 By Joshua Israelsohn, Technical Editor

GAIN CONTROL

APPLICATIONS AS DISPARATE AS TEST EQUIPMENT, AUDIO, MEDICAL IMAGING, AND CELLULAR BASE-STATION RADIOS NEED TO MANAGE SIGNAL AMPLITUDES IN THE ANALOG DOMAIN.

Image courtesy Mike O'Leary

Despite the profusion of readily affordable digital-signal processors, available as free-standing components or as modules within more highly integrated devices, many applications still require analog-signal processing to provide the best combination of cost and performance. In such cases, VGAs (variable-gain amplifiers) allow products to adapt to changeable operating environments and excessive signal dynamics. Applications vary according to signal bandwidth; linearity, distortion, and noise requirements; and

several gain-control parameters, including control method, range, curve, granularity, and precision. Most need act, not on the instantaneous voltage a signal presents, but on its envelope—a measure of the signal amplitude over one or more cycles.

Uses abound for VGAs in the audio band. As is the case with many VGA applications, audio devices derive great benefit from circuits that provide an exponential response to a control signal—so-called linear-in-dB circuits that follow the exponential response of human loudness perception. The control parameter is often a quasistatic voltage, giving rise to a family of VGA topologies collectively known as VCAs (voltage-controlled amplifiers). Note that some of the literature concerns itself with implementations that result in 0-dB maximum gains and uses the same abbreviation to refer to such devices as voltage-controlled *attenuators*. Indeed, numerous examples exist of VCAs that include the 0-dB gain point within but at neither extreme of the control range.

LOGGING IN THE NORTH

An illustrative rudimentary example comprises series-connected log and antilog functions with an offsetting mechanism between (**Figure 1**). Because the logarithm's domain includes only values greater than zero, this simple unipolar model can process only the positive half of the input range. **Figure 1b** depicts the exponential gain control, which shows the input (red) and output (orange and yellow) signals corresponding to the cases in which the control input is fixed to ln(0.5)=−0.69315, and ln(2)=0.69315. The resulting outputs are, respectively, half and twice the size of the input in the regions where the log function is defined.

Offsetting the input by, say, half the full-scale input range effectively moves the input to within the logarithm's domain, but the dc term is subject to the same gain processing as the signal. The product of the offset and gain setting appears as a gain-dependent offset at the output if the gain setting is static. But many applications demand dynamic gain control, and you could describe the same multiplication as control-signal feedthrough to the output by way of an exponential.

Practical log-antilog circuits operating in the audio band can avoid the feedthrough issue by using two complementary signal paths to process zero-centered bipolar signals (**Figure 2**). Such circuits have a critical need to accurately match the gains through their two paths across the full control range to maintain low harmonic distortion. They also need to smoothly manage the signal transitions through the zero crossings.

THAT OLD BLACKMER MAGIC

A host of VCAs traces its lineage to the 1971 Blackmer gain cell and later enhancements (**references 1** and **2**). In its simplest realization, the Blackmer cell uses a core of four bipolar transistors (**Figure 3**). Positive input-signal excursions drive down A_1's output until Q_1's emitter voltage reaches the appropriate potential to force $I_C(Q1)=I_{IN}$. The transistor's V_{BE} follows as the log of its collector current:

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right),$$

where V_T is the thermal voltage, kT/q, and I_S is the reverse saturation current determined by factors related to the transistor's fabrication. Assuming for a moment that the control voltage, V_C, is zero, Q_2's V_{BE} equals Q_1's, and, if the devices are well-matched, the collector currents have no choice but to match as well. When V_C deviates from zero, its value equals the difference between the V_{BE}s of the two transistors as required by Kirchoff:

$$V_C = V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_{OUT} \bullet I_{S1}}{I_{IN} \bullet I_{S2}}\right).$$

Well-matched devices provide $I_{S1}=I_{S2}$, and solving for the gain, G, shows that

$$G = \frac{I_{OUT}}{I_{IN}} = e^{\left(\frac{V_C}{V_T}\right)}.$$

The output amplifier, A_2, converts the output current to a buffered output voltage.

The core pnps, Q_3 and Q_4, mirror the functions of the npns, Q_1 and Q_2, for negative input signals. The same V_C controls both pairs with appropriate base connections to achieve the requisite sign change. Adding a bias voltage, V_B, eases amplifier A_1's job and helps smooth the transition between the two halves of the circuit during the signal's zero crossing—somewhat reminiscent of a Class B amplifier's output stage: The bias voltage mitigates the need for A to slew through the crossover interval between the two paths' active regions. The comparison, however, is limited; in this case, the crossover interval is not formed of a pair of V_{BE}s.

Practical VCAs are somewhat more complex. They include circuit enhancements that allow for gain-symmetry tuning and that reduce the effects of parasitic terms—most prominently, parasitic resistances in the core transistors that reduce those devices' log conformance accuracy. An example of such a device is That Corp's 2181, which offers a 130-dB control range and a maximum 0.005% THD with a 1-kHz, 0-dBV input at 0-dB gain. Balanced control inputs allow a gain increase to follow from either a positive- or a negative-going control signal—a feature that can reduce application-circuit complexity. The 2181's maximum gain-control linearity error (exponential conformance error) is 2% over a 100-dB range. The VCA's output noise is −97 dBV over 20 Hz to 20 kHz at 0-dB gain and is 11 dB poorer at a 15-dB gain. Prices for the 2181 range from \$5.17 (1000) for the A grade to \$2.70 (1000) for the C grade in an SO-8 package and \$4.70 (1000) and \$2.45 (1000), respectively, in a SIP-8.

The 2181 attains its THD performance partly at the expense of application-circuit simplicity by requiring an external symmetry trim. A sibling part, the 2180, makes the opposite tradeoff: gaining the simplicity of a factory-trimmed part at the cost of THD performance. The 2180, like its brother, comes in three grades with maximum THD of 0.01% for the A grade with a 1-kHz, 0-dBV input at 0-dB gain. That Corp's 2181 is available in a SIP-8 for \$4.80 (1000) in the A grade and \$2.55 (1000) in the C grade.

AT A GLANCE

- ▷ VGAs are available with continuously variable gains or, in simpler topologies, with gain in discrete steps.
- ▷ Discrete steps are preferable in measurement circuits or in applications that can tolerate discontinuities in the gain-control curve and benefit from the simpler control topology.
- ▷ Consider your application's requirements for bandwidth, linearity, and noise before selecting a VGA topology.
- ▷ One often-overlooked benefit VGAs bring to high-frequency signal processing is that they allow you to control a signal's amplitude without routing the signal to a control surface.

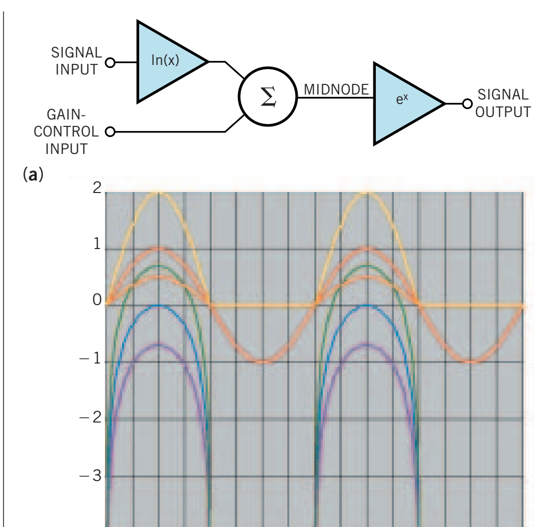


Figure 1 A simplified model (a) and simulation (b) of a log-antilog voltage-controlled amplifier can process only the positive half of the input waveform. The input waveform (red) results in the midnode waveform (blue) to which the circuit adds the dc gain-control input (green and violet). The output (yellow and orange) appears as the product of the input waveform and the log of the control input but only for values greater than zero.

EXERCISING SELF-CONTROL

With the capacity for accurate, exponential signal-amplitude control in hand, many useful functions stem from their methods of establishing the control signal. Several functions derive the control signal by detecting the program signal's peak or rms amplitude. Some, such as compressors, decompressors, and noise gates, use threshold circuits to change the VGA's behavior at a particular point in the detector's span. Others, such as the dbx companding noise-reduction system, operate primarily without a threshold.

You can implement dynamic-control functions either as feedforward circuits, in which the control signal is derived from the input, or as feedback circuits, in which the control signal is derived from the output (**Figure 4**). A circuit's compression ratio expresses the input signal amplitude increase (in decibels) required for an output amplitude increase. For example, in a circuit operating with a 2-to-1 compression ratio, a 2-dB increase in input amplitude results in a 1-dB increase in output amplitude. Feedforward designs can attain higher compression ratios with reasonable gains than can feedback designs. However, the detector in the feedforward circuit must accommodate the full input dynamic range, whereas the feedback topology reduces the detector's operating dynamic range by an amount equal to the compression ratio (**Reference 3**).

Combining the VGA's control-node sensitivity with the detector's sensitivity, you can calculate the control-voltage processor gain, G. The feedforward dynamic processor's compression ratio is

$$R = \frac{dB_{IN}}{dB_{OUT}} = \frac{1}{1-A}.$$

Compressors and program limiters have compression ratios greater than one, requiring 1>G>0. At G=0, the compression ratio is unity, and the VGA acts as a linear amplifier. Fractional compression ratios, available by setting G<0, form expanders. Finally, G>1 results in negative compression ratios, which are more useful for special effects than dynamic control.

The feedback control topology's compression ratio is

$$R = \frac{dB_{IN}}{dB_{OUT}} = A + 1.$$

In this arrangement, $G<0$ forms a compressor, $G>0$ forms an expander, and a singularity at $G=-1$ represents an unstable operating point. Though infinite compression is impossible in the feedback topology—large compression ratios require correspondingly large processor gains—ratios greater than 50 are rarely necessary in practice.

In applications that do not require reciprocal action, the choice between the feedforward and the feedback topologies is often one of engineering judgment. But reciprocal systems, such as companding noise-reduction systems that television-broadcast systems or wireless microphones use, enjoy a distinct advantage by using the feedback topology in the encoder and feedforward in the decoder: Both functions detect essentially the same signal (**Figure 5**).

Another common VCA audio application, the Dolby pro-logic decoder, uses threshold detection and VCAs to enhance the apparent channel separation and, conversely, reduce the crosstalk in surround-sound playback (**references 4** and **5**). In addition to decoding the matrix, a task within the reach of fixed-gain differential amplifiers under ideal conditions, the decoder addresses the limited front-rear separation that occurs when sound sources such as dialogue do not appear in the center of the front-stereo image.

FROM THIN AIR

As prolific as they have been, VGA architectures based on the Blackmer gain cell are essentially limited to audio frequencies (see **sidebar** "Long-lived and not forgotten"). Other approaches can provide significantly broader bandwidth, including Gilbert-cell multipliers, voltage-variable attenuators, and various topologies based on ladder networks.

VGAs operating at IF must meet stringent requirements for low noise, high linearity, and broad dynamic range. One architecture that can meet these demands at IF is the X-amp (exponential amplifier) from Analog Devices (**references 6** and **7**). A current example based on the X-amp topology, the AD8367, offers linear-in-dB gain control over a 45-dB range and maintains a gain-independent −3-dB bandwidth of 500 MHz.

The X-amp presents its input to a passive, broadband attenuator in the form of an R-2R ladder (**Figure 6**). A fixed-gain amplifier reads the ladder taps depending on which of the N stages is active. The control circuitry (not shown) needn't abruptly switch the current sources I_{E1} through I_{EN} but can smoothly interpolate between taps to realize a continuously variable exponential-gain response.

You can configure the AD8367 for symmetrical positive or negative 20-mV/dB scaling factors and operate it over a 900-mV range, corresponding to gains of −2.5 to 42.5 dB. The gain-law conformance error typically holds to ±0.2 dB over the range. In addition to the exponential amplifier cell, the 8367 features a square-law-detector circuit that allows you to implement a complete IF AGC with few external components. In such a configuration, you can use the detector output as an RSSI (received-signal-strength-indicator) output.

The manufacturer of this $4.55 (1000) VGA and detector specifies the device for minimum and maximum gain, scaling factor, gain intercept, noise figure, output IP3 (third-order intercept point), and the 1-dB compression point at 70, 140, 190, and 240 MHz. The IC, in a 14-pin TSSOP, can swing 4.3V p-p on a 1-kΩ load and 3.5V p-p on a 200Ω load.

In addition to video-signal processing, uses for VGAs at video bandwidths include such disparate applications as ultrasound systems, electronic cameras, and wireless receivers. In ultrasound applications, which include industrial inspection and human and veterinary medical diagnostics, the depth and acoustic properties of the tissues or materials the acoustic pulse encounters attenuate the reflected signal. The delay between "pinging" a surface and receiving the reflection is a measure of the distance from the transponder to a reflective feature and back.

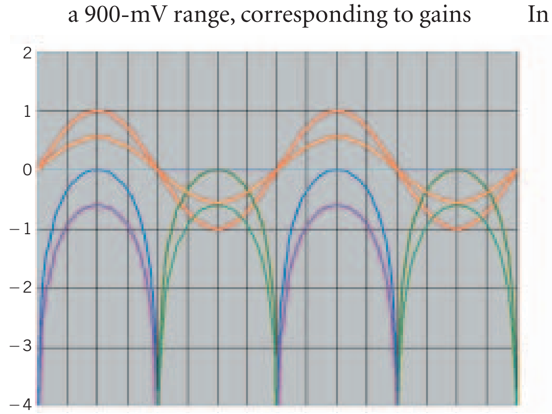


Figure 2 Complementary log-antilog paths can process the bipolar input signal but need precisely matched gains over their entire gain-control range to minimize harmonic distortion.

LONG-LIVED AND NOT FORGOTTEN

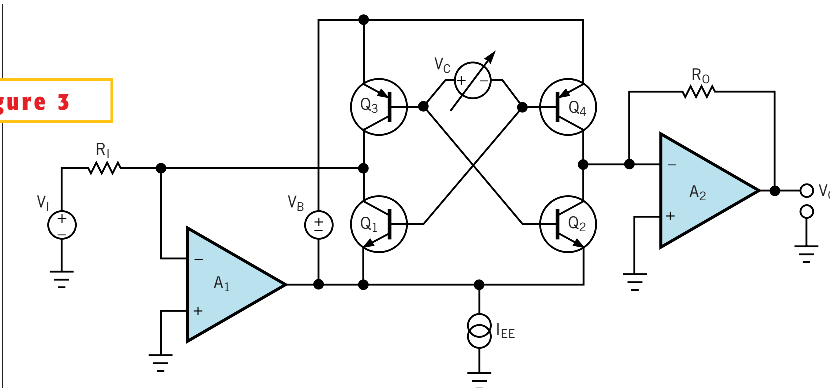
In an industry that churns designs on 18-month cycles, it is remarkable that the Blackmer gain cell, a design that the late David Blackmer patented more than 30 years ago, still engenders interest. What is even more remarkable is the number of ways designers–none more so than Blackmer himself–have found to put the cell and its descendants to work.

In addition to the well-established audio-signal-processing functions–compressors, limiters, duckers, expanders, de-essers, and noise gates–Blackmer developed the important but less well-known dbx (decibel-expansion) noise-reduction system. Though the original dbx noise reduction became largely obsolete when digital recording devices began to compete in price and performance with analog systems, broadcast-television and high-end wireless-microphone systems still use noise-reduction systems that embody its basic concepts.

Blackmer's VCAs (voltage-controlled amplifiers) also found their ways into recording consoles and paved the way for the first studio automation systems. Though later implementations have long since replaced these early VCAs, some consoles containing the original dbx 202 VCAs continue to operate more than 25 years after manufacture.

After selling dbx, which continues to operate as a division of Harmon International, Blackmer went on to found Earthworks, where he specialized in designing and manufacturing recording and measuring microphones and microphone amplifiers.

Figure 3



A simplified schematic of the Blackmer gain cell shows the complementary log-antilog paths consisting of four core transistors controlled by one control source, V_C, and one error amplifier, A_1.

Signal attenuation follows the reciprocal square law, so a receiver circuit needs to sweep its gain along an exponential curve and accommodate as much as 120 dB of received-signal strength (**Reference 8**).

Like the AD8367, the VCA2614 dual VGA from Texas Instruments can maintain its bandwidth by following a voltage-controlled-attenuator block by a gain cell. Unlike the Analog Devices part, TI's VGA buffers its input and provides a PGA (programmable-gain amplifier) as its output amplifier. The manufacturer implements the attenuator in MOS with an offset cascade of amplifiers driving the gates of the attenuator FETs. This circuit takes advantage of MOS's inexpensive manufacturing at the cost of curvature in the gain/control-voltage function for each stage. The global 10.5-dB/V typical characteristic has a series of serrations that correspond to the points where one attenuator stage gives way to the next. The resulting ripple in the gain curve exhibits a maximum magnitude of ±2 dB.

The VCA2614 scales the attenuator and the PGA gain in tandem to effect different gain ranges and sensitivities to the control voltage. Its minimum gain is always 0 dB, and the maximum can take on one of seven values from 27 to 45 dB in 3-dB increments. The VGA's −3-dB bandwidth is 40 MHz. Minimum second- and third-order harmonic-distortion levels are −45 dBc with a 5-MHz, 2V p-p output signal at maximum gain. The RTI (referred-to-input) noise at maximum gain is 4.8 nV/Ω. The $7.95 (1000) dual VGA holds the crosstalk between channels within the TQFP-32 package to −70 dB.

TI also offers an eight-channel VGA for portable ultrasound systems. Each channel features a low-noise preamplifier, balanced attenuator, PGA, and two-pole filter. The VCA8613's RTI voltage-noise spectral density is 1.5 nV/$\sqrt{\text{Hz}}$. Similar to the 2614, the 8613 lets you set the attenuation range and PGA gain for variable-gain ranges of 25 to 40 dB in 5-dB increments. The two-pole output lowpass filter has a fixed corner at 15 MHz. Its balanced topology allows a direct interface to balanced-input ADCs. The $24.95 (1000) octal VGA dissipates about 88 mW/channel in its LQFP-64 package.

TAKE A STEP

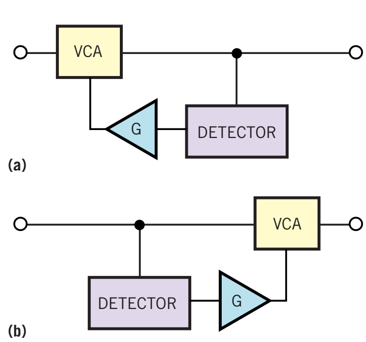
Many applications for VGAs do not require continuously adjustable gains. Those that can accommodate reasonable gain-step intervals can take advantage of simpler amplifier architectures.

PGAs are mainstays of multirange measurement instruments and data-acquisition systems. The common PGA architecture uses a selector to choose among a number of fixed resistors that determine the gain of either an op amp or an instrumentation amp.

The LTC6910-1 from Linear Technology uses a 3-bit control code to select an inverting amplifier's gain from a 1-2-5 sequence ranging from 1 to 100. The control code 000 disconnects the amplifier's input and connects the device as a unity $1.10 (1000) gain follower with its input tied to ground. The 6910, available in a SOT-23-8 package, features a typical gain-bandwidth product of 10 MHz and RTI noise-voltage density of 9 nV/$\sqrt{\text{Hz}}$, both at maximum gain. The $1.10 (1000) PGA features rail-to-rail inputs and outputs and operates on 2 mA from unipolar or bipolar supplies totaling 2.7 to 10.5V.

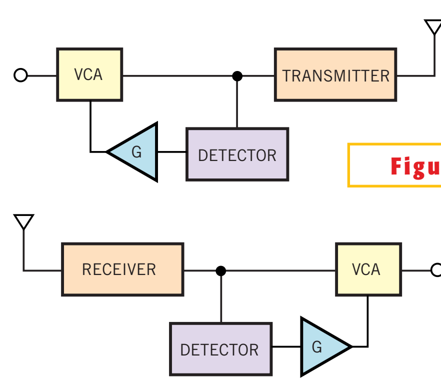
Although continuous gain adjustment is mandatory in audio and video production, postproduction, and broadcast, it is not mandatory for end-user systems, as a cursory examination of most current televisions, portable stereos, telephones, car stereos, or laptop computers will confirm. The structural simplifications that discrete-adjustment methods bring allow VGA structures to fit within more highly integrated products. The LM4851 from National Semiconductor's Boomer audio-power-amplifier line exemplifies this point. The convergence of telephonic, computational, and entertainment functions in various combinations within a single product gives rise to the

Figure 4

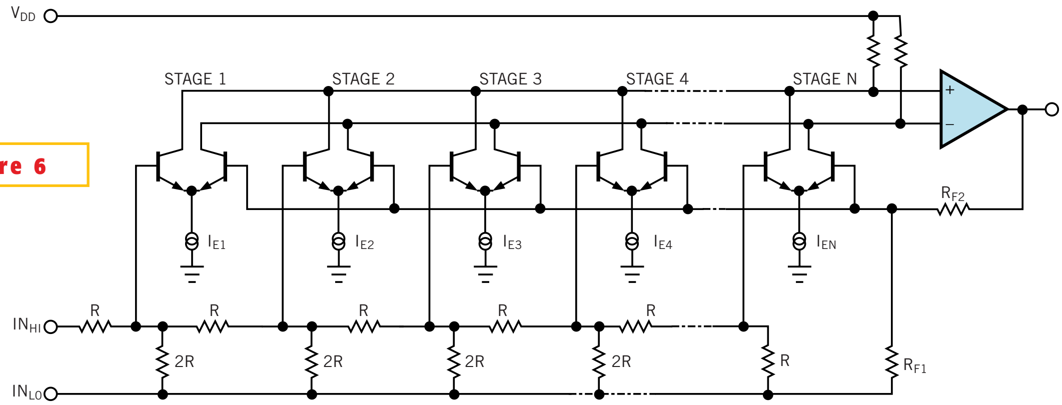


You can connect VCAs and detectors in either a feedback (a) or a feedforward (b) configuration.

Figure 5



Some functions, such as noise-reduction systems, benefit from a specific arrangement of feedforward and feedback VCA connections. Here, the encoder is wired in a feedback configuration, and the decoder uses the feedforward, so that they operate on signals that are as similar as possible.



The X-amp uses a Gaussian interpolator (not shown) to control the current sources I_{E1} through I_{EN}. Instead of switching between the attenuator's taps, the X-amp combines signals from multiple taps, resulting in a continuous attenuation curve. The output amplifier provides fixed gain and thus constant bandwidth.

need for digitally controllable, multiple-input amplifiers that can route signals among multiple outputs and shut down circuits that aren't in use for a given configuration.

National Semiconductor's LM4851 accomplishes all these tasks. The tiny, 12-bump micro-SMD, three-channel amplifier routes one monophonic and one stereophonic input to an on-chip monophonic-speaker amplifier or stereo-headphone amplifier in any combination. The same 3-bit "output-mode" configuration word shuts down those amplifiers that a particular task does not need. You can use the output mode to configure the one part for several products, thus saving on design-in and inventory costs. Alternatively, you can include the output-mode control in your product's user interface to enable end-user selectable features.

The part can adjust its stereo input gain from −45.5 to 6 dB in 1.5-dB increments. National Semiconductor designed the monophonic input for cell-phone modules with their own volume controls, so the signal paths from the mono input to the headphone and speaker outputs give 0 and 6 dB of gain, respectively. The amplifier offers 90-dB SNR. Maximum THD is 0.5% at 100 mW into 32Ω headphones or 1% at 800 mW into 8Ω, both assuming a 5V supply. At 3V, those distortion figures occur at the 20- and 300-mW points, respectively. The amplifier operates through power cycles without clicks or pops. Priced at $1.10 (1000), the LM4851 requires only one coupling cap for each of its three channels and two bypass capacitors for the supply and internally generated bias rail.

At the high-speed end of the product range, the 500-MHz AD8369 from Analog Devices bears a strong resemblance to the AD8367 but lacks that part's detector circuit and Gaussian gain-control interpolator. Instead, it uses a digital decoder that selects the attenuator taps by turning on the appropriate current sources (**Figure 6**).

The $4.20 (1000) AD8369 covers a 45-dB-gain range from 25 to 40 dB in 3-dB steps with a 4-bit control word. The part offers either parallel or serial interfaces to simplify integration with your control logic. Like its continuously variable brother, the manufacturer specifies the 8369 at 80, 140, 190, and 240 MHz. The VGA, available in a TSSOP-16 package, operates on a single 3 to 5.5V supply and typically draws 34 mA. In its power-down mode, the supply current drops to 750 µA.□

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