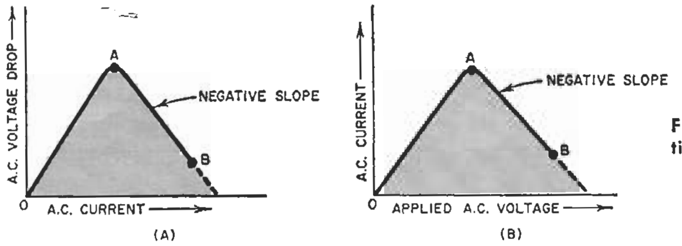


Fig. 1. Basic curves of the a.c. negative-resistance devices discussed below.

A.C. NEGATIVE-RESISTANCE DEVICES

Description of ferroresonators, nonlinear-type capacitors, semiconductor capacitors, and other similar components.

By RUFUS P. TURNER

THE author's earlier article on negative resistance was devoted to direct-current devices.[1] However, that article stated in conclusion that certain a.c. devices also exhibit the property of negative resistance, or negative impedance. This article describes devices of this type.

For simplicity's sake, throughout this article the term "negative resistance" will be used in a generic sense. But the reader will recognize that the negative quantity may be impedance or reactance, rather than resistance.

Such a.c. negative-resistance devices are not nearly as numerous as the d.c. devices, but we may reasonably expect additions to the family as research and development continue. The external manifestations of a negative characteristic are substantially the same in a.c. and d.c. devices, that is, the conduction curve has a negative slope over some part of it. In one instance, current will be the independent variable; in another, voltage will be. Thus in Fig. 1A, current is the independent variable. As the a.c. current is continuously increased, the a.c. voltage drop across the device first increases from 0 to *A* and then decreases (showing a negative resistance) from *A* to *B*. In Fig. 1B, voltage is the independent variable. As the applied a.c. voltage is continuously increased, the a.c. current flowing through the device first increases from 0 to *A*, and then decreases (showing negative resistance) from *A* to *B*.

The following sections describe the action of devices which exhibit one or the other of these conduction characteristics.

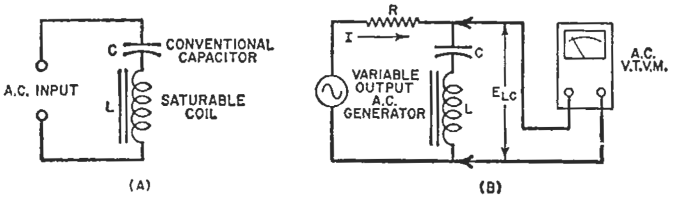
Ferroresonator

The *ferroresonator* (also called "ferroresonant circuit," saturable-reactor switch," and "ferristor") is a special type of series-resonant *LC* circuit. It really is quite simple, consisting only of a coil and capacitor connected in series (see Fig. 2A). The capacitor is a conventional one but the coil is not. The special feature of the coil is its core which saturates readily. Because of core saturation, the inductance and reactance of the coil decreases as the current is increased. An ordinary iron-core filter choke will exhibit saturation and a resulting decrease in inductance if current is raised high enough, but this usually requires a rather large current at power-line frequencies. A ferroresonator coil intended for operation between 100 kc. and several megacycles, however, is wound on a tiny, thin core of high-permeability metal and will saturate on only a few milliamperes.

The *LC* combination resonates at a frequency, f_r, determined by the inductance and capacitance values. (Resonant frequency $f_r = 1/(6.28\sqrt{LC})$. Capacitance *C* is constant, but inductance *L* varies with the current, *I*, flowing through the circuit, so the resonant frequency changes with current. (As *I* increases, *L* decreases, and f_r increases.) This is the basis of ferroresonator operation.

Fig. 2B shows a typical ferroresonant circuit. Here resistance *R* is non-inductive. The generator provides an adjustable a.c. output voltage. By adjusting the voltage, the operator varies current *I* flowing through *R*, *L*, *C* in series. The voltage (E_{LC}) across the *LC* combination is measured with a high-impedance a.c. vacuum-tube voltmeter. Fig. 2C shows circuit response. As the current is steadily increased, voltage E_{LC} rises to a peak (point *A*), then decreases to a valley (point *B*), and finally rises again to *C* and beyond. Thus, *AB* is a negative-resistance region bounded by two positive-resistance regions (0*A* and *BC*). This is a typical negative-resistance curve.

The circuit behavior may be explained in the following manner. (1) The *L* and *C* values are selected to give a resonant frequency somewhat lower than the generator frequency. Increasing the current decreases inductance *L* and tunes the circuit up to the generator frequency and finally to some still higher frequency. (2) As *I* is increased from zero, E_{LC} rises and would continue to do so if the core of the coil did not begin to saturate. Saturation (starting at point *A* in Fig. 2C) lowers the inductance and tunes the circuit toward resonance at the generator frequency. (3) At generator resonance, the net reactance of the *LC* combination is theoretically zero, therefore E_{LC} is theoretically zero. As resonance is approached, E_{LC} accordingly decreases. At resonance (point *B*), E_{LC} does not drop fully to zero because resistance losses remain to act in the circuit after resonant cancellation of the reactance. (4) As *I* is increased further, core saturation increases, inductance lowers still more, and the circuit is tuned to a frequency higher than the resonant frequency. Thus, the voltage once more rises—in this case from *B* to *C*.



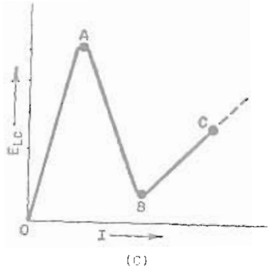


Fig. 2. (A) Basic ferroresonant circuit arrangement. (B) Test circuit showing operation of the ferroresonant element. (C) Graph of operational characteristic.

Tiny r.f. ferroresonators have been used as active elements in flip-flops, electronic counters, gates, and other computer-type devices.[2,3,4] They also have been employed as magnetic amplifiers at audio frequencies. In these particular units, *C* usually is a fairly small mica capacitor, while *L* is a coil that has been wound on a core of Permalloy foil.

Nonlinear Capacitor Element

Fig. 3A shows a series-resonant negative-resistance circuit which resembles the ferroresonant circuit described in the preceding section but behaves somewhat differently. This arrangement uses a conventional air-core coil and a nonlinear (voltage variable) capacitor. Suitable capacitors of this type contain a high-K ceramic dielectric, such as specially processed single-crystal barium titanate. As the voltage applied to the capacitor is increased, the capacitance decreases.

As in the standard ferroresonant circuit, the *L* and *C* values in Fig. 3B are selected so that the zero-voltage resonant frequency of the circuit is lower than the generator frequency. As the voltage is increased, the current rises from zero to a peak point (*A* in Fig. 3C). As the voltage is increased further, the current decreases. Thus, the current voltage curve has a negative slope from *A* to *B*.

Behavior of the circuit may be explained in this manner. (1) The increasing voltage lowers the capacitance and tunes the *LC* circuit up toward the resonant frequency (generator). The current increases because increasing capacitive reactance causes the net reactance of the circuit to decrease. (2) At resonance with the generator, the net reactance is theoretically zero, and maximum current flows. This corresponds to point A in Fig. 3C. (3) As the voltage is increased beyond this point, the circuit is tuned to frequencies higher than resonance. The capacitance continues to fall but the net reactance of the circuit increases, so the current decreases. This is represented by the negative slope, *AB*.

Semiconductor Capacitor Circuit

A ceramic nonlinear capacitor, such as *C* in Fig. 3, usually requires relatively high-voltage operation for appreciable capacitance change. Furthermore, such capacitors are quite temperature sensitive because of the Curie point of the dielectric material. To obtain low-voltage operation (from a few tenths of a volt to 1 to 6 volts r.m.s.) and at the same time to secure comparative freedom from temperature effects, semiconductor voltage-variable capacitors may be substituted in the circuit, as shown in Fig. 4. Response is the same as that shown in Fig. 3C.

In Fig. 4, the semiconductor voltage-variable capacitor (also known as Varicap, varactor, Semicap, etc.) is d.c. biased in a reverse direction to set its initial capacitance to a desired value and to prevent positive peaks of the maximum r.f. voltage from driving the semiconductor junction into the low-resistance forward direction. *C1* is a blocking capacitor to keep d.c. out of the current meter and generator. As in the preceding example, values of *L* and *C2* are chosen for zero-signal resonance below the generator frequency. Because the capacitance of *C1* is very high with respect to that of *C2*, it has negligible effect on circuit tuning.

Nonlinear Parallel Resonant Circuit

It is well known that the current in the line supplying a parallel-resonant circuit dips to a low value when the circuit is tuned to resonance at the generator frequency. If a voltage-tuned element is included in the parallel-resonant circuit, the circuit will then resonate at only one value of input voltage. The line current will then decrease at this voltage level, showing a negative slope.

Fig. 5A shows a circuit for displaying this negative-resistance effect. The parallel resonant circuit is composed of air-core coil (*L*) and a 50 µf. (µµf.) Varicap semiconductor voltage variable capacitor (*C2*). *C1* is a blocking capacitor (.005 to .01 µf.) whose capacitance is so high with respect to *C2* that only the latter determines the circuit tuning. The values of *L* and *C2* are chosen such that the zero-signal-voltage resonant frequency of the circuit is somewhat lower than the generator frequency. As the generator voltage ($E_{R.F.}$) is increased, the current ($I_{R.F.}$) increases from zero to point *A* in Fig. 5B. The increasing voltage reduces the capacitance of *C2*. At the particular level of signal voltage, the corresponding *C2* value tunes the circuit to resonance at the generator frequency, and the line current dips to point *B*. As the voltage is increased further, the capacitance decreases still more, tuning the circuit above resonance, and the current again rises to point *C* and beyond. Along the negative slope, *AB*, the current is decreasing as voltage is increasing.

For best results, the generator frequency should not be lower than 20 mc. The higher the frequency, the more pronounced is the negative-resistance effect.

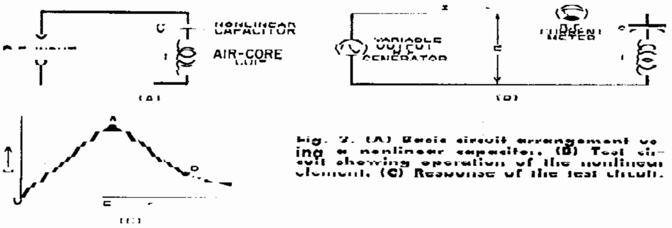


Fig. 3. (A) Basic circuit arrangement using a nonlinear capacitor. (B) Test circuit showing operation of the nonlinear element. (C) Response of the test circuit.

Diodes at Higher Frequencies

At high radio frequencies, the combined action of nonlinear capacitance and a.c. rectification provided by the semiconductor voltage variable capacitor gives rise to an a.c. negative-resistance effect (as well as to hysteresis, in some cases).

Heizman has described a microwave setup in which the capacitor diode is operated in a tunable waveguide.[5] The negative resistance and hysteresis obtained with this arrangement have been utilized for switching at microwave frequencies. The response curve is similar to those of Figs. 1B and 3C.

The conventional point-contact germanium diode has been known to exhibit negative resistance at very high frequencies.

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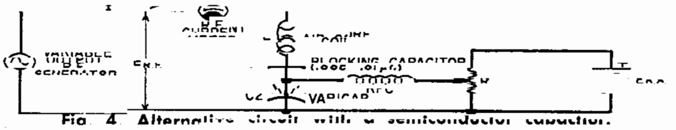
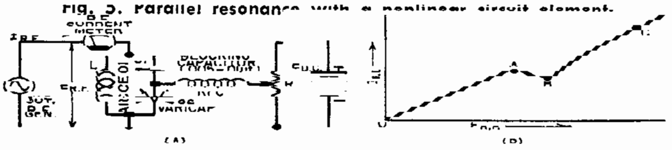


Fig. 4. Alternative circuit with a semiconductor capacitor.

Fig. 5. Parallel resonance with a nonlinear circuit element.



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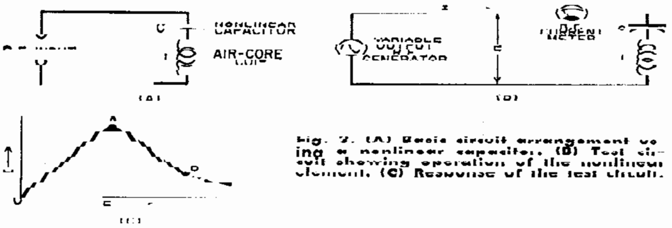

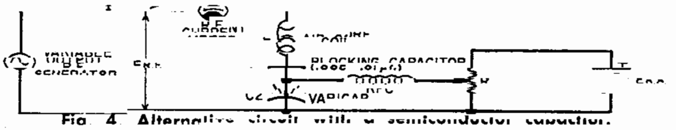

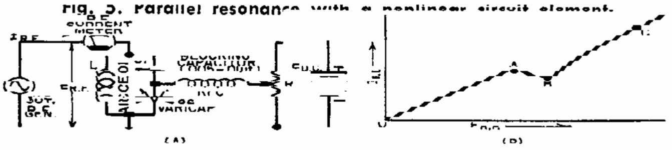

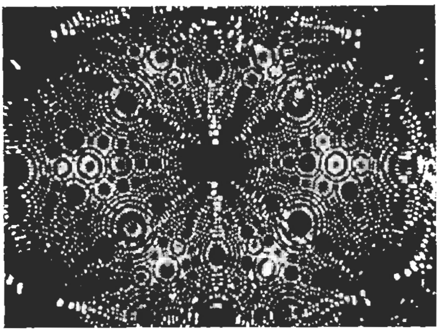

Crystalline structure of tungsten is shown on photomicrograph taken with field ion microscope. Each luminous spot in the photomicrograph represents an individual atom of matter.

Another offshoot from the early days of microscopy is the flying-spot ultraviolet microscope. The original ultraviolet instrument had several important defects which kept it from becoming widely used back in the early years of the century. One of the most important was that ultraviolet light quickly kills most forms of microscopic life which scientists were interested in observing. (It shared that fault with the electron microscope, of course.)

But two researchers at the University of Texas came up with a variation a few years ago which overcame this problem. They generated a spot on the face of an ultraviolet cathode-ray tube, which they swept in a raster through an ultraviolet microscope onto a specimen they wanted to study. The spot scans the specimen just as the beam in a TV camera scans the scene before it. Under the specimen, a photomultiplier tube collects the light, which varies in intensity as the transparency of the specimen it is sweeping varies.

The fluctuating signal developed by the photomultiplier is used to modulate the beam of a television picture tube, which is sweeping in synchronism with the ultraviolet spot. Since the spot is small and sweeps rapidly across the specimen, it has no effect on the organism being studied.

Although the combination of electronics and microscopy has already produced results of incalculable value, it seems likely that its future contributions may be even more spectacular. *RCA's* Dr. V. K. Zworykin, a pioneer in the field, recently put his thoughts on the electron microscope and its importance this way:

"Today, we know that the electron microscope has opened a great new dimension for human exploration in the world which we once labeled submicroscopic. The knowledge that has already resulted is surely only a small portion of that which has been brought within our ultimate reach as science continues to apply the electron microscope to the endless task of research." ▲

Negative-Resistance Devices

(*Continued from page* 51)

North observed that individually welded whisker diodes showed this effect when used as v.h.f. superhet converters.[6]

Such a.c. negative resistance has been observed in some conventional diode tubes operated at u.h.f.[7,8] This is a secondary effect resulting from electron transit time in the tubes. The mechanism involves the *dynamic* plate resistance of the diode, which decreases at ultra-high frequencies. When the transit time equals the period ($1/f$) of the applied voltage, $R_p=0$. At higher values of transit time, R_p is first above then below zero, its oscillating curve showing a negative slope in some portions.

Feedback Amplifiers

An amplifier provided with the proper amount of positive feedback may present negative resistance to circuitry connected to its input terminals. This applies to amplifiers of all types, such as vacuum-tube, transistor, magnetic, dielectric, and varactor. It is this very property that is utilized so widely in oscillating and regenerative circuits; the negative resistance provided by the feedback amplifier cancels the losses of the tank circuit into which it operates. A familiar example, in which loss cancellation results in a large increase in figure of merit, is the "*Q*"-multiplier.

The grounded-grid amplifier[1] operates very effectively as an a.c. negative-resistance device and has been exploited in telephony as a two-way repeater.

A general limitation of all a.c. negative-resistance devices is their requirement of an a.c. supply, which is sometimes inconvenient and which always limits the maximum speed at which the device operates. When a.c. supply and circuitry are already provided, however, or the application is of an a.c. nature to start with, and the supply frequency is high enough to permit maximum desired operating speed, a.c. negative-resistance devices offer distinct advantages. ▲

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