

ANALOG ↔ DIGITAL CONVERSION HANDBOOK

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Bill Wolff

E-5100
7/64

ANALOG—DIGITAL CONVERSION HANDBOOK

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PREFACE

The Analog-Digital Conversion Handbook represents the first attempt in the data processing industry to assemble comprehensive information on this subject in a form that makes it immediately useful to beginner or expert. All phases of conversion are covered, from concepts to calibration. Many diagrams supplement the text; and tabular summaries of terms, methods, and performance characteristics are included for comparison and reference. Circuit modules and other equipment manufactured by Digital Equipment Corporation are mentioned specifically, so after choosing the conversion method most appropriate to his needs, the reader can construct his system directly.

The use of circuit modules in constructing analog-digital converters yields several advantages. First, they are flexible. Converter systems have widely varying requirements, from pulse height analysis, where differential linearity is of utmost importance, to time-locked averaging in biomedical work, where resolution is more critical than repeatability or even accuracy. Modules permit the construction of the exact type of converter needed and, should requirements change, the same modules can be used later to build a different kind of system.

Second, modules are economical. Aside from the interchangeability mentioned above, savings are gained in the cost of construction. The typical cost of a digital-to-analog converter is about \$1,000; of an analog-to-digital converter, about \$2,000. If several systems are built, the cost per converter decreases since the same power supplies and mounting panels are used for the additional units. If the speed requirement is exceptionally high, costs will be higher.

A third advantage of using modules is that the completed converter need never go back to the factory for recalibration. Procedures for calibration and adjustment are included in this handbook. Recalibration can be carried out quickly and easily by the user.

Those modules designed exclusively for use in conversion systems are specified in detail in this handbook. The general purpose logic modules also needed are mentioned by name and type number. Complete specifications for these and over 200 other kinds of circuit modules and accessories are contained in the Digital Module Catalog, available at any Digital Equipment Corporation office. The catalog also contains much information helpful in designing and assembling digital systems.

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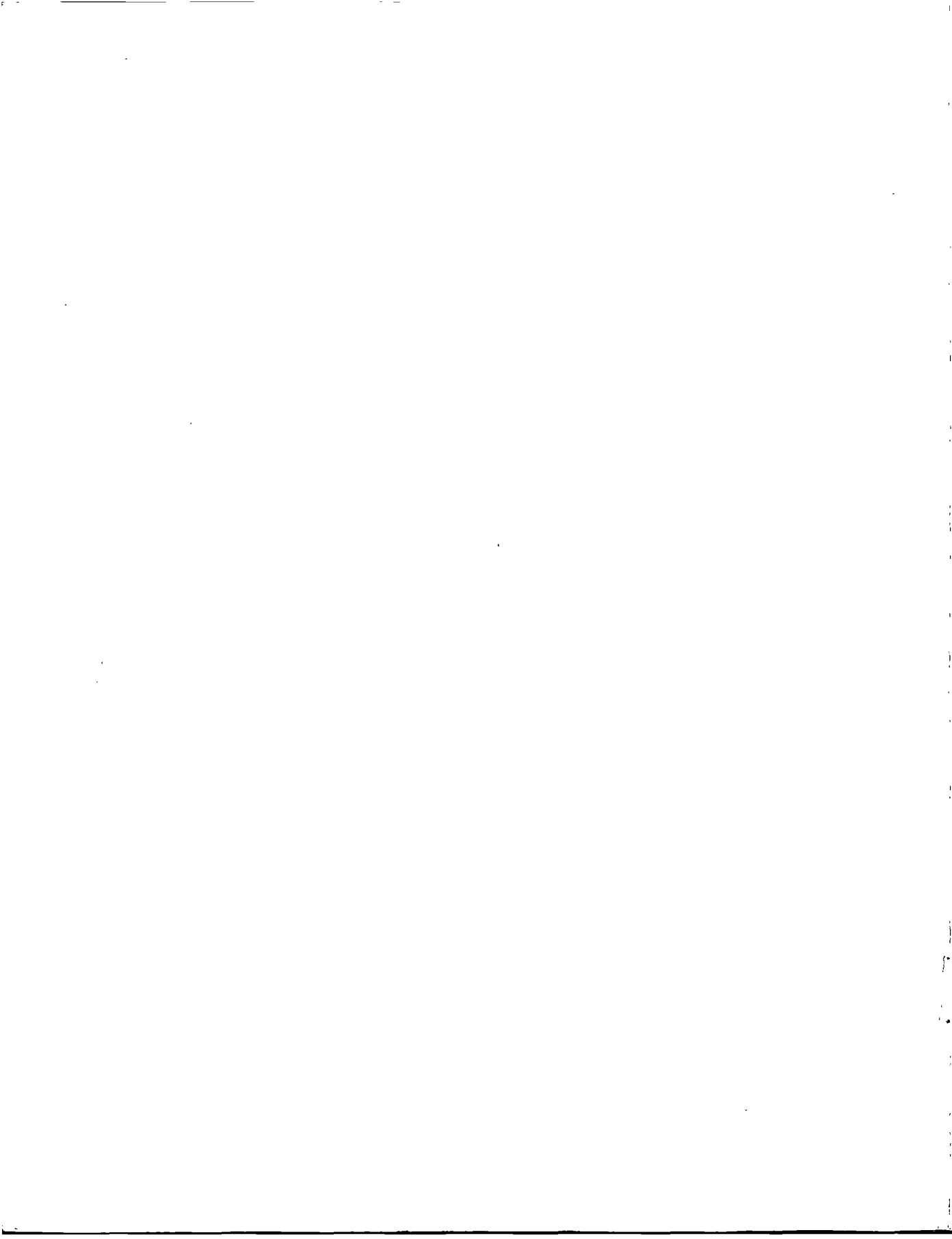
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CHAPTER I

BASIC ELEMENTS OF CONVERSION

Introduction

This chapter describes the general technique used to convert, to sample and hold, and to multiplex.

For digital-to-analog conversion, just one technique is described. Though there may be some variations, the same technique is generally applicable for all digital-to-voltage or digital-to-current converters.

Analog-to-digital conversion is somewhat more complex and thus a variety of different methods is commonly used. In this chapter, the four most common methods are described. Of these, the successive approximation converter is most generally used since it provides good performance over a wide range of applications at a reasonable cost. However, if the converter is to be used only in a single application, various other methods may be preferred for better performance or lower cost.

It is suggested that this chapter be read as a brief development of the principles of conversion, rather than a delineation of specific methods. Detailed descriptions of conversion systems will be given in Chapters 3 and 4.

Digital-to-Analog Conversion

To convert from a digital number to an analog voltage, a resistive divider network is connected to the flip-flop register which holds the digital number (see Figure 1). The divider network is weighted so that each bit of the register will contribute to the output voltage in proportion to its value.

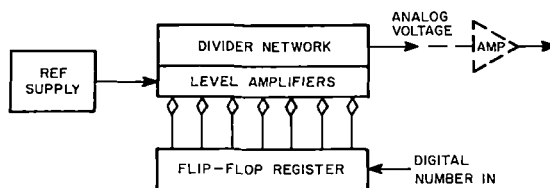


Figure 1 Digital-to-Analog Conversion

The digital input signal determines the analog output voltage, since the divider network is simply a passive element. However, because digital voltage levels are not usually as precise as required in an analog system, level amplifiers are placed between the flip-flops and the divider network. The amplifiers switch the divider network between ground and a

reference voltage supplied by a precision reference supply. The output voltage range is between these two voltage levels. In Digital systems, the range is normally 0 to —10 volts. If the digital-to-analog converter is to drive long cable or a heavy load, an operational amplifier or emitter follower is usually put on the output of the circuit to lower the output resistance.

The level amplifiers, divider network, and reference supply shown in Figure 1 are basic to a digital-to-analog converter and are described under those headings in Chapter 5.

Analog-to-Digital Conversion

The basis of analog-to-digital conversion is the comparator circuit. This circuit compares an unknown voltage with a reference voltage and indicates which of the two is larger.

SIMULTANEOUS METHOD

Figure 2 shows how a simple simultaneous analog-to-digital converter can be built using several comparator circuits. Each comparator has a reference input signal. The other input terminal of the comparators is driven by the unknown input analog signal, which is between 0 and V volts. The comparator is called "ON" if the analog input is larger than the reference input. Then, if none of the comparators are on, the analog input must be less than $\frac{V}{4}$. If C-1 is on, and C-2 and C-3 are off, the input must be between $\frac{V}{4}$ and $\frac{V}{2}$. Similarly, if C-1 and C-2 are on, and C-3 off the voltage is between $\frac{V}{2}$ and $\frac{3V}{4}$; and if all the comparators are on, the voltage is greater than $\frac{3V}{4}$.

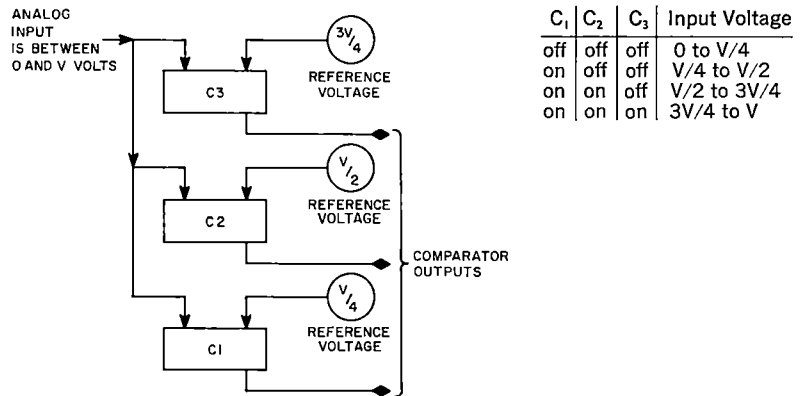


Figure 2 Simultaneous Analog-to-Digital Converter

Here, the voltage range is divided into four parts, which can be coded to give two binary bits of information. Seven comparators would give three bits of binary information. Fifteen comparators would give four bits. In general, $2^N - 1$ comparators will give N bits of binary information.

The simultaneous method is extremely fast for small resolution systems. For large resolution systems (a large number of bits), this method requires so many comparators that it becomes unwieldy and prohibitively costly.

FEEDBACK METHODS

If the reference voltage were variable, only one comparator would be needed. Each of the possible reference voltages could be applied in turn to determine when the reference and the input were equal. But a digitally controlled variable reference is simply a digital-to-analog converter. Thus the generalized analog-to-digital converter shown in Figure 3 is actually a closed-loop feedback system. The main components are the same as a digital-to-analog converter plus the comparator and some control logic. With a digital number in the DAC (digital-to-analog converter) the comparator indicates whether the corresponding voltage is larger or smaller than the input. With this information, the digital number is modified and compared again.

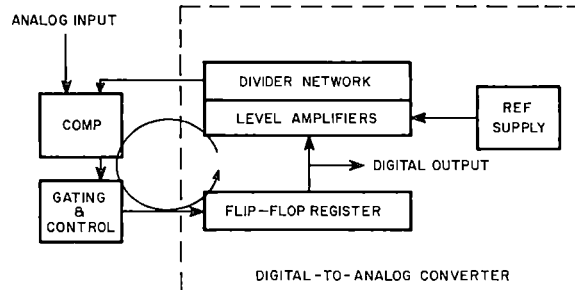


Figure 3 Analog-to-Digital Converter Incorporating a Digital-to-Analog Converter

COUNTER METHOD

Numerous methods may be used for controlling the conversion. The simplest way is to start at zero and count until the DAC output equals or exceeds the analog input.

Figure 4 shows a converter in which the DAC register is a counter, and a pulse source has been added. The gate stops pulses from entering the counter when the comparator indicates that the conversion is complete.

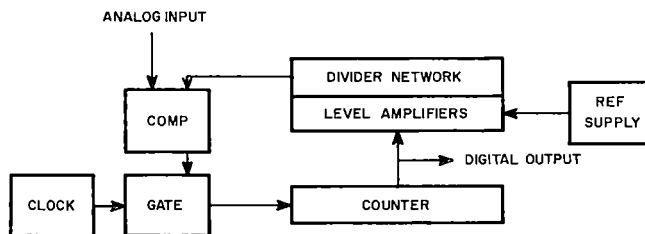


Figure 4 Counter Converter

The counter method is good for high resolution systems: As the number of bits is increased, very little additional circuitry is needed. Multiple inputs can easily be converted simultaneously (as described under Multiplexing later in this chapter). However, conversion time increases rapidly with the number of bits, since an N-bit converter must allow time for 2^N counts to accumulate. The average conversion time will, of course, be half this number.

CONTINUOUS METHOD

A slight modification of the counter method is to replace the simple counter with an up-down counter as in Figure 5. In this case, once the proper digital representation has been found, the converter can continuously follow the analog voltage, thus providing readout at an extremely rapid rate. This method, called continuous conversion, is particularly useful when a single channel of information is to be converted. The converter starts running, and the digital equivalent of the input voltage can be sampled at any time.

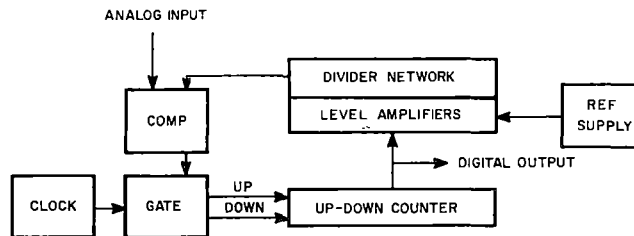
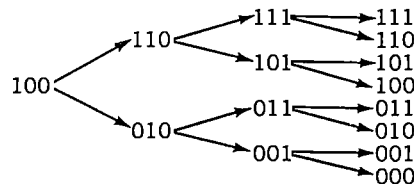


Figure 5 Continuous Converter

The continuous method is less effective for multiple inputs or for inputs that change faster than the converter can change. Each time the input makes a large change, the converter may require as many as 2^N steps to catch up. However, if a rapid rate of change is necessary, extra comparators may be added so that the up-down counter can count in units of 2, 3, 4, or more (see Chapter 3).

SUCCESSIVE APPROXIMATION METHOD

For higher speed conversion of many channels, the successive approximation converter is used. This method requires only one step per bit to convert any number. The successive approximation analog-to-digital converter operates by repeatedly dividing the voltage range in half as follows:



Thus, the system first tries 100, or half scale. Next it tries either quarter scale (010) or three-fourths scale (110) depending on whether the first approximation was too large or too small. After three approximations, a 3-bit digital number is resolved.

Successive approximation is a little more elaborate than the previous methods since it requires a control register to gate pulses to the first bit, then the second bit, and so on. However, the additional cost is small and the converter handles all types of signals about equally fast.

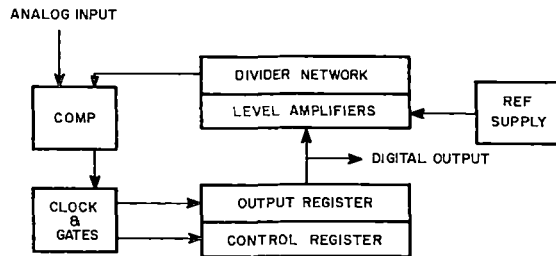


Figure 6 Successive Approximation Converter

The successive approximation method is good for general use. It handles many continuous and discontinuous signals and large and small resolution conversions at a moderate speed and moderate cost.

Sample and Hold

A sample and hold circuit is used in an analog-to-digital converter whenever it is desirable to make a measurement on a signal and to know precisely when the input signal corresponded to the results of the measurement. It is also used to increase the duration of a signal.

The sample and hold circuit can be represented as shown in Figure 7. When the switch is closed, the capacitor is charged to the value of the input signal; then it follows the input. When the switch is opened, the capacitor holds the same voltage that it had at the instant the switch was opened.

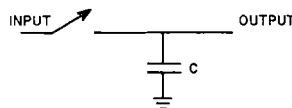


Figure 7 Sample and Hold

It is possible to build a sample and hold circuit just as shown here. Often, the same circuit is used with a high gain amplifier to increase the driving current available into the capacitor

or to isolate the capacitor from an external load on the output. In some cases, this sample and hold is made entirely differently; but from a logical point of view, it acts as the ideal component shown.

The acquisition time of a sample and hold is the time required for the capacitor to charge up to the value of the input signal after the switch is first shorted. The aperture time (see definition, Chapter 2) is the time required for the switch to change state and the uncertainty in the time that this change of state occurs. The holding time is the length of time the circuit can hold a charge without dropping more than a specified percentage of its initial value.

Multiplexing

Often it is desirable to multiplex a number of analog channels into a single digital channel or conversely a single digital channel into a number of analog channels. Multiplexing can take place in the digital realm, the analog realm, or in the conversion process.

DIGITAL-TO-ANALOG

In digital-to-analog conversion, a common problem is to take digital information which is arriving sequentially from one device, such as a digital computer, and to distribute this information to a number of analog devices. Usually it is necessary to hold the information on the analog channel even when it is not being addressed from the digital device. There are two ways to multiplex. A separate digital-to-analog converter may be used for each channel as shown in Figure 8.

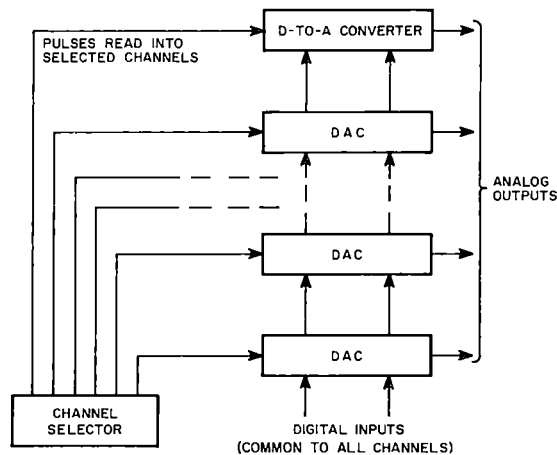


Figure 8 Digital-to-Analog Systems

In this case, the storage device is the digital buffer associated with the converter. Or, a single digital-to-analog converter may be used, together with a set of multiplexing switches and a sample and hold circuit on each analog channel. The cost of the first method is

slightly more than the cost of the second method, but it has the advantage that the information can be held on the analog channel for an indefinite period of time without deteriorating; whereas with the multiple sample and hold technique, it is necessary to renew the signal on the sample and hold at periodic intervals.

ANALOG-TO-DIGITAL

In analog-to-digital conversion, it is more common to multiplex the inputs in the analog realm. Here switches, either relays or solid state, are used to connect the inputs to a common bus. This bus goes into a single analog-to-digital converter which is used for all channels (see Figure 9). If simultaneous time samples from all channels are required, a sample and hold circuit can be used ahead of each multiplexer switch. In this way, all channels would be sampled simultaneously and then switched to the converter sequentially. The multiplex switches and sample and holds will introduce some error into the system. However, it is usually less expensive to go to higher quality sample and hold and multiplex circuits than add extra converters.

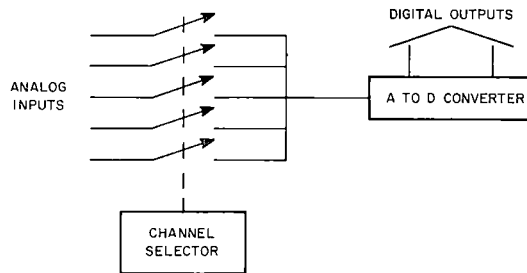


Figure 9 Multiplexed Analog-to-Digital Conversion System

In a simple analog-to-digital converter with a single comparator circuit, it is also possible to multiplex by using a separate comparator for each analog channel. One input of each comparator is tied to the voltage generating device in the converter. The other inputs are tied to the separate analog channels. The comparator to be used can be selected digitally. This method is particularly good when a small number of channels is to be multiplexed since it is quite simple and requires little additional control. For a large number of channels, separate multiplexer switches are usually less expensive and more accurate as they do not put any load on the voltage generating device of the converter.

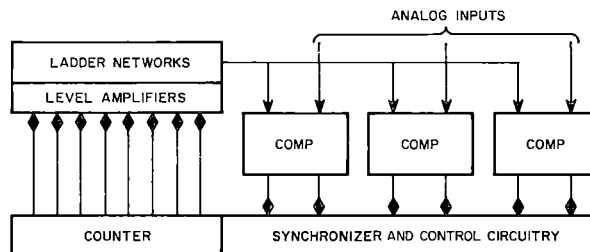


Figure 10 Counter Type Analog-to-Digital Converter with Multiplexed Input

The comparator multiplexing technique is particularly useful with the counter type analog-to-digital converter. This technique is shown in Figure 10. Several comparators are attached to one converter. The counter is cleared; then count pulses are applied. When one of the comparators signals that the digital-to-analog output is greater than the input voltage on that channel, the contents of the counter are read out. Counting is then resumed until the next signal is received.

CHAPTER 2

MEASURES OF CONVERTER PERFORMANCE

Accuracy

Since the end result of conversion is the representation of a given value in different terms, it is important to know how accurate the representation is. In systems where accuracy requirements are not too stringent, say in the order of 1 percent, an overall accuracy specification is usually sufficient. In cases where the desired accuracy is 0.1 percent or greater, it is necessary to isolate the various sources of error; and since a converter is a hybrid device, both digital and analog sources must be taken into account.

In high accuracy systems particularly, accuracy figures given in the general specifications may not include isolated sources of error, e.g., noise. Thus, it is important to know the various types of errors, their causes, how they are measured and specified, and when they are important. Figure 11 shows a breakdown of various types of errors.

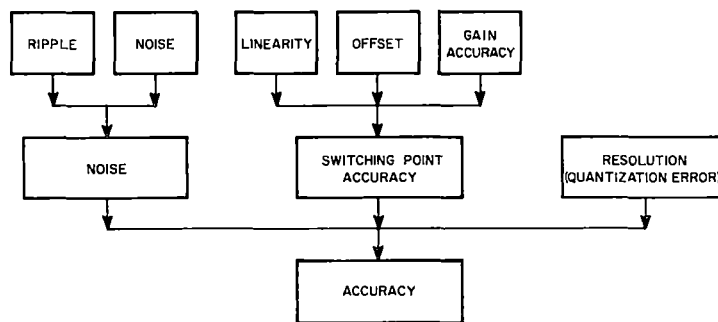


Figure 11 Measures of Cumulative Error

DIGITAL ERROR SOURCES

When a continuous signal is quantized, there is an error which is equal in magnitude to the smallest quantum. For a linear converter, the smallest quantum is the least significant bit. In most converters the quantization error is centered so that it is equal to $\pm\frac{1}{2}$ the least significant bit, written as $\pm\frac{1}{2}$ LSB.

In a continuous converter or digital voltmeter, accuracy may not be as important as avoiding chatter. That is, if the input is right on the dividing line between two quantization states, the output should not oscillate. If hysteresis is introduced so that the quantization error is just under ± 1 LSB, then oscillations will normally be avoided and the accuracy will not be greatly impaired.

The digital-to-analog converter reproduces exactly all the digital input information which it accepts. Hence digital error is not included in its accuracy specifications. However, if the input has more bits than the converter, there will be a quantization error in the readin process which should be taken into account. If desired, a $\frac{1}{2}$ LSB offset can be built into the converter so that the readin will round off, rather than truncate, more precise digital information.

ANALOG ERROR SOURCES

The dc accuracy of the converter (or switching point accuracy) depends on the offset, the gain calibration, and the linearity. Nonlinearities are due to the variation in gain (or common mode effect) in going from the smallest input to the largest input. Some of these will be long-term, because of the common mode effect of the comparator circuit in the analog-to-digital converter, for example. Some will be shorter term, because of discontinuities in the divider network or insufficient settling time of the comparator. The offset and the gain can be adjusted in the calibration until their effects are essentially negligible.

The measurement of analog error in a digital-to-analog converter is easily made by putting in a digital number (the same word length as the converter) and observing the output. In an analog-to-digital converter, the analog error is difficult to locate since the quantization error is always present. However, the point where the output oscillates approximately equally between two neighboring digital numbers is fairly well-defined. This point, called the switching point, can be measured and compared with the theoretical value.

The ripple on the reference supply and other sources of noise are often measured separately since one or the other can sometimes be neglected in the final result. The two can be separated by measuring the ripple in the reference supply and subtracting it from the measured noise, or by running the input source in the converter from the same reference, thereby giving a direct measurement of all noise sources except the reference supply ripple. In a digital-to-analog converter the noise and ripple can be measured by observing the output with a scope. In an analog converter they can be measured by observing the input range which causes the output to oscillate between two states.

DIFFERENTIAL LINEARITY

Differential linearity is the variation in the size of the required voltage change that causes an analog-to-digital converter to go from one switching point to another. That is, it is the variation in the size of the states and is generally quoted as a percent of the size of the states. It is a part of the overall linearity discussed above, but deserves special mention because of its importance when an analog-to-digital converter is being used in histogram applications. For example, when plotting the number of inputs versus the digital state, if one of the states is twice as big as its neighbor, it will tend to accumulate twice as many counts. Naturally, a very misleading output results.

Differential linearity is one of the few accuracy characteristics which is affected by the conversion technique. The differential linearity tends to be best when the converter goes

through all the states sequentially as in the counter type converter described in Chapter 1 or the ramp variation described in Chapter 3. In an approximation converter, such as the successive approximation type, the large transients which result in going from, say, half scale to quarter scale require a long time to settle down, and any hysteresis in the comparator circuit causes relatively large variations in the state size. However, the differential linearity of an approximation converter can be improved by running it at very low speed. Differential linearity is also affected by variations in the divider networks (although they are relatively small). It can be avoided by using a ramp converter.

The shorter the converter word length, of course, the better the differential linearity will tend to be. However, this gain may well be compromised, since small resolution could result in the loss or the smoothing of very sharp peaks in the histogram.

Techniques commonly used to overcome difficulties with differential linearity are: changing the offset on the converter (or equivalently the bias on the input signal) and changing the word length of the converter. Switches can be mounted on the converter for this purpose, or the change can be made programmable so that the controlling device can make the change automatically.

DISTRIBUTION OF ERROR

How much of the total error should be in the digital circuitry and how much in the analog portion? For converters in the range of up to 10 or 11 bits, the digital error generally accounts for about $\frac{1}{3}$ to $\frac{1}{2}$ of the total. Thus, a typical 10-bit system would have a quantization error of $\pm\frac{1}{2}$ LSB and an analog error of $\pm 1\%$.

If the accuracy requirement is low, the word length may be the major source of error. The total error may then be treated simply as round-off. If the accuracy requirements are stringent, it is desirable to minimize all sources of error, analog and digital. The digital error is quite simple to minimize by extending the number of bits within practical limits. A converter with an overall error of 0.1% and a word length of 20 bits would be unjustified, as for all intents and purposes the least significant bit could have been generated by a random number generator.

Requiring monotonicity is one way to assure that all the bits are meaningful. This means that all states must exist and they must be in the correct order. In terms of converter operation, as the number going into the digital-to-analog converter is increased, the output voltage must also increase; it should never dip back down at any point. Similarly, if the input voltage to an analog-to-digital converter is increased, the digital output should stay at the same value or increase and should not skip over any states.

The converter is most likely to lose monotonicity when switching between digital states such as 0111 and 1000. If the weighting of the bits is not quite correct, in a digital-to-analog converter the higher state might correspond to a lower voltage, and in the analog-to-digital converter the output might jump directly from 0110 to 1000.

Measures of Speed

DIGITAL-TO-ANALOG CONVERSION

The maximum conversion rate is theoretically limited only by the minimum time between readins to the converter flip-flops, and can easily be as high as 10 megacycles. However, such a figure may be misleading. The desired ratio of settling time to non-settling time usually determines the maximum usable conversion rate.

The settling time of a converter is measured from the time the digital readin is performed to the time when the analog output has settled to within the specified limits of accuracy. How the output approaches its final value depends on the output circuit, as discussed below.

The divider output will have high frequency transients before it begins to settle. If the output is going to a low frequency device, the transients can be ignored. In some applications, it is more desirable to smooth the transition between states than to minimize the total time, in which case the oscillations can be damped with the capacitor or a low pass filter.

If the output is from an amplifier circuit, the settling time will be determined by the maximum rate of change of the amplifier. Thus, the first readin may take longer to settle than subsequent readins, which usually do not change the converter by such a percentage of the full scale.

ANALOG-TO-DIGITAL CONVERSION

Conversion time is measured from when a request is given to when a digital output is available. In converters like the successive approximation type, where all conversions are completely independent, time must be allowed for completion of entire steps in the conversion process. In the continuous converter, the conversion time is usually just that time required to synchronize the request and get the number.

The conversion rate is usually the inverse of the conversion time. In some systems, an amplifier or comparator recovery time is required between conversions; thus the rate is lower. However, comparators manufactured by Digital Equipment Corporation do not have a recovery time. The conversion rate will also be slower if logical operations must be carried out between conversions. In some cases, such as the counter converter performing a number of simultaneous conversions or the synchronous sequential converter, the conversion rate is actually faster than the inverse of the conversion time.

If the input signal is changing with respect to time, it is very important to know when the signal had the value given by the output. The uncertainty in this time measure is called the aperture time (sometimes also called window or sample time). The size of the aperture and the time when the aperture occurs vary depending on the conversion method.

Figures 12 through 15 illustrate how the aperture varies with different conversion techniques. In each case, the upper portion of the figure shows how the converter arrives at an output. The lower portion of each figure shows how the input might be reconstructed from the Digital data.

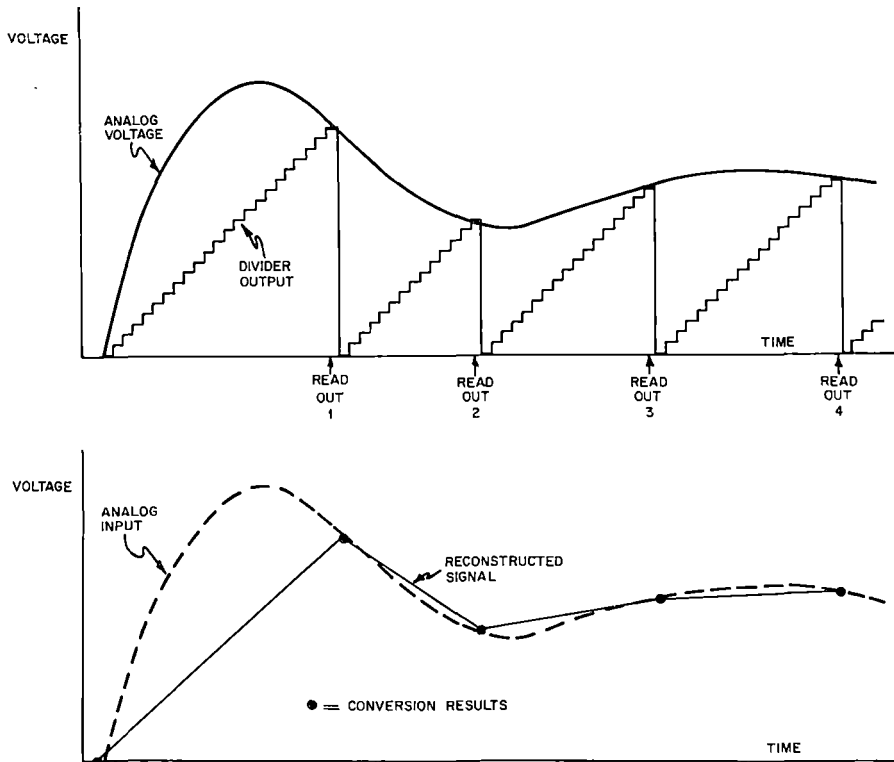


Figure 12 Counter Converter

In the counter converter (Figure 12) the aperture occurs at the end of the conversion. This is not constant with respect to the beginning of the conversion, but it may be calculated from the digital output.

For the continuous converter (Figure 13) the aperture is the time for the last step. Here the assumption is made that the input signal does not change more than ± 1 LSB between conversion steps. To meet this requirement, the maximum rate of change of the input voltage must not exceed the maximum rate of change of the converter. This is $V_{ref}/2^N \Delta T$ where V_{ref} is the full scale voltage, N is the number of bits, and ΔT is the time per step. The maximum rate of change of the sine wave is $2\pi V_p f$, or $\pi V_{pp} f$. Thus, if the converter is to follow the input, the maximum frequency components in the input must satisfy the following equation:

$$\pi V_{pp} f = V_{ref} / 2^N \Delta T$$

and if the peak-to-peak voltage is assumed equal to the converter reference, then the maximum frequency is:

$$f = \frac{1}{2^N \Delta T \pi}$$

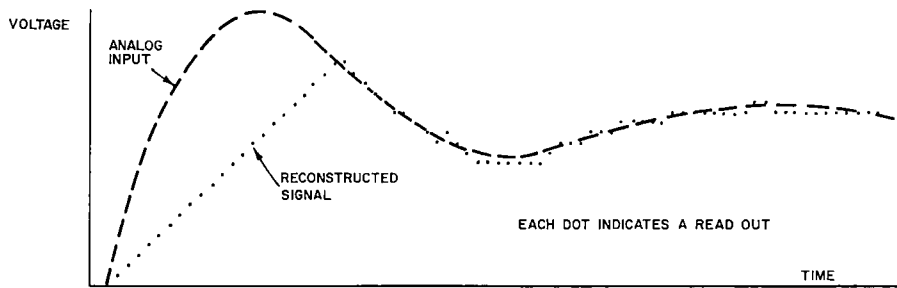
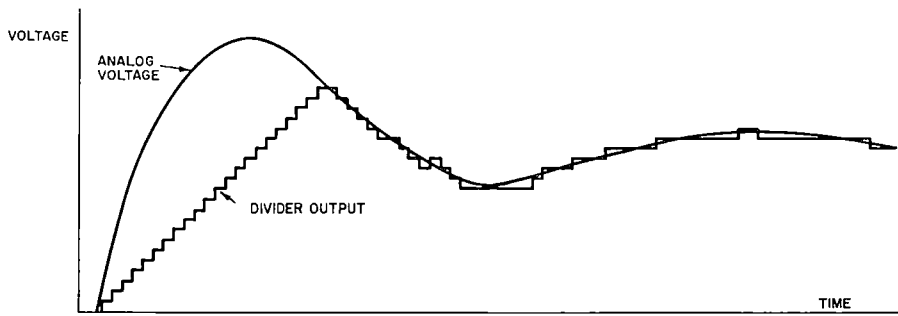


Figure 13 Continuous Converter

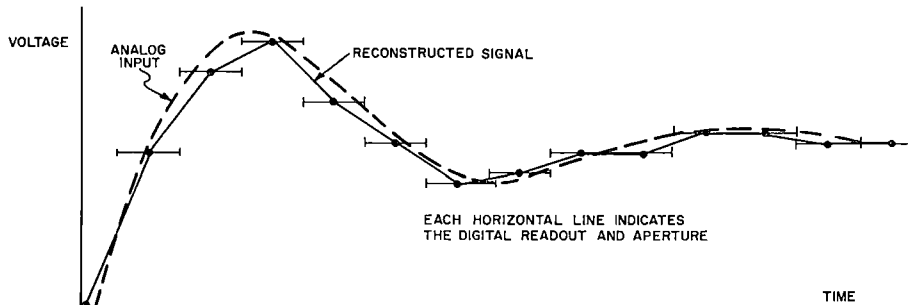
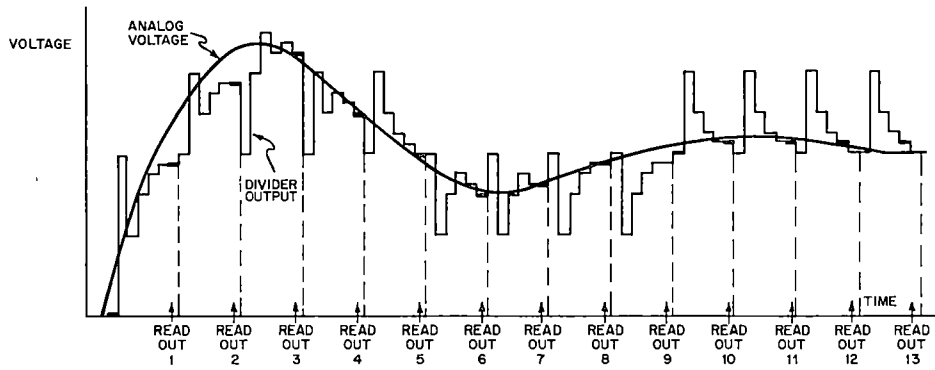


Figure 14 Successive Approximation Converter

For a successive approximation converter (Figure 14) the digital output corresponds to some value the analog input had during the conversion. Thus, the aperture is equal to the total conversion time. Aperture time of the successive approximation converter can be reduced by using the redundancy techniques outlined in Chapter 3 or by using a sample and hold circuit. The sample and hold is illustrated in Figure 15.

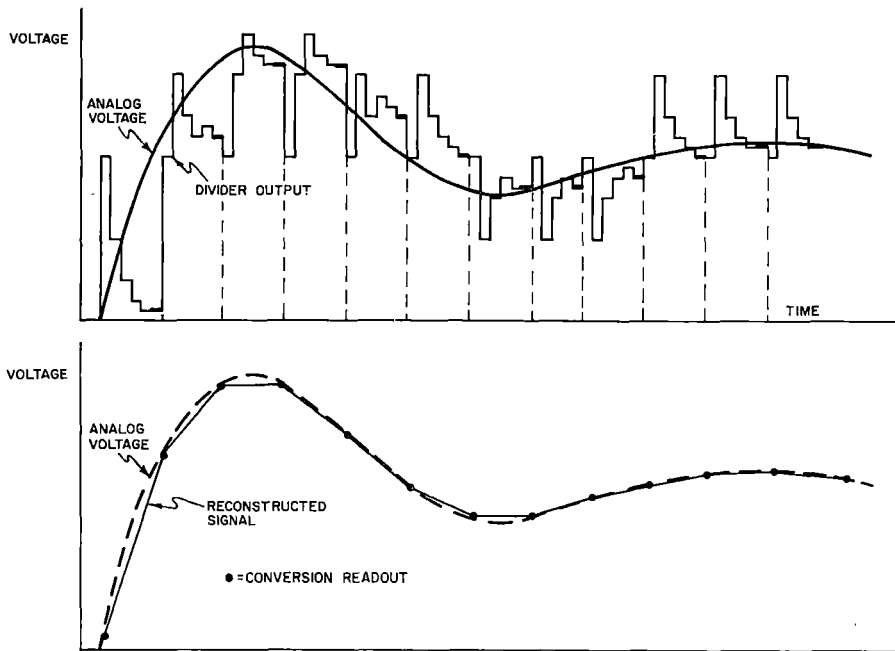


Figure 15 Successive Approximation Converter with Sample and Hold

SELECTING A CONVERSION METHOD

Chapters 1 and 2 have summarized several methods of conversion and the performance characteristics that may be expected from them. These criteria for choosing a specific conversion method are condensed in Table 1. The table is organized like the handbook with applicable chapters called out for quick reference to detailed descriptions of the methods.

The decision to choose one converter over another is principally a matter of speed, aperture, cost, and whether multiplexing or a single continuous input is to be used. Exact conversion times, aperture times, and cost depend on the number of bits, type of circuitry,

TABLE 1 ANALOG TO DIGITAL CONVERSION TECHNIQUES

Method	Best for Multiplexed or Continuous Input?	Conversion Time* 5 Bits (μsec)	Conversion Time* 10 Bits (μsec)	Aperture Time* 5 Bits (μsec)	Aperture Time* 10 Bits (μsec)	Constant Time of Aperture?	Relative Cost	Remarks
BASIC METHODS (Chap. 1 & 4)								
Simultaneous	Both	Not Applicable			Yes	Depends on resolution	Excellent for low resolution systems — operates in about 100 nanoseconds	
Counter	M	24 av.	1792 av.	1.5	3.5	No	Low	Allows many conversions simultaneously
Continuous Continuous Input Discontinuous Input	C	1.5	2	1.5	2	Yes	Low to Medium	Extremely high speed for continuous input but falls behind on sharp rate of change
	C	24 av.	1024 av.			Yes		
Successive Approximation	M	7.5	36	7.5	36	Yes	Medium	General purpose — good speed/dollar
VARIATIONS ON BASIC METHODS (Chap. 3)								
Ramp	M	16 av.	512 av.	1	1	No	Depends on resolution	Good differential linearity — low cost for low resolution systems
Section Counter	M	18	112-224	1.5	3.5	No	Low to medium	Used with digital voltmeter
Continuous with add. comp. Continuous Input Discontinuous Input	C	1.5	2	1.5	2	Yes	Medium to High	Similar to continuous but has faster responses to discontinuous or high speed signals
	C	6-12 av.	32-512 av.	1.5	2	Yes		
Successive Approximation with Redundancy	M	9	27	1.5	3	Yes	Medium to High	Good speed per dollar in high resolution systems. Small aperture, good differential linearity
ADVANCED (Chap. 3)								
Subranging	M	3-4	10-20	3-4	10-20	Yes	High	Excellent for 5 to 8 bits
Subranging with Redundancy	M	2.5	6-9	1.5	3	Yes	High	Excellent for 7 bits or more
Seq. Approx. (Non-Synchronous)	M	7.5	25			Yes	High	May make errors. Requires sample and hold
Seq. Approx. (Synchronous)	C	1.5/9†		1.5		Yes	High	†Time between conversions/total time
Quantizing Continuous Input Discontinuous Input	Both	2	3	2	3	Yes	High High	Excellent for both multiplexed and continuous inputs. Automatically follows fast input with low resolution and slow input with high resolution
	Both	6	18	2	3	Yes		

*See text

and variations in system design. The speeds given in the table were derived assuming that the system was designed for maximum speed per dollar. Actual speeds will usually be within a factor of 2 for basic conversion methods and within a factor of 5 for the others. The basic conversion methods, as described in Chapters 1 and 4, will satisfy most requirements. If Table 1 confirms the choice of one of the basic methods, the reader can go directly to Chapter 4 for specific information on the equipment required. The other methods are variations of basic methods and advanced techniques primarily for increased speed. They are described in general terms in Chapter 3.

CHAPTER 3

SPECIAL ANALOG-TO-DIGITAL CONVERSION TECHNIQUES

The analog-to-digital conversion techniques described in Chapter 1 are the most commonly used methods but not necessarily the only ones. There is an extremely large variety of techniques, not all of which have been investigated. Some of the other methods are described in the following section.

Variations In Basic Techniques

SECTION COUNTER

The counter converter is a simple technique for performing conversions. However, if the digital word becomes long, the 2^N steps required to complete the conversion may be too many.

One way to decrease the time at a minimum of cost is to divide the counter into sections. For example, a 10-bit converter could be divided into 2 sections of 5 bits each. At the beginning of the conversion the least significant counter is set to all ones and counts are inserted into the most significant counter until the comparator indicates that the input has been exceeded. The least significant counter is cleared and counted up until the correct value is reached. The maximum number of steps required to complete a conversion is 2^5 for the most significant counter and 2^5 for the least significant counter, giving a total of 2^6 steps. This is a maximum of 64 counts versus 1024 counts for the standard counter converter.

Other types of section counters might use more parts and operate by counting one counter up and the next down. The total conversion time, of course, depends on the number of sections.

The section counter technique is frequently used in digital voltmeters where the output is to be in decimal: Each section of the section counter thus represents one decimal digit.

RAMP METHOD

In the counter converter, each count input is increasing the voltage out of the DAC by one step, effectively generating a ramp out of the DAC. Thus the level amplifiers, reference supply, and divider network could be replaced by an external ramp generator circuit. If accuracy is not too important, the ramp can be made by charging a capacitor with a current source and using the linear part of the exponential. In higher resolution converters, the ramp might be made by using the operational amplifier as an integrator.

The ramp technique is somewhat faster than the counter technique because carry and DAC set up time is not required before gating the next count pulse. The differential linear-

ity, over a short span of a ramp converter, is bound to be fairly good, since the ramp is a continuous signal. Although there may be some noise, the general slope will not change significantly over a short span.

Both the ramp method and the counter technique approach the final value in small steps and from one direction only. This puts considerably less strain on the comparator circuit than a technique such as subranging or successive approximation where the comparator is receiving large input voltage changes in different directions and being asked to resolve small differences. In general, all smooth conversion techniques (the counter, ramp, and continuous converters) generally operate at a considerably faster time-per-step and produce better differential linearity than the approximation methods (subranging, successive approximation, sequential approximation, etc.).

CONTINUOUS CONVERTERS WITH ADDITIONAL COMPARATORS

A continuous converter is an extremely fast and relatively inexpensive device for following a continuous signal. However sometimes the input rate of change exceeds that of the converter. To close this gap determine if the differential error exceeds a specified amount and add or subtract a correction count in a more significant bit. For example, a small amount of logic added to a 10-bit continuous converter could measure large differences between the input and the contents of the converter. If the difference is more than $+8$ counts, it adds a count in the third flip-flop from the least significant end. If the

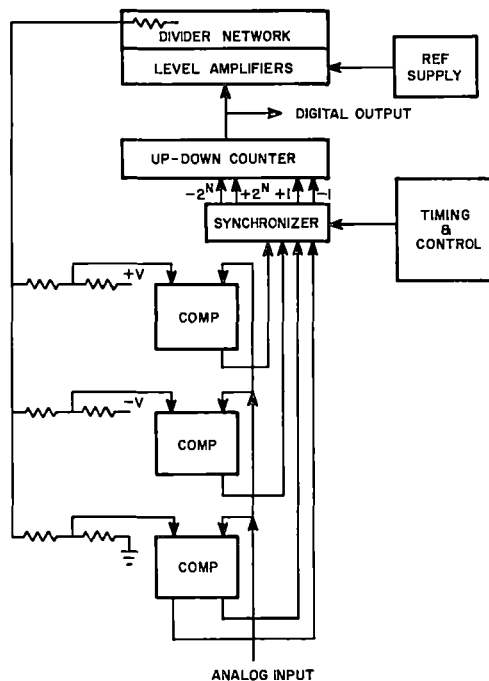


Figure 16 High Speed Continuous Converter

difference is more negative than -8 counts, it subtracts a count from this stage. Thus the converter operates on high frequency signals with reduced accuracy and on low frequency signals with the full accuracy.

A continuous converter with additional comparators is shown in Figure 16. Two comparators and additional gating and synchronizing logic have been added to a basic continuous converter.

SUCCESSIVE APPROXIMATION CONVERTER WITH REDUNDANCY

Redundancy is useful where high resolution and high speed are both required. It can also be used to improve differential linearity and aperture.

The successive approximation converter is extremely efficient; but, since the results of each step are irrevocable, each step must be allowed to settle to within the total system accuracy. For high resolution systems, the settling time can be quite long. With redundancy, the first steps are done with a limited accuracy; then a correction step is inserted to improve the accuracy. Only the correction step and the following steps need to settle to final accuracy. Steps before correction need only settle within $\pm\frac{1}{2}$ of the correction amount.

The correction can be implemented by adding or subtracting one bit, as in a continuous converter. If the steps preceding the correction are offset, only add circuitry is necessary. For fastest operation, a special divider with redundant inputs can be used so that the addition can be done without generating carries. The digital summing can be done in an output buffer where the carries will not interfere with the analog-to-digital feedback loop.

The correction step can also be used to compensate for changes in the input analog signal during earlier steps, thereby reducing the aperture. It also improves the differential linearity of the converter since a large part of the variation in state size is due to the large transients during the early conversion steps.

Advanced Techniques

SUBBRANGING

This method is very good for converting a large number of input channels since the conversion begins without assuming anything regarding the previous state of the input. It also converts quite rapidly and allows a trade-off between cost and complexity and speed. Thus, if extremely high speed is required, numerous comparators are used and not many steps are required. In the case where less speed is required, perhaps only one comparator circuit would be used.

The subbranging method operates by dividing the total input signal range by the number of subranges, selecting the appropriate subrange and then dividing this into subranges as before, repeating until the desired resolution is achieved.

Figure 17 shows how subbranging works. At the start of the conversion, the only information available about the input signal is that it lies somewhere in the range of zero to the full scale voltage, V_{FS} . The first step of the conversion divides the full scale voltage into

subranges, in this case four. Simultaneously, comparisons are made between the input voltage and the three subrange boundaries, V_1 , V_2 , and V_3 . It can be determined whether the input voltage is higher than or lower than each of these boundaries. If the input signal is lower than all of the boundaries, it must fall in the lowest range. If it is higher than V_1 but lower than V_2 and V_3 , it must fall in the next to the lowest range, and so forth. Once this information is determined, the selected subrange can be divided into four more subranges and the process repeated.

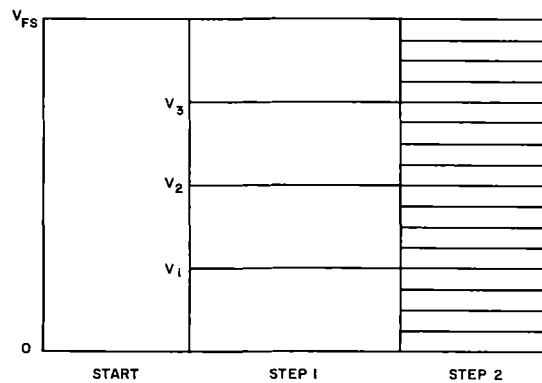


Figure 17 Subranges for a Converter with Four Subranges Per Step

If there are M ranges per step and S steps, the total resolution of this conversion will be $(\frac{1}{M})^S$. For example, a 12-bit system requiring a total resolution of $\frac{1}{4096}$ could be implemented in 12 steps $[(\frac{1}{2})^{12} = \frac{1}{4096}]$, in six steps $[(\frac{1}{4})^6 = \frac{1}{4096}]$, in four steps $[(\frac{1}{8})^4 = \frac{1}{4096}]$, or in three steps $[(\frac{1}{16})^3 = \frac{1}{4096}]$. The step resolution does not have to be an integer power of two. However, except in a binary coded decimal system where it is useful to make M equal to 10, the saving in control circuitry is usually sufficient to justify increasing the step resolution to the next power of 2.

Figure 18 shows a subranging converter. Here two digital-to-analog converters and a number of comparators are referenced at equally spaced intervals in the range between the value of the two converters. The technique is similar to the simultaneous method. The system starts with the lower DAC (digital-to-analog converter) at zero, the upper one at the maximum voltage. The output of the comparators indicates which range contains the input, say between the reference applied at C_k and the reference applied at C_{k+1} . Then the reference voltage from C_k is applied to the lower DAC, and the reference voltage that was at C_{k+1} is applied to the upper DAC. A new, smaller set of ranges is produced. The process is then repeated.

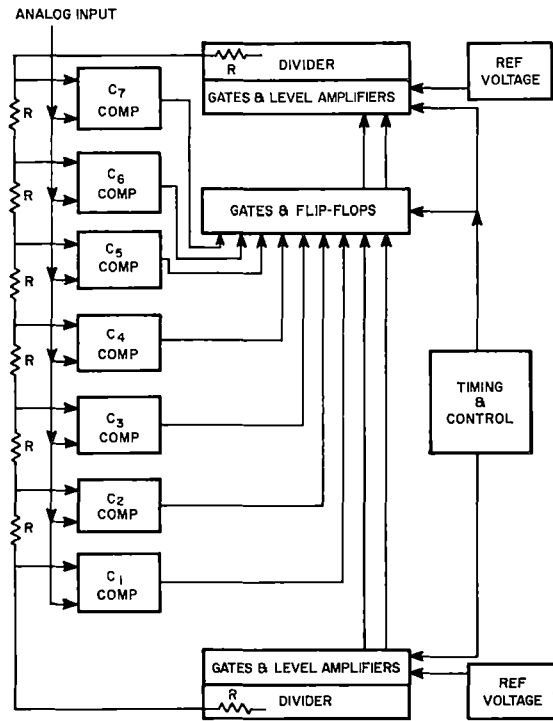


Figure 18 Subranging Converter

If the number of subranges obtained in a single step is equal to the total system resolution, this method becomes the simultaneous method described in the introduction. If the number of subranges per step is reduced to two, this method becomes the successive approximation conversion.

SUBRANGING WITH REDUNDANCY

Redundancy, as described for the successive approximation converter, can be applied in the same manner to a subranging converter. It is particularly useful here as the capacitance of many comparators in parallel causes the settling time to be quite long.

SEQUENTIAL APPROXIMATION

Sequential approximation, also called parallel approximation, uses a separate analog-to-digital converter for each binary bit of information to be obtained. There are two methods of operation, synchronous and non-synchronous.

Figure 19 shows how the non-synchronous type operates. In one example shown at the top of the figure, the analog input comes into a comparator which compares the input with half scale. If the input is larger, the comparator applies a voltage to the most significant bit of each of the DAC circuits down the line. As soon as the first comparator has

settled, the second comparator can start to make its decision. Speed is gained because there is no flip-flop delay in this system. But more important, most comparators will make decisions relatively quickly, since the analog input cannot be very close to the boundaries of more than two subranges (the last one and one other). Thus, the average amount of time required per decision is considerably less than the maximum. In a clocked system, the maximum required time must be allowed for each step. Here, only the average time is allowed.

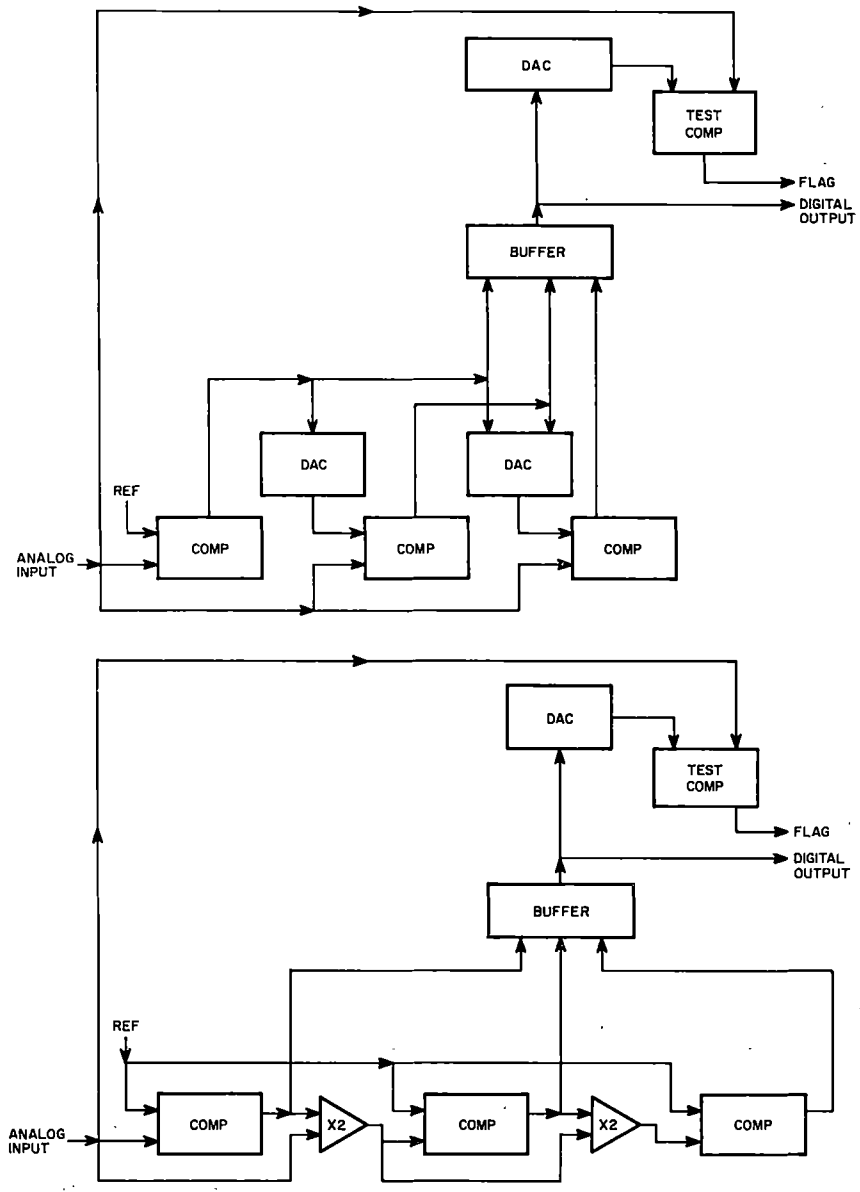


Figure 19 Non-synchronous Sequential Approximation

The converter shown at the lower half of Figure 19 is quite similar except that the individual DAC networks are replaced by operational amplifiers. The analog input goes to the first comparator. If the input is above half-scale, the comparator produces a voltage corresponding to half scale. This is subtracted from the input signal, and the result is multiplied by two and passed on to the next comparator.

In both examples, speed is gained by the fact that full settling time is not needed by those comparators which are not making a critical decision. On the other hand, some difficulties are encountered if the input signal should change slightly before the digital readout has occurred. One of the comparators may change value, but the results may not carry to the end of the chain before readout. Thus, the comparator should have built-in hysteresis so that small noise spikes will not cause an error, and the digital output should always be read into a buffer and double checked with the input.

In synchronous sequential approximation, the time required to perform a complete conversion is essentially the same as in a successive approximation converter; however, the conversion rate is much faster. Erroneous readout is eliminated, since the converter is buffered and synchronous. This type of converter is particularly useful for systems with a single input.

The synchronous or clocked type sequential approximation converter also uses one converter per bit. It differs from the non-synchronous type because there is a delay line between each converter (see Figure 20). The analog information arrives at the first comparator, which makes a decision and stores the information in a shift register for use by later converters. By the time the second converter is set up and ready to make a decision, the same analog information is just arriving at the second comparator. This converter decides on the second bit of the output word, based on exactly the same analog voltage as was at the first converter when the first bit decision was made. This process is continued for however many bits are necessary.

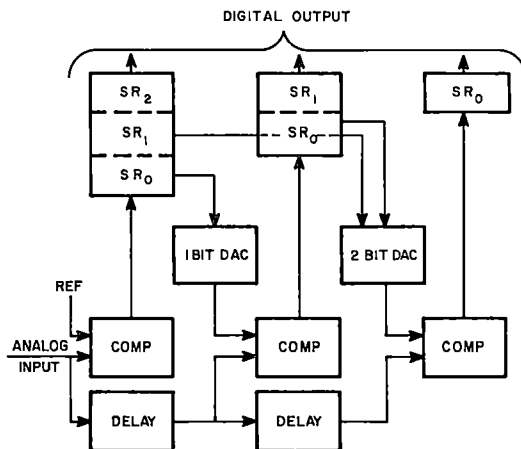


Figure 20 Sequential Approximation (Synchronous)

QUANTIZING ENCODER

The quantizing encoder was developed by Dr. Jerome Cox and Donald Glaser at the Central Institute for the Deaf. It is the most general purpose, high speed converter because it is fast for both continuous and multiplexed inputs.

The quantizing encoder uses one digital-to-analog converter, a number of amplifiers, and a number of comparators. It examines the difference between the input voltage and the DAC output, quantizes the difference to the nearest power of 2, and adds or subtracts this from the DAC. Thus, the quantizing encoder can follow a continuous signal, staying within one bit of the correct value for low frequencies. For high frequencies, it will always be within the nearest possible power of 2 of the correct answer. (Thus, if the input signal should suddenly change, the quantizing encoder will make a similar jump corresponding to the nearest power of 2 change, while the standard continuous converter could increase by only one count.)

For multiplexed input, the quantizing encoder will operate similar to a successive approximation converter but twice as fast. It requires only one step for each two binary bits (or fraction thereof). In addition, since it includes a self-correcting ability, the time per step can be quite fast.

Figure 21 shows how the quantizing encoder could arrive at the result when used as a 4-bit encoder. In the left-hand example, it is used with a multiplex input. At the start

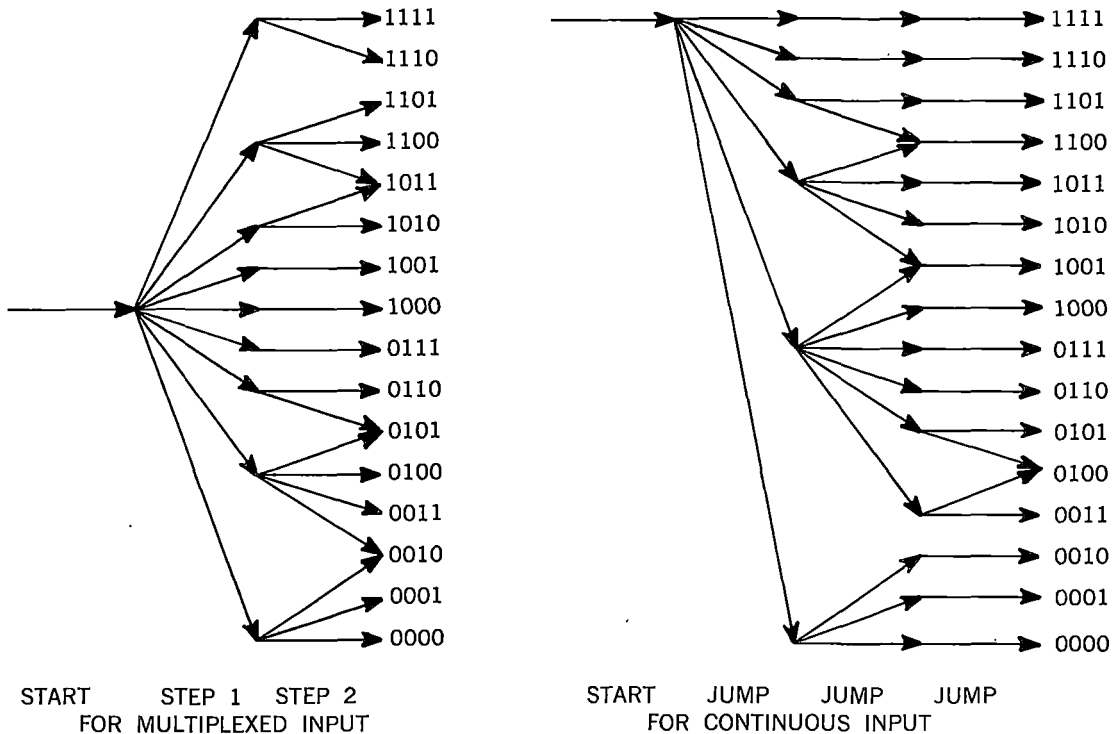


Figure 21 Quantizing Encoder Method

of the conversion the converter is set to mid-scale. At the end of the first step it will go to any of the points shown, and at the end of the second step it always has arrived at the correct answer.

The right-hand example, Figure 21, shows how the converter would react if it were holding its maximum value and the input suddenly dropped to a much lower value. If the new value were within 1 or 2 counts, it would immediately arrive at the exact answer. Otherwise, it would make a power of 2 jump to the nearest correct value.

CHAPTER 4

TYPICAL CONVERTER LOGIC

Digital-to-Analog Conversion

Figure 22 shows a typical digital-to-analog converter. The basic components of this circuit are a flip-flop register, level amplifiers, a divider network, and a reference supply. The digital signals are brought in with a pair of complementary levels for each bit. This information is jammed simultaneously into all the flip-flops and is automatically converted to the appropriate analog voltage by the divider network.

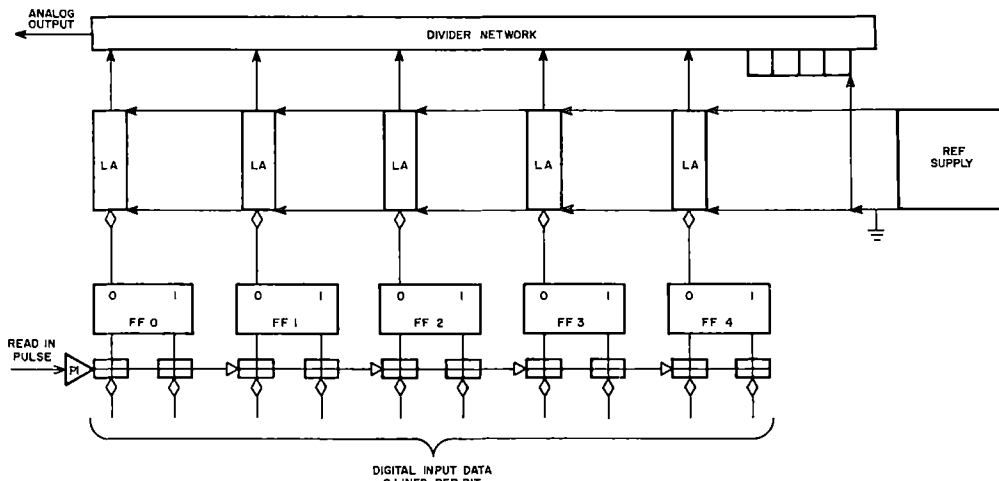


Figure 22 Digital-to-Analog Converter

The settling time of the digital-to-analog converter depends on the number of flip-flops that change, as well as the voltage difference between the two states involved. For example, in switching from a number such as 0111 to a number such as 1000, all of the flip-flops change state. Even though the two final values of the analog voltage are very close, transients occur on the divider output for the following reasons: variation in transition times from flip-flop to flip-flop and from level amplifier to level amplifier; transient current drawn from the reference supply; the fact that the flip-flops have a slower fall than rise time; and the fact that signals must propagate through the divider network. The worst case is switching from mid-scale (1000 . . .) to one count less (0111 . . .). Here the transients are as much as 1 volt, and even more with the Inverter Amplifiers Type 1667 and 4677. However, the transients are quite short in duration and return to within $\frac{1}{2}$ LSB of their final value within at most 2.5 microseconds for the medium speed combinations listed in the table. In most cases, these transients will be faster than the load can respond and hence can be ignored. For minimum transients, the Type 4679 Level Amplifiers and the metal film ladders are recommended. These units will settle to within 0.05 per cent within 2.5 microseconds.

Table 2 lists the modules which are recommended for systems of different word length. Since a digital-to-analog converter is by nature a relatively fast device, the recommended modules were selected principally on the basis of economy and accuracy consistent with the word length. The maximum conversion rate is 1 megacycle.

TABLE 2
RECOMMENDED MODULES FOR MEDIUM SPEED D TO A CONVERTER

No. of Bits	Flip-Flops	Level Amp.	Divider	Ref Supply
up to 4	4218	4667* or 1667	1563	1562**
5	4219	4667* or 1667	1563	1562**
6	4218	4679	1563	1562
8	4218	4679	1563	1562
10	4219	4678	1574	1704
12	4218	4679	1574	1704

*longer operating time for high voltage levels
**or external reference of -3 to -10 volts

If high speed transients are a problem, the Type 6227 Flip-Flop should be used to drive the divider. A small choke can be used between the flip-flop output and the level amplifier input on the more significant bits to equalize the switching times. This will reduce the transients to about a 0.5 microsecond duration on high accuracy systems. If further smoothing is desired, a low pass voltage should be used on the output.

Analog-to-Digital Conversion

SIMULTANEOUS CONVERSION

The simultaneous conversion technique is simple, inexpensive, and extremely fast for a small resolution system. Figure 23 illustrates a simultaneous converter with a resolution of 3 bits. It uses Level Standardizers Type 1501 as comparator circuits for the input. These units have a resolution of 0.1 volts and are therefore suitable for a simultaneous converter of up to 4 bits. The reference voltages for the level standardizers are made by dividing a +10 volt reference with a series of identical resistors. Although the tolerance on these resistors is not wide, in systems of 3 or 4 bits small trimming potentiometers should be put in series with the resistors so that the reference voltages can be adjusted to offset the common mode effects and the zero offset of the level standardizers. Since the level standardizers also draw a current through the resistors, the potentiometers can trim the value of the resistors to compensate for this current.

The outputs of the level standardizers are coded in a Gray code and jammed into a simple flip-flop register, made by cross-coupling inverters and diode gates. A Gray-to-binary decoder on the output produces standard binary notation.

For higher speed operation, the gates used should be Type 6115, 6113, and 6112. The clear and readin pulses can then be DEC Standard 70 nanosecond Pulses and can occur 100 microseconds apart (thus performing a conversion every 200 nanoseconds).

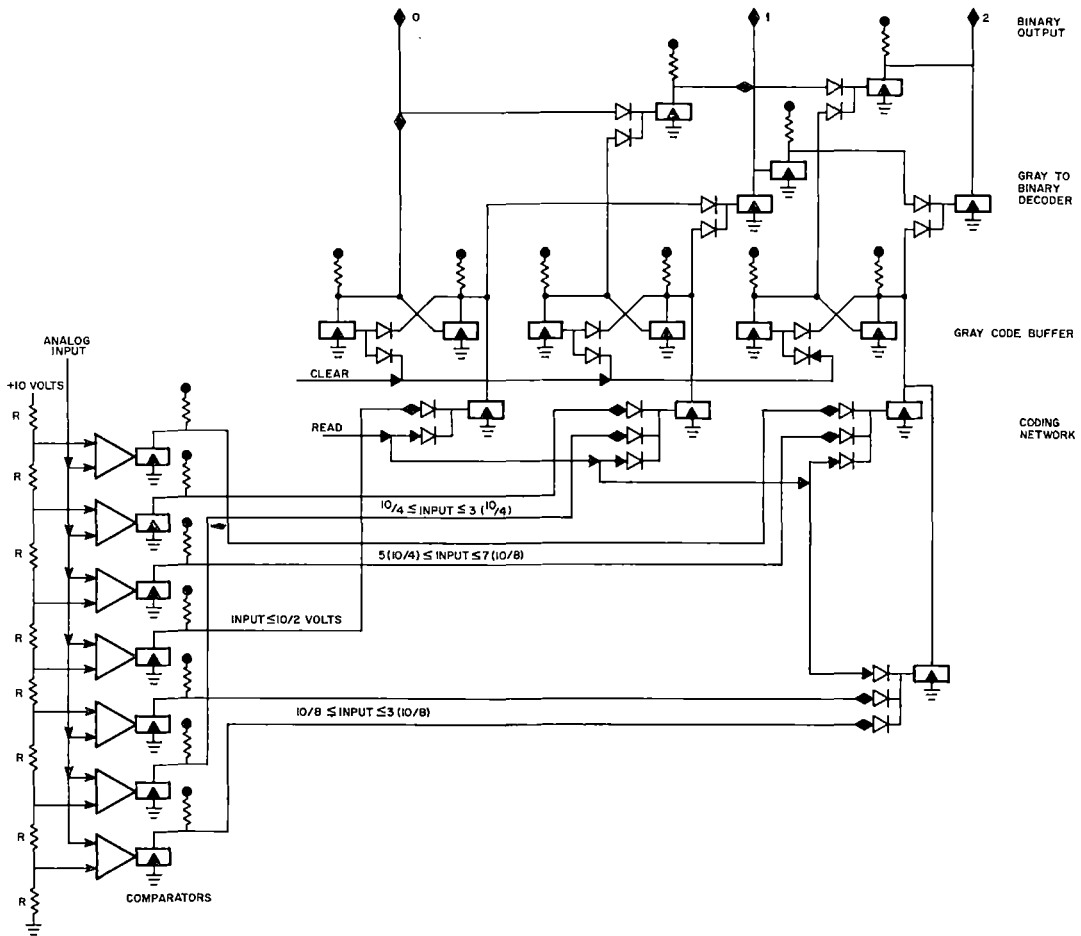


Figure 23 Simultaneous Converter

For lower speed systems, Type 4115, 4113, and 4112 gates can be used with DEC Standard 400 nanosecond Pulses. With these gates, pulses can occur 1 microsecond apart, thus giving a conversion every 2 microseconds.

For maximum speed operation the buffer register can be made with Type 6202 or 6208 Flip-Flops. The standardizer information can be jammed into the buffer with DEC Standard 40 nanosecond Pulses. In this case, conversion could be completed every 100 nanoseconds.

There are two factors which limit extending this system to large resolution systems. One factor is cost of so many comparators. The other factor is the current drawn and the input capacitance, which become extremely large if too many comparators are tied in parallel. For this reason it is recommended that the Type 1501 be used for systems of up to four bits only. Detailed information on the Type 1501 is included in the Module Catalog published by Digital Equipment Corporation.

TABLE 3 RECOMMENDED MODULES FOR SIMULTANEOUS CONVERTER UP TO 4 BITS

Maximum Conversion Frequency (Less Readout Time)	Delay Through System (nsec)	Pulse Inputs (nsec)	Comparator	Flip-Flops	Gates
10 mc	delayed FF, read & pulse simultaneous	40	1501	6202 or 6208	6106
5mc	250	70	1501	6112, 6113, 6115	
500kc	620	400	1501	4112, 4113, 4115	

COUNTER METHOD

Figure 24 illustrates a typical circuit for the counter type analog-to-digital converter. The start signal clears the counter and inserts a single pulse in the delay chain. Each time the pulse goes around the chain, one count is added to the flip-flop register. When the divider output is equal to the analog input, the comparator will switch. The next pulse sets the control flip-flop, indicating the end of conversion and inhibiting the pulse from circulating. The circuit shown in Figure 24 uses Type 4215 or 4225 unbuffered flip-flops for the counter. The control flip-flop may be any unbuffered flip-flop such as the Type 4214 or 4215. At the end of conversion, this flip-flop will be set by grounding the ZERO output terminal.

The Pulse Amplifiers Type 4604 perform pulse standardization as well as amplification. The clear pulse should be 1 microsecond in duration.

The type of delay unit depends upon the number of bits in the counter, since this determines the maximum time required between counts. If either Type 1304 or 4301 Delays are used, at least two units must be in the loop to provide the required recovery time. The Type 4303 and the delay lines do not have a recovery time requirement.

The two inputs to the 1310 Delay line pass through two diodes acting as an OR circuit. One diode is in the 1310 connected to pin X. An external high speed diode (such as the Type 1N994) should be connected to pin W.

A complete conversion requires 2^N steps, where N is the number of bits in a counter. The average number of steps is 2^{N-1} . Calculations of the time per step must take into account the following:

- Carry propagate time of the flip-flops
- Total transition time of the flip-flops
- Delay of the level amplifiers
- Delay through the ladder network
- Transition time of the comparator and settling time ($0.15 + 0.05N$ microseconds)
- Gating time
- Synchronization time (if required)

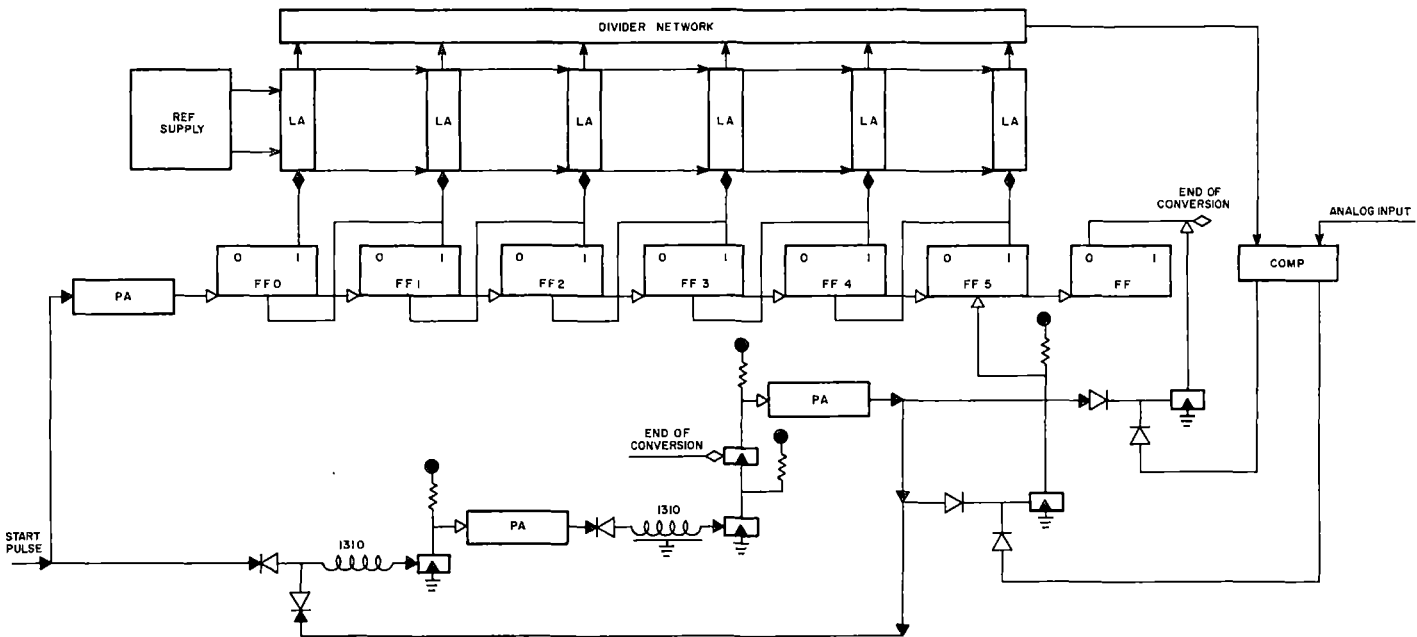


Figure 24 Typical Counter Converter

Typical speeds for the method illustrated are given in Table 4.

TABLE 4 COUNTER CONVERTER CONVERSION TIME

No. of Bits	Level Amplifier	Diode Gates	Divider Network	ΔT Time/Step (μsec)	$2^N \Delta T$ Total Time (μsec)
6	4678	4113	1574	2.2	140.8
6	4679	1113	1574	1.5	96.0
8	4678	4113	1574	2.4	614.4
8	4679	1113	1574	1.7	505.2
10	4678	4113	1564	3.3	3379.2
10	4679	1113	1574	1.9	1945.6

Alternatively, Type 4201 and Type 1201 Flip-Flops can be used in this circuit. However, the Type 4201 will not be as fast as the Type 4215, and the Type 1201 will be only slightly faster.

If buffered flip-flops are used, the control flip-flop should also be buffered and would be set through the input terminal. Also the comparator signal should not gate the counter input directly. Any noise on either the analog input or the ladder output could cause the comparator input to be in a transient state at the time the out pulse occurs. This could result in a split or partial pulse which might not propagate fully. To avoid this possibility the gating inverter on the counter may be either synchronized or eliminated, since the pulse will be inhibited from continuing through the loop.

CONTINUOUS CONVERSION

Continuous analog-to-digital conversion can be performed using an up-down counter. At each step the counter output is compared with the analog input, and a pulse is added to or subtracted from the counter, as necessary. By proper adjustment of the comparator, it is also possible to inhibit counts when the analog signal is approximately equal to the digital number. The inhibit signal is formed by adjusting the comparator outputs so that they do not switch simultaneously. For ideal operation, the two outputs should be in the same state whenever the digital feedback signal is within $\pm\frac{1}{2}$ part in 2^N of the appropriate input signal.

Synchronization (the use of control flip-flops) is required in all continuous converters. Any noise on the inputs to a comparator could cause the outputs to be in a transient state at the time they were sampled. Thus, if the signals are not synchronized, add and subtract pulses could enter the counter at the same time.

Two continuous converters are illustrated. These systems are identical except that the system shown in Figure 25 uses buffered flip-flops with pulse carry techniques for the up-down counter, while the system in Figure 26 uses the 4000 series unbuffered flip-flops with level change carry propagate.

Both illustrations consist of four basic parts: the up-down counter, the DAC, the comparator, and the synchronizer and control logic. Two control pulses are formed by a clock and

a delay unit. The synchronizer pulse sets the up-sync flip-flop if the enable level from the comparator indicates that the feedback signal is smaller than the input signal. Similarly, the down-sync flip-flop is set if the analog input is larger than the feedback input. Two sets of diode gates are used to inhibit counting which would cause the counter to overflow.

The outputs of the set flip-flops are exclusive ORed together to assure that no count signals will be generated if both flip-flops are set. After these signals have had time to set up, the clock generates a count pulse which samples the levels and produces a count up pulse or a count down pulse. At the same time the up- and down-sync flip-flops are reset so that the enable signals can be read in the next-time. All of the synchronizer and control logic should be from the same speed line. The flip-flops illustrated here are Type 1209's, the clock is a Type 1401, the delay a Type 1403, and the inverters and diode gates can be either 5 megacycle or 10 megacycle logic.

The counter can be a lower speed logic than the synchronizer if desired. In this case, the up and down count pulses should be stretched with Type 4604 Pulse Amplifiers to produce pulses of appropriate duration. In the illustration using Type 4215 Flip-Flops, the outputs are buffered since the flip-flop outputs drive a capacitor diode gate level input, a capacitor diode gate pulse input, and a diode gate input, as well as providing the signals to the DAC. The inverters used for buffering are 10 megacycle units which have a minimum of capacitance. Readout from the counter register should take place from the output of the inverter buffers so as not to exceed the loading on the flip-flops.

The continuous conversion method is applicable when the maximum rate of change of the analog voltage is less than the fastest possible rate of change in the converter. That is:

$$\left(\frac{\Delta V}{\Delta t} \right)_{\text{input}} \leq \frac{V_{\text{ref}}}{2^N \Delta T}$$

where

$$\left(\frac{\Delta V}{\Delta t} \right)_{\text{input}}$$

is the rate of change of the input analog voltage, V_{ref} is the full scale voltage of the converter, N is the number of bits, and ΔT is the time per step. ΔT is the sum of:

- Carry propagate time for the flip-flops
- Total transition time of the flip-flops
- Delay of the level amplifiers
- Delay through the divider network
- Transition time of the comparator and settling time
(0.15 ± 0.05N microseconds)
- Total transition time for the synchronizer
(2 microseconds with 4209 flip-flops)
(0.2 microseconds with 1209 flip-flops)
- Delay through gates and pulse amplifiers if in feedback loop

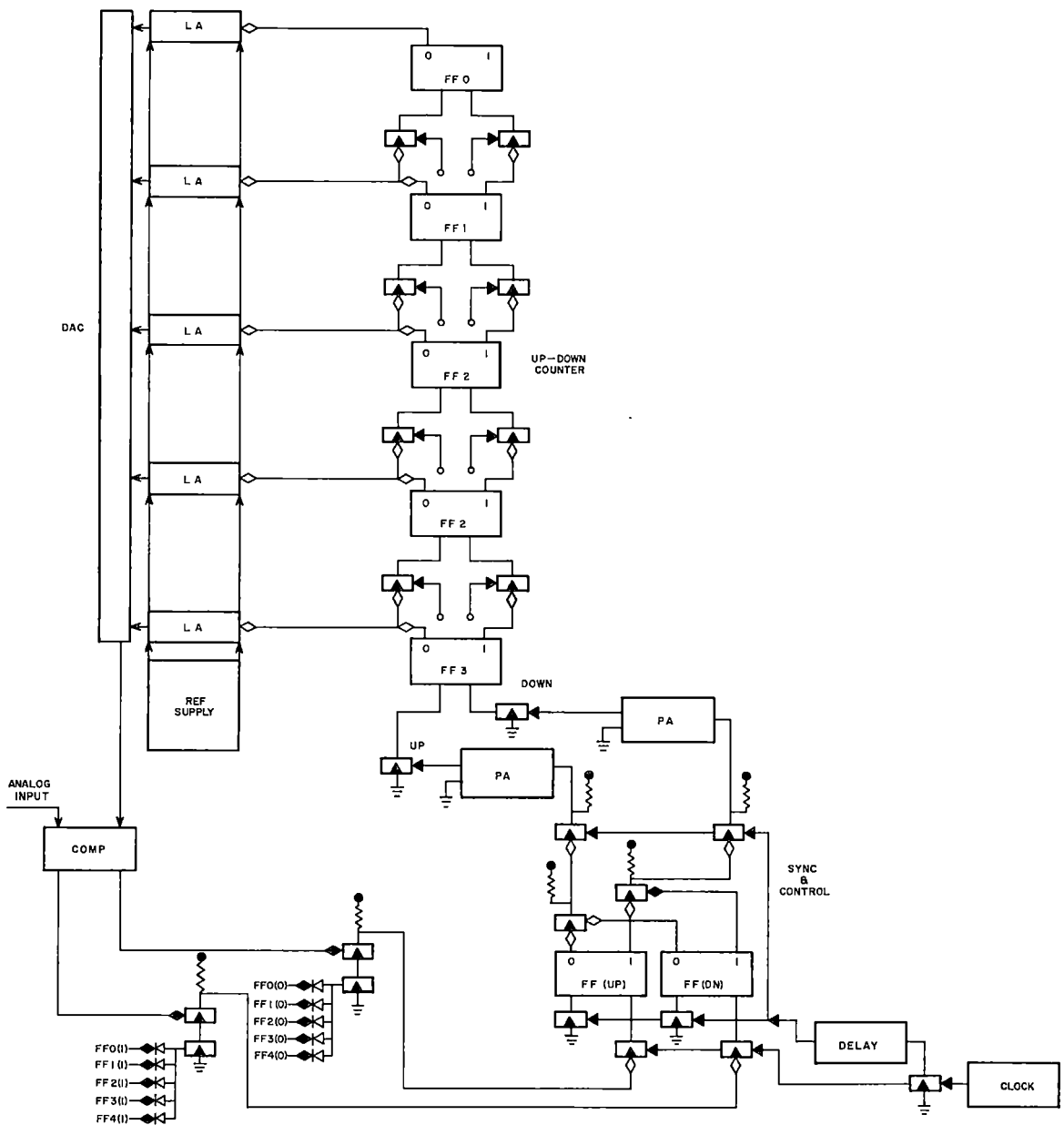


Figure 25 Continuous Converter with Buffered Flip-Flops

