The Lenkurt
SEPTEMBER 1968
DEMODULATOR

negative resistance devices

Negative resistance and impedance — effective elements in modern circuit design.

The fascinating implications of negative resistance have intrigued scientists and engineers for decades. Near the turn of the century certain "freak" devices — among them the carbon arc — exhibited negative resistance properties and were actually put to practical use.

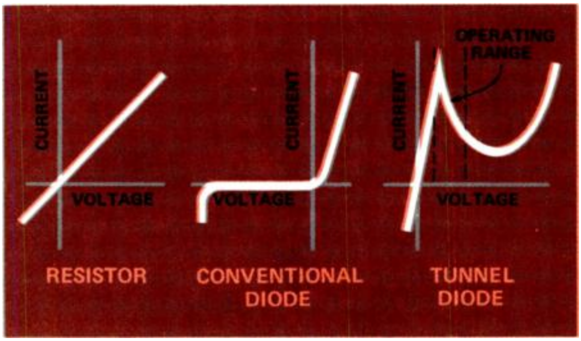
The carbon arc, the dynatron tube, and more recently the tunnel diode all fit the class of physical devices having negative resistance. Circuits using standard components can also be used to produce negative resistance and now have their own place in many new telecommunications applications.

In the dynatron tube, developed about 1918, the plate current increases when the plate voltage is reduced. A very similar negative resistance is found in the modern tunnel diode. The tunnel diode is a two-terminal device that has the ability to amplify because of a unique relationship of voltage to current over a portion of its operating range. The voltage-current curves in Figure 1 compare the ordinary resistor, a conventional junction diode, and the tunnel diode.

At a certain point on the curve of the tunnel diode, an increase in the applied voltage causes a decrease in the current. As long as the tunnel diode is operated within the limited voltage range indicated, and in a suitable circuit, the negative resistance effect may result in amplification over a range extending up to microwave frequencies.

In most ways, negative resistance can be thought of as being the reverse of positive resistance. Over the voltage or frequency range within which it is designed to operate, the negative resistance device will deliver energy to the circuit to which it is connected, in contrast to a positive resistance which absorbs and dissipates energy. In the tunnel diode, it is strictly an internal phenomenon which allows this. In the circuit devised to work as a negative resistance, it is essentially a positive feedback technique that achieves the result.

Figure 1. Comparison of the voltage-current relationships of resistor, conventional diode, and tunnel diode. The tunnel diode shows unique negative resistance characteristics over a narrow range of voltages.



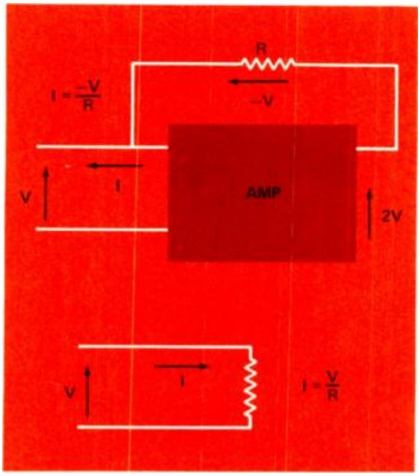


Figure 2. Feedback circuit produces negative resistance. If voltage gain is two times, current of -V/R will flow opposite to that in a conventional resistor, shown below.

Feedback Circuit

The awareness that positive feedback may be used to obtain negative resistance probably came with some of the first radio receivers. There, positive feedback circuits were used to form regenerative amplifiers. Basically, a regenerative amplifier is simply an arrangement where a controlled amount of signal is returned from the plate of a vacuum tube to the grid – or from output back to input. This signal is amplified over and over again, adding gain each time around.

A modern version of this feedback circuit – and an example of a simple negative resistance – is shown in Figure 2.

Impedance Converters

An extension of the first feedback circuits led to circuits more accurately described as negative *impedance* converters (NIC). In some respects the ideal NIC resembles a transformer with an unusual twist. If a positive impedance is applied to one end of the circuit, the negative of that impedance will be seen at the other (Fig. 3).

The reactance of a capacitor is negative and at any one frequency its value can be chosen so that this negative reactance exactly cancels the positive reactance of an inductor. This happens in every tuned circuit. But the capacitor is not behaving exactly like a negative inductor. On the other hand, if an inductor terminates one end of a NIC, the impedance seen at the other end will truly behave like the negative of an inductor at all frequencies, and is a proper negative impedance.

Working from this concept, engineers at the Bell Telephone Laboratories in the early 1940's saw the possibilities for a negative impedance telephone transmission repeater. Inserted in series with the line, the NIC would decrease the impedance, and therefore increase the line current and reduce transmission loss. The first successful version was built in 1948 and became known as the E1 repeater. It first appeared with vacuum tubes, and now transistor models are used extensively in the exchange plant of the Bell system. The E1 repeater is transformer coupled, locally powered, and designed to match the characteristic impedance of the cable.

A transistor version of the E1 repeater is shown in Figure 4. Positive

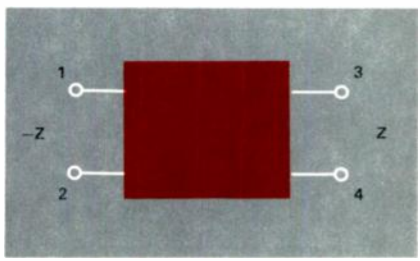
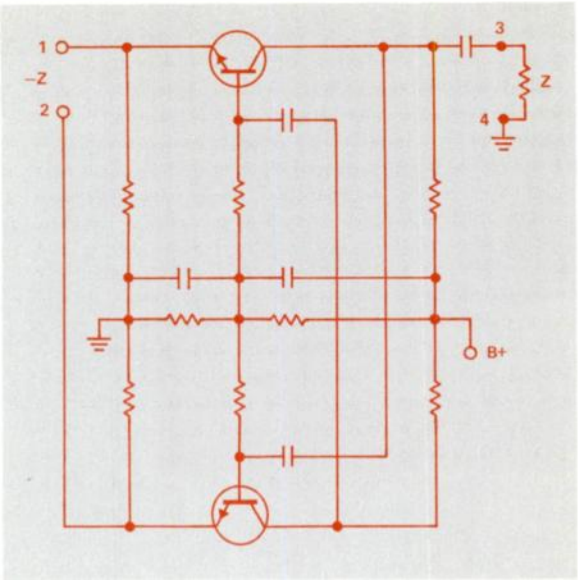


Figure 3. Positive impedance at terminals 3 and 4 will appear as negative impedance at 1 and 2.

Figure 4. The Bell E1 repeater uses positive feedback circuits to produce negative impedance characteristics. Terminals 1 and 2 are coupled to transmission line.



feedback in the circuit produces the negative impedance characteristics, while the negative feedback provides stability. The value of the impedance applied to terminals 3 and 4 appears at terminals 1 and 2 as the negative of that value. In practice, terminals 1 and 2 are effectively connected in series with the two sides of a telephone line and present to the line a series, or voltage-type negative impedance (Fig. 5).

This type converter — or booster as the application better suggests — is a very apt repeater for two-wire lines operating at voice frequency. It is relatively easy to operate at these frequencies, and because it is strictly an impedance device, the repeater provides gain to the transmission line in both directions.

Because of its nature, the E1 repeater is more likely to be found at exchange offices rather than along the line. In fact, for best impedance matching, it should appear at the midpoint of the transmission line.

NIB

More recent experimental efforts at Bell Labs are in the direction of a small two-way repeater powered by line current and spaced along a voice line much like inductive loading coils. It is, in fact, envisioned that the new

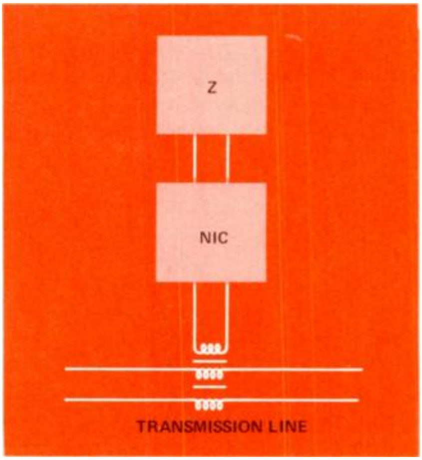


Figure 5. Connection of impedance Z and NIC to transmission line.

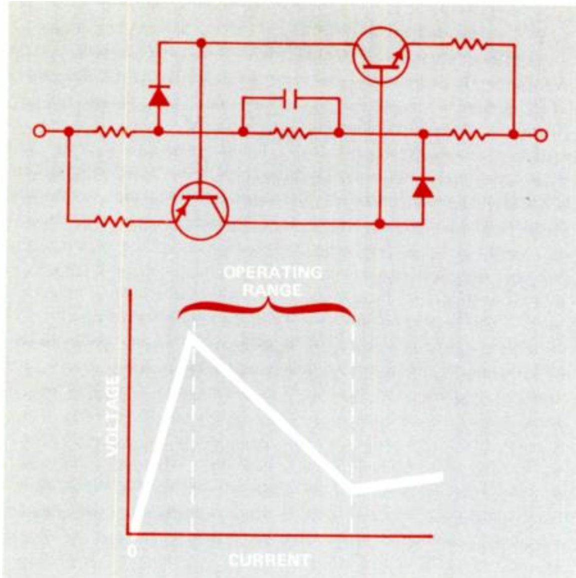


Figure 6. Bell negative impedance booster (NIB) operates in series with the line and is powered over the cable. Slope of the operating curve is stabilized by transistor emitter feedback. Diodes add to the operating linearity.

repeater could replace existing loading coils at about the same spacing.

The negative impedance booster (NIB), as Bell prefers to call it, is more a resistance than an impedance device (Fig. 6). It operates in series with the line and Bell says the NIB might someday be built into the cable during manufacture. The NIB, when perfected, would result in practically lossless and distortionless signal transmission for long rurul telephone lines, local inter-office trunks, and other voice frequency uses.

The NIB is markedly different from the E1 repeater. Spacing of the NIB would be at regular intervals down the cable, preferably not more than a quarter wavelength apart at the top frequency of the transmission band. For telephone speech a suitable spacing would be 12,000 feet. At that spacing, essentially flat, lossless transmission could be achieved up to 7 kHz – up to 18 kHz at 6,000-foot spacing.

Because no coils are used (either as inductors or as matching transformers) the circuits lend themselves well to integrated circuit techniques utilizing only resistors, capacitors and solid state devices. On long subscriber loops, cable with repeaters may be less expensive than the larger sized cable that would normally be necessary.

The main advantage of the NIB over conventional repeater amplifiers in telephone transmission is its simplicity in both construction and operation. Because it has no directional properties and boosts the signal in both directions it can be positioned almost anywhere on the line without concern for expensive hybrid transformers or level control. Additionally, the repeater provides almost automatic equalization by compensating for the increase in cable attenuation with frequency. Delay distortion in the experimental model was almost nonexistent.

Active Filters

When the transistorized NIC became available, there was interest in developing the device for service other than just cancelling losses in transmission lines. The NIC soon became a component in general circuit synthesis and was used in most early RC active filters. The NIC was the "active" element.

The NIC is also a most convenient way of making a good negative resistance device. This technique is especially useful in cancelling inductor losses in filters. Considerable work is being done at Lenkurt in this area.

The negative resistance device can be used to decrease the effect of resistance in a filter inductor, thereby increasing the Q of the circuit. Q is a convenient way to express the merit of an inductor and is derived by dividing the inductor reactance by the equivalent series resistance.

In the design of conventional LC filters, the quality of performance achievable over the pass band is limited primarily by the dissipation in the inductors. There are three ways commonly used to reduce this dissipation. The classical method is to place an equalizer network in tandem with the filter to correct the unequal losses across the frequency band concerned. As a result, the overall pass-band loss of the filter is at least 0.5 dB greater than the maximum loss in the filter without the equalizer.

Another method is to predistort the original filter design in such a manner that the pass-band loss characteristic with dissipation is close to the desired flat response. But from a technical point of view a third solution is almost ideal: the cancellation of dissipation using negative resistance.

Lenkurt Applications

A channel filter being investigated at Lenkurt involves this technique and could result in a dramatic sharpening of the edge of the pass band. Using seven ferrite inductors and five negative resistance devices, a very high Q is expected – perhaps 8,000 – with the band flat to within 0.1 dB.

The negative resistance circuit suggested for this use consists of two transistors and five resistors. The circuit is shown in Figure 8, along with the application of the circuit in a conventional filter.

Figure 7. Lenkurt-built negative resistance (left) for channel filter studies compared to Centralab package and Sylvania IC version. About actual size.

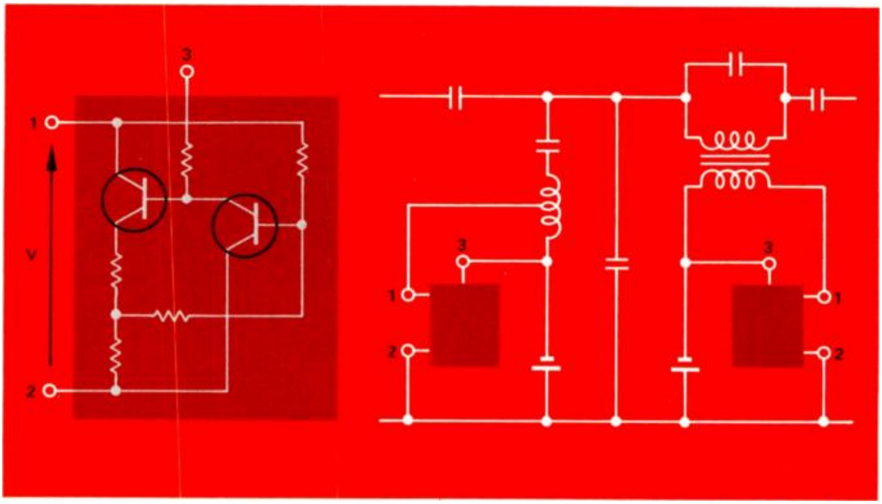


Figure 8. Negative resistance circuit (left) and how it is coupled to the filter network. Very high Q is expected from reduced dissipation in the inductors.

Negative resistance is being used to sharpen band elimination characteristics for critical data circuits. In the Lenkurt 25A data transmission equipment used by the news wire services, a special splitting filter is necessary for switching out portions of the band at various locations across the country. Engineers have said that it would have been impossible to achieve the high degree of sharpness necessary without using negative resistance techniques.

From reversing the sign of resistance (R to –R) and impedance (Z to –Z), it was historically a short step to *inverting* the impedance (Z to 1/Z – or more correctly R^2/Z). Here, another important contribution to filter design will be provided through the introduction of a device known as the gyrator which can perform this impedance inversion. The gyrator can transform the impedance of a capacitor into that of an inductor and so literally make a capacitor look like an inductor to the rest of the circuit. The capacitor, of course, is much smaller than the inductor.

Again, while the theory has existed for many years, and some circuits have been built, more recent developments have moved the gyrator closer to practicality. If perfected, the gyrator and an associated capacitor could be substituted for each bulky inductor in conventional filter networks, eliminating a great deal of size and weight. But for the moment, this relative of the NIC may be too costly for a favorable economic tradeoff.

Negative resistance and negative impedance circuits have moved from curiosities to practical devices – especially augmented by the development of transistors. Many of these applications are significant and will continue to be of interest in the expansion and improvement of telecommunications.

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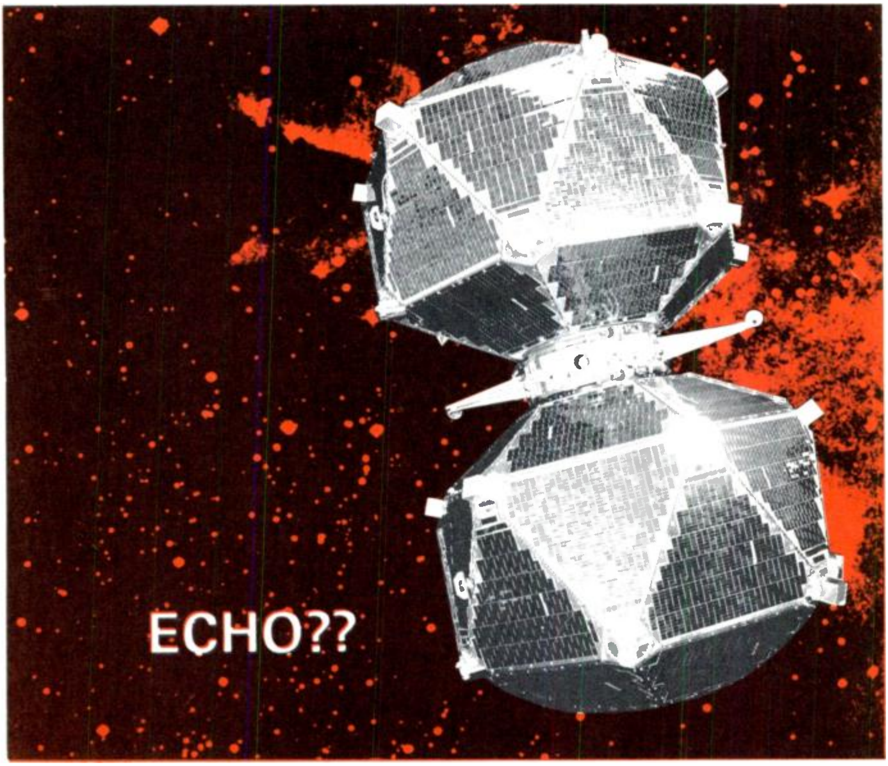

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