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# Analysis of Dynamic Performance of Half-Wave Rectifiers and its Improvements

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***Abstract*—This paper deals with the analysis of dynamic behaviour of half-wave rectifiers and compares circuit solutions using standard operational amplifiers and current conveyors as active elements. The voltage and current sourcing principle and their influence to dynamic limits of diodes are given. Using the voltage or current biasing scheme, improvements in the dynamic performance of the diodes and rectifier are shown and discussed. The theoretical conclusions are supported by experimental results.**

***Index Terms*—Current conveyor, current sourcing, rectifier, voltage sourcing.**

## I. INTRODUCTION

For the design of analogue circuits a number of active elements can be used. Probably, the most known is the voltage feedback amplifier (VFA), more often called as operational amplifier (opamp). The internal structure of the opamp generally consists of two stages: differential pair and output buffer. If the voltage buffer is omitted, the operational transconductance amplifier (OTA) is defined [1]. Another group of active elements used for the design of analogue function blocks are the current conveyors (CCs) and their three generation CCI [2], CCII [3], and CCIII [4], where the second generation current conveyor (CCII) is probably mostly discussed one.

Theoretically, thanks to the infinite voltage gain and infinite transit frequency ($f_T$) of the opamp, the behaviour of the function blocks using this active element is described by the feedback suitably created in the circuit [1]. Anyway, once real active elements are used, this advantageous feature is valid only for linear circuits or non-linear circuits operated in the frequency areas much below the value of $f_T$. In non-linear circuit design, the attention is mainly focused on rectifiers. A full-wave rectifier using two CCIIs and four diodes has been presented [5]. Based on the experimental measurements, it has been shown that compared to circuits using VFAs, better dynamic performance can be achieved, however, without any discussion of the reasons. In [5], [6] and later in [7] the voltage and current biasing scheme have been presented on circuits using current conveyors, respectively. Using these techniques, it has been shown that the dynamic performance of non-linear circuits employing conveyors as active elements can be further improved but again, without giving any description of the reasons.

In this paper, the dynamic behaviour of the diodes is given and based on the analysis results, the techniques leading to improvements of the non-linear circuits dynamic behaviour are described in more details.

## II. DYNAMIC FEATURES OF DIODES

The relation between voltage ($v_D$) and current ($i_D$) flowing through an ideal silicon diode can be described by the Shockley equation, whereas for $v_D$ > 100 mV it can be simplified to [1]

$$i_D \approx I_0 \exp\frac{v_D}{V_T}, \tag{1}$$

where $I_0$ is the reverse saturation current, and $V_T = k\mathrm{T}/\mathrm{q}$ is the temperature voltage ($V_T \approx 26$ mV at room temperature).

However, (1) is valid only for sufficiently slow changes in voltage and current, when the concentration of charge carriers across the PN junction is always steady for each value of alternating signal. In case of very fast changes in voltage and current, not enough charge carriers leading to steady state are injected into the PN junction. Therefore, during the changes between conductive (ON) and non-conductive (OFF) state of the PN junction, the times of generation and recombination representing finite speed of gradual accumulation and emptying of free charge start to apply significantly. Hence, (1) starts to be valid first after transition time that is mainly affected by two capacitances representing the space charge ($C_j$ – junction capacitance), and the excess minority carrier charge ($C_d$ – diffusion capacitance). The diffusion capacitance is dominant during the conductive state of the diode, the junction capacitance in non-conductive state [1].

To analyse the dynamic events ongoing in a diode, it is suitable to follow the behaviour of the PN junction connected in series with the resistor $R_S$ to a pulse source. In Fig. 1(a)) a basic circuit of a diode connected to a pulse voltage source is shown and in Fig. 1(b)) corresponding transient responses of voltage and current flowing through

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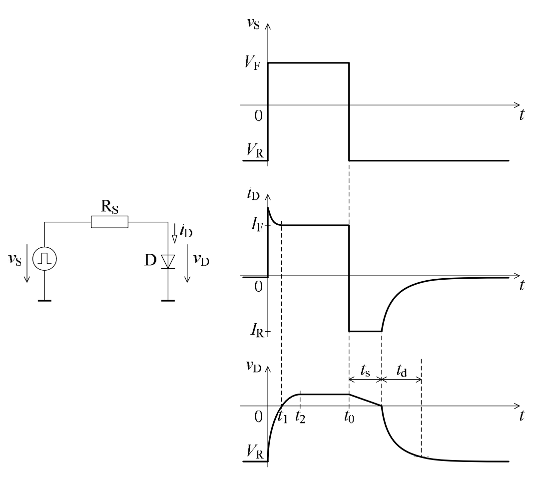
the diode are given, where the change of ON and OFF states in times $t = 0$ and $t = t_0$ is expected. For $t < 0$ the PN junction is in non-conductive state and through the circuit flows only reverse saturation current $I_0$. Therefore, almost all the reverse voltage $V_R$ is across the diode, i.e. across the junction capacitance $C_j$. At the time of $t = 0$, the current flowing through the diode is $i_D(0) \approx (V_F - V_R)/R_S$. The voltage across the diode grows from the value of $V_R$ and the capacitance $C_j$ starts to discharge with the time constant $\tau = R_S C_j$. At the time $t_1$ (turn-on time), the junction capacitor is discharged and therefore $v_D(t_1) \approx 0$ V. Then, the current stays constant $i_D(t) = [V_F - v_D(t_1)]/R_S \approx V_F/R_S = I_F$. The voltage across the diode still grows till the time $t_2$, when the concentration of minority carrier charge in the area of PN junction reaches its steady state. The stored charge $Q$ creates the diffusion capacitance $C_d$.

Now, after the PN junction reached the steady state, in time $t_0$, it comes to the change of voltage polarity of the pulse source from $V_F$ to $V_R$. If the diode should reach its OFF state, first it is necessary to let the minority carrier charge to recombine. This happens during the storage delay time $t_s$ that can be expressed as [8]

$$t_s = \tau_T \ln\left(1 + \frac{I_F}{I_R}\right), \tag{2}$$

where $\tau_T$ is the excess minority carrier lifetime. Its value is dependent on the amount of accumulated charge $Q$ and current flowing through the diode. At time $t_0$ the current drops to the value $i_D(t_0) = [V_R + v_D(t_0)]/R_S \approx V_R/R_S = I_R$ and stays constant during the $t_s$ time. Once the minority carrier charge is removed, the PN junction moves to its non-conductive state (e.g. $v_D(t) < 0$), capacitance $C_j$ starts to charge to the voltage $V_R$ and the current flowing through drops. The delay time $t_d$ is described, representing the time needed to reach the value of 90 % $V_R$ across the diode and is defined as [8]

$$t_d = R_S C_j \ln 10 = 2.3 R_S C_j. \tag{3}$$




(a) (b)

Fig. 1. (a) Basic diode circuit connected to a pulse source, (b) corresponding transient responses of voltage and current.

During the time $t_d$ the current flowing through the diode drops to the value of 0.1 $I_0$, which is very close to the reverse saturation current $I_0$. The time needed to switch OFF the diode is given as a sum of the storage delay time (2) and delay time (3)

$$t_{rr} = t_s + t_d, \tag{4}$$

and is called as reverse recovery time.

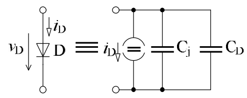



Fig. 2. Simplified model of the diode used for dynamic analysis [8].

Based on the description above, for the dynamic performance analysis of circuits containing diodes, it is suitable to use the simplified model of the diode as shown in Fig. 2. This model can be further simplified for the ON and OFF state of the diode. [8].

## III. Analysis of Voltage and Current Diode Sourcing

A very well known circuit solution realizing a half-wave rectifier employing single operational amplifier is shown in Fig. 3(a)). For positive input voltage the diode $D_1$ and diode $D_2$ is in the OFF and ON state, respectively. Hence, the structure behaves as a simple inverting amplifier with the output voltage

$$v_2 = -\frac{R_2}{R_1} v_1, \tag{5}$$

where $v_1 > 0$. Once the input voltage is negative, at the output of the opamp there is positive voltage that opens the diode $D_1$ and diode $D_2$ is in the OFF state. The output voltage $v_2$ is then zero.

The above given description of the half-wave rectifier is very simple, however, valid only for slow signals, where the recovery times (turn-on time and reverse recovery time) can be neglected compared to the period of the processed signal. As described in Section II, the biggest influence on the dynamic performance of the diode has the reverse recovery time $t_{rr}$ (4) and hence significantly affects the real behaviour of the whole non-linear function block.

Assuming the reverse recovery time of the diodes, as the input voltage changes its polarity from negative to positive, the diode $D_1$ stays open during $t_{rr1}$. Because of the turn-on time, the diode $D_2$ stays in non-conductive state. Similarly, if the input voltage changes its polarity from positive to negative, the diode $D_2$ stays open during $t_{rr2}$ and the output voltage is not zero as it is expected in theory. This behaviour can generally be seen in the transient responses of the half-wave rectifier for different frequencies shown in Fig. 4.

As already mentioned in the introduction, a full-wave rectifier using two second generation current conveyors and four diodes has been presented in [5]. This circuit can be simplified into a half-wave rectifier as shown in Fig. 3(b). Positive input voltage $v_1$ causes a current ($i$) flow through theresistor $R_1$ that is conveyed into Z terminal of the active element. This current opens the diode $D_1$.

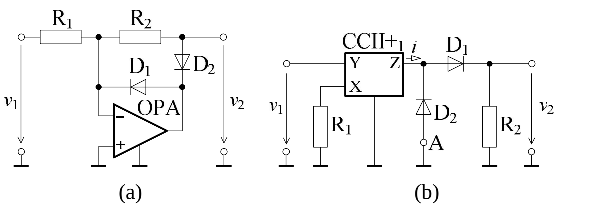


Fig. 3. Half-wave rectifier employing, (a) operational amplifier, (b) current conveyor.

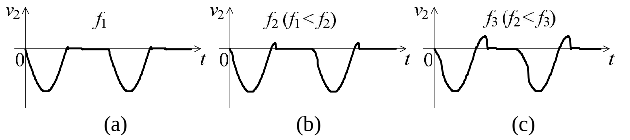


Fig. 4. The influence of the reverse recovery time of the diodes in half-wave rectifier from Fig. 3(a).

The diode $D_2$ stays in the OFF state and the output voltage of the circuit can be described as

$$v_2 = \frac{R_2}{R_1} v_1, \tag{6}$$

where $v_1 > 0$. For negative input voltage, the diode $D_2$ in ON and through diode $D_1$ flows only reverse saturation current and hence, the output voltage can be assumed to be zero.

When the input signal changes its polarity, the dynamic events ongoing in the diodes from Fig. 3(b) are the same as given in Section II. However, now the diodes are connected to a current source with high internal impedance. In case of the opamp, the diodes are connected to the voltage source with low internal impedance. From behavioural modelling point of view, this low internal impedance can be represented as a series combination of an inductor $L_0$ and resistor $R_0$ as shown in Fig. 5. Even if a high-speed opamp would be used, the inductor $L_0$ causes limitations in slew-rate of the output current that lead to even slower changes of the diodes to change their state from ON to OFF and vice versa. As seen in Fig. 3(b) no inductor is connected (from the behavioural modelling point of view), the structure based on current sourcing of the diodes is better for signal processing at higher frequency areas than the voltage sourcing approach, where operational amplifiers are used. This fact is also shown in Fig. 6, where the measured transient responses of half-wave rectifiers from Fig. 3 for frequencies 10 kHz and 1 MHz are shown (response of opamp based rectifier is inverted). The CCII+ has been realized using the UCC-N1B [9]. According to the datasheet, the frequency bandwidth of this active element is 32 MHz. Therefore, the used opamp is AD8656 [10] with the gainbandwidth of 28 MHz. The diodes are all purpose 1N4148. The values of the resistors $R_1$ and $R_2$ are 1 kHz.

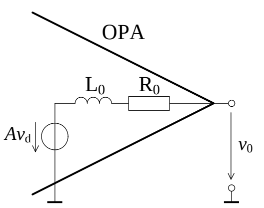


Fig. 5. Simple behavioural model of the output impedance of an opamp.

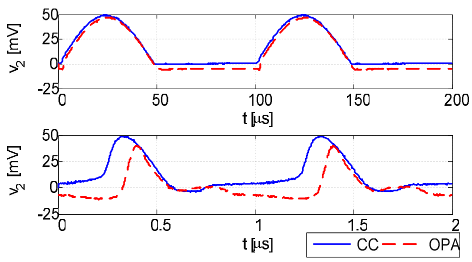


Fig. 6. Experimental measurement results of transient responses of circuits from Fig. 3 for frequencies 10 kHz, 1 MHz.

From the experimental measurements, it is clear that the behaviour of the circuits is for low frequencies very close to each other. As the frequency of the input signal rises, the recovery times of the diodes start to be more significant in the structure using opamp and the mean value of the output signal goes down.

## IV. VOLTAGE AND CURRENT BIASING

Even if using the principle of current sourcing of the diodes in non-linear circuits at higher frequency bands can be achieved, they can be seen as not that superb. However, as mentioned in Section I, to improve the dynamic performance of the non-linear structures, the voltage biasing can be used. This principle has been presented in [5], [6], but without any closer analysis.

The main part of a rectifier is the two-diode sub-circuit shown in Fig. 7(a). In Fig. 8 the simulation results are given when to the sub-circuit a current source with the amplitude of 1 mA and frequency of 1 MHz is connected. The diodes are again 1N4148. Similarly as in experimental measurements, also here the effect of recovery times can be seen as non-ideal half-wave rectification. Anyway, the delay time (3) can be reduced by keeping the diodes on the border of their conductive state, e.g. using a DC voltage source as shown in Fig. 7(b). By this approach the voltage swing ($v_{D1b}$, $v_{D2b}$) on the diodes is not as high as on the diodes in Fig. 7(a). This is also shown in Fig. 9. In this case, the bias voltage of the DC source is $V_B = 0.65$ V.

The influence of the voltage biasing to the transient responses of the current flowing through the diodes from Fig. 7(b) is shown in Fig. 10. Comparing them to the results from Fig. 8, significant improvements have been achieved in the zero crossing area. The improvement of dynamic behaviour of the conveyor based half-wave rectifier is also evident from the experimental measurement results shown in Fig. 11.

The voltage biasing scheme using simple voltage source has been presented in [5]. In [6] the voltage source is replaced just by parallel combination of a current source and resistor. From the temperature stability point of view, this technique is not very suitable.

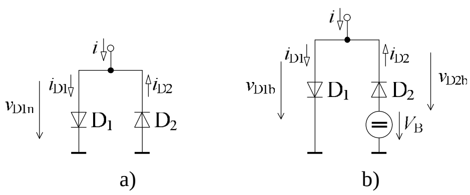


Fig. 7. Current sourced two-diode sub-circuit (a) without. (b) with the use of voltage biasing principle.

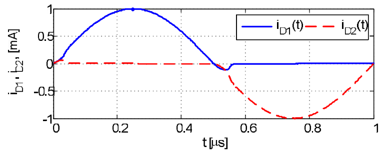


Fig. 8. Transient responses of the two-diode sub-circuit from Fig. 7(a).

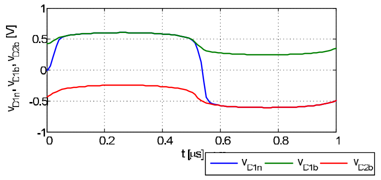


Fig. 9. Voltage swing on the diodes in the two-diode sub-circuit from Fig. 7 without/with using the voltage biasing principle.

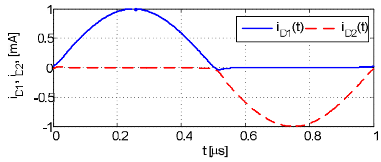


Fig. 10. Transient responses of the two-diode sub-circuit from Fig. 7(b) ($V_B$ = 0.65 V).

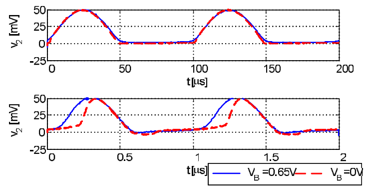


Fig. 11. Experimental measurement results of transient responses of half-wave rectifier for frequencies 10 kHz, 1 MHz using voltage biasing scheme.

The temperature dependence of (1) is given by the temperature dependence of reverse saturation current $I_0$ and temperature voltage $V_T$ and can be rewritten to

$$v_D = V_T \ln\left(\frac{i_D}{I_0}\right). \tag{7}$$

Differentiating (1) and (7) the temperature coefficient of the current at constant voltage and the temperature coefficient of the voltage at constant current in conductive operation can be calculated as [1]:

$$\left.\frac{1}{i_D}\frac{di_D}{dT}\right|_{v_D=\text{const.}} = \frac{1}{T}\left(3+\frac{V_g - v_D}{V_T}\right), \tag{8}$$

$$\left.\frac{1}{v_D}\frac{dv_D}{dT}\right|_{i_D=\text{const.}} = \frac{1}{T}\left(3+\frac{V_g - v_D}{V_T}\right)\left(-\frac{V_T}{v_D}\right), \tag{9}$$

where $V_g$ is the gap voltage, $V_g = 1.12$ V for silicon. Comparing (8) and (9) following inequality can be observed

$$\left.\frac{1}{v_D}\frac{dv_D}{dT}\right|_{i_D=\text{const.}} \ll \left.\frac{1}{i_D}\frac{di_D}{dT}\right|_{v_D=\text{const.}}, \tag{10}$$

that says that better temperature stability can be achieved by using constant current source to set the bias point of the diodes, which leads to the current biasing approach. However, even if better temperature stability can be in theory achieved using the current biasing principle, the circuit structures lead to very complex ones, as e.g. the full-wave rectifier presented in [7].

## V. CONCLUSIONS

In this paper a more complex analysis of dynamic performance of diodes used in non-linear circuits employing current conveyors and conveyor based active elements has been presented.

The advantageous use of the current sourcing of the diodes used in the structures operating at high frequency areas has been shown both by theory and experimental measurements. Furthermore, the voltage and current biasing scheme have been discussed. Even if the current biasing exhibits better temperature stability, this technique requires high number of additional active elements and is not quite suitable for the very first experimental verifications of novel circuit solutions.

In the last decade, our research in area of non-linear function block has focused on the design of full-wave rectifiers employing current and/or voltage conveyors and other conveyor based active elements, e.g. [11]–[14]. Based on the knowledge presented in this paper, the current sourcing and voltage biasing schemes have been used to operate the non-linear circuits at high frequencies.

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