Selecting the Right CMOS Analog Switch

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Abstract: This tutorial outlines the basic construction, operation, and applications of analog switches. On-resistance, flatness, and charge-injection, each a performance-related specification, are defined. Application-specific features including ESD-protection and fault-protection are explained.

Introduction

First developed about 30 years ago, integrated analog switches often form the interface between analog signals and a digital controller. This tutorial presents the theoretical basis for analog switches and describes some common applications for them. In recent years, integrated analog switches have offered better switching characteristics, lower supply voltages. Because so many performance options and special functions are available, the well-informed product designer can usually find the right part for a particular application.

Standard Analog Switches

CMOS analog switches are easy to use, so most designers take them for granted. But one still should not forget that these switches solve specific engineering problems. Conventional analog switches like the early CD4066 is now offered by many semiconductor manufacturers; their structure is shown in Figure 1.

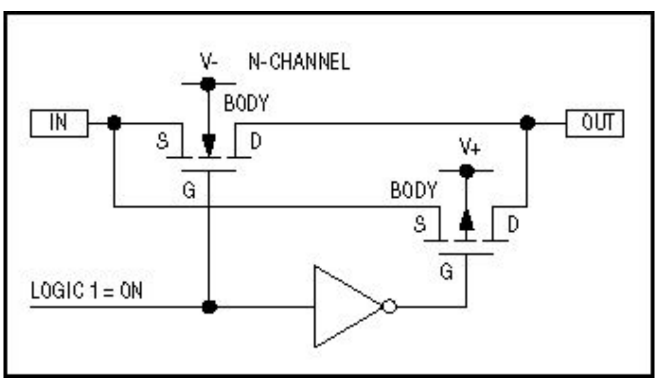


Figure 1. The internal construction of a typical analog switch features parallel n- and p-channel MOSFETs.

Connecting an n-channel MOSFET in parallel with a p-channel MOSFET allows signals to pass in either direction with equal ease. Whether the n- or the p-channel device carries more signal current depends on the ratio of input to output voltage.

Because the switch has no preferred direction for current flow, it has no preferred input or output. The two MOSFETs are switched on and off by internal inverting and non-inverting amplifiers. These amplifiers level-shift the digital input signal as required, according to whether the signal is CMOS- or TTL-logic-compatible and whether the analog supply voltage is single or dual.

Low-Resistance Switches

Taking the p- and n-channel on-resistances (R_{ON}) in parallel (product over sum) for each level of V_{IN} yields a composite on-resistance characteristic for the parallel structure (**Figure 2**). This plot of R_{ON} versus V_{IN} can be described as linear if you exclude the effects of temperature, power-supply voltage, and R_{ON} variation with analog input voltage.

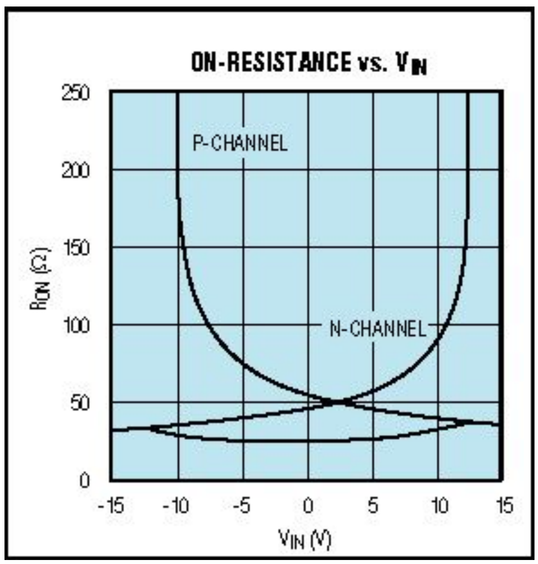


Figure 2. The n- and p-channel on-resistances of Figure 1 form a low-valued composite on-resistance.

The first analog switches operated on ±20V supply voltages and had several hundred ohms of R_{ON}. Recent products (the UM4684, for example) achieve Ω maximum R_{ON} with a much lower supply voltage. Supply voltage has a substantial effect on R_{ON}. The UM4684 specifies signal and supply voltages from 4.5V to 5.5V. As you can see, R_{ON} increases for lower supply voltages.
When selecting switches for single-supply systems, try to choose from those intended for single-supply use. Such devices save one pin, because they do not require separate V- and ground pins. As a result, this economy of pins enables a single-pole/double-throw (SPDT) switch to fit into a miniscule 6-pin SOT23 package. Many high-performance analog systems still rely on higher-level bipolar supplies such as ±15V or ±12V. The interface to these voltages requires an additional supply pin commonly labeled VL. The VL supply connects to the system logic voltage, which

is usually 5V or 3.3V. Having the input logic signals referenced to the actual logic levels increases the noise margin and prevents excessive power dissipation. Often misunderstood is the analog-switch concept pertaining to input logic levels and their effect on supply current. If the logic inputs are at ground or VCC (or VL when available), analog switches have essentially no supply current. Applying TTL levels to a 5V switch, however, can cause the supply current to increase more than 1000 times. To avoid unnecessary power consumption, you should avoid TTL levels, which are simply a legacy of the 1980s.

Signal Handling

Because analog switches can only handle analog-signal levels between the supply voltages. Under- or over voltage inputs can permanently damage an protected switch by producing uncontrolled currents through internal diode networks. Normally, these diodes protect the switch against short-duration electrostatic discharge (ESD) as high as ±2kV.

R_{ON} for a typical CMOS analog switch causes a linear reduction of signal voltage that is proportional to current passing through the switch. This might not be a disadvantage for modest levels of current or if the design accounts for R_{ON} effects. However, if you accept a certain level of R_{ON}, then channel matching and R_{ON} flatness can interest you. Channel matching describes the variation of R_{ON} for the channels of one device; R_{ON} flatness describes the variation of R_{ON} versus signal range for a single channel. Typical values for these parameters are 2Ω to 5Ω, and only 0.5Ω maximum for very low R_{ON} switches. The smaller the ratio of matching/R_{ON} or flatness/R_{ON} is, the more accurate the switch.

In most applications, you can avoid excessive switch current by modifying the circuit design. To change the gain of an op amp by switching between different feedback resistances, for example, choose a configuration that places the switch in series with a high-impedance input (**Figure 3a**). Because switch currents are insignificant, you can ignore the value of R_{ON} and its temperature coefficient. Switch current in the alternative design (**Figure 3b**) can be substantial, because it depends on the output voltage.

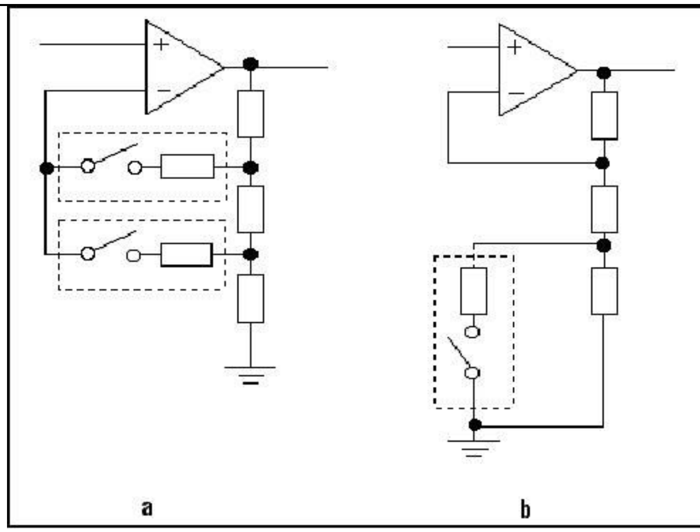


Figure 3. Gain-control circuits are good (a) or bad (b) depending on the amount of current through the switch.

Break-Before-Make

Turn-on and turn-off times (t_{ON} and t_{OFF}) for most analog switches vary from below 60ns to as high as 1µs. For "clickless" audio switches, t_{ON} and t_{OFF} are in the microsecond range to eliminate the audible clicks otherwise present when switching audio signals. The relative magnitudes are also important: $t_{ON} > t_{OFF}$ yields break-before-make action, and $t_{OFF} > t_{ON}$ yields make-before-break. This distinction is critical for some applications.

Figure 3a shows that you must take care in switching between the two gains. One switch is normally closed in a typical make-before-break application. In changing gain you must avoid opening both switches at once; that is, the second switch must close before the first switch opens. Otherwise, the op amp applies open-loop gain and drives its output to the rails. The opposite configuration (break-before-make) is also useful in switching among different input signals to a single op amp. To avoid short circuits between the input channels, a given connection must be switched off before the next one is switched on.

When a changing signal level modulates the on-resistance, causing a variation in the insertion loss, analog switches generate total harmonic distortion (THD). Consider a 100Ω switch with 10Ω R_{ON} flatness, for example. Loading this switch with a 600Ω termination produces 0.24% of THD. Consequently, for low THD you should avoid loading the output of an analog switch.

Charge-Injection Effects

As mentioned above, low R_{ON} is not necessary in all applications. Lower R_{ON} requires greater chip area. The result is a greater input capacitance whose charge and discharge currents dissipate more power in every switching cycle. Based on the time constant t = RC, this charging time depends on load resistance (R) and capacitance (C). It normally lasts a few tens of nanoseconds, but low-R_{ON} switches have longer-duration on and off periods. High-R_{ON} switches are faster. Another negative consequence of low on-resistance can be the higher charge injection caused by higher levels of capacitive gate current. A certain amount of charge is added to or subtracted from the analog channel with every on or off transition of the switch (**Figure 4**). For switches connected to high-impedance outputs, this action can cause significant changes in the expected output signal. A small parasitic capacitor (C_L) with no other load adds a variation of ΔV_{OUT}, so charge injection can be calculated as $Q = \Delta V_{OUT} C_L$.

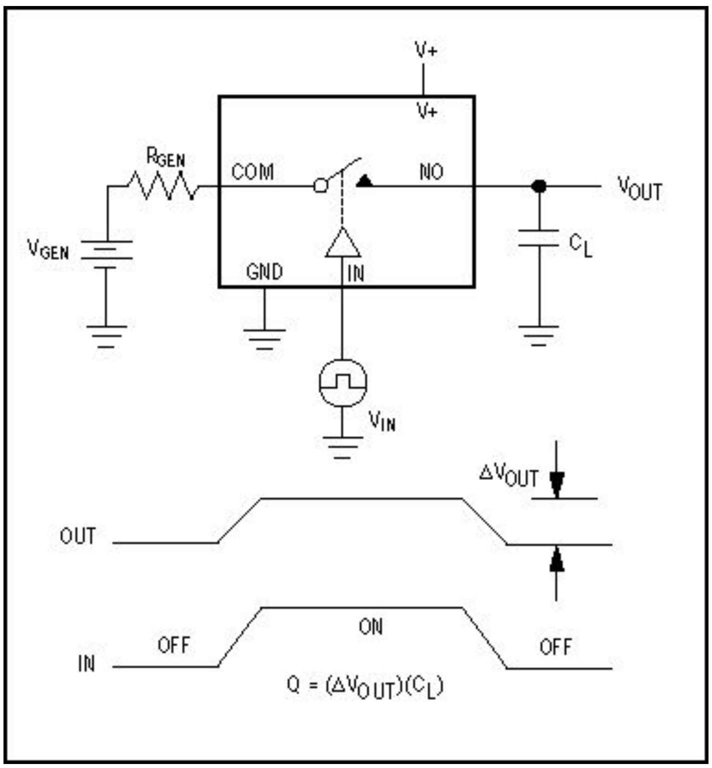


Figure 4. Charge injection from the switch-control signal causes a voltage error at the analog output.

A track/hold amplifier, which maintains a constant analog output during conversion by an A/D converter, offers a good example of this (**Figure 5**). Closing S1 charges the small buffer capacitor (C) to the input voltage (V_S). The value of C is only a few picofarads, and V_S remains stored on C when S1 opens. The held voltage (V_H) is applied to the buffer by closing S2 at the beginning of a conversion. The high-impedance buffer then maintains V_H constant over the ADC's conversion time. For short acquisition times, the track/hold's capacitor must be small and S1's on-resistance must be low. On the other hand, charge injection can cause V_H to change by $\pm\Delta V_{OUT}$ (a few millivolts), thereby affecting the accuracy of the following ADC.

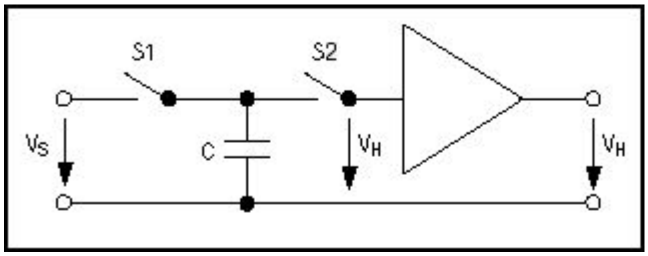


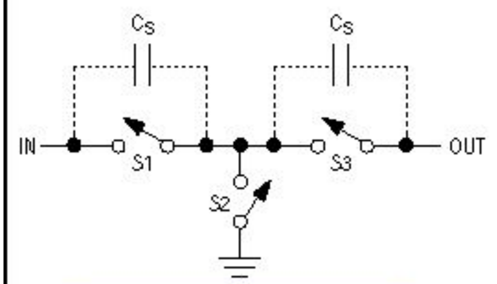
Figure 5. A typical track/hold function requires precise control of the analog switches.

Having reviewed these fundamentals, we now focus on innovative switches for special applications.

T-Switches for Higher Frequencies

The T-switch is suitable for video and other frequencies above 10MHz. It consists of two analog switches in series, with a third switch connected between ground and their joining node. This arrangement provides higher off-isolation than a single switch. The capacitive crosstalk for a T-switch turned off typically rises with frequency due to the parasitic capacitances in parallel with each of the series switches (**Figure 6**). The problem in operating a high-frequency switch does not lie in turning it on, but in turning it off.

When the T-switch is turned on, S1 and S3 are closed and S2 is open. In the off state, S1 and S3 are open and S2 is closed. In that case (the off state) the signal tries to couple through the off-capacitance of the series MOSFETs, but is shunted to ground by S3. If you compare the off isolation at 10MHz for a video T-switch and a standard analog switch, the result could be dramatic: -80dB versus -36dB for the standard switch.



VIDEO T-SWITCH	S1	S2	S3
ON	ON	OFF	ON
OFF	OFF	ON	OFF

Figure 6. The T-switch configuration attenuates RF frequencies that couple through the stray capacitance between the source and the drain of an open (off) switch.

Fault-Protected Switches

As mentioned under "Signal Handling" above, the supply-voltage rails for an analog switch restrict the allowed range for input signal voltage. Normally this restriction is not a problem, but in some cases the supply voltage can be turned off with analog signals still present. That condition can permanently damage the switch, as can transients outside the normal range of the power supply. Fault-protected switches and multiplexers guarantee overvoltage protection of ±25V and power-down protection of ±40V, along with rail-to-rail signal handling and the low on-resistance of a normal switch (**Figure 7**). The input pin, moreover, assumes a high impedance during fault conditions regardless of the switch state or load resistance. Only nanoamperes of leakage current can flow from the source.

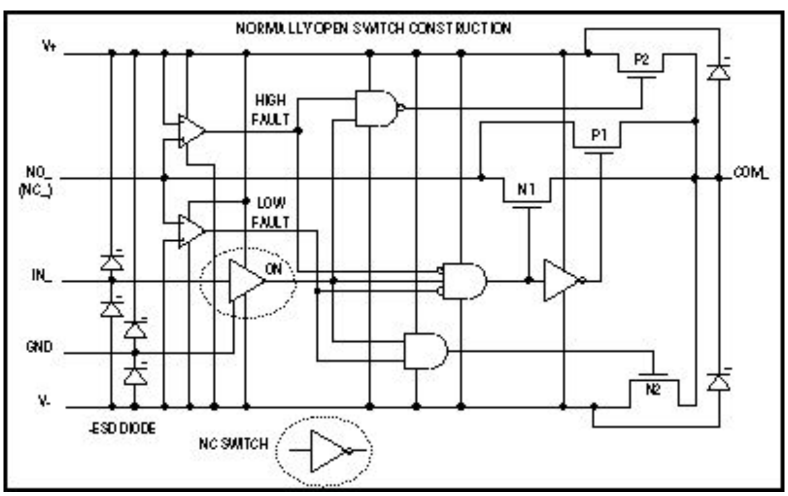


Figure 7. This internal structure shows the special circuitry in a fault-protected analog switch.

If the switch (P2 or N2) is on, the COM output is clamped to the supply by two internal 'booster' FETs. Thus, the COM output remains within the supply rails and delivers a maximum of ±13mA depending on the load, but without a significant current at the NO/NC pin.

Multiplexers

A multiplexers (muxes) is a special version of a switch in which two or more inputs are selectively connected to a single output. A mux can be as simple as an SPDT switch or come in 4:1, 8:1, 16:1, or even dual 4:1 and 8:1 combinations. The digital control for these higher order muxes is similar to a binary decoder with three digital inputs required to select the appropriate channel.

A demultiplexer is basically a mux used backwards. That is, one input connects to two or more outputs based on the decoded address data.

There are, finally, cross-point switches. A cross-point switch is usually an M x N device, whereby any or all of M inputs may be connected to any or all of N outputs (and vice versa).