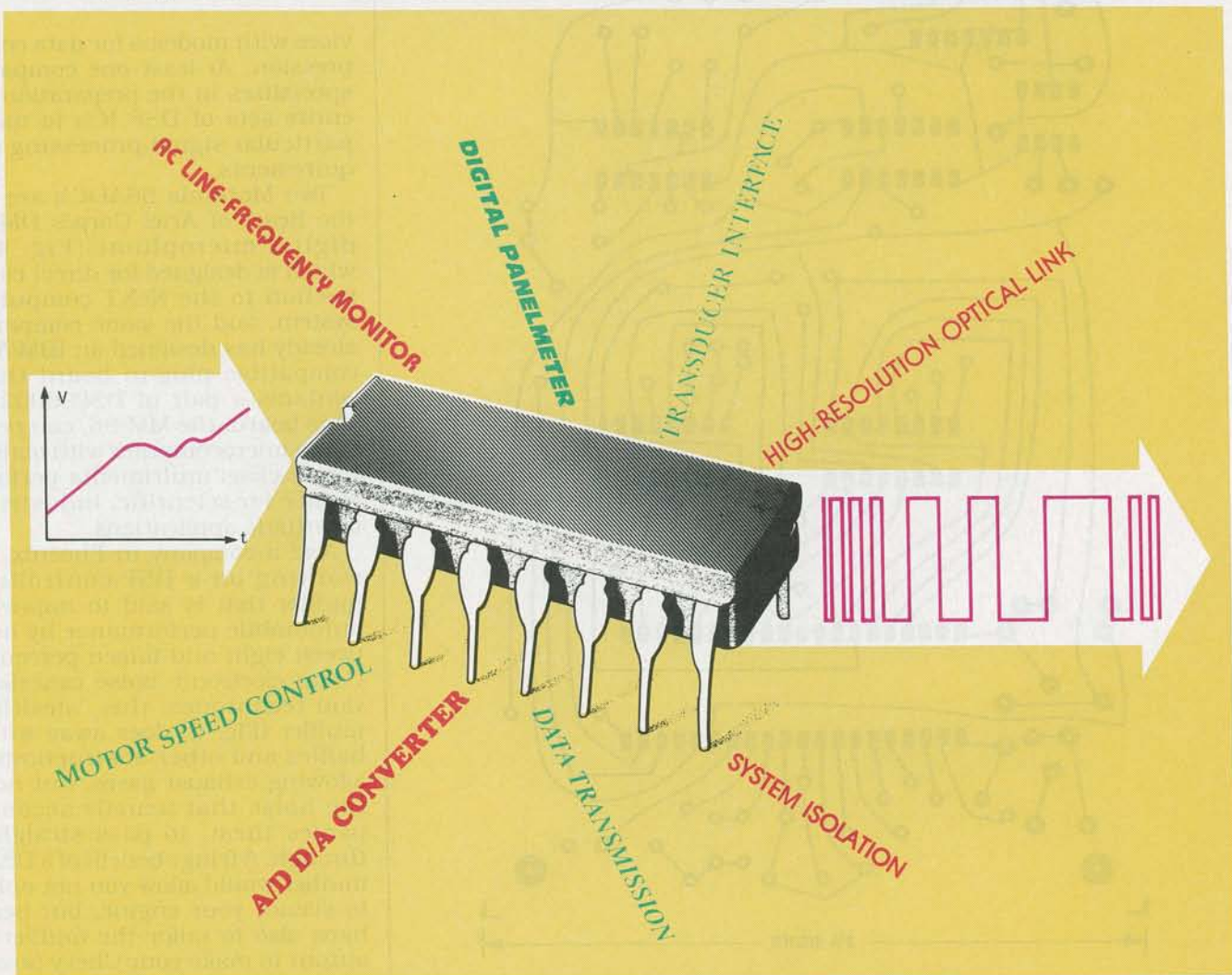


V/F CONVERTERS



**Voltage-to-frequency converters
can often be an inexpensive alternative to
A/D and D/A converters.**

HARRY L. TRIETLEY

IN TODAY'S WORLD OF HIGH-PERFORMANCE single-chip analog-to-digital converters, the simple voltage-to-frequency (V/F) converter is sometimes overlooked. However, V/F converters offer the best combination of resolution, performance, simplicity, and cost in analog-to-digital (A/D) conversion when speed is not important. They can be used for isolation, and to eliminate ground loops and shock hazards, especially in patient-attached medical instruments. Their serial outputs make them ideal for

two-wire or fiberoptic data transmission. Long-term data (flow, kilowatt hours, and so on) may be totaled or integrated by counting their output pulses.

The performance and features available in today's V/F converter IC's make it easy for you to design your own applications. V/F converter IC's may also be used to build frequency-to-voltage (F/V) converters, which can act as an interface with TTL logic. In this article we'll look at a number of IC's used in several applications.

Charge-balance conversion

Figure 1 shows a basic V/F converter using Burr-Brown's VFC32

IC, along with typical circuit values. The VFC32 operates up to 500 kHz. Typical linearity is 0.005% to 10 kHz, 0.025% to 100 kHz, and 0.05% to 500 kHz. Linearity is a measure of the V/F converter's performance, and is a function of the full-scale frequency, f_{FS} . It is the maximum deviation of the actual transfer function from a straight line drawn between 90% and 0.1% of f_{FS} . For a particular f_{FS} , the linearity error decreases with decreasing operating frequency.

The input amplifier is connected as an inverting integrator. Negative feedback holds pin 1 to zero volts. Optional components

R3 and R4 allow the offset to be precisely adjusted so that C2 neither charges nor discharges when V_{IN} is zero.

If V_{IN} is zero, C2's charge holds steady and nothing happens. When a positive input is applied, the input current

$$I = V_{IN}/(R1 + R2)$$

charges C2 so that pin 13 ramps downward. When C2's voltage crosses zero, the comparator triggers the one-shot, closing S1 and momentarily applying the 1-mA reference current to the integrator's input. That charges C2 in the opposite direction, resetting the voltage on pin 13 positive and allowing the cycle to start over.

If V_{IN} is increased, the downward ramp occurs faster, raising the pulse frequency proportionally. The full-scale input current must be less than 1 mA; the specification sheets recommend 0.25 mA full scale for best linearity. (Above 200 kHz the input may be increased to 0.5 mA for improved temperature stability.) If the input voltage drops to zero, the capacitor's charge once again holds steady and the pulses stop.

That operation is known as "charge balance" conversion—the positive charge from the 1-mA source balances the negative charge from the input. Over one complete cycle the net charge on C2 does not change. The charge

$$Q = I \times T$$

removed by the input current during a complete cycle is equal to the charge added by the timed 1-mA reference. If T is the period of one cycle, and T_{OS} is the one-shot period, then

$$Q = [V_{IN}/(R1 + R2)] \times T = 1 \text{ mA} \times T_{OS}$$

or,

$$T = [1 \text{ mA}(R1 + R2)/V_{IN}] \times T_{OS}$$

The frequency is therefore

$$f = 1/T = V_{IN}/[1 \text{ mA} \times (R1 + R2) \times T_{OS}]$$

T_{OS} is equal to

$$7.5 \text{ V} \times (C1 + 30 \text{ pF})/1 \text{ mA}$$

where 30 pF represents the internal capacitance of the IC, and 7.5 V is the internal voltage reference. A 25% duty cycle or less is recommended to achieve best linearity. That corresponds to a maximum input current of 0.25 mA.

The external one-shot capacitor C1 determines the duration of the output pulse, and is dependent on the full-scale frequency, f_{FS} , according to the equation

$$C1 \text{ (pF)} = 33 \times 10^6 / (f_{MAX} - 30)$$

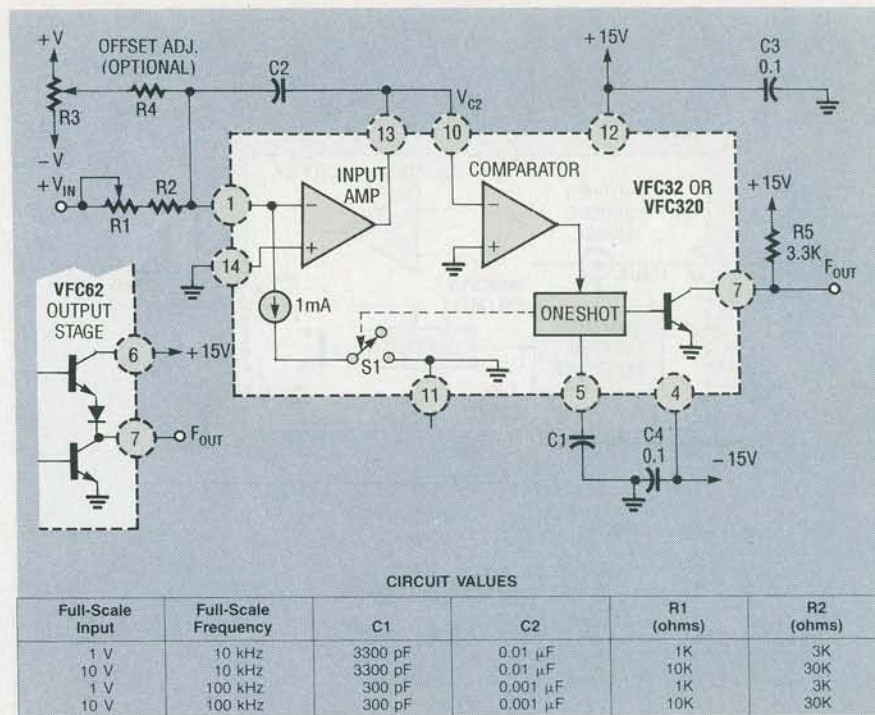


FIG. 1—A CHARGE-BALANCE V/F CONVERTER using a VFC32 IC. The positive charge from the 1-mA balances the negative charge from the input.

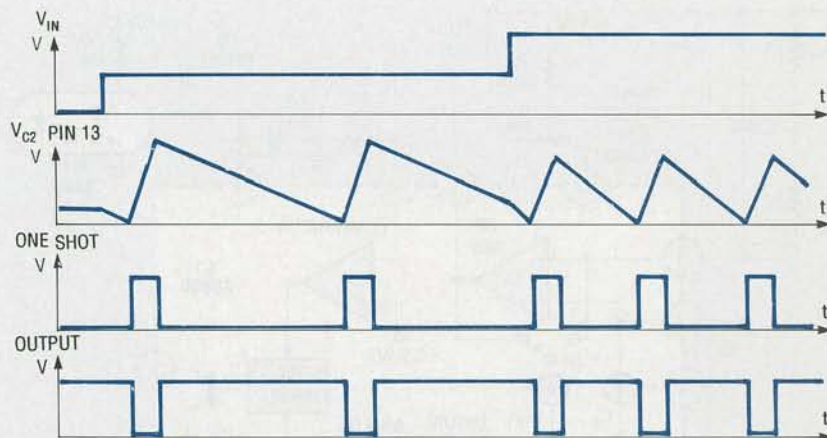


FIG. 2—V/F CONVERTER WAVEFORMS for Fig. 1.

Resistor R1 is used to trim the tolerances of C1 and IC1. A low-temperature type capacitor should be used for C1, an NPO ceramic is best for this type of application.

Notice that C2's value does not affect the frequency. The only requirement is that it be large enough to keep the voltage swing at pin 13 within the limits of the input amplifier. The manufacturer's recommendation is (100/ f_{MAX}) microfarads below 100 kHz, or 0.001 μF above 100 kHz. Low-leakage is important, therefore, a mylar capacitor is recommended. Waveforms of the Fig. 1 circuit are shown in Fig. 2.

Before moving on, let's briefly mention two upgraded versions of this IC from Burr-Brown: VFC62 and VFC320. VFC62 is pin-compatible with VFC32, but it adds an active-pullup transistor, as shown in Fig. 1. It also operates up to 1 MHz, has better temperature stability, and slightly better linearity. To use the active pullup, pin 6 must be tied to the +15-volt supply. In a VFC32 circuit (pin 6 unused) the external pullup resistor, R5, will still work. The MVFC320 has improved specifications, and is similar to the VFC62 but has pinouts and output circuitry identical to the VFC32.

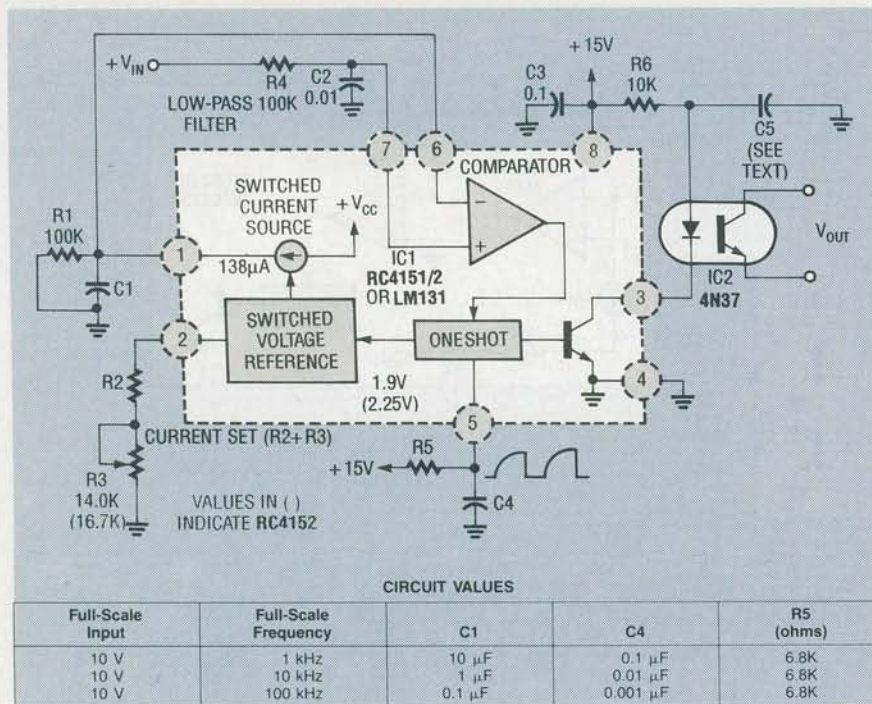


FIG. 3—A LOW-COST V/F CONVERTER WITH OPTOCOUPLER output. The output is fed to an optocoupler for input/output isolation. The circuit can be used to pulse an LED input into a fiberoptic cable.

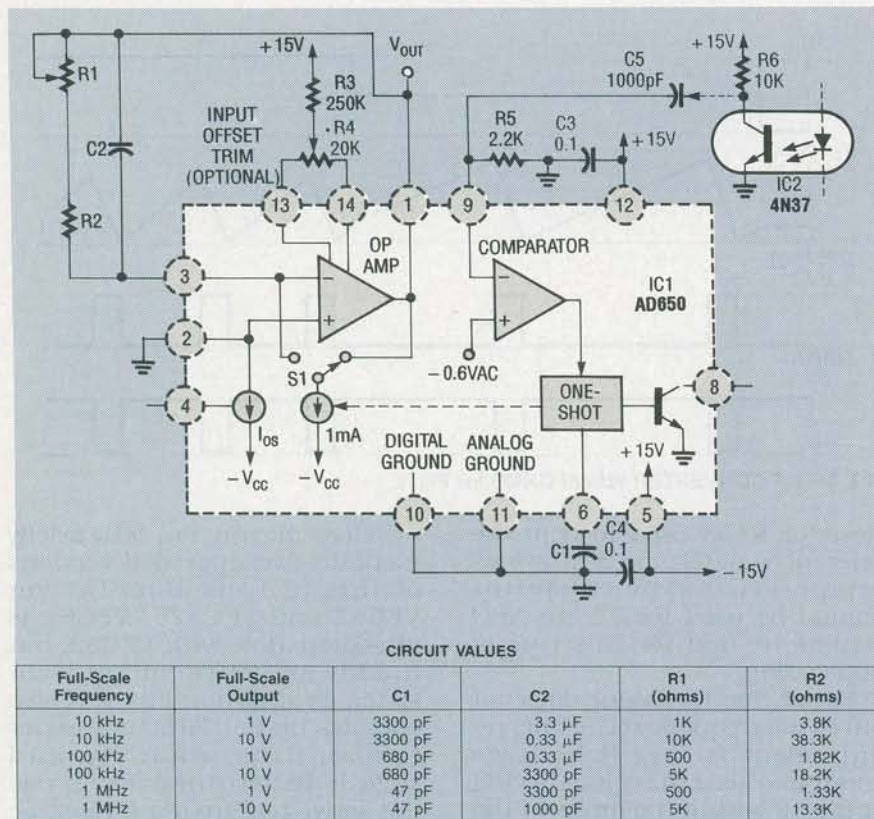


FIG. 4—A V/F CONVERTER CAN BE MADE INTO AN F/V converter using an AD650 IC.

A low-cost optocoupled output
Raytheon introduced the first V/F converter IC, the RC4151, now also second-sourced by Exar as the XR4151. Also available are

the RC4152 with better specifications and National Semiconductor's pin-compatible LM131. The LM131 is similar to the VFC32 except that it lacks the input op-

amp. By using an external op-amp it can be applied similarly to the VFC32. In fact, in low-level applications it may be advantageous to choose a high-grade external amplifier.

Figure 3 shows the RC4151's basic operation. Typical circuit values are also shown in this figure. The current source is pulsed by the one-shot, which applies a fixed charge ($Q = I \times T$) on C1. Between pulses, C1 discharges through R1. Each time C1's voltage drops below V_{IN} , the one-shot is retrigged. As V_{IN} goes higher, to so does the retrigger point and, therefore, the voltage on C1. As C1's voltage doubles so does the rate of discharge through R1. It takes twice the pulse rate to keep C1 charged. The output pulse rate, therefore, increases in proportion to V_{IN} .

In this application, the output is fed to an optocoupler for input/output isolation. The same circuit can be used to pulse an LED input to a fiberoptic cable. When the one-shot fires, pin 3 is pulled low. Capacitor C5 charges between pulses, providing a short high-current pulse to the LED. (The same effect could be obtained by omitting C5 and making R6 smaller, but the power supply pulses would be higher.)

This circuit is less linear than those using op-amp integrators and is recommended for limited input ranges which do not go to zero. For an input range of 0.01–10 V, and a full-scale output of 10 kHz, linearity will be better than 1%.

F/V conversion

Figure 4 shows how a V/F converter IC may be used to create a frequency-to-voltage (F/V) converter. The high-performance AD650, available from Analog Devices and Maxim, is similar to the VFC32 but it offers guaranteed linearity of 0.1% up to 1 MHz. Typical linearity is 0.002% to 10 kHz, 0.005% to 100 kHz and 0.07% to 1 MHz. An added offset current source simplifies the design of offset or bipolar input ranges, but we will not make use of that in our application.

In Fig. 4, the AC or pulsed input is applied to the comparator. Each time it drops below -0.6 volts, the one-shot is triggered, switching S1 to the op-amp's in-

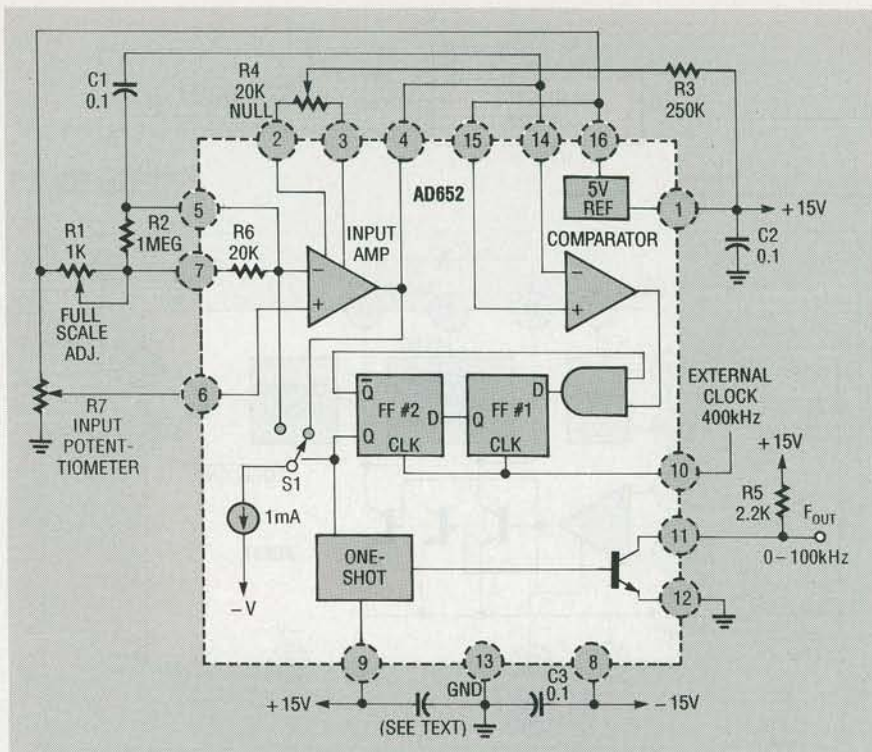


FIG. 5—AN A/D POTENTIOMETER INPUT APPLICATION. This circuit shows an AD652 IC used to convert from potentiometer position to frequency

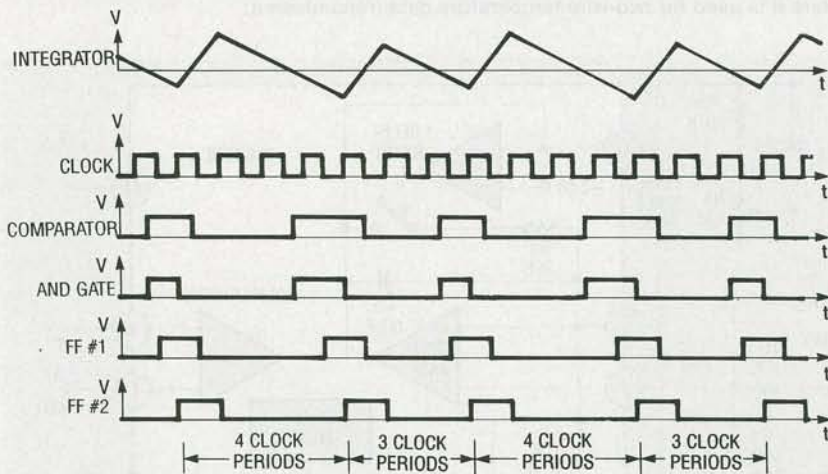


FIG. 6—TYPICAL WAVEFORMS for Fig. 5.

put and drawing a timed current pulse. Between pulses, the 1-mA current is connected to the op-amp output. (That has no effect on the overall circuit operation since the op-amp's output simply supplies an extra milliamp to the current source.)

The average current represented by the on-off pulses is

$$1 \text{ mA} \times T_1/T, \text{ or} \\ 1 \text{ mA} \times T_1 \times f_{IN}$$

where T_1 is the one-shot's pulse width, and T is the input period ($f_{IN} = 1/T$). The op-amp is connected as a low-pass filter. Each current pulse raises C_2 's output; capacitor C_2 discharges through R_1 and R_2 between pulses. The

DC output is

$$V_{OUT} = I_{AVG} \times (R_1 + R_2), \text{ or} \\ V_{OUT} = 1 \text{ mA} \times (R_1 + R_2) \times T_1 \times f_{IN}.$$

The output is proportional to frequency, with the conversion factor determined by the value of $R_1 + R_2$ and by T_1 which, in turn, is determined by C_1 . Capacitor C_2 does not affect the conversion, it only filters the ripple.

T_1 can be found by

$$T_1 \text{ (ms)} = 6.8 \times C_1 \text{ (\mu F)} + 0.0003.$$

The output becomes

$$V_{OUT} = [R_1 + R_2 \text{ (Kohms)} \times 6.8C_1 \text{ (\mu F)}] + \\ [0.0003 \times f_{IN} \text{ (kHz)}].$$

Typical component values are shown in Fig. 4.

The values of C_5 and R_5 are for TTL or other fast-risetime in-

puts, such as the optional optocoupler shown. Sine waves or other slow waveforms may need to be "squared up" by a comparator or amplifier before being fed to this circuit. The input pulse is differentiated by the high-pass R-C filter so that it does not spend much time below -0.6 volts. If pin 9 were below -0.6 volts at the end of T_1 , the one-shot would retrigger, producing an incorrect output.

Synchronized V/F conversion

The circuits we have seen so far depend on a one-shot circuit and capacitor for the charge-balance pulse width. If the one-shot period changes with temperature, time, or line voltage, so will the conversion factor.

Let's now look at an IC that's synchronized to an external clock. If the clock is crystal-controlled, the circuit's drift will be determined by the input resistor and the 1-mA source. Figure 5 shows Analog Devices' AD652 in a potentiometer input application. Figure 6 shows the waveforms. (Burr-Brown makes a similar IC, the VFC-100, lacking only in the optional offset trim capability.) The best grade of AD652 provides guaranteed temperature stability of 25 ppm/°C at 1 MHz, 50 ppm/°C at 4 MHz, with linearity of 0.02% or better at 4 MHz.

The IC's circuitry looks much like the others we've seen, but with added logic circuitry between the comparator and the one-shot. If the comparator's output goes high and flip-flop #2's Q output is high, the AND gate's output also goes high. Flip-flop #1's output will be clocked high by the next negative clock transition.

On the following positive clock transition, flip-flop #1's output will be clocked through flip-flop #2, bringing both Q and the AND gate output low. The following two clock transitions transfer this low data first to flip-flop #1's output, then to flip-flop #2. The end result is that each time the comparator goes low, a one-clock-period pulse will be produced. That pulse determines the amount of time that the 1-mA source is connected to the input.

The one-shot is used only to control the length of the output transistor's pulse. It has nothing

to do with the conversion factor. Bringing pin 9 high disables the one-shot, in which case the output pulse width will equal the clock's period.

The input from potentiometer R7 is useful for many types of measurements. In addition to rotary or linear position, the potentiometer can be attached to mechanisms such as floats, pressure, or weight gauges.

The inverting input and R7 are both connected to the IC's built-in 5-volt reference. As the wiper goes clockwise, the input amplifier integrates the difference between the 5-volt reference and the wiper voltage, so decreasing the wiper voltage increases the output frequency.

The AD652 is scaled so that, at 10 volts, the output is half the clock frequency. In fact, both the conversion rate and the 5-volt reference are laser-trimmed to better than 1%, so that it can be used without trimmer potentiometers if ultimate accuracy is not needed. In that circuit, R4 (null) and R1 (full scale) allow fine calibration to better than 0.1%. Since the input is 0–5 volts, full-scale output will be 1/4 the clock frequency.

Synchronized conversion is great for long-count accuracy but poor for pulse-to-pulse stability. That's because the 1-mA "reset" is not synchronized with the integrator's zero crossing, but is tied to the clock. Notice in Fig. 6 the first reset begins 3/4 clock period after the integrator crosses zero and lasts one clock cycle. On the next cycle, because of the relative timing of the zero crossing, reset does not begin until 1-1/4 periods later. That means the integrator has time to go further negative before reset begins and it will be less positive after reset.

The third discharge gets to zero faster. In this example it also requires only 3/4 period before reset begins. Overall, the output period jitters back and forth between three and four clock pulses. If you count the average period or frequency over 1000 pulses, for example, you will get a very accurate result. But if you try to measure individual pulses, the results will be meaningless. Use synchronized conversion for high-resolution (long-term counting) A/D conversion, or

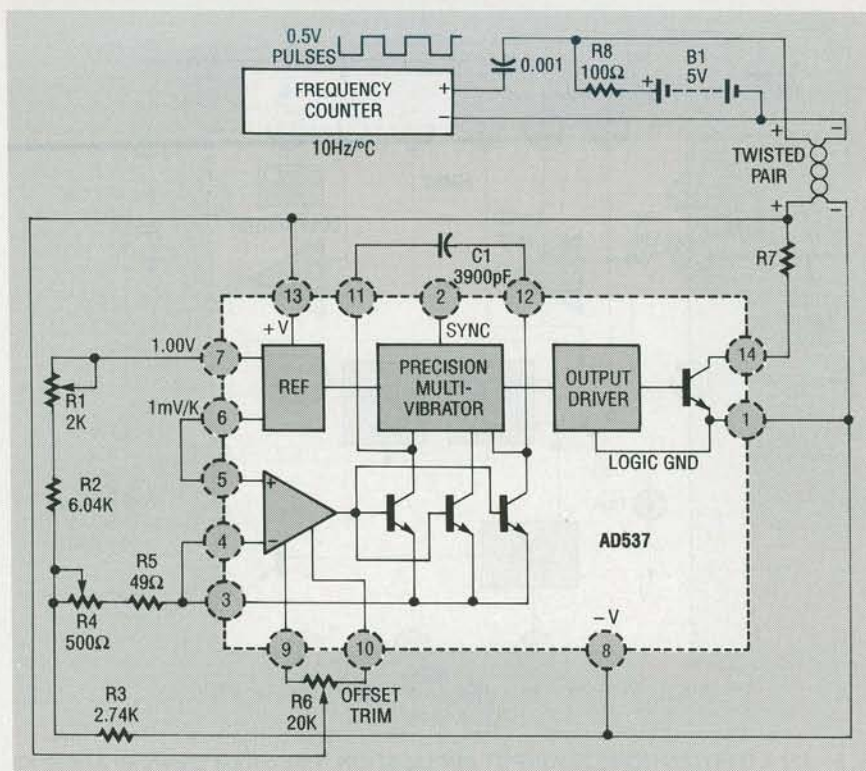


FIG. 7—A TEMPERATURE SENSOR AND V/F CONVERTER can be made from an AD537 IC. Here it is used for two-wire temperature data transmission.

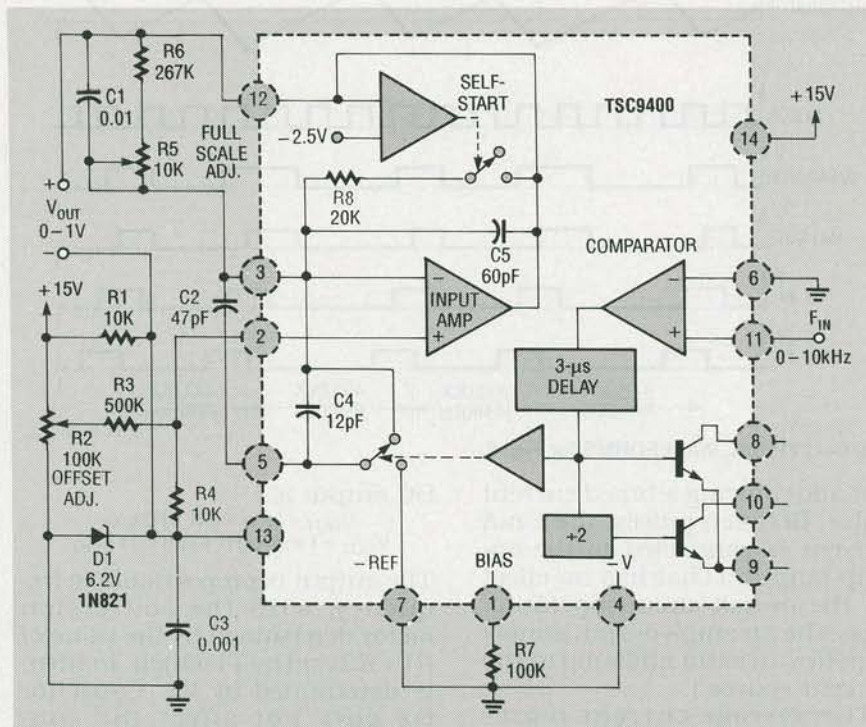


FIG. 8—A TSC9400 USED IN A SINGLE-SUPPLY F/V converter. A Zener diode offsets the IC's ground terminal. This circuit converts 0–10 kHz to 0–1 V.

data telemetry, but not for applications which count the time between individual pulses.

Multivibrator application

We'll now examine Analog Devices' AD537, which operates on

a different principle. Figure 7 shows a unique two-wire temperature transmission system.

Let's look at how conversion is accomplished first, then we'll examine the temperature input and two-wire output. Conversion

is provided by a precision multi-vibrator. The input amplifier controls three transistors in a "current-mirror" circuit. Two of the transistors provide charging current to the multivibrator's capacitor while the third controls bias levels in its circuitry. The result is linear current-to-frequency conversion from 0.1 μ A to 2 mA. Best performance is achieved when the circuit is scaled for 1 mA full scale. The IC is specified to 100 kHz with worst-case nonlinearity of 0.25% or 0.1%, depending on the grade ordered.

Because the circuit is a multi-vibrator instead of a charge-discharge integrator, its output is automatically a square wave (50% duty cycle). At 1 mA the output is $f = 0.1/C$, where f is in kilohertz and C is in microfarads.

The AD537 provides two reference outputs; one fixed at 1 volt and a second which varies with temperature (1 mV per K, where $K = \text{Kelvins}$, which is equal to $^{\circ}\text{C} + 273.15$). The circuit in Fig. 7 makes use of both references to scale the output to 10 Hz per $^{\circ}\text{C}$. At 0 $^{\circ}\text{C}$, the divided-down voltage from the 1-volt reference will balance the 273-mV temperature signal. The current in R4 and R5 will be zero, resulting in zero output. As temperature rises, the current increases about 0.4 mA per $^{\circ}\text{C}$, producing a frequency output of 10 Hz per $^{\circ}\text{C}$.

The "two-wire" output indicates that only two wires are needed to carry both the power and the output. Each output pulse modulates the supply current by drawing 5 mA through R7. The pulses are received at the other end of the twisted pair as 0.5 volts pulses across R8. The pulses are coupled through C2 to a frequency counter, or perhaps an F/V converter similar to the circuit in Fig. 4. The two-wire principle can be used with any V/F converter, not just the AD537.

Now we'll show you how to calibrate the circuit. Measure the room temperature (T) and the voltage at pin 6 (V_6). The offset voltage (V_{OS}) can be computed by

$$V_{OS} = V_6 \times \frac{273.15}{T(^{\circ}\text{C}) + 273.15}$$

Temporarily disconnect R5 and adjust R1 until the voltage across R3 equals V_{OS} . Reconnect R5 and adjust R4 for the correct output

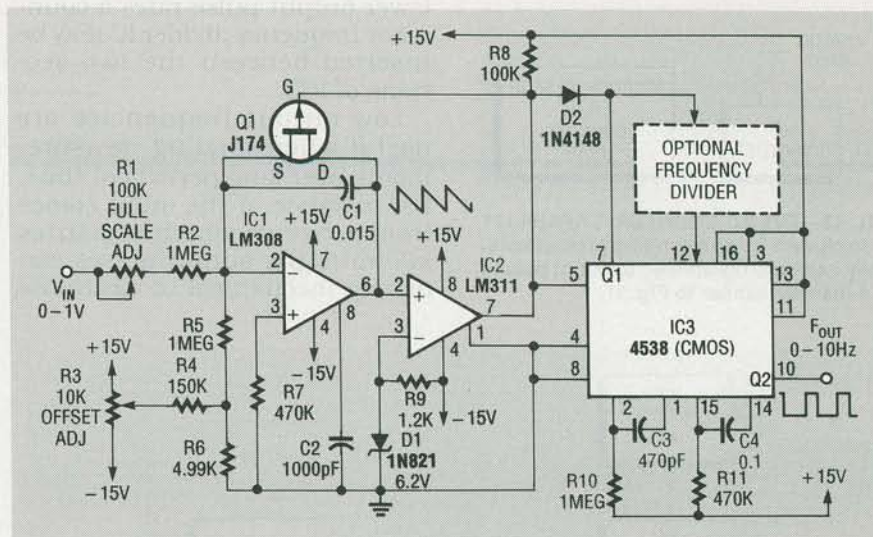


FIG. 9—A SIMPLE, LOW-FREQUENCY V/F CONVERTER built from standard IC's.



FIG. 10—ANALOG DATA CAN BE OPTICALLY COUPLED using two IC's, one as a V/F converter, the other as an F/V converter.

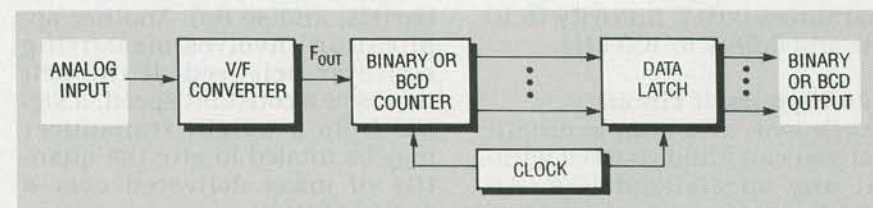


FIG. 11—A HIGH-RESOLUTION A/D CONVERTER can be made from a V/F converter and a counter.

frequency at 10 Hz/ $^{\circ}\text{C}$ (for example, 250 Hz at 25 $^{\circ}\text{C}$).

Charge-balance

Teledyne's TSC9400 family of IC's illustrates a different type of charge-balance circuit using capacitance discharge. Instead of gating a current for a fixed period of time, reset is accomplished by charging a small capacitance via the input amplifier's summing junction.

Figure 8 shows the TSC9402 in a single-supply F/V converter. Other than its reset, operation is similar to the F/V converter of Fig. 4. We will not analyze Fig. 8 in detail but will just point out the differences.

The SPDT switch inside the IC normally shorts C2 and the internal 12 pF capacitance. When the comparator trips, the switch connects C2 to $-\text{REF}$ for at least 3 μ s. Capacitor C2 charges to the

reference voltage of -6.2 V, causing a net charge flow of $Q = C \times V$. That charge is transferred to C1 (plus its internal 60 pF shunt), raising the output. Between pulses the output decays through R5. The faster the pulses, the higher the average output. As with Fig. 4, C1 does not affect the output scaling but simply determines the amount of filtering.

The TSC9402's self-start circuit insures proper startup. Depending on how power comes up it's possible that C1 may begin with a negative charge. If the IC is used in a V/F converter similar to the circuit in Fig. 1, the comparator will already have switched and no further reset pulse will occur. If C1's output ramps below -2.5 V, the self-start comparator momentarily closes the switch, discharging C1 and resetting the output to zero.

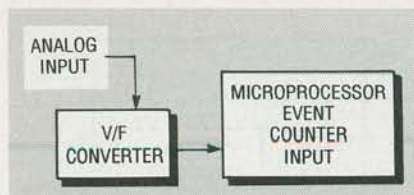


FIG. 12—EVENT COUNTER CAPABILITY is included in some microprocessors. They can be programmed to count pulses in a manner similar to Fig. 11.

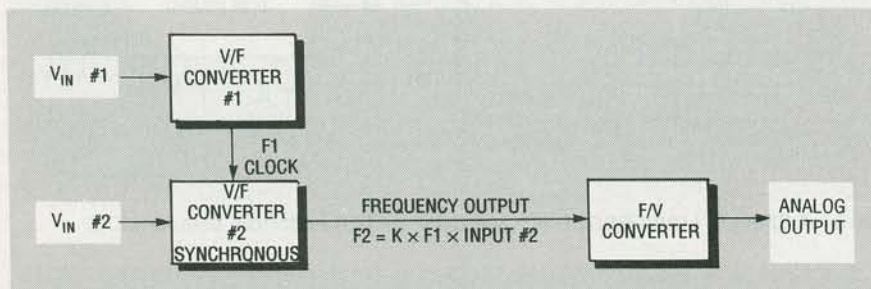


FIG. 13—A SYNCHRONOUS V/F CONVERTER produces an output proportional to both its input and its clock frequency. Shown here is the heart of an analog multiplier.

The lowest-cost version TSC9402 guarantees 0.25% linearity to 10 kHz (0.05% typical) and 0.5% to 100 kHz (0.25% typical). The best grade, TSC9401, guarantees 0.01% linearity to 10 kHz and 0.08% to 100 kHz.

A do-it-yourself circuit

Let's look at a simple circuit that you can build yourself without any specialized IC's. Although lower in performance than the IC's we've seen, it works well in low-speed applications.

The circuit of Fig. 9 charges C1 to a fixed reference level, instantly discharges it and then repeats the cycle. Op-amp IC1 is configured as an integrator. With a positive input, C1 charges until IC1's output reaches -6.2 V, at which point comparator IC2's output goes low. That turns on Q1, a P-channel JFET, and triggers the input half of IC3, a dual monostable multivibrator.

Pin 7 of IC3 is pulled low for $470 \mu\text{s}$, keeping Q1 on long enough to insure that C1 is completely discharged. Once Q1 turns off, the cycle starts over. The output section of IC3 produces a longer output pulse, 47 ms in this circuit.

Component values for R1, R2, and C1 are chosen so that, at 1 V input, it takes 100 ms for C1 to charge to -6.2 V. The cycle repeats at a rate proportional to the input, 10 Hz at full scale. For

lower output pulse rates a counter or frequency divider IC may be inserted between the two sections of IC3.

Low output frequencies are useful when totaling measurements over long periods of time. For instance, if the input comes from a circuit which measures kilowatts the output pulses can drive a mechanical or electronic

counter to indicate kilowatt-hours. Or, the input could come from a flowrate meter, in which case the totaled count would represent total flow (gallons, liters, barrels, and so on). Another application involves measuring conveyor belt feed. If the belt moves at a constant speed, a signal from a weight transducer may be totaled to give the quantity of mass delivered over a period of time.

We should point out that C1 does not integrate while Q1 is on. That represents an error in the output period, and must be kept short. Because of that, this type of circuit is not suitable for high output frequencies.

Other applications

We'll finish this article with four application ideas. In Fig. 10 a V/F and F/V converter are optically coupled to provide analog signal isolation. That system isolates ground loops and provides noise immunity in industrial measurement applications. Fiberoptic communication also provides inherently safe data transmission through areas containing explosive gases.

In patient monitoring systems, optical isolation eliminates the shock hazard, especially if the front end is battery-powered. Operation up to 100 kHz and beyond allows transient signals such as electrocardiograms to be isolated

as well as steady signals such as temperature.

Figure 11 shows how a V/F converter can be used to create a high-resolution A/D converter. Its output pulses are counted for a period of time determined by the clock. The longer the count, the higher the resolution.

The tradeoff, however, is conversion speed. Successive-approximation and "flash" converters (see **Radio Electronics** February 1987) require extremely precise (and expensive) components as resolution increases, but they can convert in microseconds. Counter-based converters are great for high-resolution conversion of DC data, but you wouldn't use one to digitize audio or video!

In some systems the counter and latch can be replaced by microprocessor software. Some microprocessors include an event counter, making the electrical interconnection very simple (Fig. 12). Others may require the use of an interrupt port and carefully thought out software. Keep the microprocessor's clock speed and instruction set in mind when setting the V/F converter's output frequency range. Maximum pulse rates of 100 kHz are probably safe with most systems.

Once again, the tradeoff is speed. Counting ties up the microprocessor's central processing unit (CPU), limiting its availability for other functions. Such systems are best for simple, low-speed applications where resolution and low cost are important parameters.

Finally, Fig. 13 uses two V/F converters to perform analog multiplication. Converter number 1 produces an output, F1, proportional to input number 1. A synchronous converter is used to convert input number 2. Since the synchronous converter's full-scale output is set by its clock (F1), frequency F2 is proportional to input number 2 multiplied by F1. If a DC output is required, an F/V converter performs the conversion.

One of the things that makes electronics fun is the ability to use basic circuits to solve unique problems. Now that we've gotten you started, let's see how many V/F converter applications you can think up!

R-E