

Analog-to-Digital Converters

Operation of a SAR-ADC Based on Charge Redistribution

Abstract

Analog-to-Digital Converters (ADCs) that convert the sampled input signal through Successive Approximation (SAR), are known as SAR-ADCs. While there are various methods of performing successive approximation, Renesas SAR-ADCs use a method known as capacitive charge redistribution.

This application note explains the functional principle of a SAR-ADC based on charge redistribution

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Related Literature

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- [SAR A/D Converter](#) page

1. Introduction

Figure 1 shows the simplified, switched-capacitor structure of a 5-bit SAR-ADC. The capacitor values are binary weighted from C , $C/2 \dots C/16$ or $C/2^{n-1}$. The last two capacitors have the same value of $C/2^{n-1}$. Only the first capacitor (connected to S_0) is switched during the charge redistribution (the actual conversion). The other capacitor remains connected to ground.

MOS-transistors implement the required $n+3$ switches, and the voltage comparator provides the appropriate steering of these switches using auxiliary logic circuitry.

The conversion process is performed in three steps:

- Sample mode
- Hold mode
- Redistribution mode (the actual conversion)

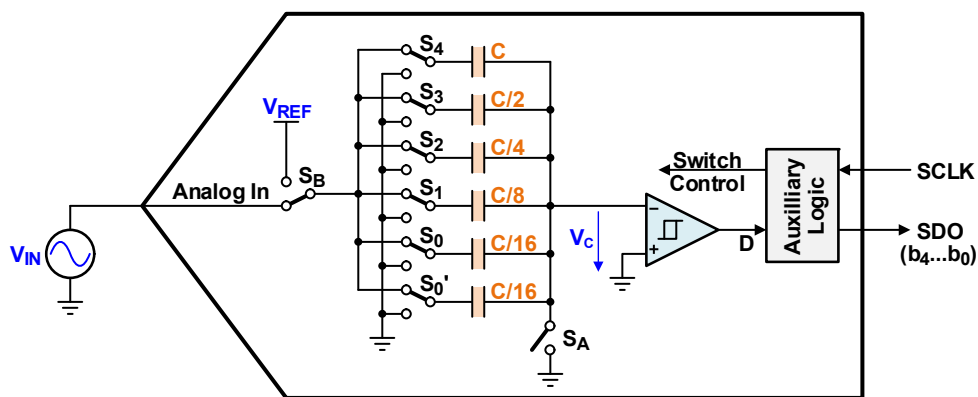


Figure 1. Simplified 5-Bit SAR-ADC Principle

2. Sample Mode

In the sampling mode (Figure 2), bus switch SB is switched to the input voltage, V_{IN} , and S_A is closed to ground. The capacitor switches, $S_4 \dots S_0'$, are turned to the common bus B and all capacitors are charged to V_{IN} . The total charge of $Q_{IN} = V_{IN} \cdot 2C$ is stored on the left plates of the capacitors.

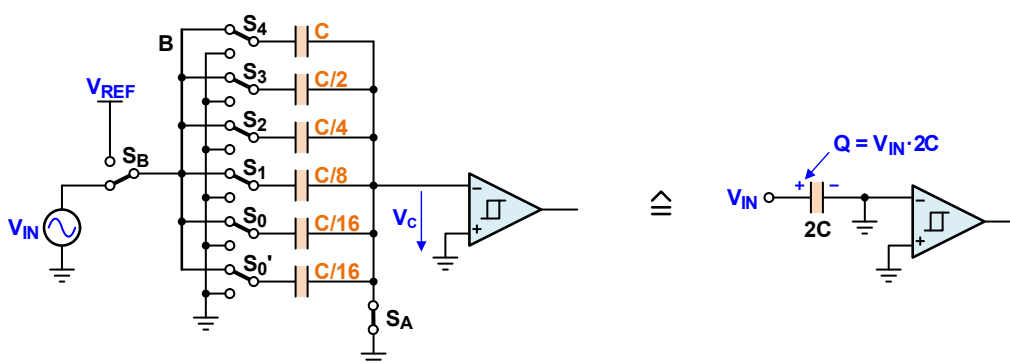


Figure 2. Sample Mode

3. Hold Mode

During the hold mode (Figure 3), switch S_A is open while the switches $S_4 \dots S_0'$ are connected to ground, thereby making the voltage at the inverting comparator input $V_C = -V_{IN}$. This means that the switched-cap circuit already has a built-in sample-and-hold function.

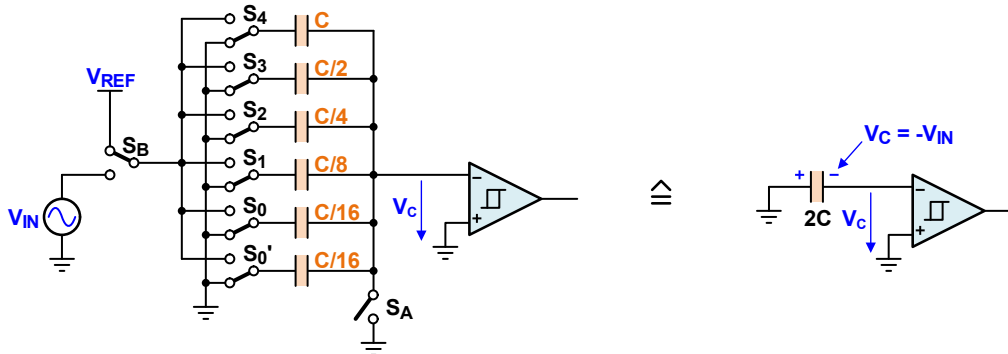


Figure 3. Hold Mode

4. Redistribution Mode

The actual conversion is performed by charge redistribution. The first conversion step, shown in Figure 4, connects C (the largest capacitor) using S_4 to the reference voltage V_{REF} , which corresponds to the Full-Scale Range (FSR) of the ADC.

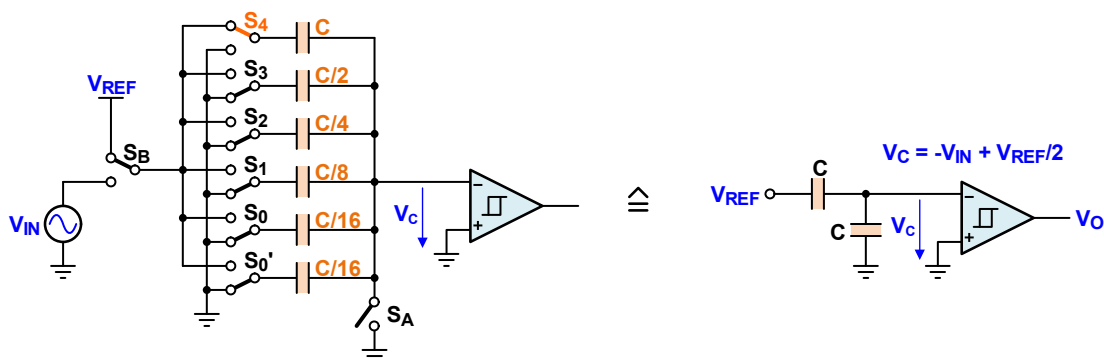


Figure 4. Conversion Step 1 Determines the MSB (Bit 4)

Capacitor C forms a 1:1 capacitance divider with the remaining capacitors connected to ground. The comparator input voltage becomes $V_C = -V_{IN} + V_{REF}/2$. This voltage is compared with the voltage potential of $0V$ at the non-inverting input. Therefore, if $|V_{IN}| > V_{REF}/2$, $V_C < 0$, and the comparator output V_O goes high, setting the Most Significant Bit (MSB) (Bit 4) = 1. However, if $|V_{IN}| < V_{REF}/2$, $V_C > 0$, V_O remains low, and Bit 4 = 0. If $V_O =$ high, S_4 remains connected to V_{REF} for the rest of the conversion. If $V_O =$ low, S_4 is switched back to GND.

This procedure is repeated for switches, S_3 to S_0 , except S_0' , which remains connected to GND for the entire conversion.

Summarizing, the conversion or charge redistribution procedure can be expressed by two equations:

(EQ. 1) $\text{If } -V_{IN} + V_{REF} \cdot X > 0 \Rightarrow V_O = \text{High [1]} \Rightarrow \text{maintain switch position}$

(EQ. 2) $\text{If } -V_{IN} + V_{REF} \cdot X < 0 \Rightarrow V_O = \text{Low [0]} \Rightarrow \text{connect switch back to GND}$

with X as the ratio of the capacitive voltage divider because of a given switch position.

Therefore, the comparator input voltage of the final conversion step is:

$$(EQ. 3) \quad V_C = -V_{IN} + \text{bit } 4 \cdot \frac{V_{REF}}{2} + \text{bit } 3 \cdot \frac{V_{REF}}{4} + \text{bit } 2 \cdot \frac{V_{REF}}{8} + \text{bit } 1 \cdot \frac{V_{REF}}{16} + \text{bit } 0 \cdot \frac{V_{REF}}{32}$$

5. Conversion Example

The following example shows the conversion process of a 5-bit SAR-ADC for $V_{IN} = 3V$ and $V_{REF} = 5V$. According to Equation 3, the comparator input voltage of the final conversion step must be:

$$(EQ. 4) \quad V_C = -3V + [1] \cdot 2.5V + [0] \cdot 1.25V + [0] \cdot 0.625V + [1] \cdot 0.3125V + [1] \cdot 0.15625V = -0.03125V$$

Sample Mode: All capacitors are connected to voltage bus B using S_4 to S_0' and to ground using S_A . Bus B is connected to V_{IN} . All capacitors are charged up to $V_{IN} = 3V$ (Figure 5).

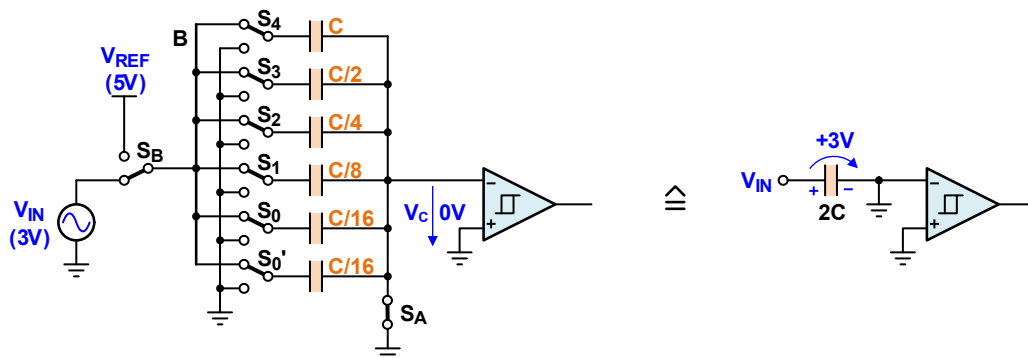


Figure 5. Sample Mode: All Capacitors are Charged up to $V_{IN} = +3V$

Hold Mode: The left side of the capacitors is connected to ground using S_4 to S_0' . The common (right) side of the capacitors is disconnected from ground using S_A , therefore, creating a comparator input voltage of $-V_{IN} = -3V$ (Figure 6).

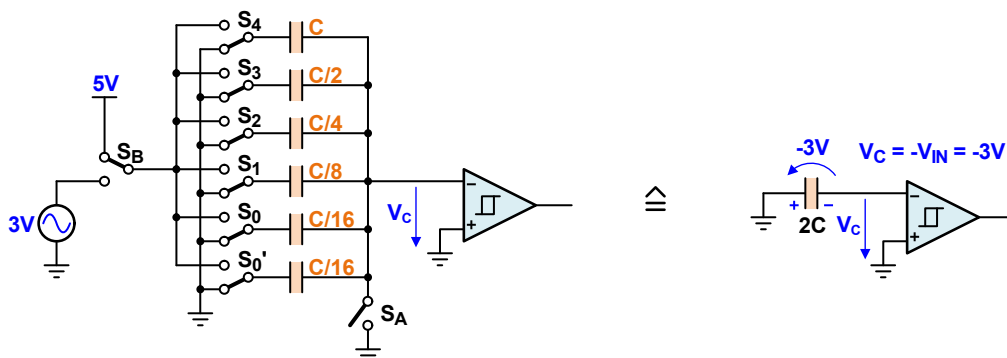


Figure 6. Hold Mode: All Capacitors are Charged up to $V_{IN} = +3V$

Redistribution Mode: The actual conversion starts by connecting S_B to $V_{REF} = 5V$.

Bit 4 (MSB): The first conversion step determines the most significant bit (MSB = Bit 4) connecting C to V_{REF} using S_4 . The ratio of the capacitive voltage divider becomes $X = 1/2$ and creates a comparator input voltage of $V_C = -0.5V$. This turns the comparator output high and sets Bit 4 to 1. It also means that S_4 must remain in the present position for the rest of the conversion process (Figure 7).

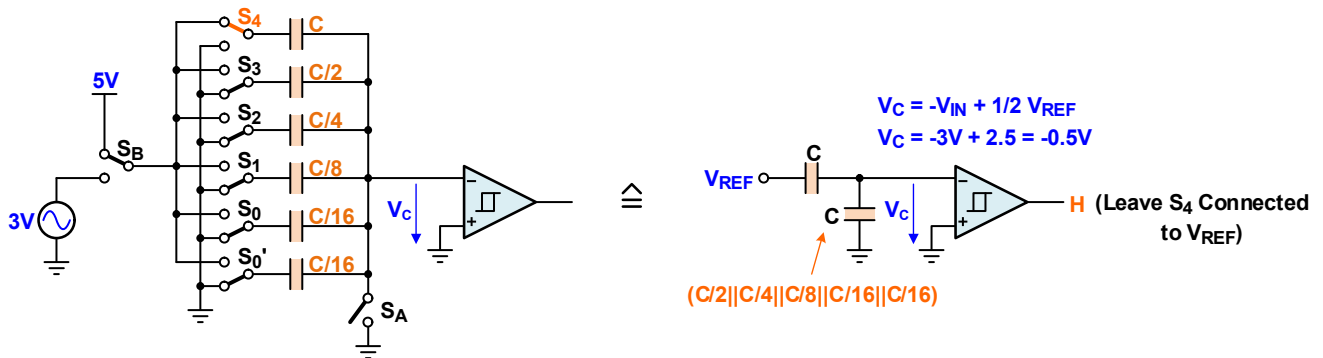


Figure 7. Bit-4 (MSB): Because $V_O = H$, Bit 4 = 1. Therefore, S_4 Must Remain in its Current Position

Bit 3: The second conversion step determines Bit 3 by connecting $C/2$ to V_{REF} using S_3 . The divider ratio changes to $X = 3/4$, causing a comparator input of $V_C = +0.75V$. This turns the comparator output low and sets Bit 3 to 0. It also means that S_3 must be switched back to ground (Figure 8).

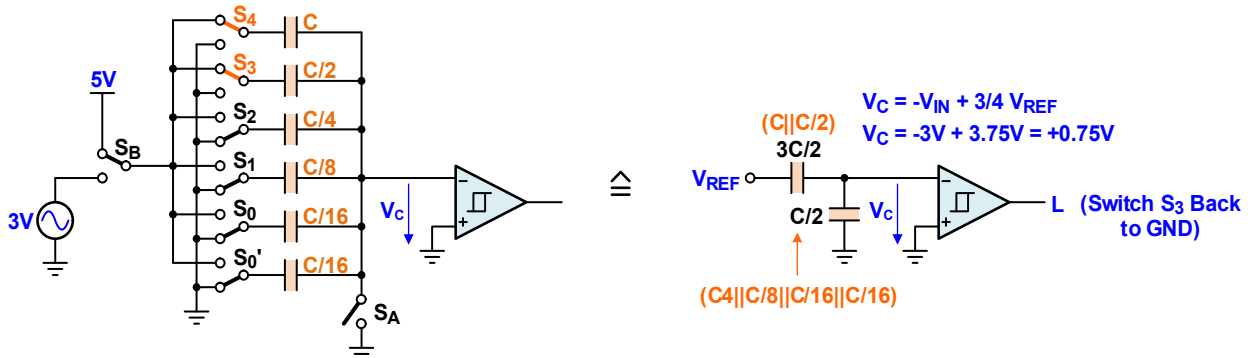


Figure 8. Bit-3: Because $V_O = L$, Bit 3 = 0. Therefore, S_3 Must be Switched Back to GND

Bit 2: The third conversion step determines Bit 2 by connecting $C/4$ to V_{REF} using S_2 . The divider ratio changes to $X = 5/8$, causing a comparator input of $V_C = +0.125V$. This turns the comparator output low and sets Bit 2 to 0. It also means that S_2 must be switched back to ground (Figure 9).

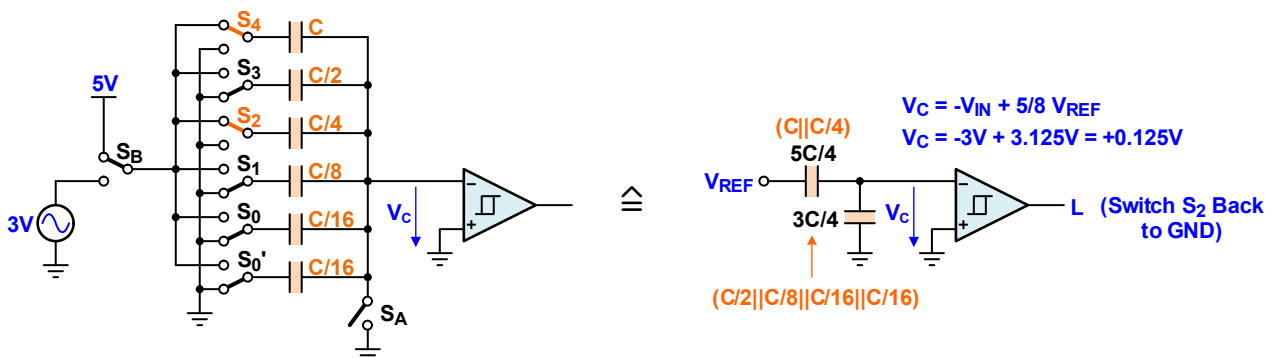


Figure 9. Bit-2: Because $V_O = L$, Bit 2 = 0. Therefore, S_2 Must be Switched Back to GND

Bit 1: The fourth conversion step determines Bit 1 by connecting $C/8$ to V_{REF} using S_1 . The divider ratio changes to $X = 9/16$, causing a comparator input of $V_C = -0.1875V$. This turns the comparator output high and sets Bit 1 to 1. It also means that S_1 must remain in the present position for the rest of the conversion process (Figure 10).

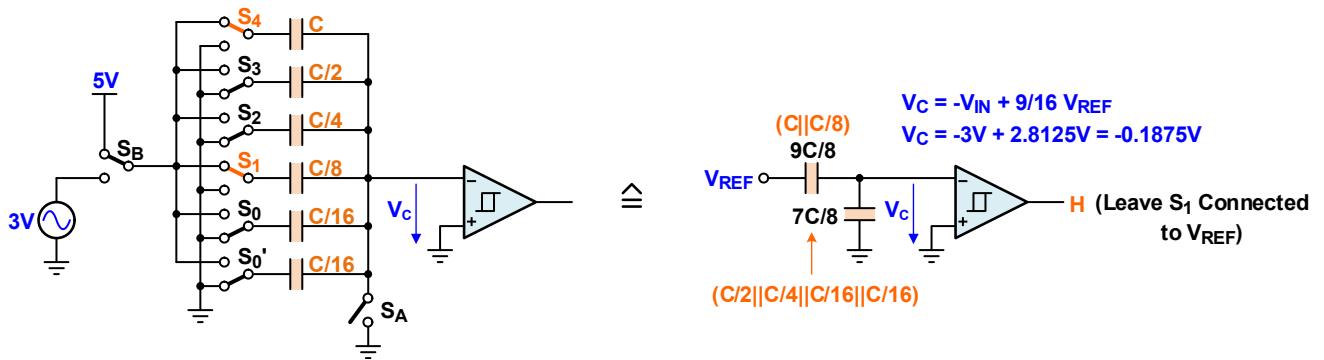


Figure 10. Bit 1: Because $V_O = H$, Bit 1 = 1. Therefore, S_1 Must Remain in its Current Position

Bit 0: The fifth conversion step determines Bit 0 by connecting $C/16$ to V_{REF} using S_0 . The divider ratio changes to $X = 19/32$, causing a comparator input of $V_C = -0.03125V$. This turns the comparator output high and sets Bit 0 to 1. It also means that S_0 must remain in the present position (Figure 11).

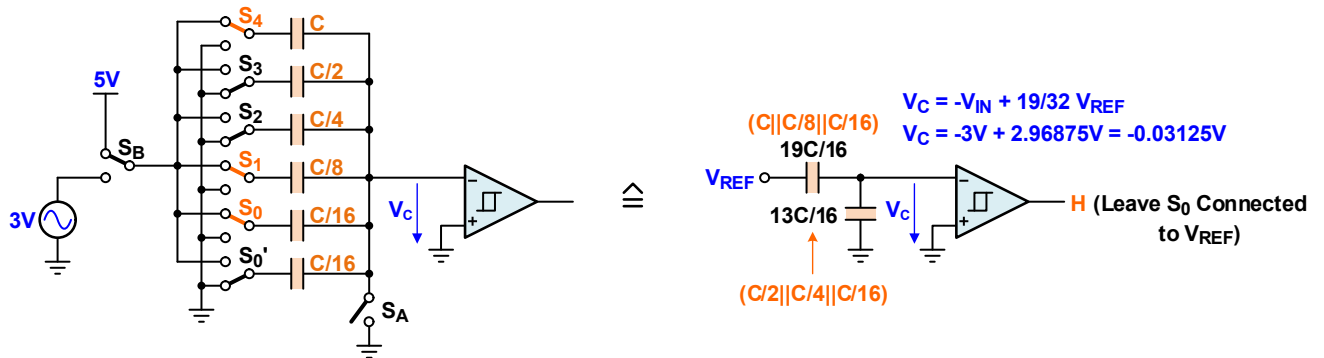


Figure 11. Bit 0: Because $V_O = H$, Bit 0 = 1. Therefore, S_0 Must Remain in its Current Position

6. Timing Diagram

Figure 12 shows the timing diagrams for the bus voltage (V_B) the comparator input voltage (V_C) the On/Off status of all switches (1 = On), and the individual capacitor voltages, V_{C1} to V_{C16} .

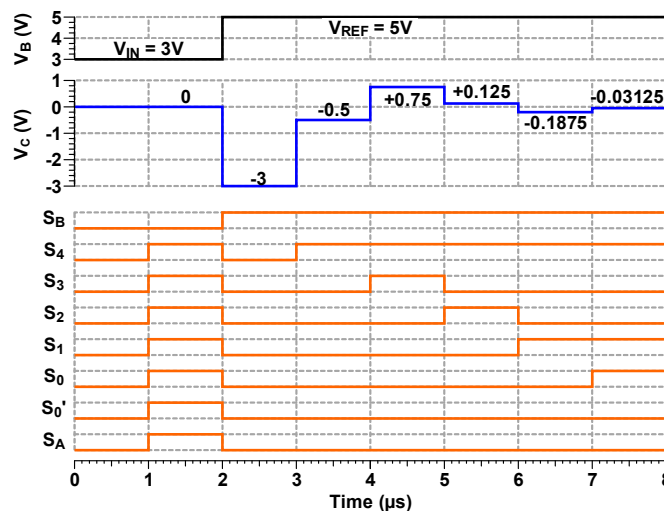


Figure 12. SAR Conversion Timing Diagram

7. Revision History

| Rev. | Date | Description |
|------|-----------|-----------------|
| 1.00 | Sep.17.20 | Initial release |

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(Rev.1.0 Mar 2020)

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