AC analysis of operational rectifiers via conventional circuit simulators

DALIBOR BIOLEK*), VIERA BIOLKOVÁ, ZDENĚK KOLKA
Dept. of Microelectronics *) Radioelectronics
Brno University of Technology
Údolní 53, 602 00 Brno
CZECH REPUBLIC
dalibor.biolek@unob.cz   http://user.unob.cz/biolek

Abstract: A novel method for AC analysis of nonlinear circuits such as operational rectifiers is described. The resulting generalized frequency responses exhibit a dependence of the quality of rectification on the frequency and magnitude of input signal. A concrete procedure of the analysis of these characteristic via SPICE-family circuit simulators is described.

Keywords: - Current mode, rectifier, OpAmp, DOCF, CDTA, CCII, generalized frequency response.

1 Introduction

Precise circuits for the rectification of low-level signals play an important role in analog signal processing. Conventional rectifiers based on voltage OpAmps and diodes produce the well-known distortion due to the combination of OpAmp finite slew rate and effects caused by diode commutation. This distortion is growing for lower levels of processed signal and for higher frequencies. As a result, the rectifier operates well in the frequency range deep below the gain bandwidth product of the OpAmp used.

An improvement can be achieved by using current-mode active elements [1], when diodes are opened and closed directly by the output currents of these elements. A concrete full-wave rectifier with CCII (Current Conveyor of 2nd generation) elements is described in [2]. Current conveyors are implemented by current multipliers EL2082C [3]. A similar principle is used in [4]. A satisfactory rectification of 20mV and 30MHz voltage is accomplished by means of current conveyor CCII01 [5], utilizing the technique of DC biasing of Schottky diodes. A rectifier with improved precision is described in [6] in which the translinear regime of diodes in bridge configuration is utilized. The bridge is fed by currents from a couple of current conveyors CCII+, which are implemented by current feedback Opamps AD844.

A further increase in the accuracy and speed of rectification is possible via IC implementation of circuits with a simple structure on the chip. In [7] and [8] some implementations based on current mirrors are described which require low supply voltage of less than 1 Volt. An implementation of the full-wave rectifier with a DOCF (Double Output Current Follower) element is given in [9]. DOCF is a simple current follower with a pair of bipolar outputs. A generalization of the DOCF is the CDTA (Current-Differencing Transconductance Amplifier) element [10]. Among other things, it can be utilized as True Current Operational Amplifier [11, 12]. All the above elements are promising building blocks of fast and precise rectifiers.

It is useful to evaluate and compare the circuit principle of the proposed and designed rectifiers, taking the quality of rectification into account, which depends on the magnitude and frequency of input signal. Because of the essential nonlinearity of these systems, the classical computer simulation is limited to transient analysis and to a simple evaluation of steady-state responses. In this paper, a simple method for comparing various circuit structures is described. This method is based on the analysis of the so-called **generalized frequency responses** (GFR). Also, a procedure for acquiring these GFRs via conventional circuit simulators will be given.

2 Generalized frequency responses

Let us consider the connection of a nonlinear stationary system S and a signal source v, which will meet the following requirements:

(a) The system is composed of arbitrary stationary passive lumped elements and DC sources.
(b) The system is excited from a single source of harmonic signal $v(t)$ of frequency f and magnitude a.
(c) The system is in periodical steady-state.

Let the circuitry composed from the nonlinear system S and the source v be called **„SAF“ circuitry** if the item (c) is true for all the frequencies of the input signal from the interval $F\in<f_1,f_2>$ and for all the magnitudes from the interval $A\in<a_1,a_2>$.

The state of SAF circuitry will be evaluated by the so-called one-point characteristic p of selected signals of the system S. For concrete values $f \in F$, $a \in A$, the one-point characteristic $p \in P$ can be, for example, an arbitrary integral or other parameters of the output signal (RMS value, peak value, etc.). However, the definition of the p parameter can also include other signals, for instance the input signal v, which can be compared with the output signal.

Let the mapping

$$K\colon (F,A) \rightarrow P \qquad (1)$$

be called **generalized frequency response** K of the system S, which is a part of the SAF circuitry.

The circuit simulator will be expected to analyze the functional dependences

$$p = p(f,a)\,,\ f \in F,\ a \in A, \qquad (2)$$

that is to say the frequency dependence of the observed characteristic, whereas the magnitude of the input signal will be a parameter.

Such a definition of the frequency response of nonlinear system is relatively general. It enables the AC analysis of assorted systems that are able to work in the periodical steady state. On the other hand, it includes the conventional AC analysis as a special case for linearized systems S in the SAF circuitry, for which the periodical steady state is simultaneously the harmonic steady state, and where the characteristic p is chosen as the magnitude of output signal or the ratio of this magnitude and the magnitude of the input signal.

For operational rectifiers, it is legitimate to choose the average value of the rectified output signal y to be the p characteristic or, still better, the ratio of this value and the average value of ideally rectified signal, which will be directly proportional to the magnitude of the input signal:

$$p = \frac{\bar{y}}{\bar{y}_{ideal}(a)} = \frac{\dfrac{1}{T}\displaystyle\int_T y(t)dt}{\text{gain}\,\dfrac{1}{T}\displaystyle\int_T v_{rect}(t)dt}. \qquad (3)$$

Here, T is the signal repetition period and gain is the designed input-output rectifier gain. A characteristic defined in this way will be called the **DC value transfer**.

In the common case when gain = 1, there will be in the denominator of (3) $1/\pi$ (or $2/\pi$) multiple of the magnitude of input signal for half-wave (or full-wave) rectification. The ideal operation of the circuit is then characterized by the value p=1. With increasing frequency and decreasing magnitude of the input signal, the deflection from the ideal operation is indicated by a change, mostly a decrease in p below one.

However, the frequency response as defined above need not reflect some non-ideal behavior at the output, which does not much affect the DC value of rectified signal. A typical case can be seen in the parasitic oscillations due to short-time disconnection of the feedback path as a consequence of diode commutation. For such a “more rigorous” analysis, it is suitable to compare the shapes of the output and expected ideally rectified signals, for instance by computing normalized root mean square (RMS) error:

$$p = \sqrt{\frac{\overline{(y - y_{ideal})^2}}{\overline{y_{ideal}^2}}} = \sqrt{\frac{\displaystyle\int_T [y(t) - y_{ideal}(t)]^2\,dt}{\displaystyle\int_T y_{ideal}^2(t)dt}}\,. \qquad (4)$$

For ideal circuit operation, i.e. $y(t) = y_{ideal}(t)$, the result is $p = 0$, while in the case of total attenuation of the output signal $p = 1$. For extra high distortions, when the mutual energy of signals y and y_{ideal} can be negative, one can obtain $p > 1$. Let us call this characteristic the **RMS error**.

In the following, a simple procedure will be shown how to evaluate the above frequency responses via widely used simulation programs.

3 Computer simulation of generalized frequency responses

It follows from the definitions of characteristics (3) and (4) that they need to be computed from their waveforms, i.e. from the transient analysis. For the harmonic input signal of a concrete frequency and magnitude, the periodical steady state is obtained by transient analysis, and then the corresponding integral quantities are calculated from the output signal. It is necessary to repeat these analysis runs in a simulation loop in which both the frequency and the magnitude will be stepped in the required manner. After finishing this simulation stage, data is available for the performance analysis. Its outputs are in the form of a set of curves of the dependence of characteristic p on the frequency, with amplitudes as parameters of these curves. The layout is illustrated in Fig. 1.

Since the common circuit simulators, except for some special cases [13], cannot find the periodical steady state in a circuit directly, it must be obtained from the defined initial conditions, mostly from the computed DC operating point, by a successive analysis. On the assumption of avoiding the initial transients, the cumulative computation of the required integral signal quantities will well converge towards correct values. The simulation time must be chosen as an integer multiple of the signal repetition period. Due to the repeated analysis for more frequencies of the input signal, the diagram in Fig. 1 represents a large amount of analyzed data. The above leads to the proposed strategy of how to select the length T_{sim} of the simulating runs and the frequencies f of the input signal:

$$T_{sim} = \frac{m}{f_{\min}}, \tag{5}$$

where f_{min} is a minimum chosen frequency of the input signal, which corresponds to the maximum repetition period, and m is the onward-estimated number of these periods, within which the computation of the integral quantities will converge to correct results.

It is necessary to step the frequency in such a way as to fulfill the condition of an integer number of periods in the simulation window for each simulation run. For the first approximation, it is possible to use the logarithmic method with a step of 2, when the frequency is doublet in the next step.

The maximum time step ΔT_{max} in transient analysis should be chosen with regard to the signal frequency in order to keep the computational errors within acceptable limits for each simulation run. Most circuit simulators do not enable a dynamic change in ΔT_{max} during stepping. Thefore we must set this parameter identical for all the runs, but with the maximum signal frequency f_{max} being taken into consideration.

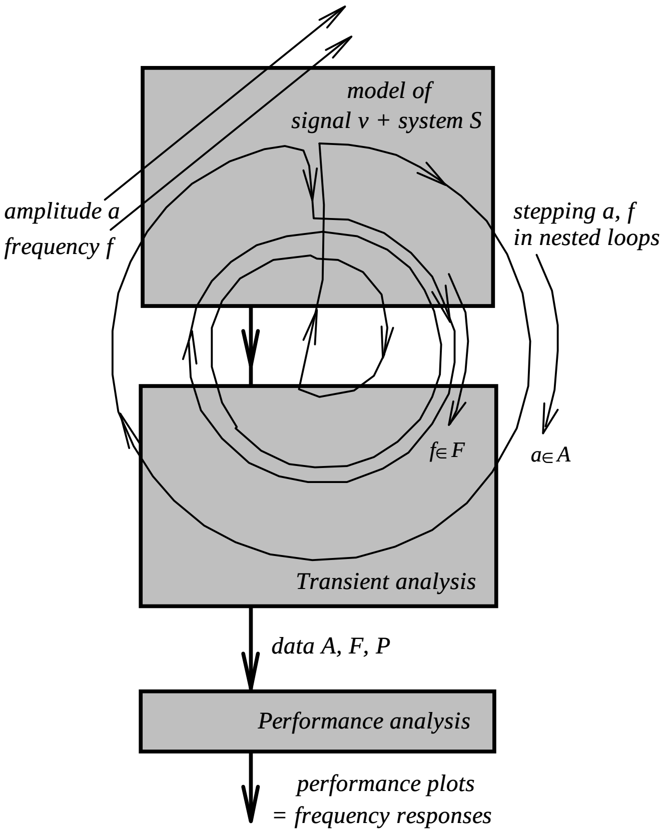

Fig. 1: Principle of computing generalized frequency responses via conventional circuit simulators.

4 Demonstration of the simulation

Let us consider the rectifier in Fig. 2. Its principle has been published in [4]. Two AD844 OpAmps are connected here as CCII+ current conveyors. In [4], the monolithic CCII01 current conveyors were used. However, there are no longer fabricated. Voltage V_x serves as DC biasing of the Schottky diodes, which positively affects the rectification process for higher frequencies. The circuit features with and without biasing are also compared in [4].

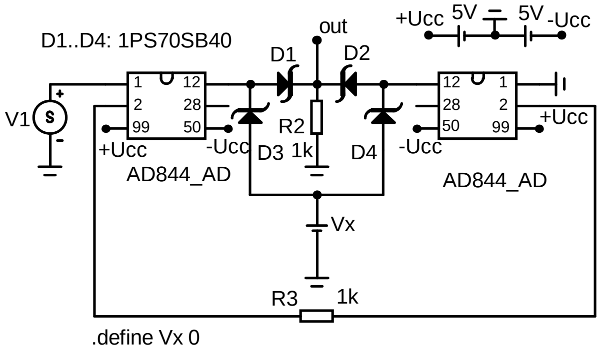

Fig. 2: Full-wave rectifier with two CCII+ current conveyors.

Let us show a more thorough comparison by computing the generalized frequency responses for two bias voltages V_x – zero and 0.3V. The MicroCap program [14] has been used for the simulation.

A preliminary analysis has shown that the real properties of OpAmps AD844 cause a rectified voltage attenuation of ca 0.922. This attenuation represents a systematic error, which can be easily corrected. That is why it was no longer considered during the computation of the frequency responses.

The transient analysis was performed repeatedly over a time interval of 10μs according to Fig.1 for input signal magnitudes of 20mV, 100mV, and 1V, and for frequencies from 100kHz to 10MHz. To eliminate transients at the beginning of the analysis runs, integral characteristics (3) and (4) of the rectified signal were computed during the second half of the analysis interval, i.e. from 5μs to 10μs. The performance analysis was finally completed. As a result, the frequency dependences of the integral characteristics at the ends of individual analysis runs, i.e. at time 10μs, were plotted in a graph. The results are given in Fig. 3.

As can be seen from Fig. 3 (a), for zero-bias voltage V_x, the 3dB bandwidth of DC value transfer is ca 9MHz for an input voltage magnitude of 1V. However, for a magnitude of 100mV, the circuit operates well only below 2MHz, and for 20mV it rectifies only to ca 470kHz. Above frequencies of 2MHz and 8MHz for magnitudes of

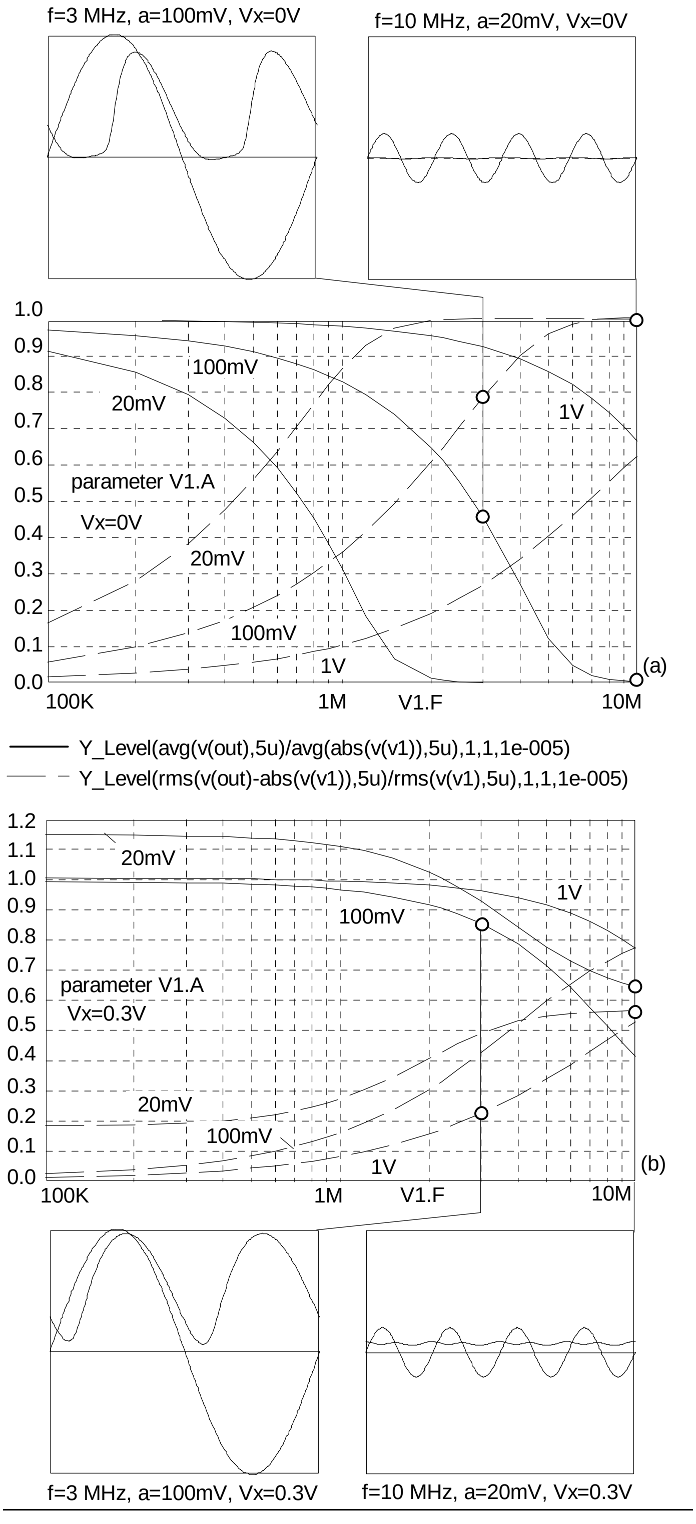

Fig. 3: Generalized frequency responses of the rectifier in Fig. 2 as a result of simulations, and the corresponding input and rectified waveforms. The diode bias voltage is (a) 0V, (b) 0.3V. The curves of the DC value transfer are shown in solid lines, the RMS error curves are dashed.

20mV and 100mV, the DC value transfer is practically zero and, simultaneously, the RMS error equals one. This indicates that the output signal is practically zero above these frequencies.

Setting the diode bias voltage (Fig. 3 b) will cause a bandwidth extension above 10MHz for an input voltage of 1V and to 5MHz for 100mV. For 20mV, the curve of DC value transfer has an atypical course: Low-frequency transfer exceeds the value 1 because of a non-negligible DC shift of rectified signal due to relatively high diode biasing. The large RMS error in the low-frequency range also confirms this fact. The given DC shift is also evident in the picture of waveforms in the bottom part of Fig. 3 (b).

5 Conclusion

The paper describes how phenomena inside the so-called SAF circuitries can be analyzed by means of generalized frequency responses via standard features of conventional circuit simulators. Here the standard features are transient and performance analyses. The method is illustrated on the simulation of low-level rectifiers, but it can also be applied to a wide class of nonlinear circuits.

Acknowledgments

This work is supported by the Grant Agency of the Czech Republic under grants No. 102/03/1363 and 102/04/0442, and by BUT research programmes MSM 262200022 & MSM 262200011.

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