# A/D Converters

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Real world signals are analog signals, representing some measured physical parameter for every instant in time. They must be converted to a discrete time signal to be interpreted and processed by computers. As their name would imply, analog-to-digital converters (A/D converters, ADCs) measure an analog input voltage and convert this to a digital output format. A/D converters therefore represent the heart of an A/D board or data acquisition system.

The main types of A/D converters used and the specific and important parameters relating to their operation are detailed in the following sections.

## Successive Approximation A/D Converters

A successive approximation A/D conversion is the most common and popular direct A/D conversion method used in data acquisition systems because it allows high sampling rates and high resolution, while still being reasonable in terms of cost. Throughput of a few hundred kHz for 12-bit ADCs is common, while 16-bit ADCs employing a hybrid conversion method (i.e. successive approximation plus a much faster method such as flash) are capable of throughput up to 1 MHz, while still being reasonable in cost. One clear advantage of this device is that it has a fixed conversion time proportional to the number of bits, n, in the digital output. If the approximation period is T, then an n-bit converter will have a conversion time of around nT. Each successive bit, which doubles the ADCs accuracy, increases the conversion time only by the period T. The functional diagram of an n-bit successive approximation A/D converter is shown in Figure 3.

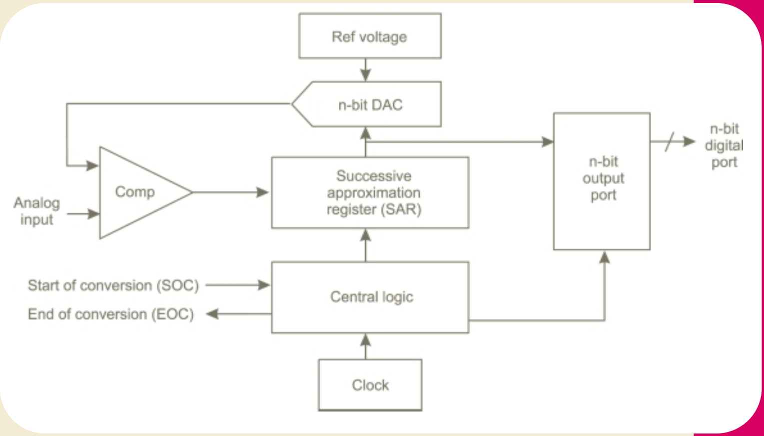

Figure 3 - Functional Diagram of an n-bit Successive Approximation A/D Converter

The successive approximation technique generates each bit of the output code sequentially, starting with the most significant bit (MSB). The operation is similar to a binary search and is based on successively closer comparisons between the analog input signal and the analog output from an internal D/A converter.

The A/D converter starts the procedure by setting the digital input to the D/A converter, so that its analog output voltage is half the full scale voltage of the A/D device. A comparator is used to compare the D/A analog output to the analog input signal being measured.

If the analog input signal is greater, the most significant bit (MSB) of the D/A converter input is set to logic 1 and the next most significant bit of the D/A converter input is set to logic 1, setting the analog output of the D/A at 3/4 of full scale voltage. If the analog input signal was less, the MSB of the D/A input is cleared to logic 0 and the next most significant bit of the D/A input is set to logic 1, setting the analog output of the D/A at 1/4 of full-scale voltage.

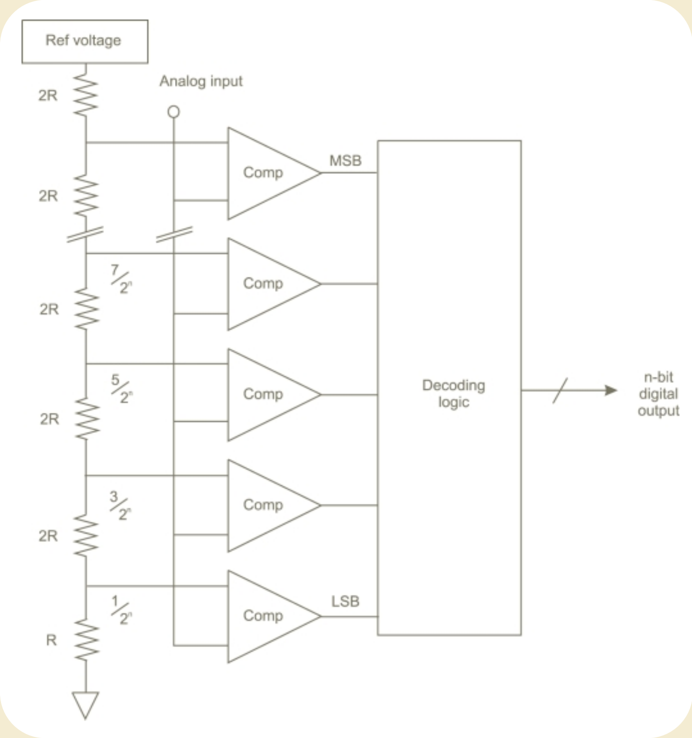

Figure 4 - Functional Diagram of an n-bit Flash A/D Converter

Each step effectively divides the remaining fraction of the input range in half, then again compares it to the analog input signal. This is repeated until all the n bits of the A/D conversion have been determined. It is obviously important that the analog input signal to the A/D does not change during the conversion process, hence the use of sample and hold circuits.

## Flash A/D Converters

Flash A/D converters are the fastest available A/D converters, operating at speeds up to hundreds of MHz. This type of device is used where extremely high speeds of conversion are required with lower resolution, for example, 8-bits.

Figure 4 shows the functional diagram of an n-bit flash A/D converter. Each of the 2n-l comparators simultaneously compares the input signal voltage to a reference voltage determined by its position in the resistor series, and corresponding to the output code of the device. Flash A/D conversion is quicker than other methods of A/D conversion because each bit of the output code is found simultaneously, irrespective of the number of bits resolution. However, the greater the resolution of the device, the greater the number of comparators required to perform the conversion. In fact, each additional bit doubles the number of comparators, and therefore increases the size and cost of the chip.

Flash A/D converters tend to be found in specialist boards, such as digital oscilloscopes, real-time digital signal processing applications and general high-frequency applications.

## Integrating A/D Converters

Integrating A/D converters use an indirect method of A/D conversion, whereby the analog input voltage is converted to a time period that is measured by a counter. The functional diagram of a dual-slope integrating A/D converter is shown in Figure 5a.

The operation of a dual slope integrating A/D converter is based on the principle that the output of an integrating amplifier to a constant voltage input is a ramp whose slope is negative and proportional to the magnitude of the input voltage.

At the start of the A/D conversion, a fixed counter is cleared to zero and the unknown analog input voltage is applied to the input of the integrating amplifier. As soon as the output of the integrating amplifier reaches zero, a fixed interval count begins. After a predetermined count period, T, the count is stopped.

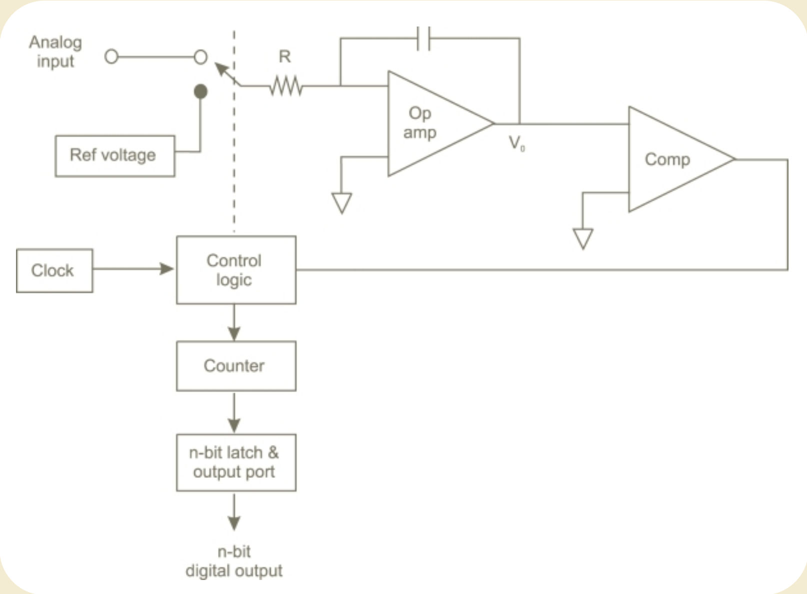

Figure 5a - Functional Diagram of an n-bit Dual Slope Integrating A/D Converter

For a positive analog input voltage, the output of the integrating amplifier has reached a negative value proportional to the magnitude of input analog signal. This is shown in Figure 5b. If the analog input varies during the fixed count time interval, then the output of the integrating amplifier is proportional to the average value of the input over the fixed time interval. This is especially useful for elimination of cyclical noise and/or mains hum appearing at the input.

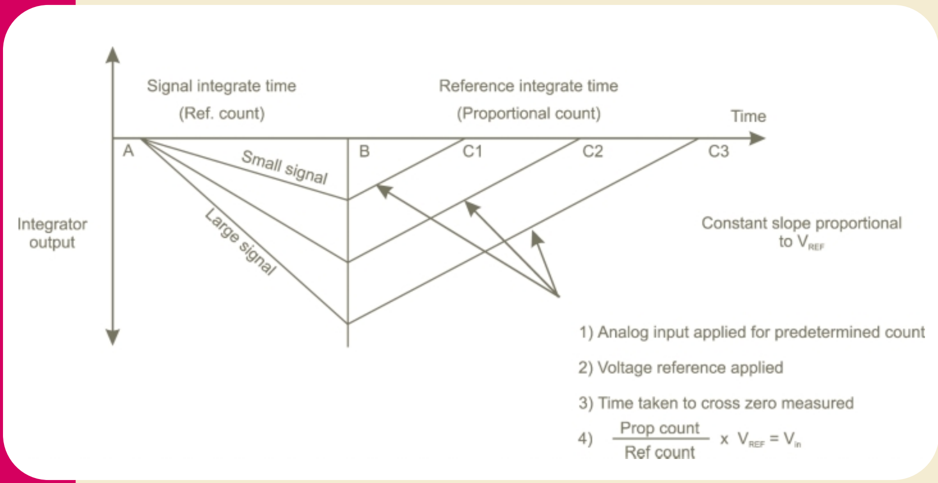

Figure 5b - Voltage appearing at $V_o$

At this point the count register is again cleared. A negative fixed voltage reference is now applied to the input of the integrating amplifier and the count begins. When the output of the integrating amplifier again returns to zero the count is stopped. The average value of the input analog signal is equal to the ratio of the counts multiplied by the reference voltage. This is very effective in averaging and therefore eliminating cyclical noise appearing at the analog input.

Integrating A/D converters generally include an additional and preceding phase, during which the device carries out a self-calibrating, auto-zero operation. The stability, accuracy and speed of the clocking mechanism, the duration of the count period, and the accuracy and stability of the voltage reference, determine the accuracy of the device.

These devices are low speed, typically a few hundred hertz maximum. However, they are capable of high accuracy and resolution at low cost. For this reason they are principally used in low frequency applications, such as temperature measurement, in digital multimeters and instrumentation.

## Important A/D Parameters

Analog to digital conversion is essentially a ratio operation, whereby the analog input signal is compared to a reference (full-scale voltage), converted to a fraction of this value, then represented by a digital number.

In approximating an analog value, two operations are performed. Firstly the quantization or mapping of the analog input into one of several discrete ranges, and secondly the assignment of a binary code to each discrete range. Figure 6a shows the ideal transfer function of a 3-bit A/D converter with a unipolar (0 V to FSV) input. The horizontal axis represents the analog input signal as a fraction of full-scale voltage (FSV) and the vertical axis represents the digital output. An n-bit A/D converter has 2n distinct output codes.

While not used in practical DAQ systems, a 3-bit A/D converter represents a convenient example since it divides the analog input range into 23 = 8 divisions, each division representing a binary code between 000 and 111. Figure 6b shows the ideal transfer function of a 3-bit A/D converter with a bipolar (-FSV to +FSV) input. This is equivalent to the unipolar transfer function except that it is offset by -FSV.

With regard to Figure 6, some of the important parameters of A/D converters are discussed below.

## Code Width

This is the fundamental quantity for A/D converter specifications, and is defined as the range of analog input values for which a single digital output code will occur.The nominal value of a code width, for all but the first and last codes in the ideal transfer characteristic, is the voltage equivalent of 1 LSB of the full-scale voltage. Therefore, for an ideal 12-bit A/D converter with full-scale voltage of 10 V the code-width is 2.44 mV.

Noise and other conversion errors may cause variations in code width, however, the code width should not generally be less than 1/2 LSB or greater than 3/2 LSB for practical A/D converters.

## Resolution

Resolution defines the number of discrete ranges into which the full scale voltage (FSV) input range of an A/D converter can be divided to approximate an analog input voltage. It is usually expressed by the number of bits the A/D converter uses to represent the analog input voltage (i.e. n-bit) or as a fraction of the maximum number of discrete levels which can be used to represent the analog signal (i.e. 1/ 2n).

The resolution only provides a guide to the smallest input change that can be reliably distinguished by an ideal A/D converter, or in effect its ideal codewidth. For example, when measuring a 0 - 10 V input signal, the smallest voltage change an A/D converter with 12-bit resolution can reliably detect is equal to:

1/4096 * FSV= 10/4096=2.44mV

Therefore, each 2.44 mV change at the input would change the output by ±1 LSR or ±0 x 001h. 0 V would be represented by 0 x 000h, while the maximum voltage, represented by 0 x FFFh would be 9.9976 V. Due to the staircase nature of the ideal transfer characteristic, a much smaller change in the input voltage can still cause the A/D converter to make a transition to the next digital output level, but this will not reliably be the case. Changes smaller than 2.44 mV will not therefore be reliably detected. If the same 12-bit A/D converter is used to measure an input signal ranging from - 10 V to +10 V, then the smallest detectable voltage change is increased to 4.88 mV.

## Input Range

Range refers to the maximum and minimum input voltages that the A/D converter can quantize to a digital code. Typical A/D converters provide convenient selection of a number of analog input ranges, including unipolar input ranges (e.g. 0 to +5 V or 0 to +10 V) and bipolar input ranges (e.g. -5 V to +5 V or-10 V to +10 V). On A/D boards the input range is usually selectable by on-board jumpers.

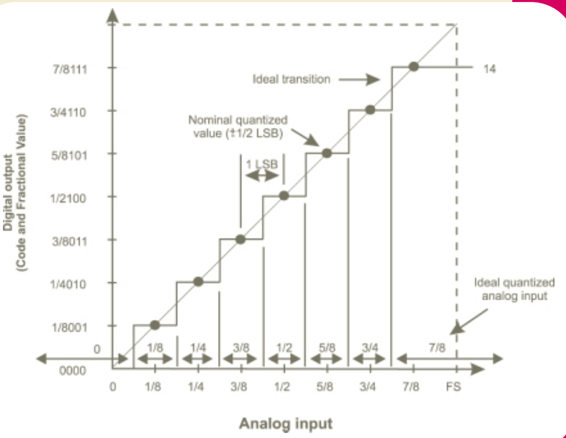

Figure 6a - Transfer Function with Unipolar Input

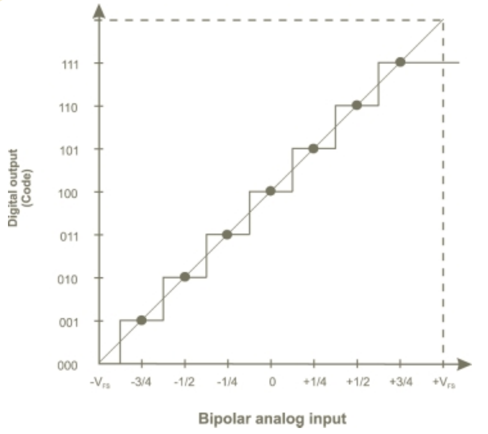

Figure 6b - Transfer Function with Bipolar Input

Figure 6 - Ideal Transfer Function of a 3-bit A/D Converter

Note that the transfer functions of Figure 6 show that the maximum input voltage is 1 LSB less than the nominal full scale voltage (FSV). If it is essential that the A/D's input range goes from 0 to FSV, then for some A/D converters it may be possible to adjust the voltage reference to slightly above nominal FSV so that this can be achieved. This increases the real full scale range and the LSB value by a small amount. For an input range of 0 - 10 V a code of 0 x 000h now represents 0 V while 0 x FFFh represents 10 V.

## Data Coding

While most A/D converters express unipolar ranges (i.e. 0 - 10 V) in straight binary, some return complementary binary, which is just the binary code with each bit inverted. Where A/D converters are used to measure voltages in bipolar ranges (i.e. -10 V to +10 V) there is an increased number of ways of representing the coded output (offset binary, sign and magnitude, one's complement and two's complement).

Most commonly, and for simplicity, A/D converters usually return offset binary values. This means that the most negative voltage in a bipolar range (-5 V for a range -5 V to +5 V) is returned as 0 x 000h, while the highest digitally coded value of 0 x FFFh (for a 12-bit ADC), represents 4.9976 V. 0 x 800h represents the mid-scale voltage of 0 V.

## Conversion Time

The conversion time of an A/D converter is defined to be the time taken from the initiation of the conversion process to valid digital data appearing at the output. For most A/D converters, conversion time is identical to the conversion rate. Therefore, an A/D converter with a conversion time of 25 μS is able to continuously convert analog input signals at a rate of 40,000 / sec.

For some high speed A/D converters, pipelining allows new conversions to be initiated before the results of prior conversions have been determined. An example of this would be an A/D converter which could perform conversions at a rate of 5 MHz (200 ns conversion time), but actually took 675 ns (1.48 MHz conversion rate) to perform each individual conversion.