Analog-to-Digital Converter Primer

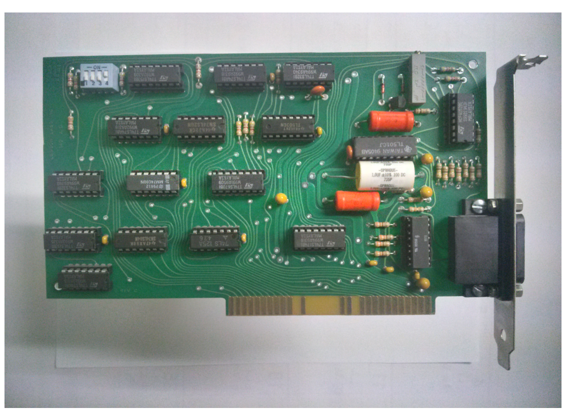
There are four main types of A/D converter - flash, integrating, successive approximation, and Sigma Delta. We will briefly describe and compare them. There are other types of A/D converter that will not be included here. Some are hybrid types, and some are variations on the above four basic varieties. All A/D converters need to compare an unknown input voltage to some sort of reference voltage. Time figures in, also. A flash converter can digitize a signal nearly instantaneously. Other A/D types need a clock, or time reference, of some sort, in addition to a voltage reference. Each data point has a voltage resolution and a time resolution. If the signal being measured is unchanging, time matters little. If it is changing quickly, timing is critical. Overall accuracy is limited by the accuracy and stability of both the voltage and the time references.

Flash

A flash converter is a series of comparators in parallel, with their outputs encoded as a binary word. The digitized converter output is essentially continuous. It takes a lot of circuitry to build a flash converter. One comparator is needed for each non-zero output code, so a 4-bit flash converter needs 15 comparators, a 5 bit converter needs 31 comparators, etc. The reference voltage for each comparison is derived from a string of resistors that divide down the reference voltage. Flash converters are best for highest speed with lowest resolution. The complexity and power consumption of a flash converter gets excessive quickly as bits are added. Analog Devices once made a 14-bit flash converter. That is about as far as a simple flash converter has been stretched.

Integrating

The most common and useful integrating converter is the dual slope converter. There are more complex variations, but we will stick to the basics, here. First, for a known period of time, a capacitor is charged in proportion to an unknown voltage. Then, the capacitor is discharged at a known rate until it is back to where it started from. The length of time needed to discharge the capacitor is proportional to the unknown voltage. Dual slope converters reject high frequency noise very well because they are intrinsically averaging. They can't have extreme resolution without being very slow, because the clock that counts out the capacitor discharge has to count incrementally up to the answer. If the clock ran at one Megahertz, it would take a full second to reach 20-bit resolution (1 part in 1,048,576, or 2 to the 20th).



Model 140 +/- 40,000 count multi-slope integrating A/D converter. The Model 140 uses a chip designed for digital voltmeters at the core. The white capacitor is the integrating cap.

For best line frequency rejection, the integration period for a dual slope converter in the US must be an integer multiple of 1/60th of a second. By the time you include the discharge period and allow some time for auto-zeroing, these converters generally run no faster than 30 samples per second, and often half or one quarter of that. A dual slope converter with 1/10th (6/60) of a second integration period will reject both 60 and 50 cycle noise. Why? Because at 60 Hertz, the integration period covers exactly 6 cycles, while at 50 Hertz, it covers exactly 5.

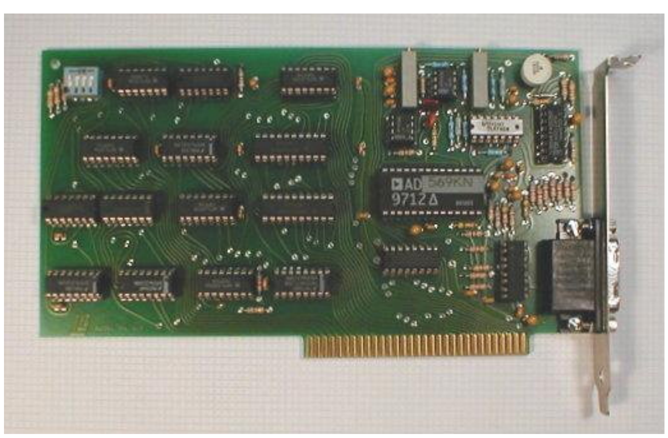
A digital voltmeter will typically contain a form of dual slope A/D converter. For DC, or slowly changing voltages, you can't read a display any faster than a few times a second, so the relatively slow response is not a problem. The meter will read the average voltage during the last integration period. Relative simplicity, moderate resolution, good accuracy and low power all recommend dual slope converters for voltmeters, especially battery-powered meters.

Successive Approximation

If you need to go faster than an integrating A/D with more resolution than a flash A/D the choice used to be limited to successive approximation. Eight-, 12- and 16-bit successive approximation converters have been widely used for decades. The principle of successive approximation is evident in the name. On each pass through the process, the result is refined. One output bit is established each time through.

A successive approximation converter includes a D/A converter. A voltage is generated internally and compared to the unknown input. Start by comparing the input to exactly one half of full scale, as produced by a D/A converter. If the unknown input is higher, the voltage is above mid scale, so the most significant bit of the answer should be set, otherwise it should be cleared. At this point, the process has executed once, and there is one bit of the answer established. The process then repeats, with the second-to-most-significant bit being tested. The unknown input is compared to either one quarter or three quarters of full scale depending on the result of the first test. Again, if the unknown input is higher, leave the bit set, otherwise clear it. At that time, there are four possible answers; below a quarter, a quarter to below a half, half to below three quarters, and three quarters and above.

Each time through the loop one additional bit is appended to the result and the uncertainty of the input voltage is cut in half. An 8-bit converter will make 8 passes and can fix the voltage to within one part in 256 (2 to the 8th).



Model 134 16 Bit Successive Approximation Converter at 40,000 samples per second, built around a fast 16-bit DAC chip. The clock comes from the computer bus, and the voltage reference is the white circular component in the upper right.

Successive approximation converters are a little more complex, but are much faster. Testing one more bit doubles the resolution, so only 16 tests yield an answer with 2 to the 16th resolution, or 1 part in 65536. Accuracy, as opposed to resolution, is not as easy to obtain as in an integrating converter. For starters, you need an accurate DAC to make the comparisons. The linearity can never be better than what you are comparing to. Then, if the voltage changes while you are stepping through all the bits, the instantaneous answer may not be attainable, because of an earlier decision based on outdated voltage information. For better time resolution, a successive approximation converter needs a sample and hold circuit preceding it to store the input voltage at a known instant of time.

Furthermore, the accuracy of each bit needs to match the overall accuracy specification. Take the first, most significant bit. If the decision to leave it set is imperfect, then all the other bits will be cleared because the actual answer was a little below half scale. Look for a “no missing codes” specification to show that this problem has been addressed. “No missing codes” doesn't insure good linearity, but at least it means the converter will pass through mid scale without a discontinuity. You may see a specification that an A/D is monotonic. That means the result will always increase with increasing voltage. Monotonicity is essential to keep feedback loops from getting stuck at discontinuities. As with the integrating type, absolute accuracy will also be limited by the accuracy of the reference voltage that supplies the D/A converter.

Because the result from a successive approximation converter is based on instantaneous voltage during the conversion window, there is essentially no noise rejection. Frequencies above one quarter of the sample rate should be pre-filtered in order to avoid aliasing and the associated counter-intuitive results.

Model 141 20-bit Delta Sigma converter at 3.5 kHz with 4 input channels, 2 of the channels are dedicated for self-calibration.

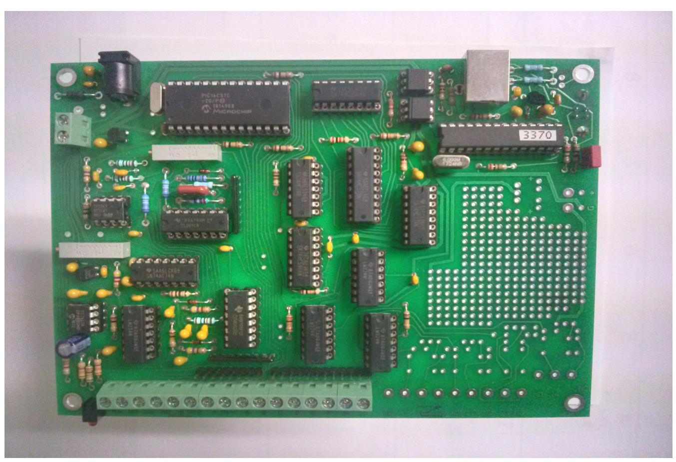
Sigma Delta

Sigma Delta converters are sometimes called Delta Sigma converters. We will use the terms interchangeably. Adding more bits to a successive approximation converter gets harder and harder because the DAC used for comparison quickly becomes the limiting factor. Adding more bits to integrating converters requires impractically higher clock frequencies or overlong conversion times. A new topology came of age in the 1990s to fill the need for higher resolution at reasonable speeds.

Basically, a Sigma Delta converter reconstructs a voltage to track the input voltage by filtering a series of ones and zeros produced by a precise, single-bit D/A converter. At each clock, the reconstructed voltage changes one tick up or down depending on whether the reconstructed voltage is above or below the unknown input voltage. The slew rate of the reconstructed voltage, and therefore of the A/D converter, is thereby limited, but its resolution can be extended by stretching the filtration period so that more ones and zeros are included. The long series of data is reduced through digital filtration techniques to reject higher frequencies while responding to lower frequencies and to DC. The noise introduced by the one bit D/A is called quantization noise, and it can be reduced to near nothing through digital filtering.

The accuracy of a delta sigma converter is limited primarily by the accuracy of the one bit D-to-A converter. The D-to-A needs to put out a very precise one or zero with clean edges and exact, reproducible timing. Given a digital signal with full analog precision, the filtered digital information becomes the analog feedback. Quantization errors tend to be canceled, so over time, the reconstruction of the input voltage gets better and better. Only one comparator is needed, so as long as it is consistent, any comparator errors can be calibrated out of the answer. To get even more resolution without impractically high clock frequencies, the base comparison can be expanded to two or more bits, though extra care is required to maintain linearity and accuracy with multi-bit systems.

These converters have another advantage. They can be run at different clock rates and the length of the digital filtering can be programmatically changed. The frequency response of the system will track with the clock rate and filter characteristics. That flexibility can provide the noise rejection advantages of integrating converters combined with higher conversion rates. The programmability allows easy optimization of the speed versus resolution trade off.



The Model 333 is a 20-bit Delta Sigma converter built from discrete parts. The larger microcontroller does the control, oversight, and digital filtering. The smaller microcontroller provides a USB interface. Features include optical isolation, self calibration, protected high impedance differential inputs, digital Input/Output, and optional relays with a prototyping area.

One disadvantage of Delta Sigma converters is that they are slower when multiplexing inputs. The digital filter has to settle on a new channel before the conversion is valid after switching channels. Even with that limitation, Delta Sigma converters have become the preferred general purpose A/Ds, and they are being adapted to more applications even now, 30 years later.

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