-amplitude signals, but it can be modified for high-amplitude signals as well. Furthermore, the proposed circuit is very simple for implementation in the BJT technology and no buffering is needed if the load driven has low impedance. Concept of the generalized frequency response is used to evaluate high-frequency performances of the rectifier. Current conveyor based on current steering output stage presented here, overcomes the problem of limited current and voltage transfer accuracy.

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