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A Review of Switched Capacitor (SC) Circuits

Engineering
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ABSTRACT

This paper will explain the basic concepts of the operation of the switched capacitor circuits. Switched capacitor techniques have been developed in order to allow for the integration on a single silicon chip of both digital and analog functions and play a critical role in mixed-signal, analog to digital interfaces. Switched capacitor circuit replaces a resistor with switches and capacitors and works by passes charge into and out of a capacitor by controlling switches around it. Characteristics of SC circuit are determined by capacitance ratio.

I. INTRODUCTION

This paper will describe the basic ideas behind the use of the switched-capacitor to replace resistors. Switched Capacitor circuits play a critical role in analog/digital interfaces, particularly highly integrated applications [5]. By comparison, conventional analog circuits use the ratio of resistances to set the transfer functions of amplifiers and like circuits, and the magnitudes of resistances to determine the operation of current-to-voltage and voltage-to-current converters. The RC product values in active filters and signal generators are used to determine the frequency responses of those circuits.

When one move to the silicon chip and strives to achieve the same functionality in a much reduced area and using the tools of MOS technology, this is what one discovers. First, switches, small-value capacitors, and decent op-amps are easy enough to realize in MOS technology. Second, using that same technology, it is very difficult and wasteful of silicon die area to make resistors and capacitors with the values and accuracy encountered in audio and instrumentation applications. As we will see in the subsequent sections, designers have overcome these difficulties by realizing that (1) resistors can be replaced by MOS switches that are rapidly turned on and off, and MOS capacitors, and that (2) the time constants arising from these simulated resistances and the MOS capacitors are given in the form of capacitance ratios. The fact that capacitor ratios control the time constants means that these constants now can take advantage of the superior matching of capacitances fabricated on silicon, as well as their ability to track each other with temperature [6].

This paper is organized in the following manner. Section II introduces basic switched capacitor circuit operation by means of switched capacitor resistor. Section III describes detail of MOSFET switches used in SC circuits. Section IV explains the nonlinear effects of switches. Section V describes the issues of implementing the SC circuits and summarizes the advantages of SC circuits.

II.SWITCHED CAPACITOR RESISTOR SIMULATION CIRCUIT

The most basic and simplest switched capacitor (SC) circuit is the switched capacitor resistor, which is made up of one capacitor C and two switches S1 and S2 as shown in fig.1. Switches S1 and S2 are control by two non-overlapping clocks which connect to the capacitor with a given clock frequency alternately to the input and output of the SC.

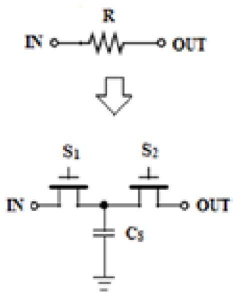

Figure.1. Switched capacitor resistor simulation parallel circuit

A charge q transfers from the input to the output, in each switching cycle at the switching frequency f. Charge q on a capacitor can be given by:

q=CV (1)

When switch S1 is closed, the charge transferred from the source to CS is:

$q_{IN}=C_S V_{IN}$ (2)

When switch S2 is closed, the charge transferred from CS to the load is:

$q_{OUT}=C_S V_{OUT}$ (3)

The charge transferred in each clock cycle is:

$q=q_{IN}-q_{OUT}=C_S(V_{IN}-V_{OUT})$ (4)

The current flowing in the switched capacitor circuit can be given as:

$I=qf$ (5)

Substituting for q in the above equation:

$I=C_S$ (6)$(V_{IN}-V_{OUT})f$

The voltage across the circuit from its input to output can be given as:

$V=V_{IN}-V_{OUT}$ (7)

Using Ohm's law and putting values of I and V from above equations, value of R can be derived as:

(8) $$R=\frac{V}{I}=\frac{V_{IN}-V_{OUT}}{C_S(V_{IN}-V_{OUT})f}$$

So,

(9) $$R=\frac{1}{C_S f}$$

Thus, the SC can be replaced with a resistor whose value depends on capacitance value and switching frequency.

Above derivation is for switched capacitor resistor parallel emulation. Some other configurations are also possible for switched capacitor resistor [2, 4]. These possible configurations and equations of their equivalent resistance are summarized below.

A. Series Resistor Equivalent Circuit

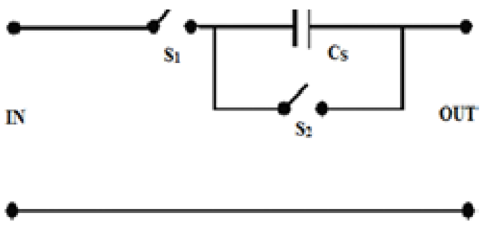

Figure.2. Series resistor equivalent circuit [4]

Equation of Equivalent Resistance:
(10)

$$R = \frac{1}{C_S f}$$

B. Series-parallel Resistor Equivalent Circuit

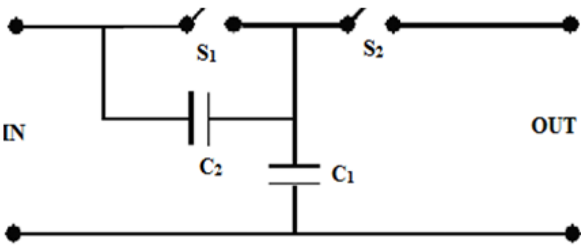

Figure.3. Series-parallel resistor equivalent circuit [4]

Equation of Equivalent Resistance:
(11)

$$R = \frac{1}{f(C_1 + C_2)}$$

C. Bilinear Resistor Equivalent Circuit

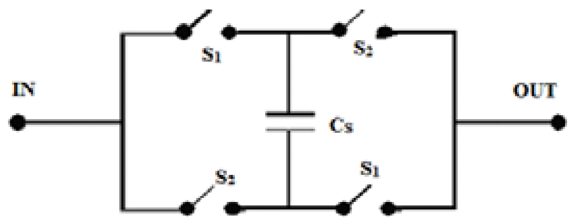

Figure.4. Bilinear resistor equivalent circuit [4]

Equation of Equivalent Resistance:
(12)

$$R = \frac{1}{4C_S f}$$

III. MOSFETS AS SWITCHES

As shown in fig.1 MOSFET is used as a switch in switched capacitor circuits. A MOS transistor can be used as a switch because it has the properties which are necessary for sampling. These properties are it can be on while carrying zero current and the drain to source voltage don't need to follow the variation of the gate voltage [2]. So, if we neglect capacitances from the gate to the drain/source, we find that the gate control signal does not interfere with information being passed through the switch [1]. The switch can be a PMOS, an NMOS or a CMOS transmission gate as shown in fig.5.

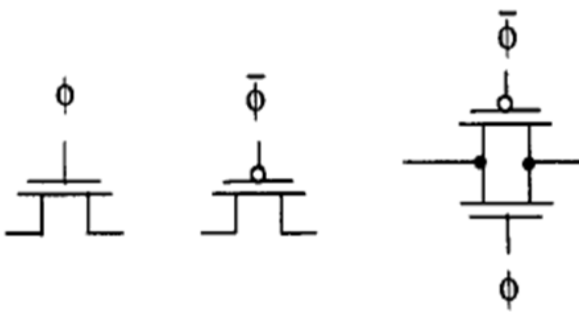

Figure.5. MOSFETs used as switches (a) an NMOS (b) a PMOS (c) a CMOS transmission gate [1]

The sampling speed of MOSFET switch is depends on the on resistance of the switch and the value of the sampling capacitor. To accommodate higher voltage swing the on resistance of the switch should be low [3]. Fig.6 shows the on resistance of a PMOS, an NMOS and a CMOS transmission gate switch [1].

While MOS switches may offer considerable benefits, they are not without some detraction. Two nonideal effects typically associated with these switches [1]. These two effects are summarized in next section.

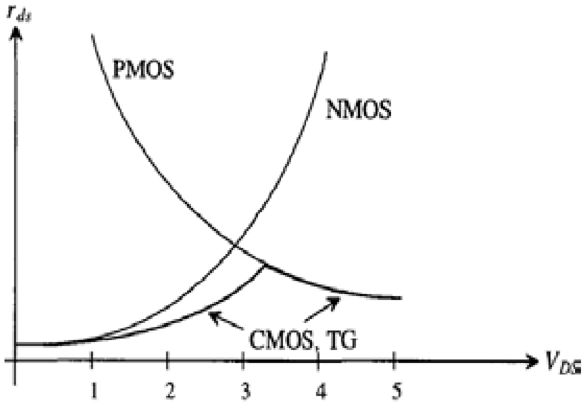

Figure.6. On resistance of MOSFET switches [1]

IV. NONLINEAR EFFECTS OF MOSFET SWITCHES

Mainly two nonideal effects pronounced in MOSFET switches named as – charge sharing effect and clock feedthrough effect.

A. Charge Sharing Effect

Charge injection can be understood with the help of Fig. 7. When the MOSFET switch is on and VDS is small, some charge under the gate oxide resulted from the inverted channel. When the MOSFET turns off, this charge is injected onto the capacitor and into Vin. Since Vin is assumed to be a low-impedance, source-driven node, the injected charge has no effect on this node but the charge injected onto Cload results in a change in voltage across it [1].

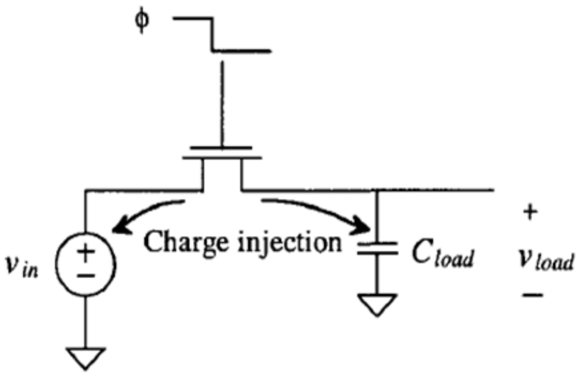

Figure.7. An NMOS switch to show charge injection. [1]

B. Clock Feedthrough Effect

Clock feedthrough can be understood with the help of Fig. 8. The capacitances between the gate/drain and gate/source of the MOSFET are modelled with the assumption that the MOSFET is operating in the triode region. When the gate clock signal goes high, the clock signal feeds through the gate/drain and gate/source capacitances.

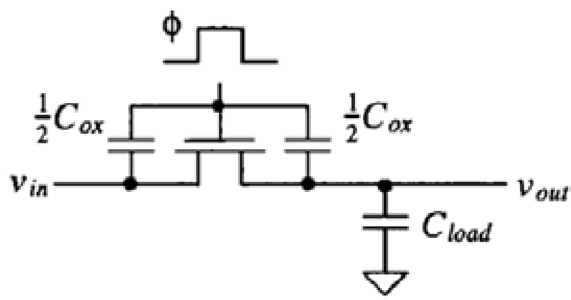

Figure.8. Illustration of capacitive feedthrough [1]

Now, as the switch turns on, the input signal, Vin is connected to the load capacitor through the NMOS switch. The result is that C load is charged to Vin and the capacitive feedthrough has no effect on the final value of Vout. When the clock signal makes the transition low, that is, the n-channel MOSFET turns off. A capacitive voltage divider exists between the gate-drain/gate-source capacitance and the load capacitance. As a result, a portion of the clock signal appears across C_{load} as

(13)

$$\Delta v_{load} = \frac{C_{overlap}(V_{DD} - V_{SS})}{C_{overlap} + C_{load}}$$

Where $C_{overlop}$ is the overlap capacitance

$$C_{overlap} = C_{ox} W . LD$$

(14) Where LD is the length of the gate that overlaps the drain/source.

V. PROS AND CONS OF SC CIRCUITS

The pros of switched capacitor circuits are as follows.

- MOSFET switches contribute nonideal effects to the SC circuits.
- The MOSFET switch has non-zero voltage dependent on resistance which is not desirable.
- SC circuits have more stray capacitances as compare to conventional circuits.

Despite of these issues SC circuits are favorable because they have many advantages as well. Some cons of SC circuits are as summarized below.

- SC circuit can be used as a replacement of resistor in integrated circuits and it is easier to fabricate SC reliably with a small area and wide range of values as compare to resistor.
- Characteristics of SC circuit are determined by capacitance ratio.
- SC has the benefit of adjusting its value by changing the switching frequency.

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