High-voltage Analog Switches with Current-mode Control

Mariusz Jankowski

***Abstract*—The Paper presents a number of high-voltage analog switch designs. All of them are current-controlled designs, which make them well prepared to operation in presence of high voltage drops of transmitted signals. Possible application areas for presented structures are discussed.**

***Index Terms*—High-voltage circuits, analog switches, current-mode control, current transmission, voltage transmission.**

I. INTRODUCTION

SWITCHES are subcircuits, utilized in numerous types of different circuits. They can be used both in analog and digital signal processing domain, both for voltage and current flow control [1]. For low-voltage circuit use, single MOS type transistor or CMOS transmission gate is usually enough to pass full range of voltages and current flows. Such designs, mainly CMOS gates are widely utilized in logic circuits, e.g. in multiplexers [3].

Maximum safe operation voltages between low voltage transistor terminals are usually similar or identical. Owing to this simple switches mentioned above can be safely used in low-voltage circuits, while covering all voltage-range of processed signals [2].

Design of high voltage switches is more challenging task. Important difference between low and high voltage domain is the very construction of high-voltage transistors. Low voltage transistors are usually fully symmetrical structures, which means that drain and source terminals are defined by application of these transistors.

In domain of high-voltage MOS devices situation is quite different [4]. First of all, such MOS transistors are structurally asymmetrical, which may lead to some limitations of high-voltage application, because safe operation voltage-ranges in such devices may significantly differ for different terminal pairs. Most common example is quite typical limitation of gate-source voltage to 5 – 5.5 V, while gate-drain voltage and source-drain voltage may safely reach tens of volts.

Such limitations cause important application troubles for low-voltage-like switches in high-voltage domain. First, such structures become not symmetrical as a high-voltage swing is allowed usually only on one side of the switch, namely gate-drain path. This is not always forbidden, there is a number of tasks for which such structures are applicable. Still, these are not versatile solutions, and their operation must be well checked beforehand or controlled during operation of the circuit incorporating such structures.

Other problem with low-voltage switch adaptation for high-voltage domain is a way of switch control. Classic voltage control cannot be applied in a direct way. Some other means of switch control must be applied. Current can flow throughout all voltage range in high-voltage domain circuits. So it is a good way of providing means of control over switch operation.

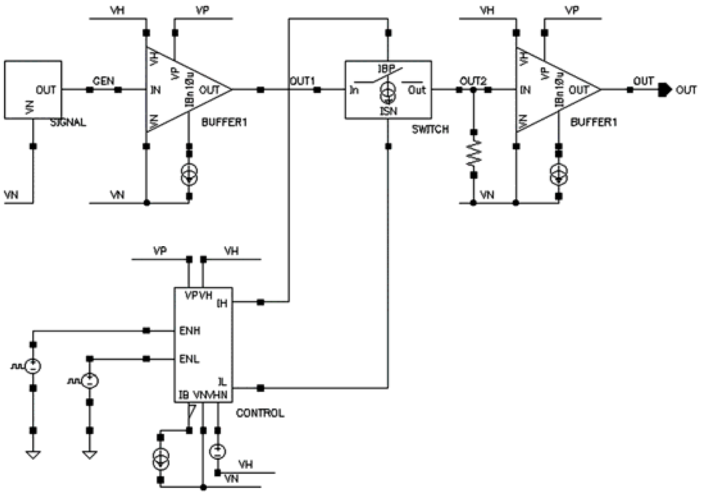

Fig. 1. Test bench for voltage-mode switches.

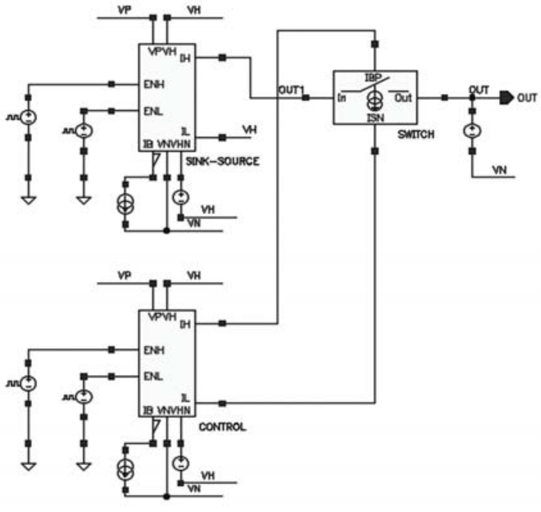

Fig. 2. Test bench for current-mode switches.

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High-voltage switch itself is a MOS-based device and as such requires voltage based control circuitry. This seeming contradiction can be solved with use of a simple current-voltage converter in connection with pass transistors.

Initial structure of high-voltage switch can thus be defined as follows: high-voltage MOS transistor as voltage/current pass device with low-voltage gate-source voltage control module driven with current passing through this control module. Such switch is driven by current source or sources. Owing to this way of control the switch itself can float through most of the voltage-range of the high-voltage circuits.

Proposed switch solutions are investigated with application of test benches shown in Fig. 1 and 2. Voltage mode test bench presented in Fig. 1 uses analog high-voltage input signal provided to the input of switch under test through a voltage buffer (Fig. 3). Output side of the switch is loaded with identical voltage buffer and additionally with one variable resistor for resistive load simulations.

Current-mode test bench is presented in Fig. 2. It consists of switch and switch-control circuitry, and current source/sink and output voltage source. The latter simulates low-impedance input of a current-mode stage following the switch.

II. One Pass-transistor Solution

Proposition of the simplest version of high-voltage switch devised according to above rules is presented in Fig. 4. This circuit is equipped with one pass transistor and resistor driven with single current source. Resistor is placed on the input side of the switch in order to use output of the stage before the switch as a sink for the switch-driving current. If the driving current is equal 0, switch is open, if proper current goes through the switch resistor, the switch transistor driven with the resistor voltage connects switch input to output. Possible extension of this design is Zener diode placed in parallel with resistor as a safety device. It disables possibility of the pass MOS transistor damage due to possible voltage surge between its gate and source. Unfortunately, test bench simulations show that such solution doesn't work as expected. Fast transients of the input signal cause the switch to conduct and change voltage level on the resistor added on output side of the switch (Fig. 5).

Solution to this problem may be an exchange of input and output sides of the switch. Simulation shows that current forced through the switch is still able to make it conduct, while it is expected to stay closed. Additionally, the resistor of the switch is buffered from its input side by the gate-drain structure of the passing transistor itself. When the switch goes off, fast transient of the input signal do not turn the switch on and isolation of the switch sides is sustained (Fig. 6). However, it is true only for one specific cases, when output side of the switch is connected to highly resistive input of following stages, presence of low-input circuitry on the output side of the switch simply makes it fail.

Such situations occurs when a stage at the output of the switch is also reconnected to some kinds of driving circuitry. In such situation active outputs of low-impedance drivers are present at both sides of the switch. This way the switch again faces a problem of control circuit exposure to the low-impedance circuitry, described for its first version. Persistence of this effect shows drawback of simple asymmetrical one pass-transistor solutions. Similar problems were observed for various one pass-transistor switch variants tested by author. Obtained results show that efficient high-voltage current-controlled switch should be a symmetrical structure.

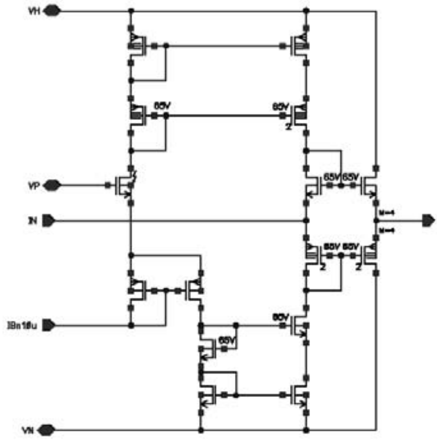

Fig. 3. High-voltage buffer for voltage-mode switch test bench.

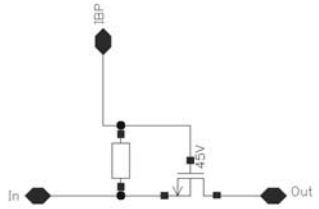

Fig. 4. Structure of simple high-voltage switch.

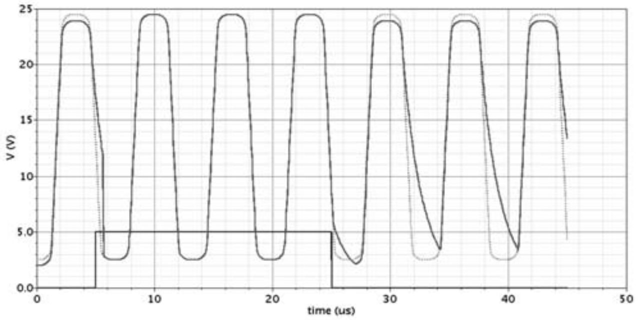

Fig. 5. Voltage-mode operation of the switch shown in fig. 4.

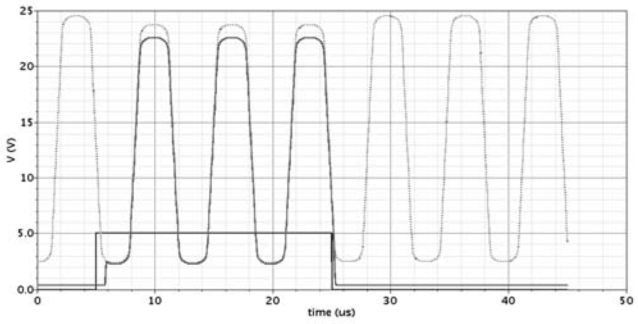

Fig. 6. Voltage-mode operation of reversed version of the switch of fig. 4.

III. TWO PASS-TRANSISTOR APPROACH

Simplest upgrade of the presented switch, based on analysis of proposed solutions, is cascade concatenation of two presented simple switches, forming a structure shown in Fig. 7. The switch control resistor is now buffered from both sides by high-voltage MOS transistors and voltage-mode simulation shows its proper operation (Fig. 8).

Simulation shows that forcing current through resistor placed between two MOS transistor leads to proper turning the switch on, but still, this switch shows another limitation to its operation. It draws all control current from - or sinks it to - the output of the preceding stage, so it can influence operation of such stage unless this stage is robust enough to cope properly with this additional load. Precise current flow switching is also impossible as this switch would simply consume part of processed current signal, falsifying its value.

This is disappointing conclusion, because switches that use one control-current are very handy if the semiconductor process or a system under design does not offer possibility of implementation for high-side current sources with enable functionality.

In such situations a PMOS transistor version of the circuitry with control current provided by low-side current source may be sufficient solution.

Further in the paper it will be shown that such solutions offering improved functionality are possible.

The problem of current load imposed on preceding stage is significantly minimized in circuits presented in Figure 9. a, b, and c. In all these solutions control current is both sourced and sunk by control sources.

Owing to this feature, only difference of the control currents is sunk to or sourced from the preceding stage. Still, there is crossing of the signal path and control current path, which excludes these solutions from precise current switching applications.

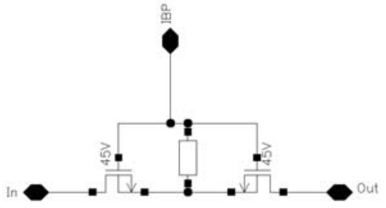

Fig. 7. Basic structure of symmetrical high-voltage switch.

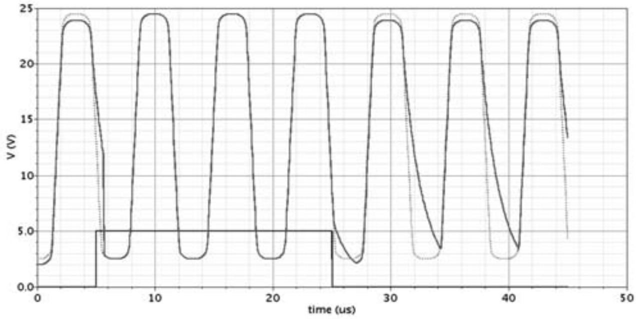

Fig. 8. Proper operation of a switch presented in fig. 7.

Circuit shown in Fig. 9.a is direct extension of circuit presented in Fig. 4. Zener diode is a safety device here. Voltage used for pass transistor driving is produced by current and resistance values.

Circuit in Fig. 9.b is an improved version of the previous solution. It can operate also in case of permanent over-current condition. When it happens, the Zener diode limits voltage drop between its terminals to approximately 6.2V and resistive voltage divider provides only its fraction between gate and source of the pass transistor. This virtue makes possible to use this solution in situation when both control current and resistors value are poorly defined. In such situation the over-current mode control may become primary way of switching control. Excess control-currents cause the Zener diode to conduct and stabilize voltage drop on the divider resistors. Fraction of so stabilized voltage used to drive the pass transistor depends on resistance ratio, and this can be easily controlled with proper layout techniques.

Circuit in Fig. 9.c is an optimized version of the previously presented structure. It makes voltage-range of switch operation more symmetrically placed in ground-to-supply voltage-range. It is obtained due to improved connection of the resistor divider to the pass transistor.

All switches presented above have same limitation, they cannot be used for current switching due to using signal path as a source/sink for fraction of control-current. This problem can be initially solved with switches that offer control path isolated from signal path. Because control device is connected between gate and source of pass transistors and physically is connected to the signal path, logical solution is using another MOS transistor with gate connected to the signal path, as a switch control device.

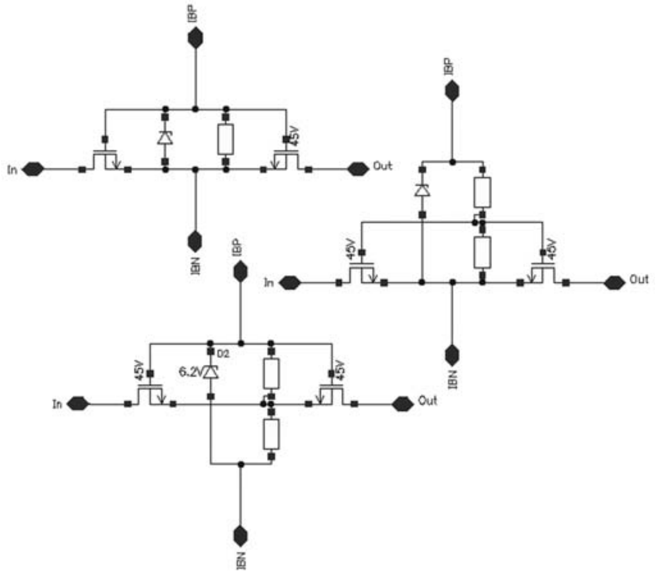

Fig. 9. Two control-current switch (a - upper),
diode-controlled switch version (b - middle),
optimized diode-controlled switch-version (c - lower).

Switch presented in Fig. 10.a is a very simple solution of that kind. It offers separation of control-current and signal paths. Moreover, only one control-current is required to control this switch. Simulation shows proper operation of such circuitry, due to proper choice of control transistor and passing transistor. Though, it must be stressed here, there are specific issues related to such transistor connection.

Current-voltage conversion on control transistor is highly nonlinear. It is difficult to obtain high gate-source voltage without using high currents. Switch in Fig. 10.b overcomes this limitation by using additional resistor. Here resistor works as a main current-voltage conversion device and control transistor is mainly a buffer between the resistor and a signal-path. Lower currents are enough to properly drive this circuit.

Unfortunately, when such switches turn off, gate-source voltage of control transistor does not go down to zero. The pass-transistor gate-source voltage is kept close to its threshold voltage value. In specific cases, like fast voltage signal transients or current forced throughout such switches, they might open and thus fail. In conducted simulations these two switches working in current-switching mode behave properly but when turned off they both need much more time to settle down and extinguish currents flowing throughout them. E.g. switch presented in Fig. 9.a, passing 20 uA current cuts the current down to 2 nA on 600 ns after cut-off signal happens, while switch in Fig. 10.a needs 180 us to extinguish same value current to 2 nA. Fig. 11 presents comparison of current flow through the switches 9.a and 10.a, in case of on-to off-state transition.

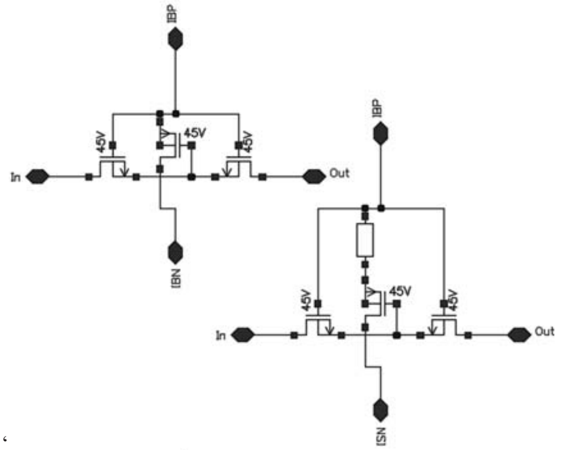

Fig. 10. Current-mode enabled switch (a - upper), version with improved I/V conversion (b - lower).

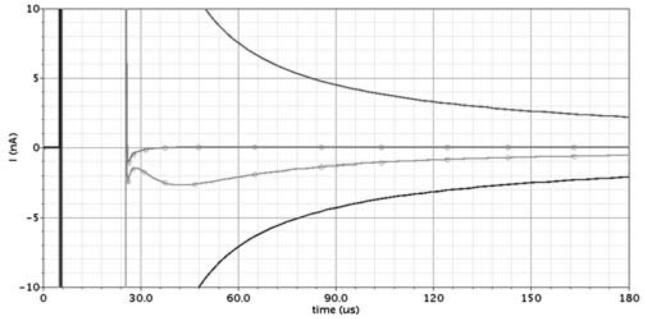

Fig. 11. Comparison of current flow through 9.a (solid line) and 10.a (solid circle-marked line) switches during switching-off process.

Improved versions of switches are presented in Fig. 12. Switch in Fig. 12.a corresponds to Fig. 10.a switch and switch in Fig. 12.b corresponds to Fig. 10.b switch. In both cases cut-off reliability is assured by means of high value resistor shorting the control transistor. High value of the resistor ensures low current-leaks while switches are on and gate-source voltage equal 0 during cut-off state.

The pay-off is lost ability, or at least lost high quality, of current-mode operation due limited current-leaks through the shorting resistor. Still, these switches can be used as reliable circuits in voltage-mode circuitry and they require only one control current and do not cause any problems with entering cut-off state while passing current-mode signals. Other possible drawback of this solution is high value of the shorting resistor, which is connected with increased area occupied by the switch and large parasitic capacitors, limiting its bandwidth.

One more improvement of a switch structure is presented in Fig. 13. In this case the driving circuitry is a two-stage solution. First stage consists of an MOS transistor and a resistor connected in series. This stage is always biased. The other stage is made of resistor connected to the other resistor and pass transistor gates. During the on-state biasing current is forced into resistor placed in series with the MOS transistor, while there is no current flow through the other resistor. During off-state part of biasing current is sunk through the other resistor, which lowers gate-source voltage of the pass transistors to ~ 0 V. Such control mode requires permanent current flow but this switch can operate in both voltage- and current-mode.

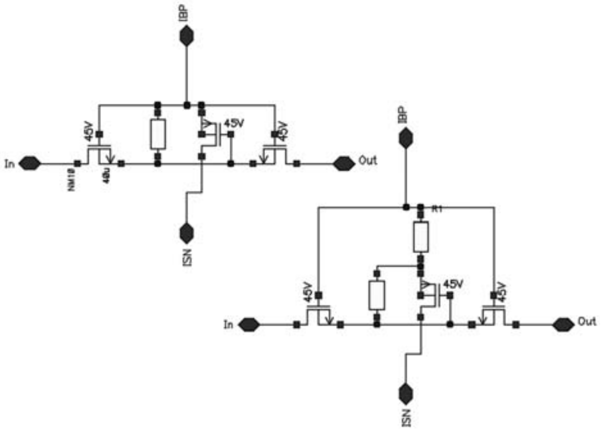

Fig. 12. Complex current-mode enabled switch (a - upper), version with improved I/V control (b - lower).

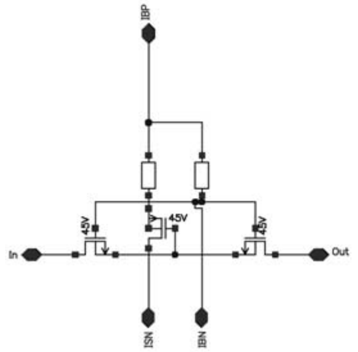

Fig. 13. Two-current controlled complex current-mode switch.

IV. CONCLUSION

In this paper an approach to design set of high-voltage current-controlled switches has been presented. Introduced circuits offer different abilities and are applicable for different application fields in high-voltage domain analog circuits and systems.

Variety of design versions get flexibility of choosing high-voltage switches best fitted to specific solutions, offering several compromises between switch operation quality and its design and control complexity.

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