HAVE YOU CONSIDERED V/f CONVERTERS?

They Offer High Resolution at Low Cost
Use Them for Digitizing, Isolating, Integrating, and Much More

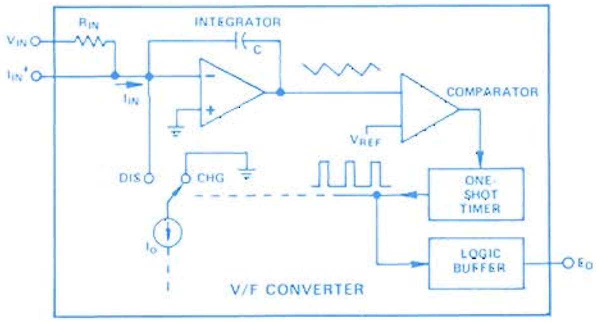
by Fred Pouliot

Voltage-to-frequency converters are now available as small, economical modules characterized by high resolution, low nonlinearity, and excellent temperature-stability.* In many data-handling applications, they have proved to be an excellent alternative to both analog and digital techniques.

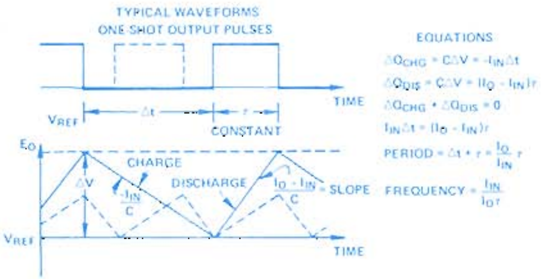
Voltage-to-frequency converters, of the kind to be discussed, are signal-processing devices that accept an analog input and convert it to a train of pulses having fixed width, fixed height, and a rate that is directly proportional to the input voltage or current. For an arbitrary voltage input, $0 \leqslant V_{IN} \leqslant V_{MAX}$, and a corresponding full-scale frequency, f_{MAX}, the frequency of the output pulse train, f, is

$$f = f_{MAX} \frac{V_{IN}}{V_{MAX}} \qquad (1)$$

V_{MAX} is usually 10V, often with 50% overrange capability. The relationship between analog input and the output frequency is inherently monotonic, making it possible to construct V/f-based analog-to-digital converters of extremely high resolution, exhibiting no missing codes, even in the presence of widely-varying ambient temperature. Noise rejection is inherently quite high, first because of the internal integrator, and second – in cases where the output is counted – because of the integrating effect of the count.



(a) Block Diagram



(b) Waveforms and Equation. Dashed line shows waveforms for doubled input (near I_{MAX}, f_{MAX})

Figure 1. A Charge-Balance V/F Converter

HOW IT WORKS

Figure 1a is a block diagram of a V/f converter of the *charge-balance* type, a modern form of conversion that results in high linearity and stable performance. The input current – whether furnished directly to the summing point or determined by the input voltage and R_{IN} – flows at all times through the feedback capacitor, C, tending to charge the capacitor at the rate $-I_{IN}/C$, proportional to the input. During the *charging* portion of the cycle, a precisely-determined current, I_O, somewhat larger than I_{MAX}, and opposite in polarity to I_{IN}, is steered to ground.

When the output of the integrator reaches the internal reference voltage, V_{REF}, the crossing trips a comparator, which initiates a pulse of fixed amplitude and precise duration, from a one-shot timer. This pulse is buffered and transmitted to the output. The timer also operates a switch that steers the current I_O to the summing-point of the integrator, discharging it linearly for the pulse duration, τ, at a rate $(I_O - I_{IN})/C$.

At the conclusion of interval τ, I_O is switched to ground again, and C is once more charged by I_{IN}.

If I_{IN} is constant, the amount of charge $(I_{IN}\Delta t)$ acquired during charging is equal to the amount discharged $(I_O - I_{IN})\tau$, and the equations in Figure 1b show that the pulse frequency is

$$f = \frac{I_{IN}}{I_O\tau} \qquad (2)$$

When the input level, I_{IN}, changes, the integrator immediately changes to the correct rate; the period starting with the next discharge cycle will be accurately determined. For typical commercially-available devices, with f_{MAX} = 10kHz, τ is somewhat less than 100μs; I_{MAX} is usually about 0.5mA, equivalent to 10V in 20kΩ. When used with a counter, the resolution depends on the counting period; a device with a maximum frequency of 10^5Hz will have ten times the resolution of a 10^4Hz device, or 10X faster response at the same resolution.

LONG-TERM INTEGRATION WITH V/f's

Voltage-to-frequency converters are rapidly replacing purely-analog circuitry in applications requiring long-term integration. Conventional integrators use a high-quality capacitor and an amplifier selected for low drift and negligible bias current. With the use of high-quality components and considerable care, integration times of several minutes, or even an hour, can be realized with accuracy to within 0.1%. Eventually, errors due to dielectric absorption, leakage, finite open-loop gain, bias current, and drift limit the accuracy; and finally, over a long-enough period, the amplifier simply runs out of output range and drifts into limits. For integration periods of one hour with accuracy to within 0.1%, the cost of the capacitor becomes prohibitive, since a leakage rating of 3.6 x 10^6 megohm-microfarads is required.

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*For data on V/f converters from Analog Devices, use the reply card.

The V/f converter, when combined with a low-cost counter, as shown in Figure 2, offers both improved accuracy and virtually unlimited integration time, with an overall reduction in system cost. To accomplish integration with a V/f converter, one needs only to apply an input voltage, then count the output pulses. The accumulated count is proportional to the integral of V_{IN} over any arbitrarily-chosen period, and is limited only by counter capacity.

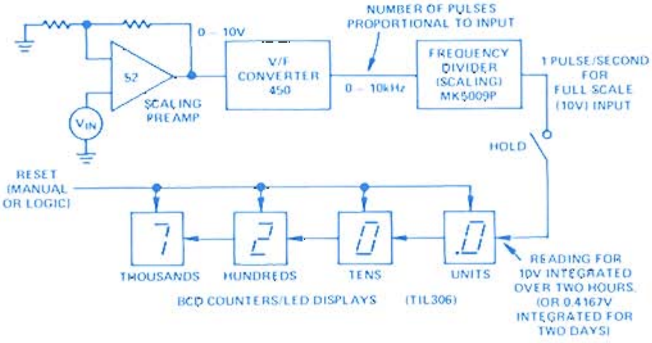

Figure 2. V/F converter as a long-term integrator with arbitrary display calibration. Frequency division ratio can otherwise be chosen to provide direct readout in any desired units.

The system shown in Figure 2 displays, in numeric form, the integral, over an arbitrary time interval, of an analog voltage. It is based on a 10kHz VFC, Model 450, from Analog Devices. The input voltage, V_{IN}, is amplified by a high-accuracy, low-noise op amp (Model 52), which provides 10V full scale to the converter input. The 10kHz-full-scale output pulse train of the VFC is applied to the input of an MOS counter-time-base circuit, MK5009P, used as a frequency divider with a division ratio of 10,000:1. The output of the divider produces one pulse/second for full-scale input. These pulses increment decade counters-and-displays, TIL306. With 10V constant input, the displayed digits are a direct representation of the integration time in seconds and may be used for calibration. The count continues until a manual or logic command places the counter in *hold* by disconnecting its input, or resets the count.

With input of +10V, 9999 seconds are required to produce a displayed reading of 9999. With less input voltage, proportionally more time will be required to fill the counter, or, if the counter is allowed to count for the same time period, it will display a proportionally smaller value before being reset.

V/f converters as long-term integrators of analog signals are practical and useful, but there are some limitations. The effect of drift on the accuracy of integration of *unipolar* signals is simply related to the ratio of the input offset to full-scale input. For example, if the offset is 10µV, and full-scale input is 10V, drift error will always be 1ppm of full-scale; if the *average* input signal is 10mV, the drift error will be only 0.1%, no matter how long the integration continues, as long as sufficient counter capacity has been provided. If the converter is used as an integrator in a control loop, with input variations of ±5V about a +5V set point, input offsets will result in small "position" errors of the fed back signal.

A/D CONVERSION WITH VFC's (Figure 3)

A VFC continuously tracks the input signal without the need for clock pulses, convert-command signals, or any form of external control logic. The direct count of its output pulses, over a time period (vs. measurement of its frequency by discrimination techniques, phase-locked loops, etc.) produces a binary or BCD (binary-coded decimal) digital number, which represents the average value of the input during the counting period. The VFC pulses require but a single wire-pair for transmission, unlike parallel converters, which, for n bits, require n + 1 wires, or serial converters, which require some form of synchronization. Of course, the V/f converter is much slower; even a 100kHz converter still requires 4096 counts (41ms) for 12-bit resolution. Though the VFC continuously tracks the input, it differs substantially from the tracking up-down counter-comparator type of converter, in requiring only a single wire-pair for communication. Furthermore, it is all but unaffected by spike-type errors, since their effect, at worst, is generally limited to one count.

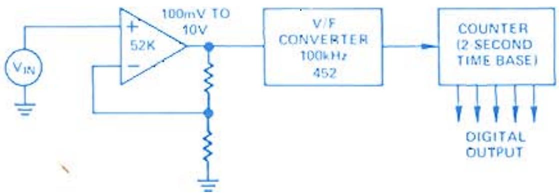

Figure 3. V/F converter used as a nearly 18-bit binary (5½BCD) A/D converter. Resolution is 1 pulse in 200,000, or 0.05% of smallest input signal (or 5ppm of full scale).

Readily-Adjustable Scaling for Faster Conversion Rates

When using V/f converters in analog-to-digital conversion, in applications where system resolution requirements permit, it is often advantageous to offset and rescale the input for the sake of faster conversion rates. Such may be the case when data is to be transmitted or recorded. To accomplish the offsetting, a current is applied to the appropriate V/f input. For Model 452, a 100kHz VFC, full-scale is normally obtained with a 10V input. If an offset current of 0.05mA (equivalent to 1V in, or 10% of normal full scale) is applied to the current input, the new full scale range will be from 110kHz for 10V input to 10kHz for 0V input instead of 100kHz to 0 (most VFC's have sufficient overrange tolerance to handle the increased full-scale output accurately).

The improvement in conversion speed is evident. Without the offset, minimum conversion time is 10ms to guarantee the occurrence of a single pulse, for a 10mV input; with the offset, one output pulse will occur every 100µs for zero input, and every 99µs for 10mV (10.1kHz).

Bipolar signals with 20V peak-to-peak range can be converted by adding an offset equal to one-half the full-scale range. When counted by a binary counter, the digital output will be *offset-binary*-coded (identical to 2's complement with the most-significant bit complemented). For model 454, a 0.33mA offset would allow a 0 to 10kHz output to correspond to a ±10V input range.

The easy adjustability of output count, by using frequency division or an arbitrary time base, allows the digital output number to directly reflect engineering units, representing flow rate, force, pressure, or other transducer inputs.

EXCELLENT RESOLUTION AT LOW COST

An inexpensive 10kHz VFC offers resolution of 1 part in 10^4 when integrating over a 1-second period. This exceeds the resolution available in a 13-bit A/D converter (1 part in 8192). Nonlinearity is typically 0.005% (model 450J), which is comparable to that of a 13-bit ADC. Unlike successive-approximation converters, differential linearity to within 0.01LSB is readily obtained at this resolution and is maintained despite wide temperature excursions. Therefore, a low-cost 10kHz V/f converter compares most favorably in linearity and resolution to that of a 13-bit ADC. The comparison becomes considerably more dramatic when a 100kHz converter (model 452) is used over a time base greater than 1 second.

Figure 3 shows how resolution of 0.05% of the *smallest* input signal can be accomplished for a signal spanning two decades. Expressed differently, the resolution here is an amazing 0.0005% (5ppm) of full scale! At the lowest input level, 100mV, 0.05% represents 50μV. The stability of the VFC is consistent with this requirement; the number of output pulses differs by no more than one count when counted during successive 2-second intervals.

HIGH NOISE REJECTION

Unlike successive-approximation or tracking-type A/D's, which can give completely erroneous output codes for large spike inputs, the VFC inherently has high noise rejection.

The output pulse train is counted over relatively-long periods. Noise that appears as a repetitive waveform is averaged out completely over the measuring interval, except for fractional cycles. For example, if the interfering signal is a 60Hz sinewave, the worst-case contribution to the output, which occurs when the measuring interval is one-half cycle too short or too long, is 1/120 of the ½-cycle average, when the measuring interval is in the vicinity of 1 second.

If the count time is an integral multiple of the line period, rejection is theoretically infinite – and better than 80dB in practice. Since the counting period for V/f converters is determined externally, it can be set to provide maximum rejection for the most-troublesome noise frequencies. For example, multiples of a counting period of 0.1Hz will reject line frequencies of 50 or 60Hz. And if the fundamental has an integral number of cycles during the counting period, and is therefore strongly rejected, the harmonics will also be rejected.

LIMITATIONS OF V/f CONVERTERS

In the face of their many advantages, there are only two significant drawbacks to their increased usage in data transmission:

1. They are slow in converting small signals.
2. They require a device, such as a counter, to interpret the output digitally, or an integrator (or f/V converter) for analog readout (where the purpose of conversion was to transmit the analog signals through a noisy environment).

The speed of conversion of a VFC is determined by the full-scale count and the amplitude of the signal being measured:

$$\text{Conversion time} = \frac{\text{Desired full-scale count}}{\text{Max. input to be measured}} \bullet \frac{\text{Unit's F.S. input}}{\text{Unit's max. frequency}}$$

For example, if a 10kHz VFC is to be used to measure inputs from 0 to 2.5V with resolution of 1 part in 1000, the conversion time is (1000/2.5) (10V/10kHz) = 0.4 seconds, minimum.

To improve the speed, here are two reasonable solutions: First, a higher-resolution converter, such as the 100kHz Model 452, could be used to decrease conversion time by a factor of ten. Second, using the current input, one could select an external scaling resistor such that the full-scale input current (normally 500μA) is realized when 2.5V are applied, which will further reduce conversion time by a factor of 4. In this example, a 5kΩ external resistor would be used.

For digital applications, the need for an external counter at the receiving end can be fulfilled at very low cost. There are several low-cost counters available in IC form. For example, the SN7490 BCD counter and the SN7493 binary counter are available in the U.S. at less than $1 each in reasonable quantity. For under $5, a counter with latches, drives, and displays is available, the TIL306.

MORE APPLICATIONS

The most popular applications for V/f converters are those shown in Figures 2 and 3, the long-term integrator and the quantizing element of an A/D converter. There are many other applications where the great flexibility and ease of use of the VFC make it an excellent solution for design problems. Here are a few examples.

Figure 4 shows a digital thermometer, based on the ~(-2mV/°C) change of forward drop of a diode with temperature. For good repeatability and accuracy, a silicon transistor, connected as a diode, is inserted into the probe, forming a reasonably small and convenient sensing element. Back at the instrumentation circuit, transistor Q_1 and its associated components form a constant-current source for the temperature-sensing element, Q_2. An offset current is applied to the VFC by R1, R2, R3 to fix one end of the range, so that direct readout in °C may be obtained. For a display of the temperature range from 0° to 100°C to three significant digits (i.e., with a resolution of 0.1°C), the number of pulses accumulated during the measurement interval must increase by one for a temperature increase of 0.1°C. Each degree C represents a change of 1mV at the converter input, for which the output will change by 10 counts per second. A 1s time base gives a sensitivity of 10 pulses/s/°C.

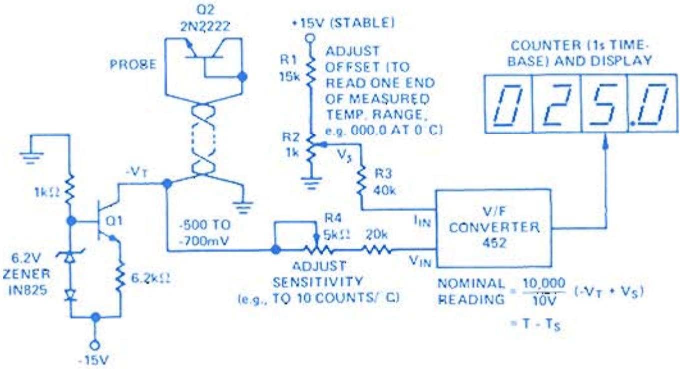

Figure 4. V/F converter as digital thermometer with 0.1°C resolution.

The instrument is calibrated by placing the sensor in ice water and adjusting the offset control until some reading greater than zero appears. The sensor is then placed in boiling water, and the span is adjusted until the reading is 100.0 (corrected for altitude) greater than for ice. The sensor is returned to the ice bath, and the span is readjusted if the difference is no longer "100.0"; this process is iterated until the difference is "100.0" exactly. If necessary, the offset should be readjusted during this process to maintain the minimum reading greater than zero. The last step, when the span is correct, is to adjust the offset for a reading of 00.0 when measuring the ice bath.

Figure 5 shows a means of using V/f converters to obtain accurate ratio measurements at high resolution. This scheme is an excellent alternative to analog dividers, such as the 434*. Accuracy to within 0.1% can be obtained for signals spanning a range greater than 1000:1.

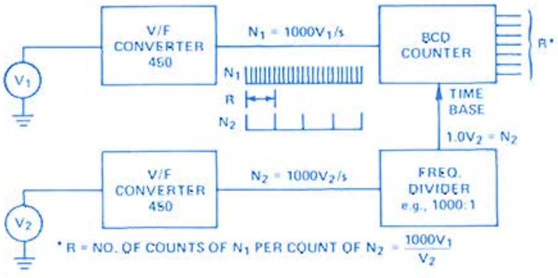

Figure 5. Wide-Range ratiometer (divider of voltages).

A pulse rate proportional to V_1 is applied to the counter's input. The counter is gated for intervals proportional to the period between pulses that occur at a rate proportional to V_2. The total count in each such period is proportional to the ratio of the number of pulses of V_1 to one pulse of V_2, hence the ratio of V_1 to V_2. The frequency-divider ratio is chosen for the required resolution for the specified dynamic range in the shortest time. For best accuracy, (or in low-level applications requiring common-mode rejection), instrumentation pre-amps (see page 23) may be used ahead of the VFC's.

A somewhat similar technique may be used to obtain the fastest possible response from a VFC with a given resolution, at any input level. Since all the information, for a given input voltage, is contained in the time for a single period, each period of the VFC is used to gate a train of pulses at an accurately-known high rate into a counter; at the beginning of the next period, the counted number is strobed into a set of latches, the counter is reset, and another cycle begins. Thus, the output of the latches continuously reads the period of the last pulse-pair, which is accurately proportional to $1/V_{IN}$.

If the reciprocal of V_{IN} is undesired, it can be easily dealt with in subsequent steps of digital computation, or by the use of a read-only memory programmed for reciprocation.

Figure 6 shows an optical-isolation circuit that uses V/f conversion, for accuracy to within 0.1% and a common-mode capability greater than 1500V. The output pulses from a VFC are transmitted via an optical coupler and are then counted on the low-voltage side of the circuit. CMV is limited only by the characteristics of the optical coupler and the power-supply used for the VFC.

As shown in Figure 6, the output is digital, as provided by a counter. If an analog output is needed, a frequency-to-voltage converter can be used at the output of the photocoupler to recreate the input analog signal with appropriate isolation.

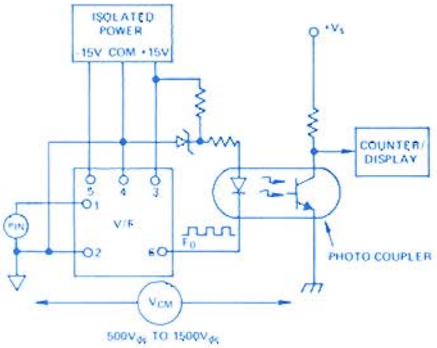

Figure 6. Optically-Isolated A-D conversion.

MORE APPLICATION IDEAS

The range of applications for VFC's is by no means limited to the few examples discussed here. V/f's are also useful wherever analog signals must be sent from one location to another that is separated by time, space, hazards, or a noisy environment. To cope with the last three, the input signal is converted to a train of pulses, transmitted (either directly over wires, or, by modulating a carrier, via radio) to the destination, then converted back to analog (or to digital) by a f/V converter (or a counter). For compression of signals having extremely-wide dynamic ranges, log-antilog converters, such as the 755*, may be used ahead of the VFC and following the FVC.

To deal with *time* separation, V/f's make excellent modulators for multi-channel recording (and subsequent playback) of analog data, even at dc, using low-cost audio tape recorders. A VFC is used for each data channel to be recorded. The current inputs are used to bias each converter to a different zero-signal frequency, and the inputs are scaled so that there is adequate channel separation between the output frequency bands of the several VFC's. Their individual outputs are passed through flip-flops to produce symmetrical square waves of ½ the original frequency. These are then low-pass filtered and summed (with a resistor network and/or op amp) to drive the tape-recorder input.

At the recorder output, band-pass filters are used to drive f/V converters (one filter and converter per-data-channel). The FVC outputs are offset by an amount necessary to compensate for the original offset applied to each VFC input. The output of each FVC is then a replica of the (narrow-band) analog signal applied to the input of the corresponding VFC.

Other uses of V/f conversion include feedback control, phase-locked loops (VCO's), alarm-setting devices, and special-purpose digital panel meters.

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*Use the reply card to request information on high-accuracy dividers, such as the one-quadrant 434 (YZ/X) and the two-quadrant 436 (10Z/X).

*Use the reply card to request data on Analog Devices log converters, such as the 755, the 752, or the 757 log-ratio module.