Novel Structure of CMOS Voltage-to-Current Converter for High-Voltage Applications

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ABSTRACT

This paper is focused on design of (high-voltage) voltage-to-current (V/I) conversion circuit. The presented circuit is a specialized solution of a specific design problem. It has been developed to work in pair with current-to-voltage (I/V) converter which cancels possible drawbacks of the V/I converter working as a stand-alone device. Circuitry presented in this paper has been simulated using the data for HV SoI process. The results are included in the paper.

Keywords: voltage-to-current conversion, high-voltage Silicon-on-Insulator process, high-voltage design, voltage signal inversion

1 INTRODUCTION

High-voltage semiconductor processes enable production of integrated circuits that offer extended functionality over their low-voltage counterparts. Apart from new design capabilities, also some new design problems arise. Usually high-voltage MOS transistors allow drain-source and drain-gate voltages up to tens of volts, but offer limited gate-source voltage. Moreover, high-voltage MOS devices, due to their layout structure, offer poor matching possibilities. Due to these high-voltage MOS device properties, many low-voltage circuit topologies cannot be directly turned into their high-voltage analogs. Some extra design effort is required to ensure proper and safe circuit operation.

The research presented in this paper originated from necessity of interfacing a large current-mode processing module inside voltage-mode integrated circuit. Change from high-voltage mode to current-mode of signal processing can help avoid serious design problems. Most of current-mode signals processing can be performed with current mirrors, which can be based on low-voltage transistors, protected only against voltage swings by high-voltage MOS devices. In other words, current-mode signal processing remains a low-voltage process, only signal transmission may become a high-voltage process.

Current-mode module placed inside a voltage-mode integrated circuit must be able to accept and output high-swing voltage signals present in the voltage-mode circuitry. Thus, both high-voltage/current and current/high-voltage conversion circuits are required. There are several solutions to such tasks. The proposed V/I converter structure offers interesting set of features and a short signal-processing path. In addition, extension of the proposed structures with a single device provides I/V conversion capability, and is able to provide precise output voltage values.

2 PROPOSED V/I CONVERTER

Proposed circuitry originates from automotive high-voltage application. Here very low power consumption or low supply voltage are not important factors, as in case of many modern solutions of V/I converters, like the ones presented in [1]. The circuitry is designed to work properly with 24 V of high supply voltage and 5 V of low supply voltage, which are safe values for the used process - HV 0.8 µm BCDMOS SoI. Operation frequency of the proposed solution is below 1 MHz. Originally it was designed to work with edge-rounded trapezoidal waveform with base frequency around 200 kHz. Such circuitry does not require very high operation speeds, like e.g. presented in [2], where low-voltage and low-power demands are rightly justified.

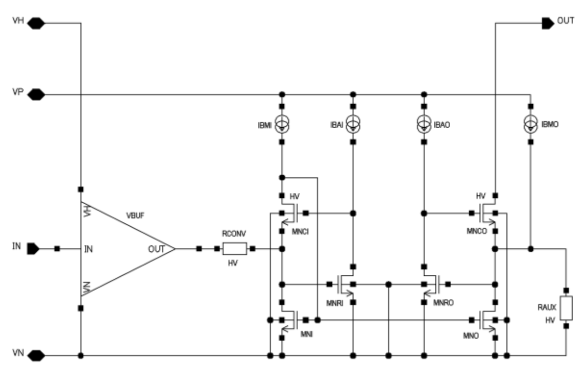

Figure 1: The proposed V/I conversion circuit.

The proposed V/I conversion circuit consists of three main components presented in Figure 1. The input voltage buffer VBUF (component 1) sources a current that flows one way through the conversion resistor RCONV (component 2); next, the current mirror (component 3) receives the produced current and provides a conditioned copy at its output.

The input voltage buffer is required to provide precise unity gain and DC level of processed voltage. Typical robust high-voltage source follower buffer is enough for such a task. Figure 2 presents example of a high-voltage structure. Other buffer topologies are also possible.

The RCONV resistor is the high-voltage U/I conversion device. In the simulation a Poly2 device has been implemented. It is important for the utilized resistor to offer linear, constant resistance, regardless of a voltage drop on the resistor and terminal potential over the bulk level. Sometimes there is no proper HV resistor device accessible in the used process. It is then possible to use several series-connected low-voltage resistors. Still, it is very important to use highly resistive layers to reduce size of the combined resistor and reduce parasitic capacitances, which may limit applications of the final V/I converter.

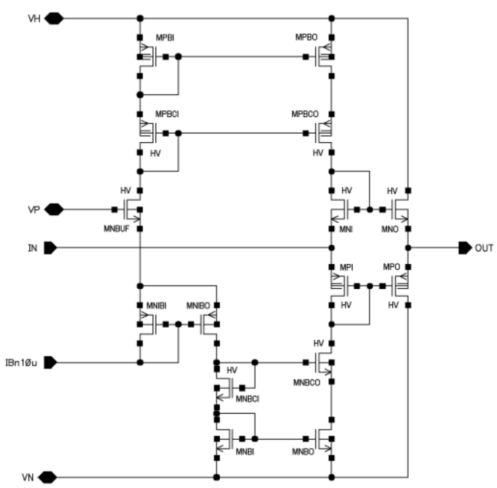

Figure 2: High-voltage unity-gate voltage buffer.

The unity-gain current-mirror is chosen to provide very high current mirroring precision. It uses a regulated cascode topology, and it connects with the conversion resistor in a manner similar to the one used in folded-cascode structures. As a result, the input resistor connection node has virtually constant potential, as it is a connection point for a gate of a cascade regulating transistor MNR1. This point referred to as an auxiliary connection point. It can be stated that both input and output sides of the current mirror have main (drains of MNCI and MNCO) and auxiliary (drains of MNI and MNO) input and output side current connection nodes. Figure 1 shows that apart from bias current flowing through cascade regulating transistors, also main input node and auxiliary output node are used to provide some bias currents. These bias currents help stabilizing operation points of input and output side mirror transistors. The conversion current is added to a bias current at the mirror input. Finally, the output bias current is subtracted from output mirror current and thus the output conversion current is produced and delivered through the main output node.

The constant potential of the auxiliary input node is not as important as a fact that it is virtually equal to the potential of the corresponding auxiliary output node. Based on this feature proper offset current can easily be provided to the output conversion current. The RCONV conversion resistor is placed between the voltage input and the auxiliary input node of the current mirror. As the potential of the auxiliary input node is different that the ground level, the produced input current is referred to this level and not to the ground level. This is a disadvantage, e.g. from the I/V conversion point of view. Access to the auxiliary output node that has potential equal to that of the auxiliary input node enables simple remedy to the mentioned disadvantage. It is enough just to connect auxiliary RAUX resistor – identical to the V/I conversion device – between auxiliary output node and the ground node. Through the auxiliary output node, it sources additional current from the main output node, thus increasing the output conversion current.

The input side conversion current flowing through the conversion resistor is proportional to voltage drop between the input and the auxiliary input node. The current sourced from the main output node through the auxiliary output resistor is proportional to voltage drop between auxiliary output node (at the same potential as the auxiliary input node) and the ground node. Thus, the output conversion current at the main output node finally is proportional to the voltage drop between the input voltage and the ground level, which ensures proper V/I conversion process.

3 CIRCUIT EXTENSIONS

3.1 Multiple outputs and amplification

The output signal of the V/I converter is produced by a current mirror. Generally, current mirrors can have more than one output. Such situation is also possible in case of the proposed V/I converter. To provide additional conversion current copy it is enough to exactly copy structure of the existing output side of the current mirror in the V/I converter. If additional amplification of the conversion current is required, all bias currents must be also amplified and the auxiliary output resistance value must be proportionally reduced.

3.2 I/V conversion

An obvious feature of the proposed solution is presence of the conversion resistor. It is a known fact, that resistance is a parameter that is poorly controlled in semiconductor processes. Significant efforts to avoid resistors in V/I converters can be observed and all-MOS converters are proposed to cope with resistor drawbacks [1]. On the contrary, resistance proportion value for two or more resistors can be quite well controlled by means of placement and matching. So, resistive conversion device seems a drawback of a proposed solution. The V/I converter should either avoid application of resistors of rely on resistance value proportion, not a resistor value itself (there are some exception circuits that use resistors [3]).

In fact, the proposed solution is devised with this latter option in mind. The V/I converter has been introduced to enable application of current-mode signal processing modules instead of using high-voltage mode signal processing modules. Simply, during design it was found that required processing is far easier in current domain.

To enable such current-mode intrusions into generally voltage-mode signal processing path, a set of V/I and I/V converters must be accessible. The presented V/I converter is the most important part of such set. The missing I/V converter consists of just a converter resistor, identical, or in general case proportional, to the V/I conversion resistor. As a result, conversion ratio of the proposed V/I converter is poorly defined, as well as the ratio of the resistor-based I/V converter. Nevertheless, combined voltage-current-voltage conversion ratio of these to converters put together is well defined, as it is based on resistor value proportion.

Finally, it is not very important, that current-mode processing involves poorly (though linearly) defined output currents, as the back conversion into voltage domain removes the resistor-imposed drawback and the final voltage-mode signal has proper amplitude and offset.

3.3 Example of application

Good example of simple and useful application of a set of V/I and I/V converters with a processing unit between is a function block, which in fact is a cause of the presented research. Inversion of high-voltage waveforms may be a challenging task. It can be made with use of high-voltage fully differential OPAMP. To make things somewhat easier this task can be completed with a combination of single ended high-voltage OPAMPs. Though, if in addition some amplification and level shifting functionality is required, the voltage-mode processing of high-voltage signals remains a demanding task.

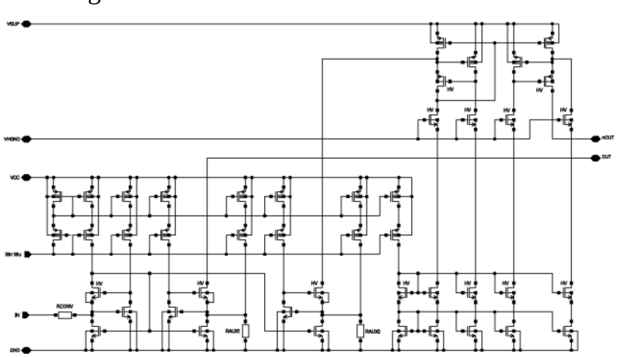

Figure 3: The simulated voltage inversion circuit.

Current-mode processing is known for its convenience of performing many arithmetic operations. Also, as mentioned earlier, application of precise cascode or regulated cascode mirrors enables application of low-voltage well-matchable transistors for precise operations, while using high-voltage MOS transistors as cascode and buffer devices. This way, both required functionality and signal processing precision is obtained.

Figure 3 presents a signal inversion circuitry. In this example no voltage amplification is present, so one of the output voltages should follow the input voltage (with extra time-delay, of course), while the other output voltage is expected to be inversion of the input voltage.

Bandwidth of the signal processing module is expected to be above 1 MHz, as it was designed to work with edge-rounded trapezoidal waveform of basal frequency equal about 200 kHz. Both low- and high-voltage trapezoidal waveform generators for such applications are presented in [4], while interesting low-voltage generator equipped with edge-rounding functionality, is presented in [5].

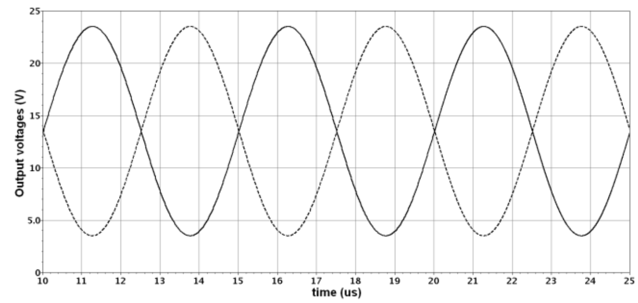

Figure 4: Recreated input voltage and produced inverse input voltage as effects of V/I/V signal processing chain for 10 V 0-p, 200 kHz input voltage sine waveform.

Change from low-voltage range waveform to current-mode processing in high-voltage range can be made with application of circuits based on V/I OPAMP-based converter discussed in [6]. All adaptation is to use basic circuit version with resistor-based conversion and add a high-voltage current mirror. Just as in the circuit proposed in this paper, precise voltage-current-voltage conversion can be obtained, additionally offering low-voltage to high-voltage signal range conversion.

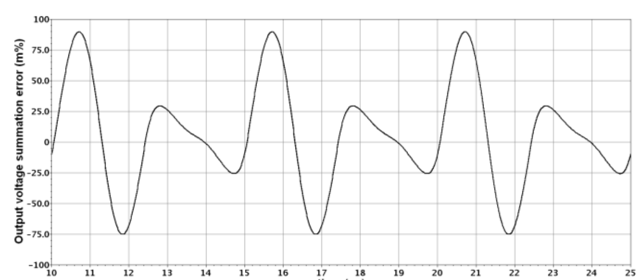

Figure 5: Output voltage summation error for 10 V 0-p, 200 kHz input voltage sine waveform.

4 SIMULATIONS

The simulated circuit is supplied from 5 V low supply voltage and 27 V high supply voltage. 27 V voltage should be treated as increased 24 V, possible in some automotive electric installations. The conversion resistor value is equal to 100 kOhm. The input voltage signal has an offset equal 13.5 V, which is half of a high supply voltage. All parameter simulation, except for frequency dependent, are made for 200 kHz input voltage waveform (which is a condition similar to the original automotive application of the proposed circuit), of 0.5-13.5 V 0-p amplitude.

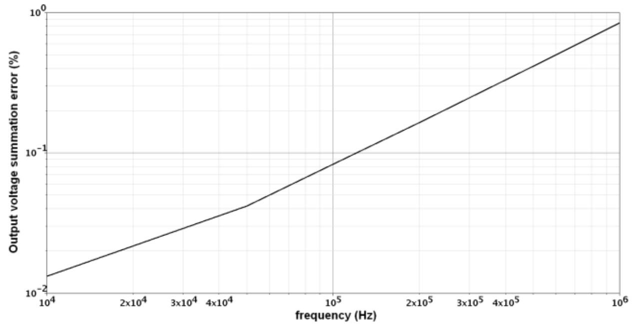

Figure 6: Output voltage summation error versus frequency, current summation error has same values.

Figure 4 presents straight and inverse outputs produced by V/I/V signal processing path. Figure 5 presents the output voltage summation error. Very low error values can be observed for 200 kHz frequency. Figure 6 shows how the errors value increases with frequency.

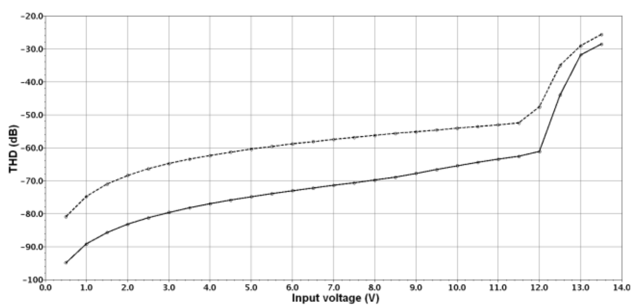

Figure 7: Total harmonic distortion (THD) for 200 kHz input sine waveform; output voltage – solid line, inverse output voltage – dashed line. Values for output currents are depicted by circles and are identical to those of voltages.

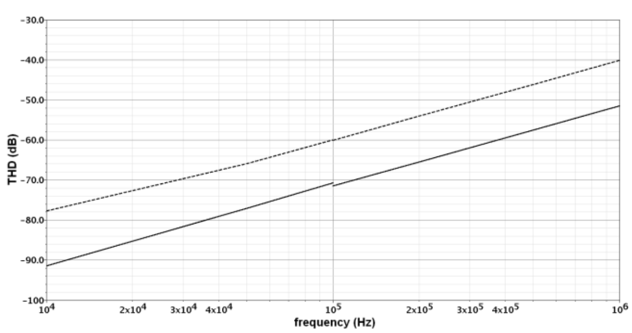

Figure 8: Total harmonic distortion versus frequency; output voltage - solid line, inverse output voltage - dashed line. Values for output currents are identical.

The simulated bandwidth of the signal converter is about 9 MHz, but according to Figure 6, at 1 MHz the summation error is already at about 1 %, which limits the applicability of the converter for higher signal frequency.

Figure 7 presents total harmonic distortion values for different input voltage amplitudes. Maximum input 0-p voltage amplitude is equal about 11.5 V. Figure 8 presents dependence of the THD versus input voltage frequency, for 10 V 0-p input sine waveform. Also here signal quality deterioration can be observed, as input signal frequency increases toward 1 MHz.

5 CONCLUSION

The V/I converter, presented in this paper offers good operation quality due to short signal path. In connection with the related I/V converter based on a single resistor, it offers very precise combined voltage-current-voltage conversion, forming a kind of interface for current-mode signal processing modules placed inside generally high voltage-mode signal path.

Application of such V/I and I/V converter sets may enable easy execution of various operations on signals, like summation, subtraction, amplification, copy generation, level shifting, inversion, etc. Such operations would be quite difficult to perform in the case of standard high-voltage circuits.

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