WHAT HAS RESISTANCE, CAPACITANCE, INDUCTANCE, COUNTER-EMF, AND EVEN NEGATIVE RESISTANCE?

The Ubiquitous NEON LAMP

BY JIM KYLE

WHEN SIR WILLIAM RAMSAY and M. W. Travers in 1898 first distilled neon from 15 liters of liquid argon, they surely didn't know that they were lighting up the world with millions of garish electric signs. They probably didn't realize either that they had found the basis for the glow lamp—a device that eventually would be one of the important components in electronic curcuits.

The neon glow lamp is a relatively "old" device. In the 1940's it was principally used as a low-brightness indicator light. About the same time, its voltage-regulating qualities were recognized. Simple audio oscillators with neon lamps as the only active elements were built 15-20 years ago, but only within the past 10 years have designers begun to realize the number and scope of electronic circuits in which the neon lamp can perform a unique service that is reliable and economical.

As a computer element, the neon lamp performs a memory function and, as a bonus, gives visual indication of the stored information. The neon-lamp oscillator converted to a frequency divider is used in electronic organs to produce six-octave coverage from 12 master tone generators. In digital logic circuits, certain characteristics of the neon lamp make it an excellent on-off switch. Other new applications include improved voltage regulation, time delay and (in conjunction with photocells) control.

Basic Characteristics. The usual neon glow lamp consists of two electrodes (an anode and a cathode) in a miniature glass bulb filled with a gas which is usually *not* pure neon. Commercial neon almost always contains traces of both helium and argon; and mixtures are often used purposefully to achieve specific electrical characteristics.

Not all neon lamps have only two electrodes. Some lamps have a third electrode so that the device can be "triggered" with lower applied energy than is required by the conventional two-element lamps.

The gas within the lamp acts as an almost perfect insulator until a critical "breakdown" voltage is reached. This voltage ranges from 65 to 200 volts depending on such design factors as electrode spacing, gas pressure, gas mixture, etc. When the breakdown voltage is reached, the gas ionizes and becomes a relatively good conductor of electrical current. At this time, the voltage across the lamp drops to a level less than the breakdown voltage. Known as the "maintaining" voltage, this level ranges from 48 to 80 volts, depending on lamp design and is almost constant regardless of current flow in the lamp. These characteristics are shown in Fig. 1. If the voltage drops below the maintaining level, or if current flow through the lamps drops below the minimum, the gas deionizes and returns to its insulating condition.

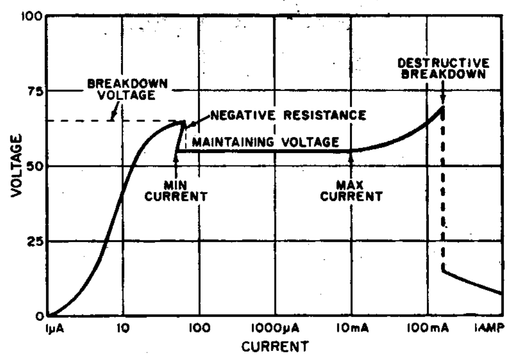

Fig. 1. Typical voltage-current characteristics of a neon glow lamp. The values apply to no specific type. Current flow before breakdown may be much less than indicated (note that the current scale is logarithmic rather than linear). Normal operating region is plateau between minimum and maximum current points indicated. Destructive breakdown changes characteristics so as to render neon useless.

At such times the resistance of the lamp is on the order of 1000 to 10,000 megohms shunted by 0.5 pF, which may be considered to be an open circuit. When the gas is ionized and the lamp is conducting, the resistance is between 1000 and 10,000 ohms. This million-to-one change in resistance is what makes the neon lamp an effective logic or switching element.

The neon lamp is a low-current device; normal operating currents range from 0.1 to 10 mA. Theoretically, a tube such as that whose characteristics are shown in Fig. 1 could be operated at currents up to 100 mA. However, destructive breakdown occurs very rapidly at high currents; and, for this reason, a resistor is always used in series with a neon lamp to limit the maximum current. The size of the resistor is not critical; the higher its resistance, the lower the current; and the lower the current, the longer the lamp life. However, with low current, light output is reduced and the time delay before breakdown (discussed in the next paragraph) is increased. The value of resistance actually used is thus usually a compromise with a range of 47,000 to 220,000 ohms being typical.

Since it takes a finite time for the gas in the lamp to break down and conduct, the neon lamp has a built-in time-delay characteristic. The delay ranges from several hundred milliseconds for slow lamps operated just at breakdown voltage to 4 microseconds for fast lamps driven at high voltage levels. The principal effect of the time delay is to set an upper frequency limit of about 200 kHz for the use of neons in oscillators, frequency dividers, and logic circuits.

The life of a neon lamp frequently exceeds that of the remainder of the equipment in which it is used. Average life rating is about 7500 hours. However, this is *on* time so that the actual life depends on the duty cycle of the circuit. Total life may run as high as 50,000 hours (6 years).

To sum up, the neon lamp has a constant terminal voltage when conducting, undergoes a million-to-one change in resistance between *off* and *on* states, remains *on* after being turned *on* by a brief pulse, and provides visible indications of its *on* state.

Neon-Lamp Oscillator. When a capacitor is charged and discharged at a fixed rate, it can be used in a circuit known as a relaxation oscillator. A neon lamp, a resistor, and a timing capacitor form one of the simplest of relaxation oscillators. See Fig. 2.

The capacitor charging rate is determined by the value of the resistor. When the voltage across the capacitor reaches

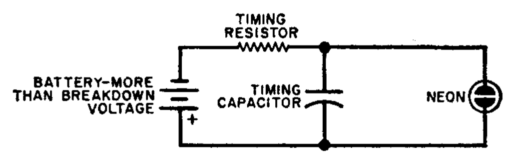

Fig. 2. Basic neon oscillator circuit includes only voltage source, resistor to establish current level, capacitor to be charged, and neon glow lamp. Resistor should have a value of about 100,000 ohms.

the lamp's breakdown rating, it is turned *on* and the capacitor discharges through this newly opened path.

When the capacitor voltage drops below the lamp's maintaining voltage, however, the neon switches *off* and the discharge stops. Thus, after the first cycle of operation, the voltage across the capacitor swings between the maintaining and breakdown voltages—normally a variation of about 10 volts.

The waveform of the oscillating voltage is essentially a sawtooth, and oscillators of this type were used as timebase generators in early oscilloscopes.

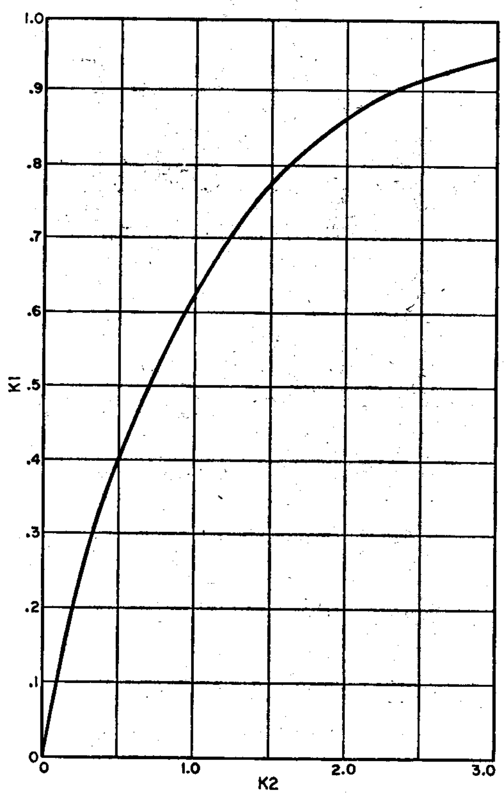

Fig. 3. Relationship of constants K1 and K2.

The frequency may range from as low as one cycle in 45 minutes to as high as 20 kHz.

The frequency of the neon-lamp oscillator is determined by the characteristics of all three components. For a high capacitance, a high resistance, or a large difference between breakdown and maintaining voltages, the frequency is low. The voltage level of the output is determined almost entirely by the difference between breakdown and maintaining voltages.

The actual design of an oscillator is not an exact process; but, since the circuit may be trimmed to the desired operating frequency by adjusting either the resistance or capacitance, the inaccuracies of the design procedure are of little importance.

The first design step is to calculate a constant, *K1*, which is defined as the difference between breakdown and maintaining voltage for the lamp to be used, divided by the difference between supply voltage and maintaining voltage. The value of *K1* should be less than 0.63 for best results. With *K1* calculated, Fig. 3 can be used to determine another constant, *K2*. The *RC* time constant of the resistor and capacitor can then be calculated from the equation

$$RC = K2/\text{frequency}$$

where frequency is in hertz. As a starting point use at least 470,000 ohms for *R1* and vary *R* and *C* as necessary to obtain the proper time constant.

To reach the desired oscillator frequency, it is always necessary to design the circuit to generate a higher frequency. Therefore, the first step in making a new design is to look up the desired frequency in Table 1 and base the design on the "Use Frequency."

Neon-Lamp Frequency Dividers. The circuit of Fig. 4 can be used as a frequency divider. With additional modifications, it can also be used to provide exact frequency division from 2 to 10, while simultaneously preventing the lower output frequency from being fed back to the input.

TABLE 1
Compensation For Ionization

DESIRED FREQUENCY (Hz)	USE FREQUENCY (Hz)
10 - 100	5% greater
200	215
300	330
400	460
500	600
750	900
1000	1250
1500	2100
2000	3000
3000	4800
5000	9000
7500	14.25 kHz
10 kHz	20 kHz
15 kHz	34 kHz
20 kHz	48 kHz

This application of the neon lamp is used widely in electronic organs. A single master tone generator for each of the 12 tones of the musical scale is constructed. Frequency dividers then scale each tone down an octave at a time to cover the desired musical range. Since at least 5 octaves are required for each of the 12

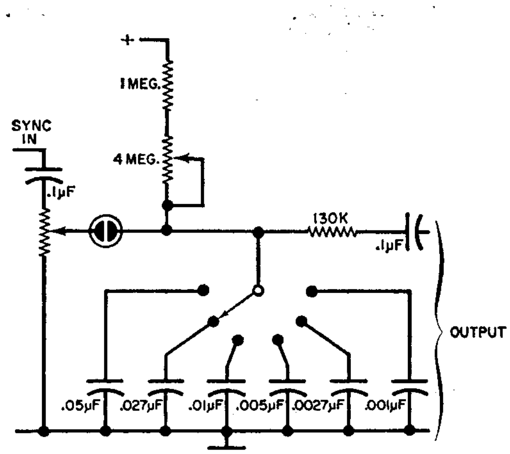

Fig. 4. Neon sawtooth oscillator with facilities to change frequency (six switched positions) and synchronize from external circuit. Supply voltage is usually 3 times breakdown level of the neon glow lamp. This circuit appears in some oscilloscopes.

tones—a minimum of 48 dividers—the simplicity and economy provided by the neon circuit are of great importance.

One stage of such a multiple divider circuit is shown in Fig. 5. This stage has an input at a frequency of 523.3 Hz and produces an output at 261.7 Hz, middle

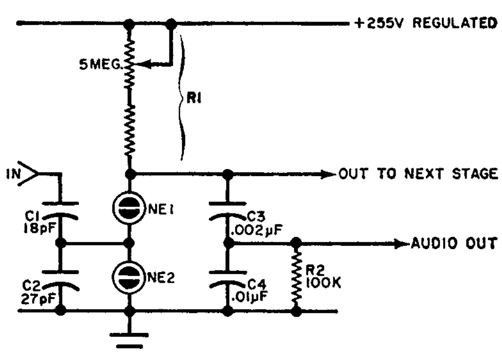

Fig. 5. This is a single stage of a frequency divider using neon glow lamps. Input capacitors aid in preventing reverse feedthrough and the output is chosen to produce a low source impedance. Resistor R1 is adjusted to bring frequency into synchronizing range so that circuit automatically produces integral submultiple of input frequency. This circuit is designed to divide by two; dividing by ten in a circuit very similar to this is often practical.

C on the scale. Here's how it works. The neon lamp of Fig. 6A is actually *NE1* and *NE2* of Fig. 5. It is the use of two lamps and two capacitors which prevents feedback of output signal to the input.

In the absence of any input signal, the circuit oscillates; the frequency of self-oscillation is adjusted by *R1* to be slightly lower than the desired output frequency. Each time the previous stage fires, a negative-going pulse is generated across *C1* and *C2*. The pulse amplitude divides across the two capacitors according to the ratio of their capacitances, so about 40% of the pulse is applied to *NE2*. Unless the neon is already about to fire (due to self-oscillation), the pulse will have no effect. If the neon is just ready to fire, the pulse will cause breakdown.

When *NE2* breaks down, the difference between its firing and maintaining voltages is applied to *NE1*, and it fires also. This causes *C3* and *C4* to discharge at a time determined precisely by the signal from the previous stage. The oscillation of this circuit is then locked at a frequency exactly half that of its input signal if the self-oscillation frequency is slightly less than half that of the input. Wave forms are shown in Fig. 6B.

The values shown for *C1, C2, C3,* and *C4* are not particularly critical, being determined in part by the specific frequencies involved. The ratios of their values, however, play an important role in circuit operation. In this application, it is essential that none of the low-frequency tone finds its way back into the preceding stage. Since *C1* is so much smaller than either *C3* or *C4*, any signal coming back from the next stage (by way of that stage's *C1*) will be attenuated by a volt-

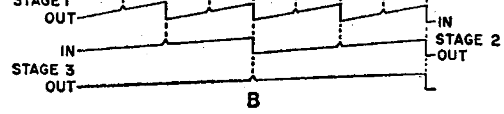

Fig. 6. Frequency divider operation is basically a relaxation oscillator as shown at A. Waveforms at B show how the divider operates. Input of one stage is output of previous stage. Output of third stage is only 1/8 the frequency of the input. Process could be repeated to produce low frequencies.

age ratio of approximately 500:1, or about 55 dB. The large value of *C4* also assures a low source impedance for each of the audio outputs, while the small values of *C1* and *C2* provide high-impedance drive for the neon circuit, to minimize loading of preceding stages.

Neon Lamps as Timers. The high leakage resistance of the neon lamp makes it particularly useful in timing circuits. While semiconductor devices are now being used in many timing applications, the neon lamp offers significant advantages. It can withstand much higher voltages and more severe environmental conditions; and when its life is exhausted, its failure is gradual rather than sudden.

While any type of neon can be used in

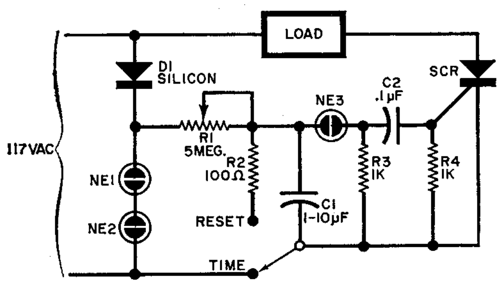

Fig. 7. In this practical timer circuit the output pulse is used to turn on the silicon controlled rectifier (SCR). Inexpensive SCR's may be used for loads up to 150 watts. Load receives pulsating d.c. and cannot be used with a synchronous motor or transformer. Text describes how this circuit works.

timer circuits, best results are obtained with special lamps (such as Signalite's RT2-32-1A) which have a radioactive material inside the bulb to stabilize breakdown characteristics. Ordinary glow lamps may give erratic results in critical applications.

A practical neon timer circuit is shown in Fig. 7. The output of *NE3* is used to trigger an SCR at the expiration of the desired timing period.

With the switch on RESET, both the timer and the load are disconnected from the power line, and timing capacitor *C1* is discharged through resistor *R2*. When the switch is set to TIME, the time circuit is connected to pulsating d.c. provided by *D1* from the 117-V a.c. power line and regulated by *NE1* and *NE2*. The load circuit remains open since the SCR has not been gated *on*.

As soon as *S1* is set to TIME, *C1* begins to charge at a rate determined by adjustable timing resistor *R1*. With pulsating d.c. rather than steady current available, the charging of *C1* takes approximately three times as long as would be indicated by the *R1C1* time constant. When the voltage across *C1* reaches the breakdown point for *NE3*, the lamp fires, partially discharging *C1* through *R3* and producing a positive-going pulse across *R3*. This pulse is coupled through *C2* to the SCR gate, turning the SCR *on* and applying power to the load. Once the SCR is *on*, the timer circuit becomes superfluous although it continues to operate as a low-frequency oscillator. When power is removed from the load by switching to RESET, *C1* is discharged through *R2* and the SCR turns off. The circuit is then ready for another cycle.

Applications in Digital Circuits. Because of the difference between breakdown and maintaining voltages, neon lamps can be used in a number of digital circuits suitable for computers and computer-type devices. One of the simplest of these circuits is the neon flip-flop shown in Fig. 8.

Operation of this circuit depends upon the values of *R1*, *R2*, and *R3*, and the closeness with which the characteristics of the two lamps are matched. If *R1* is equal to *R2*, and *R3* is much larger, the circuit will operate as a flip-flop. When voltage is first applied, either neon lamp may turn on. As soon as one lamp fires, the voltage drop across *R3* lowers the voltage across the second lamp so that it

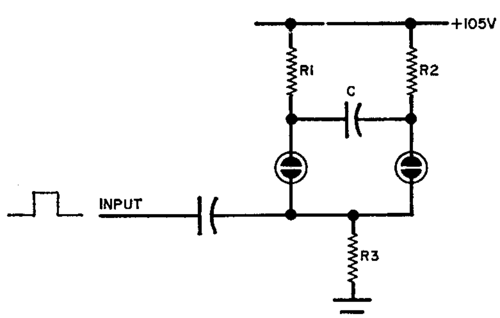

Fig. 8. Flip-flop circuit switches from one neon lamp to the other upon application of a positive-going pulse input signal. If resistor values are not proportioned properly, circuit may either oscillate or act as monostable (one-shot) multivibrator. Practical circuit is shown in next diagram.

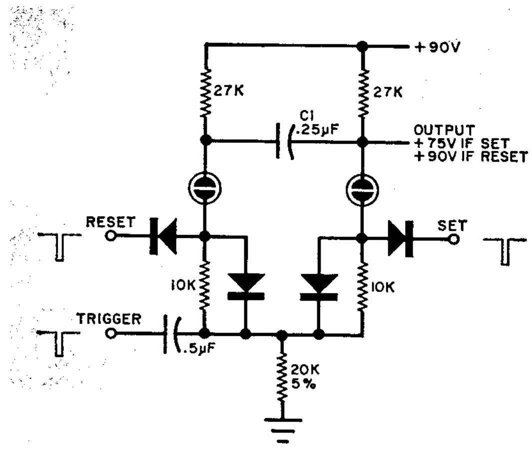

Fig. 9. This circuit could be used to construct binary counters or other digital circuits. Each of the flip-flops may be driven directly by output of preceding flip-flop. Use identical diodes, at least equivalent to 1N91. The 1N34 diode will not work.

can't fire. The capacitor is charged to the voltage developed across *R1* or *R2* (whichever is carrying current). Now a positive input pulse, greater than the difference between breakdown and maintaining voltage, temporarily reduces the voltage across the *on* neon, turning it *off*. The charge on the capacitor is then sufficient to turn the other lamp *on* and the status of the circuit is reversed.

While a single flip-flop of this type demonstrates the simplicity of the basic circuit, some modifications are necessary to allow several to be connected in series for any practical counting applications. Such a modified circuit is shown in Fig.

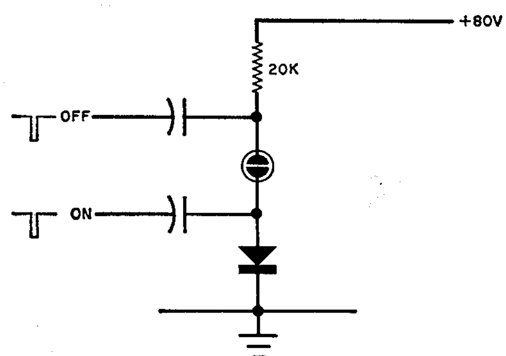

Fig. 10. Single neon-lamp memory circuit is turned on by negative-going pulse at lower input or positive-going pulse at upper input. Circuit turns off with opposite polarities. Supply voltage and resistor value are relatively critical; once turned on, lamp must remain on after pulse has decayed.

9. By permitting easy current flow in one direction but inserting resistance in the other, the diode-bypassed resistors increase the sensitivity of the circuit, so that the major portion of the triggering pulse is delivered to the neon which is *on*. When this neon turns *off*, *C1* turns the other *on*. The diode-gated set and reset inputs permit control of the starting condition of the flip-flop.

A single neon lamp can perform a digital memory function, since a higher voltage is required to turn it *on* than is required to maintain it, once fired. Such a single-bit memory circuit is shown in Fig. 10. Here the supply voltage is between the maintaining and breakdown voltages of the lamp so that it will re-

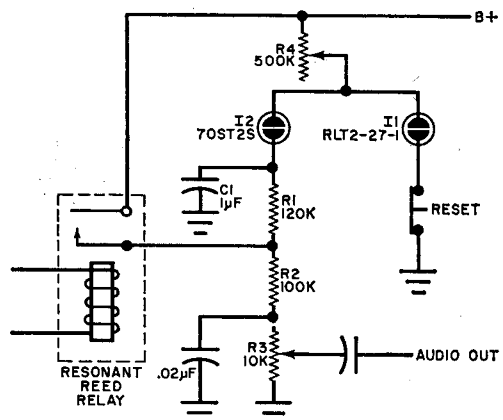

Fig. 11. Practical use of the neon-lamp memory appears in E.F. Johnson "Tone Alert". Neon lamp I1 is visible to operator, lamp I2 is hidden inside metal case of the unit. When call is received, I1 is turned on and stays on until reset switch is operated. Lamp I2 is in audible warning circuit.

main *off* when voltage is initially applied. To turn the neon *on* and thus store a single information bit, a negative-going pulse at least equal to the difference between maintaining and breakdown voltage is applied to the *on* input. This pulse adds momentarily to the supply voltage, bringing it above breakdown and firing the neon.

A memory circuit based on this principle, but using a second neon to provide a starting condition, is employed in E. F. Johnson, Inc.'s "Tone Alert." The basic circuit is shown in Fig. 11.

The Tone Alert is a selective calling system used in CB and Business Radio transceivers. In use, the receiver/speaker is muted until a special audio tone signal is received and the reed relay vibrates at its resonant frequency. Rather than turn on the speaker, the Tone Alert reed system applies B+ supply to the memory circuit.

In the memory circuit, neon lamp *I1* has a breakdown rating of 155 volts minimum while the maximum breakdown rating of *I2* is 120 volts. Thus, when the circuit is first energized, *I2* will always fire first. The maintaining voltage of *I2* is too small to permit *I1* to fire. Since *I1* is the "call received" indicator, the operator knows that no call for him has been received.

When a call comes in and the vibrating reed applies B+ voltage to the junction of *R1* and *R2*, both terminals of *I2* receive essentially full supply voltage and the voltage across it goes to zero. Lamp *I2* switches *off* and *I1* immediately comes *on*, indicating that the call has been received. At the same time, a portion of the square wave produced by the vibration of the reed relay is picked off by *R3* and applied to the receiver's audio circuits to indicate audibly that the call is being received.

If the operator is not present, the audible indication will not be answered. However, when the operator returns, *I1* will still be glowing to inform him that a call came in during his absence. When he answers the call, the "Reset" switch breaks the ground lead of *I1* and extinguishes the indicator. Lamp *I2* then fires, returning the circuit to its initial condition.

Voltage Regulation. The maintaining voltage of a neon diode is almost constant over the full operating range of current. With proper design, the voltage can be held to within 0.5 volt—and even an indicator neon will hold voltage constant within 5 volts under most circumstances.

This fact makes the neon lamp an excellent source of reference voltage for any type of voltage-regulator circuit. For low-current operation, the lamp can be used in the same manner as a VR tube. Such an application is shown in Fig. 12. Here, a neon lamp regulates the screen voltage for a crystal oscillator to provide improved frequency stability.

For moderate-current applications, the circuit of Fig. 13 can be used. The 6U8A tube specified is capable of providing up to 20 mA to a load, and output voltage may be set to any value between 75 and 150 volts. Regulation is to within 1.5 volts under worst conditions; when output voltage is set to 75 (best case), voltage drops by only 0.5 volt at maximum

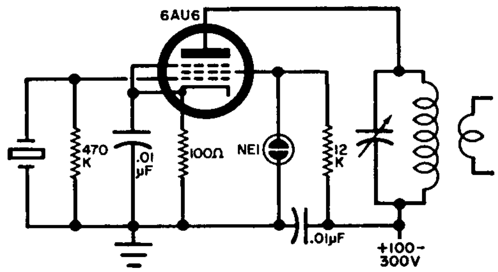

Fig. 12. In a crystal oscillator circuit such as this, the constant maintaining voltage of the neon lamp is used to regulate the screen voltage on the 6AU6, thus providing improved frequency stability.

load. For slightly more current, a 6JT8 may be substituted with modification of the pin connections, or separate 6AU6 and 6AQ5 tubes may be employed.

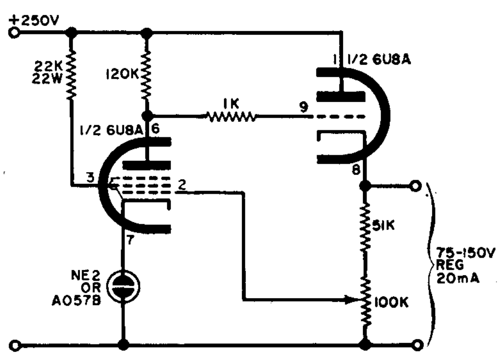

Fig. 13. Here the neon lamp holds a constant voltage on the anode of the first stage of a 20-mA regulated supply. The output is adjustable from 75 to 150 volts due to the feedback to the screen grid. Regulation 0.5 volt for the 75-volt output.

An unusual precision voltmeter which makes use of a neon lamp as its voltage reference is diagrammed in Fig. 14. This circuit's requirements are critical when it comes to the neon; the Z82R10 Signalite unit specified provides a reference voltage across *R2* of 1 ±0.012 volt. Resistor *R1* must be initially adjusted to provide calibration, but the circuit then maintains its accuracy indefinitely. The unknown input is applied to voltage divider *R3* and compared to the accurate reference. When the null indicator (an inexpensive 50-0-50 μA FM tuning indicator, zero-center) indicates zero, the input voltage is equal to the ratio of the total resistance of *R3* to the resistance between its rotor and ground. If a 10-

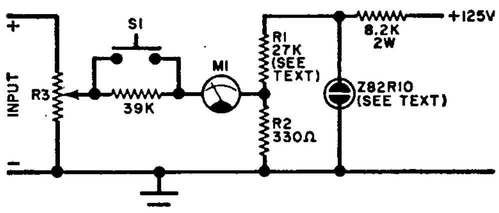

Fig. 14. The neon lamp specified here provides a reference voltage across R2 of 1 $\pm$ 0.012 volt. This is compared to the input in the null-indicating meter, making a highly accurate precision voltmeter.

turn indicator and an accurate 10-turn potentiometer are used, voltage can be read directly. The 39,000-ohm resistor avoids damage to the null indicator in initial stages; when the null is approached, *S1* shorts out this resistor to provide maximum sensitivity.

Miscellaneous Applications. The list of ways in which neon lamps can be used (in addition to the general circuit applications already discussed) is virtually endless. Some specific circuits designed for various purposes are described here.

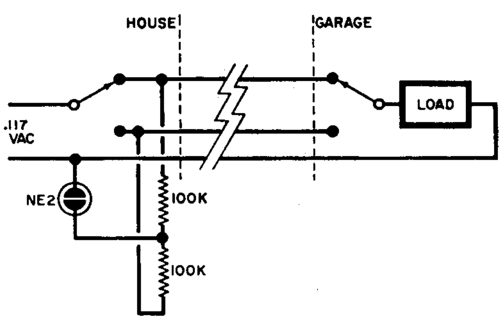

Fig. 15. In a circuit designed to indicate when a remote load is energized, the neon lamp is lit only when switches at both ends are connected to the same side of the power line. The neon indicating circuit can be repeated at load end of the line.

If you have three-way switches in your home or business, you may frequently have wondered whether the circuit they control is *off* or *on*. Since the *off* position is determined entirely by the position of the remote second switch, there's no direct way of determining the position of this switch. But one neon, used as an indicator, together with two resistors, provides a pilot light which may be installed at either end of the circuit. A bonus is the fact that the condition of the bulb or device operated by the switches is also indicated.

The circuit is shown in Fig. 15. It may be duplicated at both switches if desired although the illustration shows only one. Operation depends on the neon's requirement for breakdown voltage before firing. When both switches connect to the same line, both the load and the neon are across the 117-volt circuit and both are on. One of the resistors limits neon-lamp current while the other is disconnected. When the switches are on opposing lines, the load is *off*. Should the load circuit form a voltage divider which permits only half the line voltage to be applied to the lamp; this is insufficient to fire it and it remains dark indicating that the load is *off*. Should the load circuit open, as in the case of a burned-out light bulb, one of the two resistors is disconnected and the neon lamp lights.

Thus, if the neon is *on* and stays *on* when the switch is operated, the load circuit is open. If the neon is *on* but goes off when the switch is operated, the circuit is complete but *on*. If the neon is *off*, the circuit is complete and the load is *off*.

Another neon-indicator circuit provides indication of the sequence in which four s.p.s.t. switches are operated. This circuit, shown in Fig. 16 and requiring a dozen neon lamps, can become the basis of a game to test individual reaction time or can also be applied to more serious problems.

All switches are single-pole single-throw with locking action. The first switch to close causes all three lamps connected to it to light. Each of these three is in parallel with one lamp of another switch, and the supply voltages for these other lamps are reduced to below the breakdown point. Thus, the second switch permits only two lamps to light. This reduces voltage for a second lamp associated with each of the remaining switches, so that the third switch lights only one lamp. Similarly, the final switch cannot light any indicators.

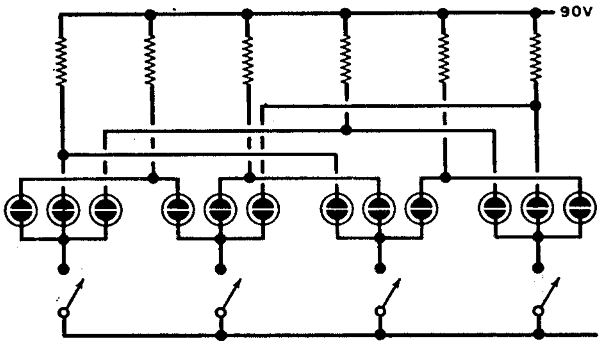

Fig. 16. In this sequencing circuit, when only one switch is closed, three lamps associated with it are lit. Subsequent closing of another switch lights only two of its lamps due to lowered voltage drop across one resistor. Last switch lights no lamps.

Resistor values are not critical—anywhere from 10,000 ohms to 1 megohm should suffice—and neon lamps need be matched only to the extent necessary to assure that none of them breaks down at a level less than the maintaining voltage of any of the others.

An inexpensive VTVM capable of indicating either 9 or 12 volts with an accuracy of 0.2 volt, yet having no moving parts is shown in Fig. 17. While a zener diode is shown for voltage reference, it could be replaced by a third neon lamp and voltage divider if desired. In operation, both plate-circuit lamps glow; and, if the input voltage is correct, both glow with equal brightness. If the input voltage is higher than desired, the HI lamp glows brighter; and vice versa.

The final circuit is a safety tester to check leakage current of a.c.-operated devices. According to Consumers' Union, a leakage current of 100 μA r.m.s. is acceptable, 100 μA to 1 mA is dangerous, 1 to 5 mA shows that repair is needed, and greater than 5 mA is unacceptable. The circuit, shown in Fig. 18 tests for 200 μA, 1 mA, and 5 mA with three different probes. The battery and voltage divider maintain voltage across the neon just below the breakdown level. The ground (GND) lead is fastened to the ground point against which leakage is to be checked, power is applied to the device to be tested, and the probes are touched to the device case one at a time, starting with the 5-mA probe.

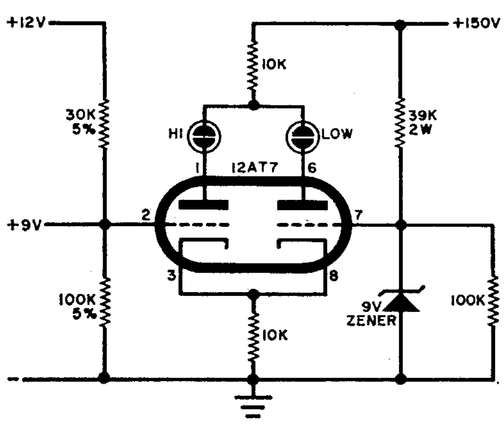

Fig. 17. Inexpensive VTVM has two lamps that glow with equal brightness if the 9- or 12-volt input is correct. If input is high, HI lamp glows brighter, and vice versa. Third neon could be used to replace zener diode as voltage reference if desired.

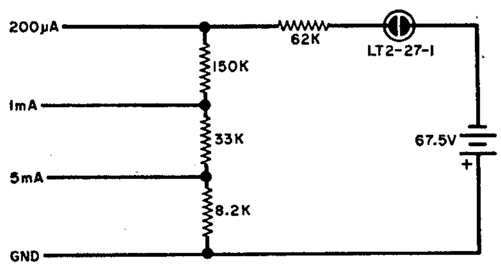

Fig. 18. To check a.c.-operated devices for safety where leakage currents are concerned, this simple circuit uses one neon lamp in series with a 67.5-volt battery. Three separate probes are used. If lamp lights when the 5-mA probe is used, leakage is too high and device is considered unacceptable.

If leakage current exceeds the probe rating, the voltage developed across that part of the voltage divider by the leakage current brings the neon-lamp voltage above breakdown and it fires; otherwise it remains dark and the next more sensitive probe can be tried. If the lamp remains dark for all three probes, leakage current is well within bounds.

Summing Up. Neon lamps have far more uses than most of us suspect. Those given here, although extensive, are only a small sampling chosen to illustrate the variety of possible applications. -30-