FET pair and op amp linearize voltage-controlled resistor

by Thomas L. Clarke
Atlantic Oceanographic and Meteorological Laboratory, Miami, Fla.

A matched field-effect transistor pair can be combined with an operational amplifier and a few resistors to form a circuit in which one FET's drain-to-source resistance (R_{ds}) bears a precisely linear relationship to a control voltage (V_c). Though a single FET can serve as a voltage-controlled resistor, the relationship of R_{ds} to the gate-to-source voltage (V_{gs}) is nonlinear.

The basic idea in this circuit is to control V_{gs} through a feedback loop that senses if the amount of current flowing through the FET, and hence its R_{ds}, is of the proper value. As shown in Fig. 1, this is accomplished by deriving a signal from half of the FET and applying it to a "summing" node at the inverting port of an op amp.

The output of the op amp is connected to the gate of the FET, thus forming a closed loop. The resulting change in V_c causes a proportional change in R_{ds} because the op amp is a linear device, and because input voltages are compared to a fixed voltage (V_{ref}) at the noninverting terminal. Depending on the configuration, R_{ds} can be made proportional to V_c or its reciprocal.

In the circuit to be seen at the left of Fig. 1, R_{ds} varies in proportion to the reciprocal of the control voltage, as is indicated by the following equation:

$$R_{ds} = |V_{ref}|R_c/(|V_c|-|V_{ref}|)$$

where V_{ref} is assumed to be between 0 and V_c. A voltage divider may be used to derive V_{ref}. Moving V_{ref} to the drain of the FET, as in the circuit to the right, the following equation holds:

$$R_{ds} = |V_{ref}|R_c/|V_c|$$

where V_{ref} should be a well-regulated source, since it may have to supply considerable current. These equations are based on the facts that V_c draws current from the negative input of the op amp through R_c and that this voltage drop results in current flow into the terminal by the FET. The application of Kirchhoff's law then yields the above relationships.

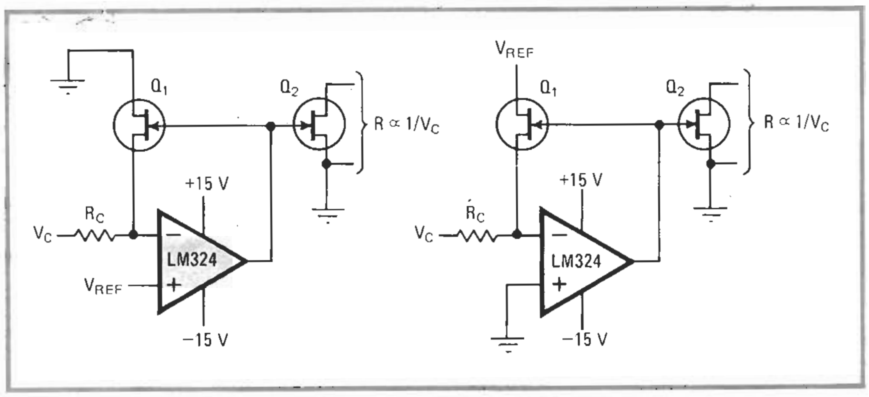
As shown in the circuit at the left of Fig. 2, R_{ds} may also vary in direct proportion to the control voltage. Therefore, the relationship becomes:

$$R_{ds} = R_c|V_c|/(V-|V_c|)$$

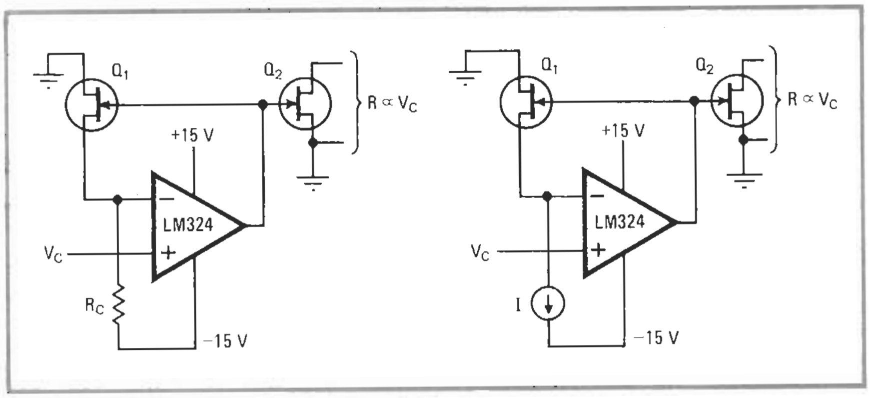
where V_c is greater than $-V_p$ but less than 0 v. This circuit, while not as linear as those of Fig. 1, can be improved significantly by replacing R_c with a current source, I, as shown at the right of Fig. 2. The relationship then simply becomes:

$$R_{ds} = |V_c|/I$$

The circuits are built with Siliconix 285 dual FET chips and LM324 op amps. Use of high-speed op amps such as the LM318 would permit more rapid variations of resis-



1. Voltage-controlled resistance. Unused half of FET Q_2 can function as voltage-controlled resistor in external circuits. R_{ds} is inversely proportional to control voltage in both circuits. V_c values are negative for n-channel FETs, positive for p-channel FETs.



2. Direct proportional control. R_{ds} varies linearly with V_c in both circuits. If V_c exceeds V_{ref} or breakdown voltages of FET in either figure, a resistor should be inserted between output of operational amplifier and gate of FET to prevent burnout.

tance. No stability problems are encountered because the FET introduces negligible phase shift in bandpass frequencies of the op amp. Optimal results are obtained, of course, with FETs formed on a common substrate, and if desired, p-channel devices may be used for positive control voltages. □

Potentiometer OK with FET setup to keep linearity

When a single field-effect transistor is used as a voltage- or current-controlled resistor, its resistance characteristic unfortunately becomes highly nonlinear at high signal levels, notes D. S. Gibbs, an applications engineer at Ferranti Ltd., Oldham, England. But, by using two FETs—either p-type or n-type devices, one inverted and the other noninverted—**you can cancel out the nonlinearity of each FET and obtain an extremely linear resistance characteristic.**

It's done with a potentiometer. The input control signal is applied to the wiper of the potentiometer whose resistance element is connected between the source of one FET and the drain of the other. The gate of the first is then grounded, as is the source of the second. Then the drain of the first and the gate of the second are tied together, with the output taken between these two terminals. The potentiometer can now be used to balance the two FETs so that signal distortion can be minimized.

FET-controlled op amp permits wide dynamic range

by Henry E. Santana
Hewlett-Packard, Loveland Instrument Division, Loveland, Colo.

When a field-effect transistor is operated as a voltage-controlled resistor, it is usually limited to a relatively small dynamic signal-voltage range. This is due to the nonlinearity of its drain-source resistance over a wide range of drain-source voltage.

But a wide-range voltage-controlled amplifier can be realized if a pair of FETs is connected in the bridge configuration shown in the diagram. The inverting terminal of the operational amplifier is kept at virtual ground, permitting the range of each FET's drain-source voltage to remain small, regardless of how broad the actual signal-voltage range is. This also assures that the excursions of V_{DS} will remain well within the FET's pinch-off region.

The circuit's voltage-transfer function can be written as:

$$A_V = -(R_2/R_1) + N(R_1+R_2)/R_1 + NR_2r_{on}[1 - (V_{GS}/V_P)]$$

where r_{on} is the on-resistance of the right-hand FET, V_{GS} is the gate-source voltage, and V_P is the pinch-off voltage. Variable N represents a resistance ratio:

$$N = r_{on}/(r_{on}+R_1)$$

If N is very small, and r_{on} is much less than R_1, then:

$$AV = -(R_2/R_1)(V_{GS}/V_P)$$

Although N must be small, it must, nevertheless, be greater than zero for the circuit to work. The control voltage for the circuit can range from 0 to V_P, and the peak ac input-signal voltage is determined by $I_{DS}R_1$.

Applications for this voltage-controlled amplifier include automatic gain control, true rms conversion, amplitude compression, and signal modulation. □

Designer's casebook is a regular feature in Electronics. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $50 for each item published.

Wide-ranging. Voltage-variable amplifier can operate over a broad range of input-signal voltages. The FETs, which function as voltage-controlled resistors, are wired in a bridge configuration. Their inherent resistance nonlinearity is avoided by limiting each FET's drain-source voltage range, no matter how large the signal voltage becomes. The op amp's inverting input is held at virtual ground.