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SWITCHED CAPACITOR CIRCUIT, AN OVERVIEW

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ABSTRACT: In switched capacitor circuits, it is quite common to use MOSFET switches, integrated capacitors (IC) and non-overlapping clocks for carrying out switching operations. MOSFET switches are far from ideal switches mainly when they are operated with small operating voltages. Some investigations have been carried out on the performance of switched capacitor resistors (SCRs) with the switches operated under varied conditions.

This paper will explain the basic concepts underlying the operation of the switched capacitor, as well as the use of switched-capacitors to realize compact and versatile circuits already familiar to the undergraduate student of electronics. One set of example circuits include easily tunable active filters; specific examples of filter designs that incorporate switched-capacitors will be developed, and the use of a commercially available switched-capacitor integrated circuit, the MF10, to implement the designs will be shown. Another example circuit is an instrumentation amplifier that is more compact and has a higher CMRR than the conventional realization. Linear Technology's LTC1043 serves as the vehicle for this circuit. By demonstrating the utility of the modern switched-capacitor IC in these two important electronic functions, it is hoped that instructors and students in engineering technology will include the study of the switched-capacitor in advanced electronics courses.

KEYWORDS: Switched capacitors, Switched capacitors resistors, Switched Capacitor Integrator, Switched Capacitor Filter, Switched-Capacitor Amplifier, SCR, FET, MOSFET, EMOSFET.

I. INTRODUCTION

The principles of operation of ideal SCRs and, the extent to which SCRs can be represented by a conventional resistor are described. The effect of switch resistance on the value of SCR and the attempts to compute the SCR values taking the I-V characteristics of the switches are discussed. The behavior of SCR [1] when connected along with conventional capacitors and resistors are considered. We caution on the use of SCRs in the place of conventional resistances as they mimic the behavior of conventional resistors only under some special circumstances. Switched capacitor circuits are based on the principle that “charge transfers from a higher voltage node to a lower voltage node”. This is generally carried out in two steps, charging a capacitor to a voltage V1 through a switch and discharging it to a lower voltage V2, through another switch. Under equilibrium conditions the charge drawn from the high voltage node is the same as the charge delivered to the low voltage node. This charge transfer takes place [2] in one clock period and the average rate of charge transfer is taken as the DC current, even though the current is impulsive (for ideal conditions). The ratio of voltage difference to the current is taken as the effective resistance of the SCR. Switched Capacitor acts like a resistor whose value depends on capacitance Cs and switching frequency f. The switched capacitor resistor is used in place of simple resistors in integrated circuits. Many configurations are suggested, and two of these are given.

Before detailing the operation of switched-capacitor circuits, it will be useful to understand the motivation behind, and applications of, these circuits. Basically, switched-capacitor techniques have been developed in order to allow for the integration on a single silicon chip of both digital and analog functions. Because very large scale integrated (VLSI) circuits rely on MOS transistors and pico-farad range MOS capacitors, any realization of analog circuits on a chip will have to use these elements. By comparison, conventional analog circuits use the ***ratio*** of resistances to set the transfer functions of amplifiers, and the ***magnitudes*** of resistances to determine the operation of current-to-voltage and voltage-to-current converters. Finally, the ***values*** of RC products are used in active filters and signal generators to determine the frequency responses of those circuits. When one moves 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 [3,4]. 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.

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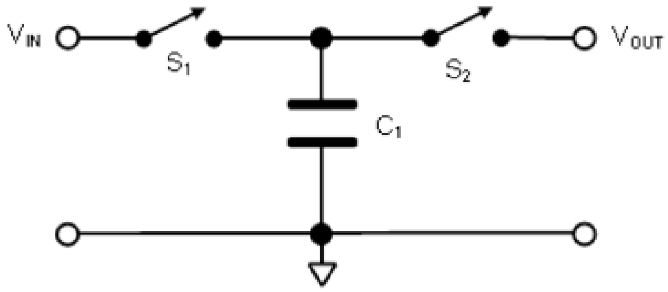


Figure 1, Basic Switched Capacitor circuit

The most simple switched capacitor circuit is shown in figure 1, the switched capacitor resistor. It consists of one capacitor C_1 and two switches S_1 and S_2 which connect the capacitor alternately to the input, V_{IN} and the output, V_{OUT}.

II. BASIC SWITCHED-CAPACITOR OPERATION

The essence of the switched-capacitor is the use of capacitors and analog switches to perform the same function as a resistor. This replacement resistor, along with op-amp based integrators, then forms an active filter. Before delving too far into actual filter designs, however, it makes sense to ask why one would want to replace the resistor with such an apparently complex assembly of parts as switches and capacitors. It would seem from the multiplication of parts that the switched-capacitor would be area intensive. As a matter of fact, for the resistor values that one seeks in certain filter designs, this is not the case. Furthermore, the use of the switched-capacitor will be seen to give frequency tunability to active filters. Figure 2[3,4] shows the basic setup for a switched-capacitor, including two N-channel Metal-Oxide Semiconductor Field-Effect Transistors (NMOS) and a capacitor. There are two clock phases, ϕ and $\bar{\phi}$, which are non-overlapping. The MOSFET's, either M1 or M2, will be turned ON when the gate voltage is high, and the equivalent resistance of the channel in that case will be low, $R_{ON} \approx 1k\Omega \rightarrow 10k\Omega$. Conversely, when the gate voltage goes LOW, the channel resistance will look like $R_{OFF} \approx 10^{12}\Omega$. With such a high ratio of OFF to ON resistances, each MOSFET can be taken for a switch. Furthermore, when the two MOSFET's are driven by non-overlapping clock signals, then M1 and M2 will conduct during alternate half-cycles.

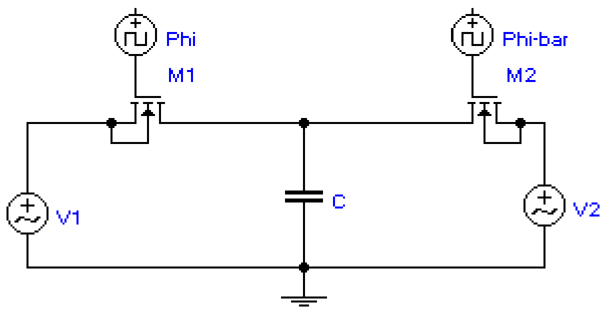
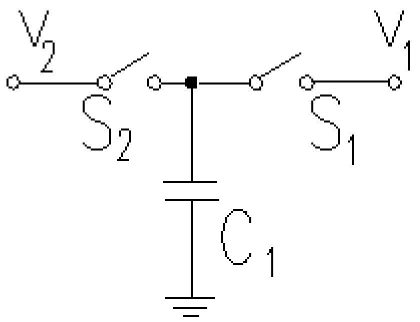


Figure 2. Two NMOSFET's, driven by alternating, non-overlapping clock signals, comprise the basic switched capacitor network.

The Switched Capacitor Resistor

To understand how switched capacitor circuits work, consider the circuit shown with a capacitor connected to two switches and two different voltages.



If S_2 closes with S_1 open, then S_1 closes with switch S_2 open, a charge (q is transferred from v_2 to v_1 with

$$\Delta q = C_1(v_2 - v_1).$$

If this switching process is repeated N times in a time (t, the amount of charge transferred per unit time is given by

$$\frac{\Delta q}{\Delta t} = C_1(v_2 - v_1)\frac{N}{\Delta t}.$$

Recognizing that the left hand side represents charge per unit time, or current, and the the number of cycles per unit time is the switching frequency (or clock frequency, f_{CLK}) we can rewrite the equation as

$$i = C_1(v_2 - v_1)f_{CLK}.$$

Rearranging we get

$$\frac{(v_2 - v_1)}{i} = \frac{1}{C_1 f_{CLK}} = R,$$

which states that the switched capacitor is equivalent to a resistor. The value of this resistor decreases with increasing switching frequency or increasing capacitance, as either will increase the amount of charge transfered from v_2 to v_1 in a given time.

The Switched Capacitor Integrator

Now consider the integrator circuit. You have shown (in a previous lab) that the input-output relationship for this circuit is given by (neglecting initial conditions):

$$v_o(t) = -\frac{1}{RC_2}\int v_i(t)dt = -\omega'\int v_i(t)dt$$

We can also write this with the "s" notation (assuming a sinusoidal input, Ae^{st}, s=jw)

$$V_o(s) = -\frac{\omega'}{s}$$

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If you replaced the input resistor with a switched capacitor resistor, you would get

$$\omega' = \frac{1}{RC_2} = f_{CLK}\frac{C_1}{C_2}$$

Thus, you can change the equivalent w' of the circuit by changing the clock frequency. The value of w' can be set very precisely because it depends only on the ratio of C_1 and C_2, and not their absolute value.[5,6]

Switched Capacitor Filter

In this lab you will be using the MF100, or LMF100 (web page, datasheet, application note). This integrated circuit is a versatile circuit with four switched capacitor integrators, that can be connected as two second order filters or one fourth order filter. With this chip you can choose w' to either be 1/50 or 1/100 of the clock frequency (this is given by the ratio C_1/C_2 in the discussion above),. By changing internal and external connections to the circuit you can obtain different filter types (lowpass, highpass, bandpass, notch (bandreject) or allpass).[7]

2nd Order Filters	
Filter Type	**Transfer Function**
Low Pass	$H_{LP}(s) = \dfrac{H_{OLP}\omega_0^2}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$
High Pass	$H_{HP}(s) = \dfrac{H_{OHP}s^2}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$
Band Pass	$H_{BP}(s) = \dfrac{H_{OBP}\frac{\omega_0}{Q}s}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$
Notch (Band Reject)	$H_N(s) = \dfrac{H_{ON}\left(\omega_0^2 + s^2\right)}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$

The pinout for the LMF100 is shown below (from the data sheet):

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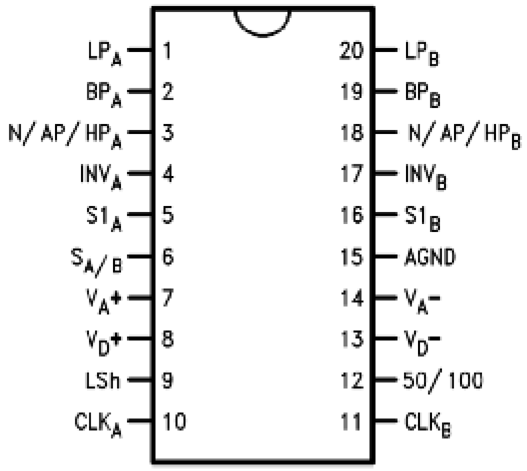
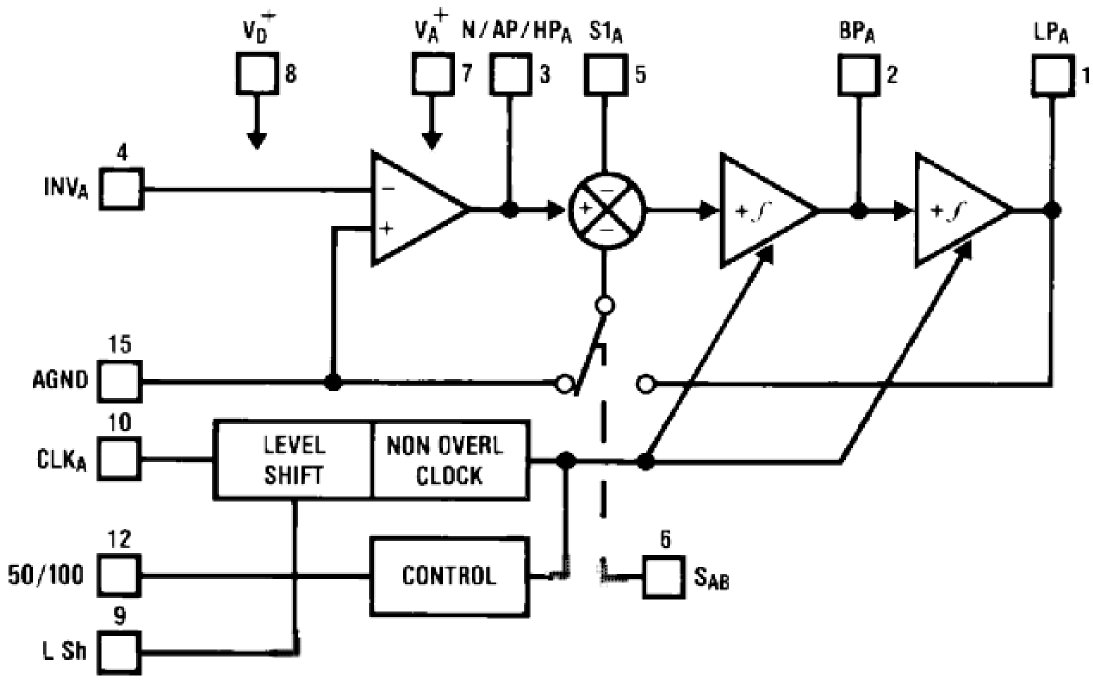


You can see that the chip, for the most part, is split into two halves, left and right. A block diagram of the left half ((and a few pins from the right half) is shown below.



The pins are described on page 8 of the datasheet. I will describe a few of them here:

- 50/100 - determines if the value of w' is $w_{CLK}/100$, or $w_{CLK}/50$.
- CLK_A - is w_{CLK}.
- INV_A - the inverting input to the op-amp
- $N/AP/HP_A$ - an intermediate output, and the non-inverting input to the summer. Used for Notch, All Pass or High Pass output.
- BP_A - another intermediate output, the output of the first integrator. Used for Band Pass output.
- LP_A - the output of the second integrator. Used for Low Pass output.
- $S1_A$ - an inverting input to the summer.
- S_{AB} - determins if the switch is to the left or to the right. That is, this pin determines if the second inverting input to the summer is ground (AGND), or the low pass output.

The two integrators are switched capacitor integrators. Their transfer functions are given by,

$$\frac{\omega'}{s}$$

where w' is $w_{CLK}/100$, or $w_{CLK}/50$, depending on the state of the 50/100 pin. Note that the integrator is non-inverting.[8]

Switched capacitor differencing circuit

The objective of this activity is to extend the switched capacitor concept beyond the single capacitor and switches circuit that can be built around the CD4007 transistor array. More complex configurations require multiple capacitors and switches. Analog switches and multiplexers such as the CD4066 and CD4053 can be used.

III. MATERIALS:

1 - CD4053B triple analog SPDT switch
2 - 1 nF capacitors (102)

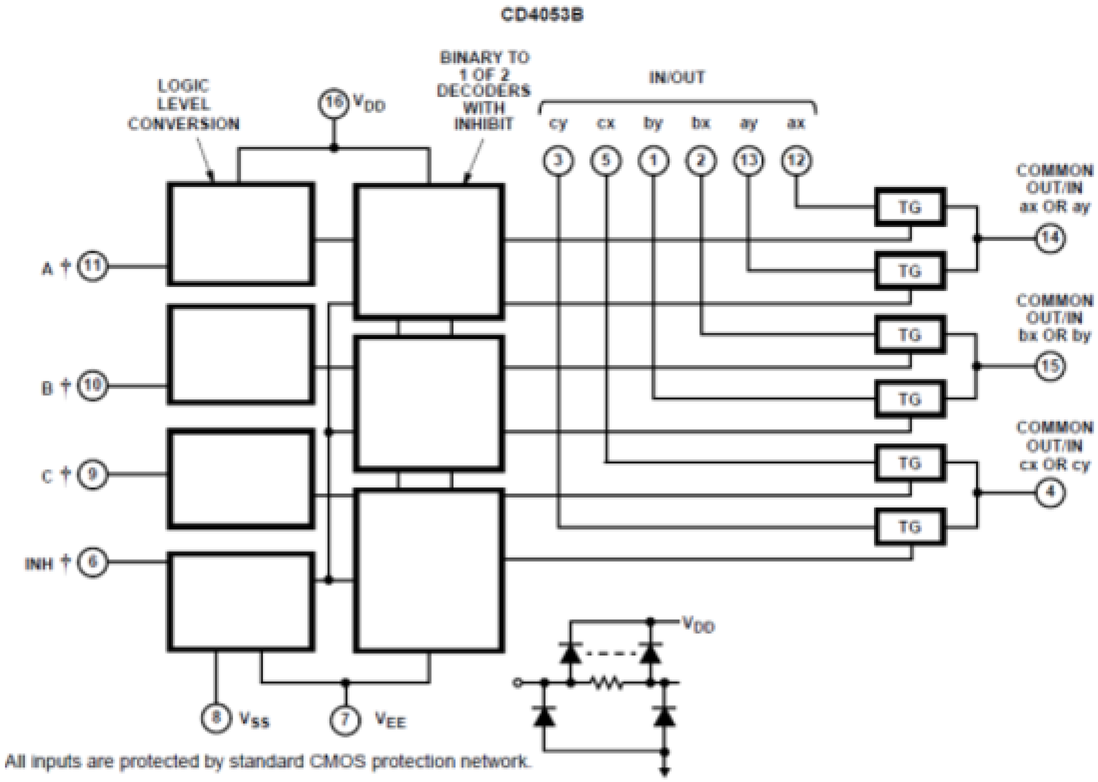


Figure 3 CD4053 Block diagram / Pinout

A switched capacitor differential to single ended configuration is shown in figure 4. Build this circuit on your solder-less breadboard using two of the three SPDT analog switches in the CD4053. V_{DD} of the CD4053 should be connected to the +5 V power supply (Vp) and V_{EE} connected to the -5 V power supply (Vn) and finally with V_{SS} connected to ground. The differential inputs, V_{IN+} and V_{IN-} should be connected to the waveform generator outputs AWG1 and AWG2 respectively. The single ended output, V_{OUT} should be connected to scope channel 1+.

Switch control signals for both switches A and B should both be connected to digital pin DIO 0. Be sure to connect the inhibit input (pin 6) to ground to enable all the switches. It is probably also a good idea to ground the unused C control input as well.

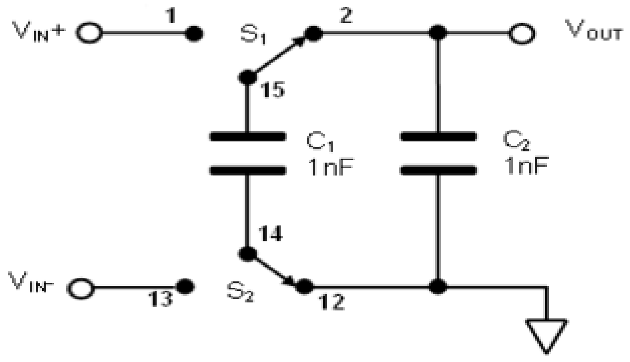


Figure 4 differential to single ended circuit

Switched-Capacitor Implementation Amplifier ¾ LTC1043

Although the initial impetus for the development of the switched-capacitor was the opportunity and need to synthesize active filters that would be compatible with MOSFET technology, the early 1980's found many other uses for the switched-capacitor. Linear Technology has developed the LTC1043 [9], which contains dual switched capacitor networks, along with an on-chip non-overlapping clock generator, oscillator, and charge balancing circuitry. The clock generator controls both of the switch networks, while the charge balancing circuitry is designed to cancel any effects due to stray capacitance. The on-chip oscillator has a fixed frequency of 185 kHz. An external capacitor can be connected across pins 16 and 17 (for the instrumentation amplifier) to yield any desired clock rate. The desired clock rate can be found from

$f_{CLK} \cong \frac{4440}{C_{ext} + 24pf}$; the 24-picofarad capacitance is the internal capacitance responsible for the oscillator's fixed frequency.

Among the circuits developed from the LTC1043 are instrumentation amplifiers, lock-in amplifiers for detecting extremely small parameter shifts in sensor applications, and signal conditioners for platinum resistance temperature detectors (RTD), relative humidity sensors, and LVDT's. The instrumentation amplifier is a standard op-amp circuit presented in many electronics texts [5-6], and is designed to amplify small difference signals such as might be found in measurement or transducer applications. At the same time, common-mode or noise signals picked up by the lines feeding the amplifier must be suppressed, especially as these signal levels are often larger in amplitude than the sought-for difference signals. **Figure 5** shows the LTC1043 combined with a standard non-inverting op-amp to give an instrumentation amplifier with a common-mode rejection ratio (CMRR) of >120 dB. **Figure 6** shows the same circuit with the ½ LTC1043 as a black box.

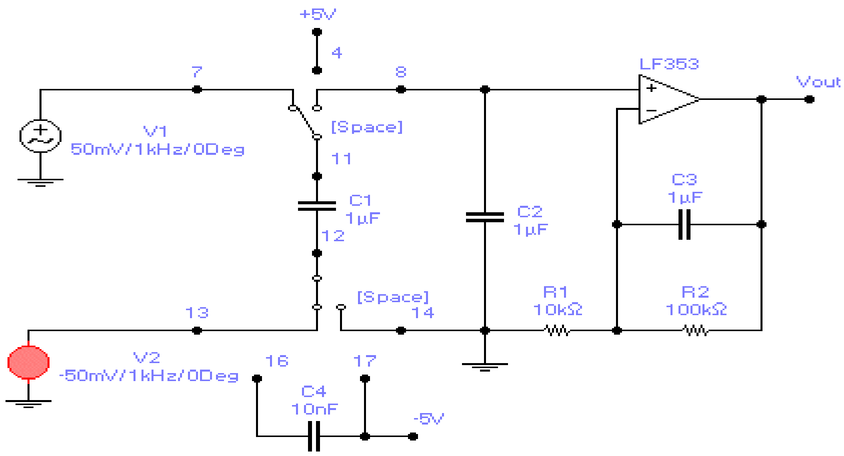


Figure 5. Instrumentation amplifier using ½ of LTC 1043 switched-capacitor, along with LF356/353 op-amp in non-inverting configuration.

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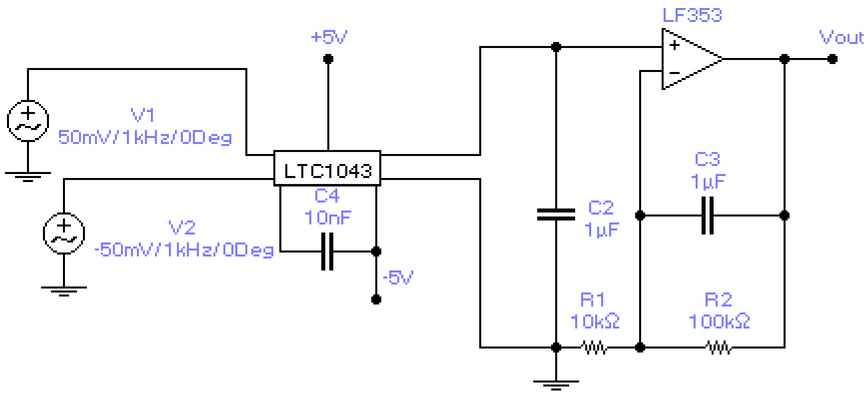

Figure 6. Switched-capacitor-based instrumentation amplifier, with ½ LTC1043 shown as a black box. The pin numbers in Figure 13 are the pins in the black box in this figure.

The operation of this circuit is as follows. First, the dual switch, when flipped to the left, charges the capacitor C_1 up to the difference $V_1 - V_2$. Second, on the next clock pulse, the switches will then dump the charge represented by that voltage difference onto C_2. Third, the continuous clocking from the oscillator will force C_2 to eventually develop a voltage equal to the difference voltage. Finally, the difference voltage, with the common-mode signal stripped off by the LTC1043 is amplified by the op-amp. It is interesting to observe several features of this circuit and compare them to the standard instrumentation amplifier. By using the capacitor C_1 (the so-called "flying capacitor"), the common-mode voltage present at the inputs is looking into a capacitive voltage divider, between the C_1 and the LTC1043's parasitic capacitance. This parasitic capacitance is typically less than 1 picofarad, so the AC value of the CMRR is > 120 dB. By comparison, Analog Device's AD624 instrumentation amplifier can go as high as 130 dB for high gains, up to 60 Hz. Because of the capacitive voltage divider from the LTC1043, this instrumentation amplifier shows higher CMRR, over a wider range of voltage gains, and to a higher frequency.

IV. CONCLUSION:

In the last decade or so many active filters with resistors and capacitors have been replaced with a special kind of filter called a switched capacitor filter. The switched capacitor filter allows for very sophisticated, accurate, and tuneable analog circuits to be manufactured without using resistors. This is useful for several reasons. Chief among these is that resistors are hard to build on integrated circuits (they take up a lot of room), and the circuits can be made to depend on ratios of capacitor values (which can be set accurately), and not absolute values (which vary between manufacturing runs).

This paper has presented the essentials of operation of switched-capacitor networks, with a special emphasis on its use in designing active filters. Unlike active filters based on the conventional op-amp, switched-capacitor filters have critical frequencies that are easily pin-settable. Furthermore, they require less power than the conventional op-amp based network because of their reliance on CMOS technology. Finally, for the functionality provided on a single chip, they take up less room on circuit boards. Alternate use of the switched-capacitor network in an instrumentation amplifier has also been presented. The operation of this device is a little easier to digest for some students than discussion of active filters; it is hoped that instructors and students can use the information herein to extend their acquaintance with modern integrated circuits.

V. REFERENCE:

[1] Soclof, S. (1991). Design and applications of analog integrated circuits. Prentice Hall.
[2] Allen, P. E., & Holberg, D. R. (2011). CMOS analog circuit design. Elsevier.
[3] Design with Operational Amplifiers and Analog Integrated Circuits, by Sergio Franco. McGraw-Hill Book Company, New York, 1988. Chap. 13.
[4] Bipolar and MOS Analog Integrated Circuit Design, by A.B. Grebene. Wiley-Interscience, John Wiley & Sons, New York, 1984. Chap. 13, pp. 703-752.
[5] Electronic Devices, 5th Edition, by T. L. Floyd. Prentice-Hall, Englewood Cliffs, NJ, 1997. Chap.
[6] Microelectronic circuits, 3rd Edition, by A. Sedra and K.C. Smith. Saunders College Publishing/HRW, Philadelphia, PA, 1991. Chap. 2.

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[7] APLACÔ 7.0 User's Manual, Helsinki University of Technology, Circuit Theory Laboratory & Nokia Corporation Research Center, 1998. Available at http://www.aplac.hut.fi/

[8] "Fast Analysis of Nonideal Switched-Capacitor Circuits using Convolution," H. Jokinen, M. Valtonen, and T. Veijola. 11th European Conference on Circuit Theory and Design, Davos, Switzerland, 1993, pp.941-946.

[9] ***Applications for a Switched-Capacitor Instrumentation Building Block,*** by Jim Williams. Linear Technology Application Note 3, July 1985.