High-Voltage Current-Controlled Analog Switches for Various Kinds of Application

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Abstract— **The Paper presents several high-voltage analog switch designs. All of them are current-controlled solutions, which make them highly resilient to high voltage drops of transmitted signals. Possible field of application for all presented structures is discussed.**

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

I. Introduction

SWITCHES are circuits, used in various types of circuits. They can be used both in analog and digital domain, both for voltage passing and current flow control [1]. In low-voltage 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].

Also, maximal safe operation voltages between pairs of low voltage transistor terminals are usually similar or identical and usually cover all possible operation voltage range from ground to supply [2]. This often assures that various transistor interconnections are safe by a rule.

Design of high voltage switches is a more challenging task. Important difference between low and high voltage domain is the very construction of such transistors. Low voltage transistors are usually fully symmetrical structures, which means that drain and source terminals are defined by application of such 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 application. Also, safe operation voltage-range in such devices may significantly differ for different terminals. Most common example is limitation of gate-source voltage to 5 – 5.5 V, while gate-drain voltage and source-drain voltage may safely reach tens of volts.

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Such limitations cause important application troubles for low-voltage-like switches in high-voltage domain. First, such structures are 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 they operation must be well checked beforehand or controlled during operation.

Other problem with low-voltage switch adaptation for high-voltage domain is a way of switch control. Classic voltage control cannot be applied in direct way. Some other means of switch control must be applied.

Electric current can be transmitted throughout all voltage range also in high-voltage domain circuits and so it is good way of providing switch control. High-voltage switch itself is 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 transistor.

Initial structure of high-voltage switch can thus be defined: 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 with 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 tested with use of test benches shown in Fig. 1 and 3.

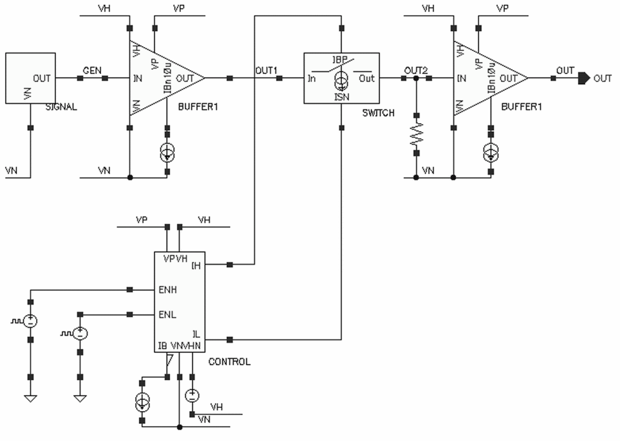

Fig. 1. Voltage-mode switch operation test bench

Voltage mode test bench presented in Fig. 3 consists of analog high-voltage input signal provided to the input of switch under test through voltage buffer (Fig. 2). Output side of the switch is loaded with identical voltage buffer and additionally with one variable resistor for low resistance load simulations.

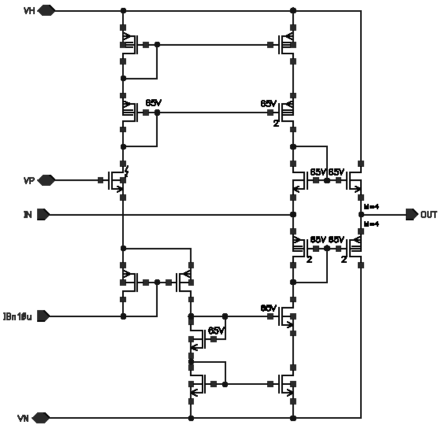

Fig. 2. High-voltage buffer for voltage-mode test bench

Current-mode test bench is presented in Fig. 3. It consists of switch and switch-control circuitry, current source/sink and output voltage source. It simulates low-impedance input of current-mode input stage following the switch.

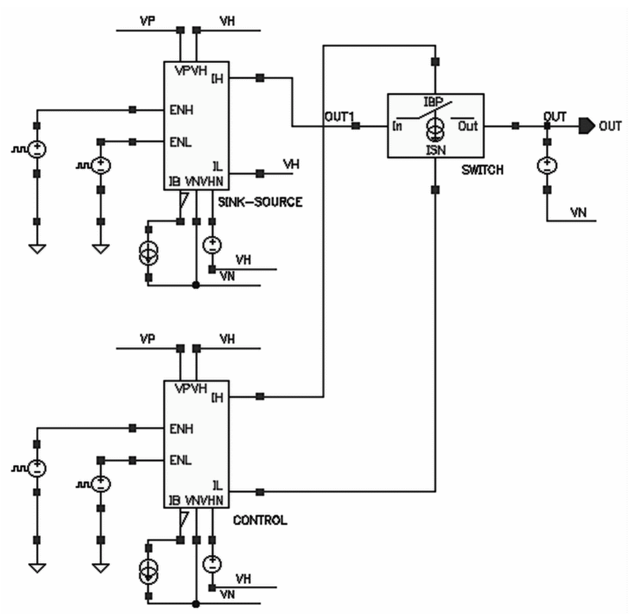

Fig. 3. Current-mode switch operation test bench

II. One Pass-transistor Approach

Proposition of the simplest version of high-voltage switch devised according to above rules is presented in Fig. 4.

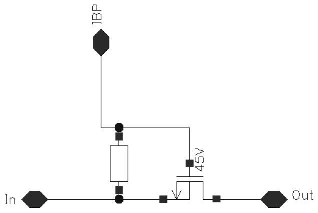

Fig. 4. Simple high-voltage switch structure

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).

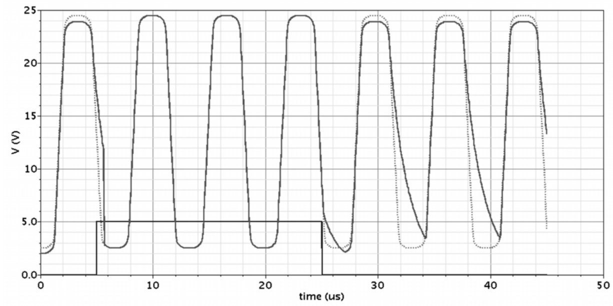

Fig. 5. Voltage-mode operation of the fig. 4 switch

Solution to this problem seems to be a change of input and output sides of the switch. Simulation shows that current forced through the switch is still able to make it conduct. 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 case, when output side of the switch is connected only to highly resistive input of following stage.

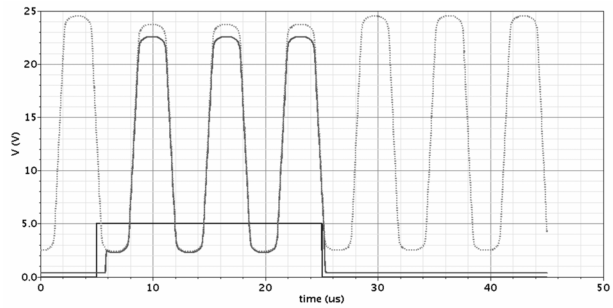

Fig. 6. Voltage-mode operation of the reversed fig. 4 switch

Presence of low-input circuitry on the other side of the switch simply makes it fail.

In practice such situations occurs when a stage at the output of the switch is reconnected to another 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 driver output, described for its first version. 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.

III. Symmetrical Two Pass-transistor Approach

Simplest amendment to the proposed switch, based on analysis of proposed switches, is cascade concatenation of two presented simple switches, leading finally to 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).

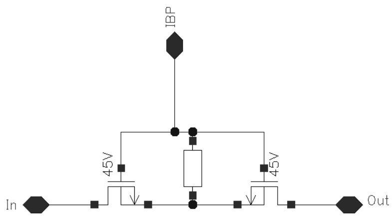

Fig. 7. Simple structure of symmetrical high-voltage switch

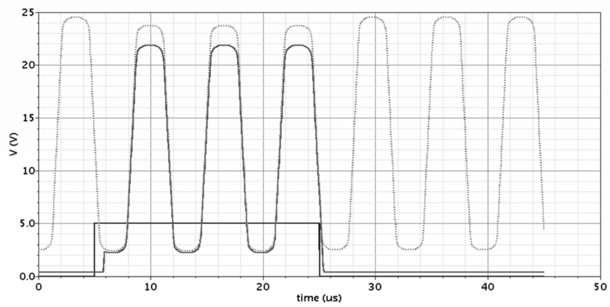

Fig. 8. Proper operation of the fig. 7 switch

Simulation shows that forcing current through resistor placed between can lead to turning the switch on, but still, this switch has 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 source/sink the directed current, falsifying value of processed currents.

This is disappointing conclusion, because one control-current circuitry is not only simpler in design. It is also very handy if the circuit does not offer implementation possibility for high-side current source with enable functionality.

In such situation a PMOS transistor version of the circuitry with control current by low-side current source would be appreciated solution.

Further in the paper it will be shown that such solutions with better properties 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 sources and sunk by devoted 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, which excludes these solutions from current flow switching tasks.

Circuit shown in Fig. 9.a is direct extension of circuit presented in Fig. 4. Zener diode is a safety device here. Pass transistor driving voltage is decided by current and resistane values.

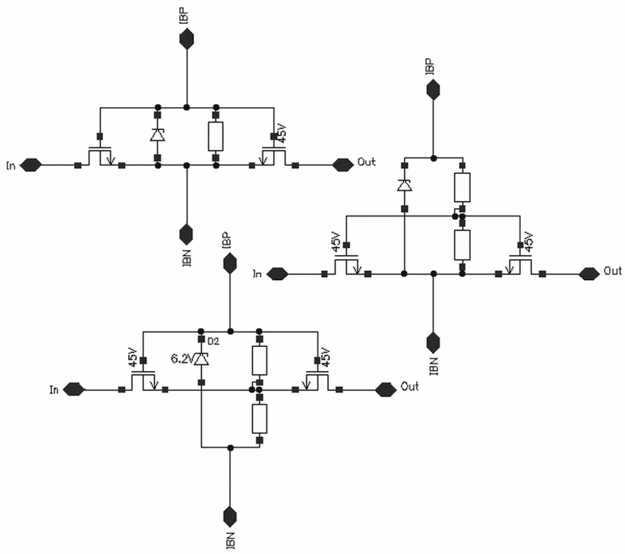

Fig. 9. Two control-current switch (a - upper), diode-controlled switch version (b - middle), optimized diode-controlled switch-version (c - lower)

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 resistor 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 switch control. Excess control-current 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, only. Resistor ratio can be easily controlled with device sizing.

Circuit in Fig. 9.c is an optimized version of the previously presented solution. 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 current or source/sink. 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.

Switch presented in Fig. 10.a is the simplest solution of that kind. It offers separation in 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 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.

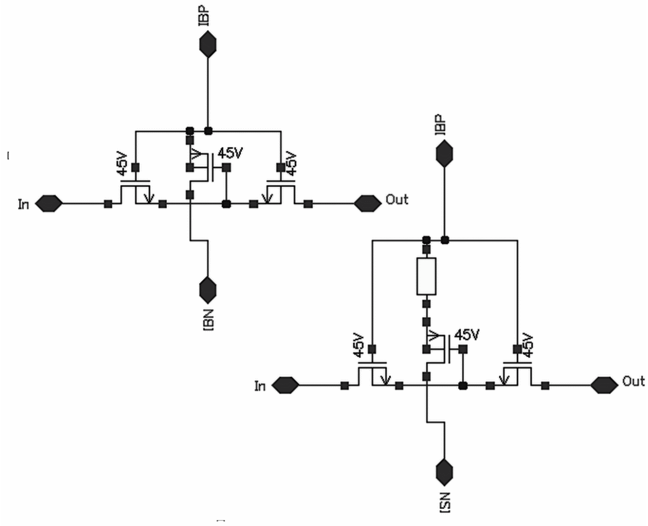

Fig. 10. Current-mode enabled switch (a - upper), improved current-voltage conversion version (b - lower)

Unfortunately, when such switches go 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, while switch in Fig. 10.a needs 180 us to extinguish 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.

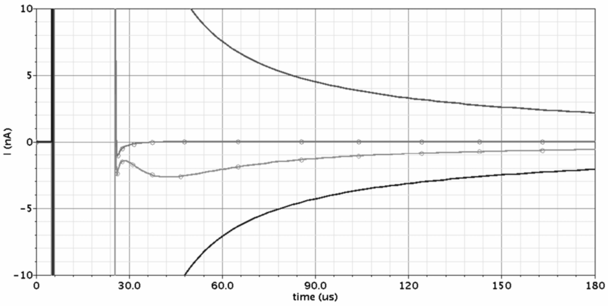

Fig. 11. Comparison of current flowing through 9.a (solid line) and 10.a (solid circle-marked line) switches during switching-off process

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 improvement is made 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.

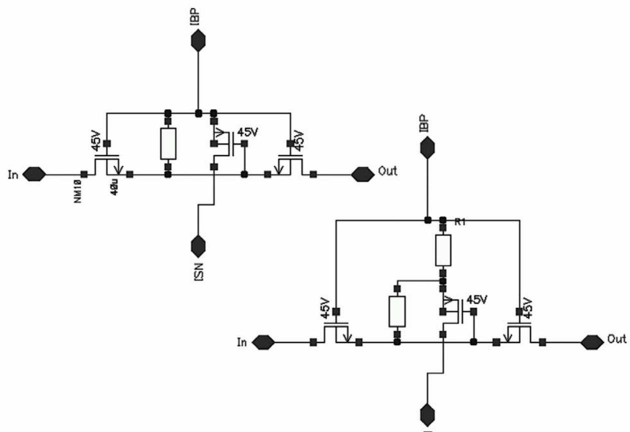

Fig. 12. Complex current-mode enabled switch (a - upper), improved current-voltage control version (b - lower)

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 is high value of the shorting resistor. Its layout may tend to be large, which is connected with area consumption and large parasitic capacitors.

One more 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 one resistor in series.

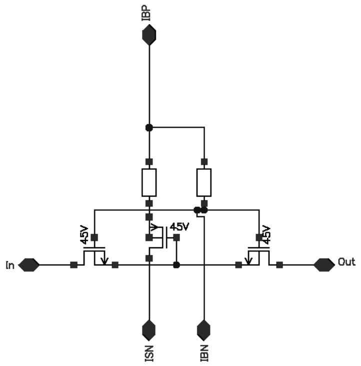

Fig. 13. Two-current controlled complex current-mode enabled switch

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 some current flow but this switch can operate in both voltage- and current-mode.

IV. Conclusion

In this paper approach to design high-voltage current-controlled switches is presented. Introduced circuits offers different abilities and application fields, which shows ways of optimization, applicable to high-voltage domain analog circuits and systems.

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