Electrical Tech Note — 539

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Analog to Digital Converters

The process of converting an analog signal into a digital signal is discussed along with some of the major issues to be considered in the process. Signals can be processed as analog signals and stored for future use on bulky magnetic discs and tapes, but digital processing is generally much faster and more versatile, and storage of the data in digital form is generally more compact and easier to transmit. An understanding of the processes used in data conversion and analysis is important when selecting the proper type of instrumentation for a particular application. The several leading methods for analog to digital conversion will be discussed.

Converting an analog input signal with infinite values is not as simple as it may seem at first glance. First it is necessary to determine the number of discrete steps or digital divisions that will be provided over the range of analog input data. Since the input data will be converted to a binary code the number will be the number of combinations that are possible with the number of binary bus lines minus one, such as 15 steps for a 4-bit bus and 255 steps for an 8-bit bus. *Resolution* is the range of values divided by the number of steps.

$$\text{Number of increments} = (2^n - 1)$$

$$\text{Resolution} = \frac{\text{Range of values}}{\text{Number of increments}}$$

Example of resolution: Assume the analog input signal is a voltage with a range of 0 to 3 volts. If the instrument has a 4-bit bus the number of increments will be $(2^4 - 1) = 15$. Divide 3 volts by 15 increments to get a resolution of 0.2 volts. If an 8-bit bus has been used the number of increments would have been 255 and the resolution would have been 0.012. For a 10-bit bus the number of increments would have been 1023 and the resolution would have been 0.0029.

Choosing a number of increments is not so easy either. Most input signals are subject to noise contamination and if the number of increments is too high and resolution too small it may be noise that is causing a change in discrete digital values. This cannot always be avoided and it is necessary to know to what precision a digital measurement can be taken reliably. It is suggested that the *resolution-to-noise ratio* be at least 6dB, which means in the case of voltage that the minimum voltage resolution should be at least two times the maximum expected value of noise voltage.

The analog signal is continuous in time while the analog-to-digital converter requires an increment of time to do the conversion. This conversion time is different for the various types of ADC techniques. A signal may change in value during the conversion time, therefore, values are taken at discrete time increments by a device called a *sample and hold*. The sample and hold may be as simple as an electronic switch controlled by a timing pulse and consisting of a capacitor to hold the voltage level to be converted.

If the input signal frequency is higher than half the sampling rate of the analog-to-digital converter then the ability of the system to produce a reasonable reconstruction of the original analog signal is compromised. This is called *aliasing* which is demonstrated in Figure 539.1. Sometimes a low-pass anti-aliasing filter is added to the signal input to attenuate the high frequencies.

When input signals are very low, such as near zero, the signal may be varying but less than the resolution of the converter and the output is unchanging or straight line. A process called *dithering* is sometimes used to boost the signal slightly so it is more likely to result in an output change if it is truly varying over time. *Dither* is an oscillating noise signal added to the input signal with the amplitude of the dither about half the resolution of the converter.

Before examining the different techniques for converting an analog signal to a digital output first examine the process of the conversion as illustrated in Figure 539.1. This conversion is very crude with only 15 increments and a resolution of only 0.2 volts. Also the sampling rate is very slow for the rate at which the signal is changing with time. These limitations are deliberately introduced into the example to dramatize some of the problems with the ADC process. In Figure 539.1 eight sampling points have been indicted and the digital values are shown at the bottom of the graph. The digital value is the value on the stair-step graph that is just below the actual value unless the value is the same as one of the stair-step values. The graph to the right is a digital-to-analog (DAC) reproduction of the original input signal. The effect of aliasing due to low resolution and slow sampling rate are evident.

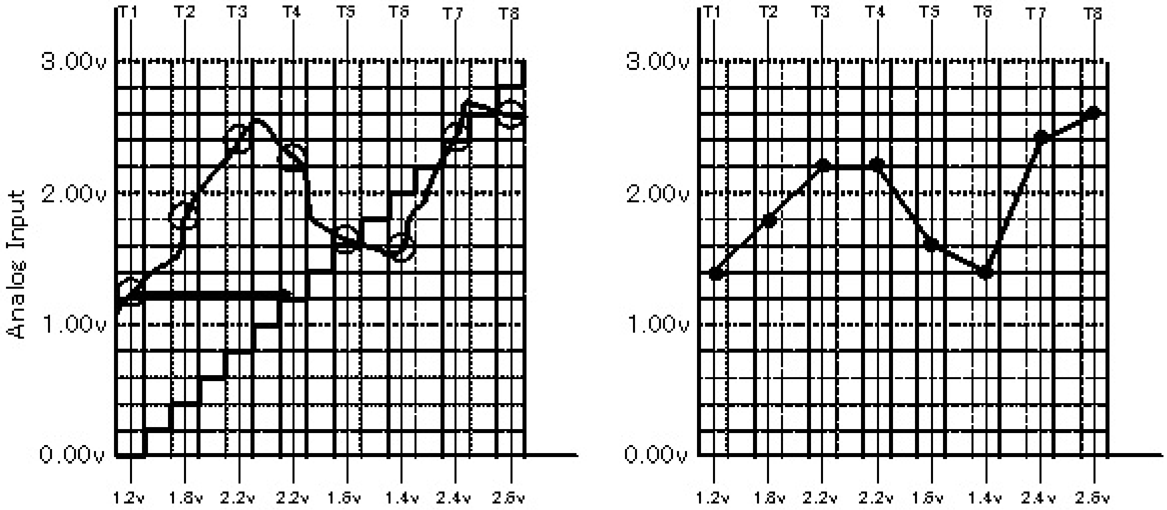

Figure 539.1 *The process of subdividing the voltage range into increments is illustrated with the stair-step graph. An analog signal is superimposed over the graph to illustrate the process of converting the analog signal into a digital signal. The graph to the right is a representation of the original input signal based upon the digital values from the analog-to-digital converter.*

Successive Approximation: This method of converting an analog input to a digital value is fast. For an 8-bit converter it takes only eight clock pulses to determine the value. The heart of the converter is an op-amp comparator that determines if the analog input value is higher or lower in value than the value stored in the successive approximation register (SAR). Depending upon the range set for the input signal, the most significant bit (MSB) which is line eight (2^7) is given a value of half the maximum range. Assume the analog input is 15.0 volts and the range is 50.0 volts. The MSB register will be given a value of 25.00 volts. Each successive register will be given a value of half the previous register. For this example the value in register (2^6) will be 12.5000, in register (2^5) the value is 6.2500, for (2^4) the value is 3.1250, for (2^3) the value is 1.5625, for (2^2) the value is 0.7813, for (2^1) the value is 0.3906, and for (2^0) the value is 0.1953.

For the example the first number (25.0) is compared with the actual value and found to be too high, so the value in the next register (12.5) is subtracted to give 12.5. This value is too low so the value in the next register (6.25) is added to give 18.75. This is too high so the value in the next register (3.125) is subtracted to give 15.625 which is too high. The process continues as illustrated in Figure 539.2 until a value of 15.04 is determined as the last value. This will be the digital value used for the analog number 15.00.

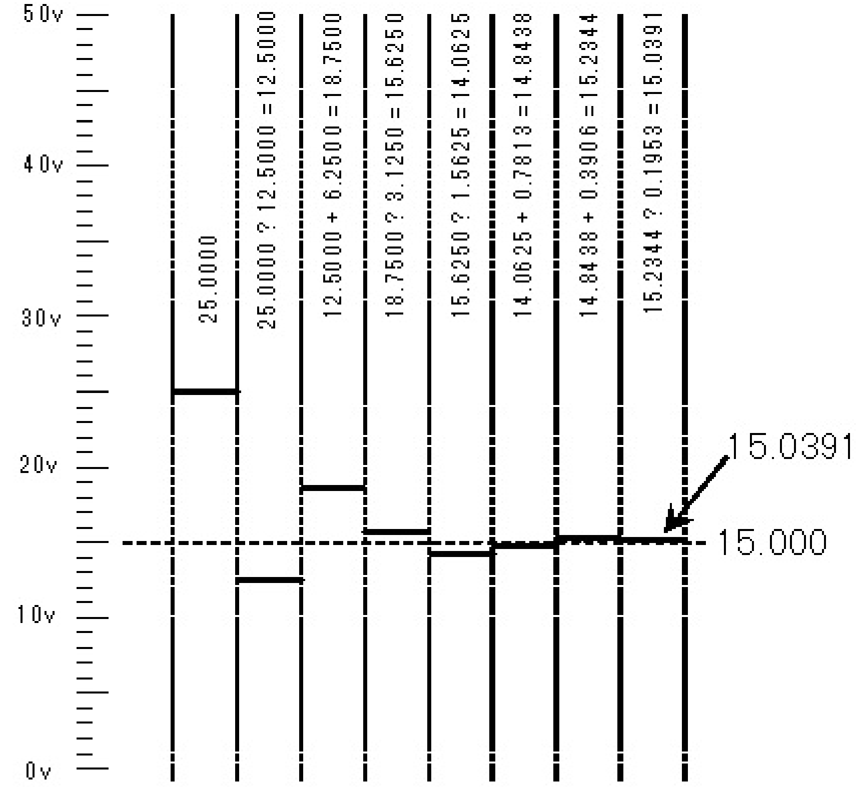

Figure 539.2 *With successive approximation half the full scale is compared with the analog input value and if the actual value is higher half the first value will be added, if not the value will be subtracted. The process will continue until all eight values have been compared. The final value will be the digital value used to represent the analog number.*

Flash Converter: This is probably the fastest means of converting an analog input into a digital number, but generally the resolution is low and the complexity of the device is high. The device consists of a precision voltage divider to produce a precise comparison voltage. For a 3-bit converter eight resistors in series are required with seven op-amp comparators. The input analog voltage is supplied to all seven comparators and instantly a 3-bit digital code is produced. If a 4-bit converter is required it will take eight more comparators and precision resistors and only 15 increments are available. If an 8-bit comparator is needed with 255 increments, it will take 256 precision resistors in series for the voltage divider and 255 comparators.

Integrating Converter: This type of converter is sometimes called the dual slope converter. The heart of the converter is an integrating op-amp with a capacitor in place of a feedback resistor. The device also has an internal reference voltage that is opposite in polarity to the unknown input analog voltage. When an analog voltage is applied to the converter the capacitor begins charging and that charging rate depends upon the level of the unknown voltage applied. An internal counter allows the capacitor to charge for a set time interval and then the charging is cut off. The output of this process is from the integrating op-amp as an increasing voltage ramp that is fed into an op-amp comparator. At the instant the unknown analog input is disconnected the opposite polarity known voltage is applied to the integrator which begins a down slope to the integrator output. The counter is set to zero and counts the interval required to discharge the capacitor to zero. The time required to discharge the capacitor is proportional to the unknown analog input voltage. Because this technique is reasonably fast and reasonably accurate, it is a popular means of making an analog to digital conversion.

Tracking Converter: This type of converter is easy to perform, but it tends to be slow. The analog input is fed into an op-amp comparator which enables an AND gate to allow a clock to start an up counter, usually a MOD-256 counter. This counter supplies an 8-bit count to a digital-to-analog converter that supplied a stair-step voltage to the other input of the comparator. The voltage from the reference voltage to the comparator increases in steps until it slightly exceeds the level of the unknown analog input voltage. At this point the counter stops and the value of the count indicates the level of the analog input voltage. The device is reset and the count begins for the next value. The time interval required to determine the unknown analog voltage is variable and depends upon the length of the count. It could take up to 256 clock counts to determine the value of the analog voltage or if that voltage is small, it may take only a few counts.

Conclusion: Some type of analog to digital conversion technique is an essential part of digital measurement instrumentation. For the person who must make selections of the best type of instruments for an application it is important to know how this instrumentation operates, the attributes of each method and the limitations.