Function Generation With

Use of high-gain d-c amplifiers and voltage feedback to design accurate electronic switches is applied to precision limiters, gates, comparators, multivibrators, timers and integrator resetting circuits. Present and future applications make the technique an important design tool

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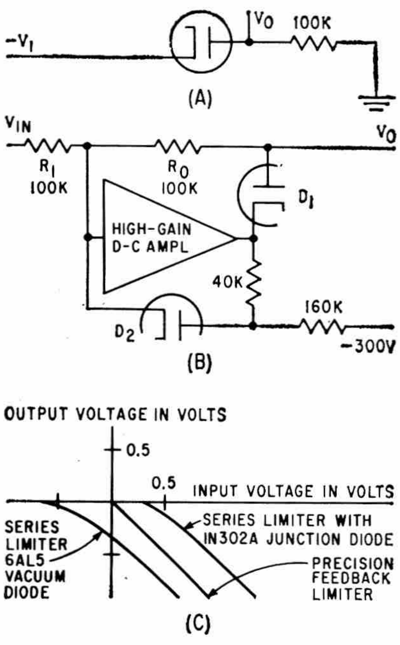

FIG. 1—Conventional series limiter (A) and precision feedback limiter (B) characteristics are compared (C)

MODERN ELECTRONIC ANALOG computers can add, subtract and integrate d-c voltages with component accuracies considerably better than 0.05 v. Such performance is obtainable at relatively low cost with the aid of chopper-stabilized d-c amplifiers and precision network components. In addition, modern time-division multipliers permit multiplication of d-c voltages with comparable accuracy.

This accuracy is not matched by the diode series, shunt and feedback limiters commonly used to implement various nonlinear system characteristics in electronic analog computers.[1, 2, 3] Finite forward and back resistance of diodes and bias circuits as well as breakpoint-voltage variations can produce errors as large as 1 v.

The precision limiter circuit shown in Fig. 1B employs voltage feedback to realize a vastly improved limiter characteristic. For positive input voltages, D_1 conducts, and the circuit acts like any phase-inverting operational amplifier of gain $-R_o/R_1$. Diode forward resistance and contact potentials are effectively divided by the high loop gain of the feedback circuit.

As the input voltage becomes negative, D_1 begins to cut off. This opens the feedback loop through R_o, so that the high amplifier gain cuts D_1 off sharply by increasing its cathode voltage. Diode D_2 limits the amplifier output voltage to some positive value; and feedback through D_2 keeps the summing-point voltage, and hence the limiter output voltage, accurately at zero.

Figure 1C compares the actual 0.01-cps transfer characteristics of a precision limiter with those of conventional series limiters.

Figure 2 shows two modified precision limiters that do not re-

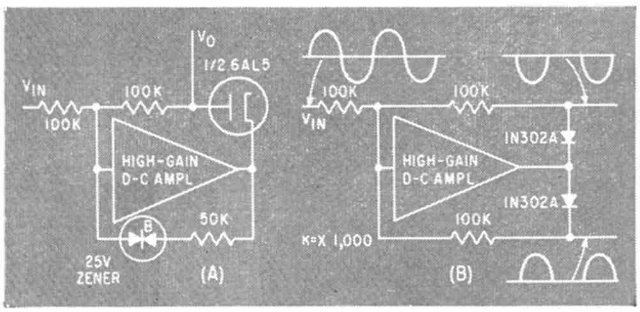

FIG. 2—Modified precision limiters (A) and (B) do not require a bias supply. The 50-k resistor limits Zener current

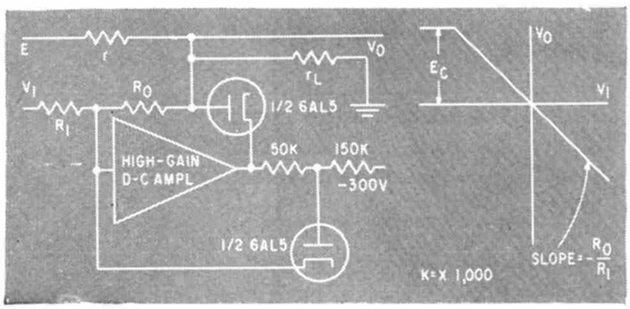

FIG. 3—Diodes and bias voltage of new precision limiter can be reversed to obtain a lower limit

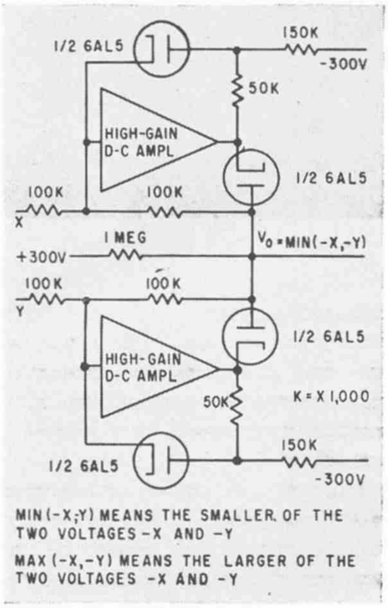

FIG. 4—Reversal of diodes and bias provides output of max (—X, —Y)

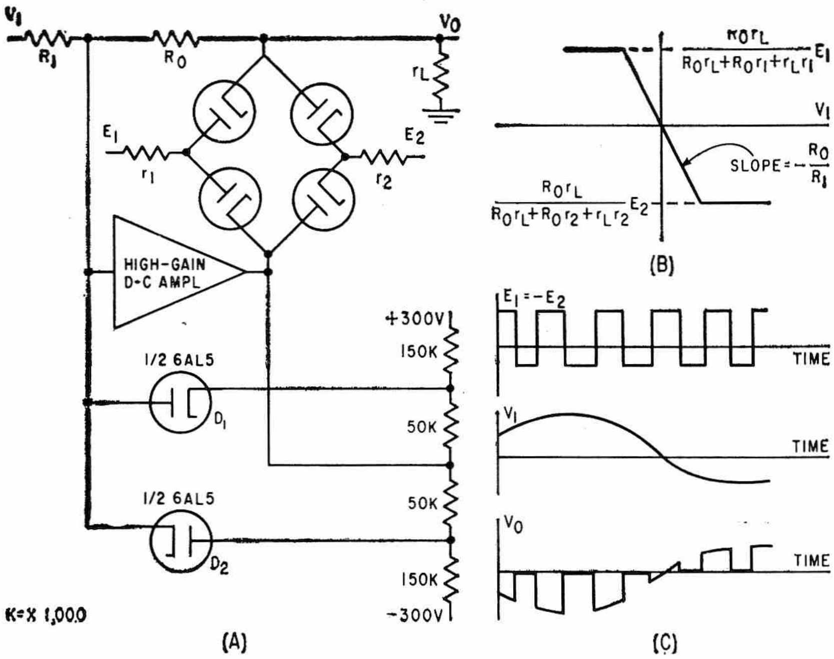

FIG. 6—Dual precision limiter (A) has a sharply defined characteristic (B). Application of push-pull gate pulses results in precision switch action (C)

quire a bias supply. In Fig. 2A, D_2 of Fig. 1B and its bias circuit have been replaced by a Zener diode.

In Fig. 2B the built-in 0.2-v bias of the silicon-junction diodes yields two different limiter characteristics from the same circuit. The small bias for the second diode is sufficient for precision-limiter action and the built-in bias is not evident in the limiter output, since there it is effectively divided by the loop gain.

Instead of limiting at zero, the new limiter circuit of Fig. 3 limits at a precisely adjustable level $E_c = R_o r_L E/(R_o r + r_L + R_o r_L)$. Voltage E can be positive or negative and may, indeed, be a variable voltage. The output voltage will always be the smaller of the two voltages $-R_o V_1/R_1$ and E_c (amplitude-selector circuit). Note that E_c depends on the load resistance r_L.

As with all precision limiters, the output impedance is low only in the linear part of the characteristic. If r_L and R_o are sufficiently large, r may be replaced by a diode to reduce the output impedance when limiting.

The accurate amplitude-comparison circuit of Fig. 4 combines two precision limiters to yield $V_o = \min(-X, -Y)$ at very low output impedance. The circuit is related to Howe's amplitude-comparison circuit[4] which depends on the saturation limiting of d-c amplifiers without chopper stabilization. This new circuit permits chopper stabilization and thus substantially better accuracy. It may be used as a gate to turn either input voltage off and on. Reversing the diodes and bias voltages in Fig. 1 to 4 reverses the limiter characteristics.

The diode-bridge limiter shown in Fig. 5 is used in some commercial analog computers to establish upper and lower limits in a single operation. Thus, if the input voltage V_1 exceeds the upper limiting level $r_L E_1/(r_L + r_1)$, diodes D_1 and D_4 are off while D_2 and D_3 are on. This action is reversed if $V_1 < r_L E_2/(r_L + r_2)$. Series pairs of diodes conduct in the linear portion of the characteristic. Since the diode-bridge limiter is a series limiter, its limiting action is much better than that of the more familiar dual-shunt and feedback limiters.[5] By applying positive and negative gate pulses, this circuit can be used as an electronic switch (bridge modulator).[6]

The dual precision limiter of Fig. 6 combines a diode bridge and precision-limiter action. In the linear portion of the characteristic, the circuit acts like an accurate phase-inverting feedback amplifier essentially unaffected by the bridge circuit. As soon as the bridge begins to limit, the feedback loop opens. The high-gain amplifier drives the bridge decisively into its limits, and a sharply-defined limiter characteristic is obtained. Diodes D_1 and D_2 constitute a conventional shunt limiter to keep the summing

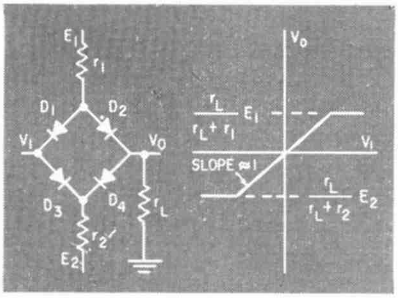

FIG. 5—Diode-bridge defines upper and lower limits

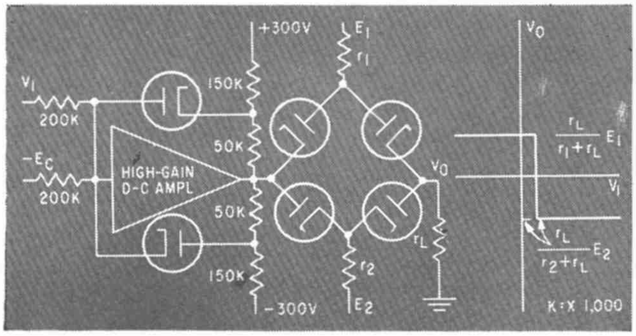

FIG. 7—Output of comparator is used for accurate computations

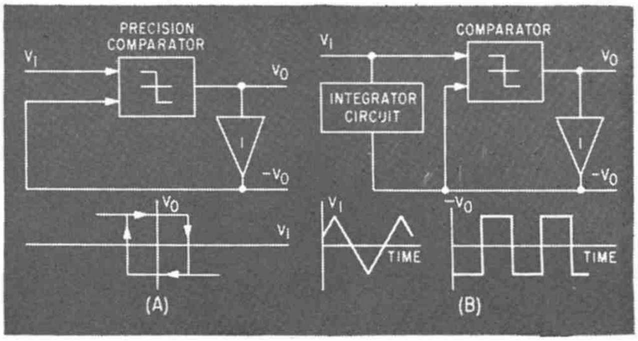

FIG. 8—Bistable (A) and free-running (B) multivibrators

point at zero. The shunt limiter can be replaced by a pair of back-to-back Zener diodes in low-frequency applications.

The upper and lower limiting voltages need not be equal and opposite and may be variable. Since all four bridge diodes cease to conduct if $E_1 < E_2$, application of push-pull gate pulses yields a precision switch with negligible forward resistance as illustrated in Fig. 6C.

Comparators and Multivibrators

In d-c analog-computer usage, a comparator is an output-limited high-gain d-c amplifier; its output voltage changes abruptly from one limiting level to the other whenever the algebraic sum of the input voltages changes sign.[1,3] In Fig. 7, a conventional feedback-diode limited comparator[1] drives a diode-bridge limiter decisively into either limit to produce an accurately limited comparator characteristic. Whereas the conventional comparator serves mainly for switching or relay-driving purposes, the output voltage of the precision comparator can be used in accurate computations.

Combining a comparator and a phase-inverting d-c amplifier in a regenerative loop produces a bistable multivibrator[1] with the transfer characteristics indicated in Fig. 8A. The improved circuit shown produces push-pull output voltages suitable for driving diode-bridge gates (Fig. 5 and 6) without an additional phase inverter.

Addition of the integrator loop shown in Fig. 8B gives a free-running multivibrator.[1] When a precision comparator is used, a remarkably useful l-f signal generator (0.01 to 2,000 cps) for accurate triangular waveforms and pulses permitting precise amplitude and pulse-width modulation are obtained.

Each of the timer circuits of Fig. 9 combines a precision limiter with a d-c integrator and may be regarded as an analog of the familiar phantastron circuit.

Each circuit produces a sharp rise in the amplifier output voltage as the latter reaches the limiting level set by a precision limiter. In each case one can reverse diodes and voltages to produce outputs of opposite polarity.

Integrator Reset Circuits

Before a computer run, each integrator of an electronic differential analyzer must be reset to a given initial condition by charging the integrating capacitor to the initial-condition voltage.[3] Alternatively, one may discharge the integrating capacitor to zero and add the initial-condition voltage E in a succeeding amplifier.

Figure 10A shows an electronic resetting circuit of the latter type; such a circuit can reset the integrators of a repetitive analog computer to zero twenty times per second.[8] The resetting circuit of Fig. 10B is a considerable improvement, since it permits one to set initial-condition voltages different from zero without an external summing amplifier. The modifications shown just about double the capacity of the computer in question. The triode switches in Fig. 10A and 10B can be replaced with diode-bridge switches with excellent results.[6] If the resistance appearing in series with the switch of Fig. 10B is objectionable, the switch must be drawn through a simple cathode follower.

Figure 11 shows an accurate resetting circuit which would replace the usual relay resetting circuit of a slow d-c analog computer.[3] The circuit operates essentially like the circuit for resetting the timer of Fig. 9B. The double diode-limiter circuit operates in the reset condi-

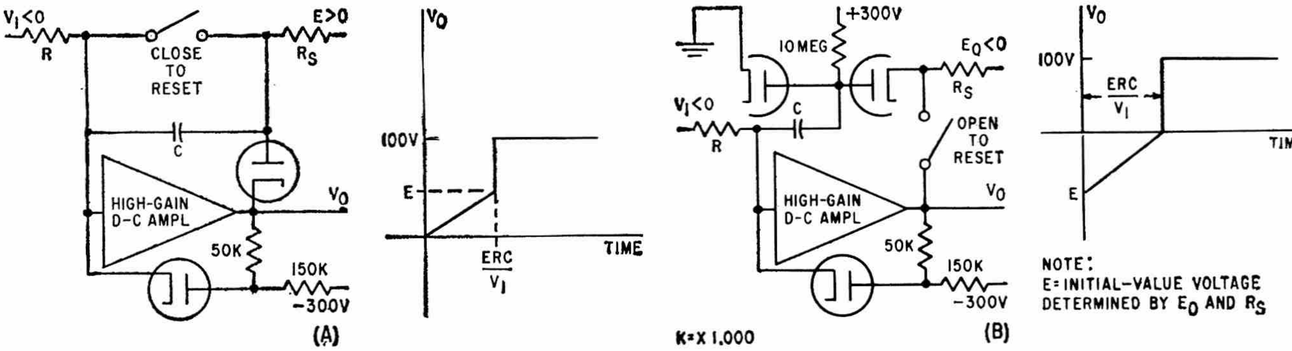

FIG. 9—Precision timing circuits can be reset by push button or relay (A) and by electronic switch (B)

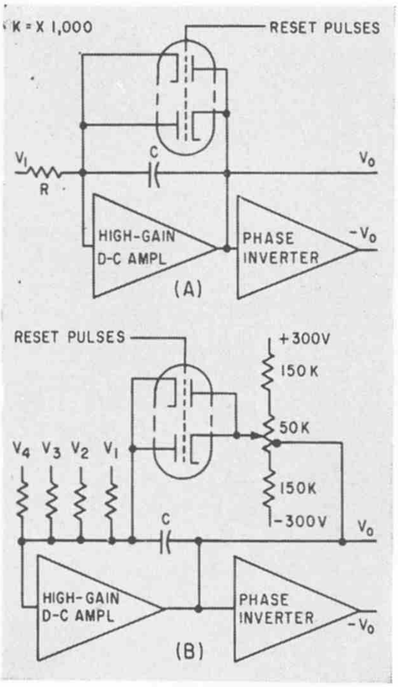

FIG. 10—Resetting circuit (A) is modified (B) to double capacity of computer

tion; the new circuit uses four instead of two diodes in an attempt to shunt diode-leakage currents from the bias supplies to ground.

Performance

With suitable chopper-stabilized d-c amplifiers, reference-voltage supplies and precision network components, the limiter circuits of Fig. 1 to 3 yield static accuracies better than 0.05 volt, as exemplified by the limiter characteristic shown in Fig. 1C.

As in the case of electronic multipliers, the static accuracy of a nonlinear operational-amplifier circuit may be compromised by frequency-response requirements. The sharp break characteristics of precision limiter circuits depend on high open-loop gain and may deteriorate somewhat above 2 cps because of wiring and patchbay capacitances in multipurpose computers. The situation is much more favorable in circuits with short leads.

The high capacitance (25 $\mu\mu$F) of most silicon-junction diodes capable of standing 100 v inverse voltage may necessitate the use of vacuum diodes that have low capacitances (5 $\mu\mu$F) but relatively large plate resistances (1,000 ohms). In this connection, Lofgren[9] has suggested the use of two vacuum diodes and two junction diodes in each bridge circuit.

Figure 12 shows a simple precision limiter and its transfer characteristic at 5 kc. The separation between forward and return traces is due to phase shift, not hysteresis. Optional diode D_3 reduces the output impedance when limiting. Using Philbrick K2-X d-c amplifiers, the ideal limiter characteristics, are approximated to within 0.5 v at 5 kc for sinusoidal input of 40 v peak-to-peak. The switching step shown in Fig. 12 is minimized by small back bias (0.2 to 0.5 v) on D_2.

Applications

Nonlinear operational-amplifier circuits of the type described permit analog-computer representation of nonlinear characteristics (dead space, limit tops, backlash and hysteresis) in dynamic systems and simulated modulation systems with excellent accuracy. The new circuits can frequently replace operational relays and thus permit faster computer operation.

These accurate analog switching and comparison techniques can be used in various automatic checkout and quality-control devices. In the laboratory the new circuits have proved extraordinarily useful in the design of the following special computing elements: quadrant switches for trigonometric function generators[10], electronic decommutators[11], analog-to-digital converters[11], simple and remarkably accurate triangle-integration multipliers[11]

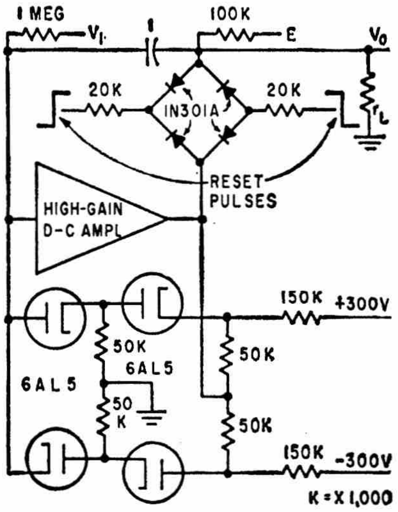

FIG. 11—Accurate resetting circuit uses new voltage divider to minimize effects of limiter-diode leakage and contact voltage

and a novel amplitude-distribution analyzer for estimation of probability densities.[12] Related switching techniques can be applied to analog computers with automatic-programming features such as automatic scale-factor changes, analog storage or memory circuits and sample-hold circuits. Higher frequency versions of these circuits

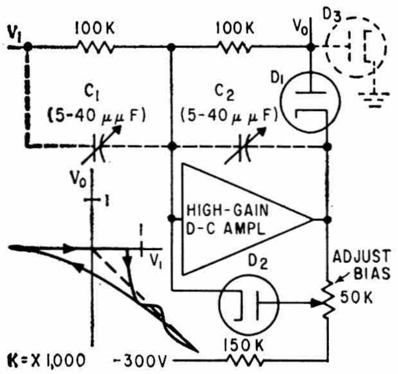

FIG. 12—For h-f operation of precision limiter, capacitors are adjusted to obtain best frequency response without ringing

will make possible new applications in storage and sampling devices.

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