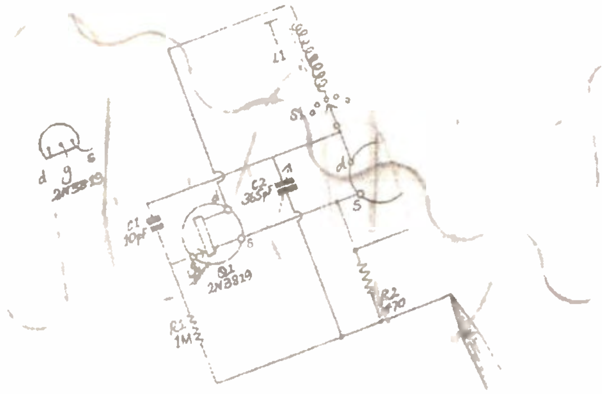
Special Series

PRACTICAL OSCILLATOR DESIGNS



RAYMOND HAIGH

Most text books deal with oscillators in a theoretical way. This series, prepared with the electronics enthusiast and experimenter very much in mind, is intensely practical. Tried and tested circuits are fleshed out with component values, and their vices and virtues are exposed.

PART FOUR – NEGATIVE RESISTANCE OSCILLATORS

THE PHENOMENON of negative resistance has been known and understood since the earliest days of radio. Indeed, its application to oscillatory circuits pre-dates the thermionic valve. Put simply, it occurs when the current flowing through a device or circuit is rising whilst the voltage across it is falling and Ohm's law appears to have been reversed.

Cavity magnetron oscillators, which depend on negative resistance, are used in many homes for generating the microwaves which heat food. They also power the RADAR (RAdio Direction And Ranging) systems which help to ensure the safety of travellers by air and sea.

Some rather unusual transistor circuits which exploit negative resistance, form the subjects of this article.

MAINTAINING OSCILLATIONS

The sudden application of a direct voltage to a tuned circuit formed by an inductor (coil) and capacitor shock-excites oscillations. Because of resistive losses (mainly in the coil), the oscillations gradually fade away, their duration and magnitude being directly related to the Q factor of the tuned circuit (the higher the Q the lower the resistive losses).

Oscillations can be maintained by connecting an amplifier to the tuned circuit and feeding back energy in order to continually repeat the excitation. Earlier articles in the series have described a number of oscillators of this kind.

The feedback eliminates or cancels out the resistive losses. Viewed in this way, it can be said to create negative resistance.

It follows that devices and circuits which display negative resistance, even those which do not function as amplifiers, can also be used to maintain oscillations. An electric arc, Hull's Magnetron, the Esaki or tunnel diode, all have a characteristic which exhibits falling voltage with rising current; i.e. *negative resistance*.

They function by cancelling out the resistance in the tuned circuit so that the oscillations can continue. When circuits of this kind are analysed from the feedback standpoint, the positive feedback is said to exist within the device itself.

NEGATIVE RESISTANCE

Negative resistance is created when the current flowing through a circuit is *rising* whilst the voltage across it is falling, and Ohms law appears to have been reversed. Devices which display this characteristic can maintain oscillations in a tuned circuit by cancelling out its resistive losses.

The technique was used by early radio pioneers before the invention of the thermionic valve. Today, powerful microwave generators and devices on the frontiers of semiconductor technology exploit the phenomenon of negative resistance.

TUNNEL DIODE

A Japanese scientist, Leo Esaki (*b* Osaka, Japan 12 Mar 1925 – now an American citizen), first described his tunnel diode in 1958. A two-terminal device, it represents a particularly vivid example of the phenomena of negative resistance, which enables it to function as an oscillator.

Tunnel diodes comprise a junction of p and n-type semiconductor material and, in this respect, resemble conventional junction rectifiers. Pure silicon and germanium have to be doped with impurities before they can function as semiconductors. Pentavalent impurities, such as antimony, phosphorous and arsenic, convert the silicon or germanium into n-type material. If a trivalent impurity, such as boron, gallium or indium, is added, a p-type semiconductor is produced.

Normal junction diodes have impurity levels of about one part in 10^8. Esaki discovered that if the doping levels are increased to around 1 part in 10^3, the characteristics of the diode are completely changed.

The current/voltage characteristic of a typical tunnel diode is displayed in Fig.1b. Conduction is high in the reverse direction (p side of the junction negative with respect to the n side) and current rises with forward voltages until a peak is reached.

Beyond this point, increasing the forward voltage reduces the flow of current and the diode displays negative resistance. A further increase in

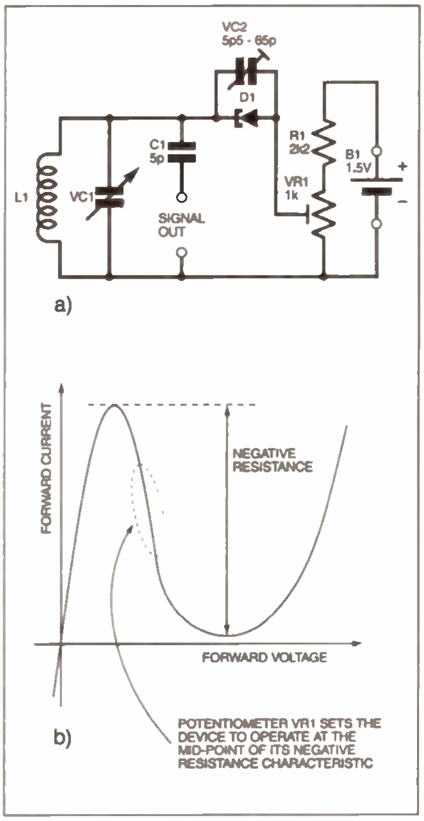


Fig.1a. Typical circuit diagram for Esaki's tunnel diode negative resistance oscillator and (b) tunnel diode current/voltage characteristic.

forward voltage restores the normal current/voltage relationship, and the biasing of the device is critical.

A typical circuit diagram of a negative resistance oscillator using a tunnel diode is given in Fig.1a. The tuned circuit formed by coil L1 and variable capacitor VC1 determines the frequency of oscillation, and the resistor network, R1 and VR1, reduces the voltage of a single cell (B1) to the few hundred millivolts needed to bias tunnel diode D1 to the correct operating point. Preset potentiometer VR1 enables the bias voltage to be adjusted to suit different devices.

When working at medium and high frequencies, shunting the diode with a trimmer capacitor, VC2, makes the circuit more willing to oscillate. As the frequency of operation increases into the v.h.f. and u.h.f. region, this component can be dispensed with.

Tunnel diodes are low-cost, low noise devices, capable of operating at very high speeds. When they were introduced in the late 50s it was widely anticipated that, because of these attributes, they would find wide application in the then new computer industry.

However, they have the disadvantage of low output voltage swing and, being a two-terminal device, there is no isolation between input and output and this causes circuit design problems. These drawbacks, combined with the dramatic developments in transistors, seem to have eased the tunnel diode into an early obsolescence.

MORE NEGATIVE

Following Esaki's discovery of the tunnel diode, more work was done during the 60s on the development of negative resistance devices of this kind. Significant discoveries were made, and much effort seems to have been expended on the invention of acronyms.

In 1964, American scientists, R. L. Johnston and B. C. de Loach, working at the Bell laboratories, discovered the IMPATT (IMPact, Avalanche, Transit Time) diode. The application of a d.c. voltage to these devices results in the direct generation of microwaves.

Three years later, Americans, Prager, Chang and Weisbrod, developed the TRAPPATT (TRAPped, Plasma, Avalanche, Transit Time) diode. Comparatively high efficiencies were claimed for these devices, but the maximum operating frequencies are somewhat lower than those achieved by the IMPATT diode.

In 1968, a British scientist, G. T. Wright, described a new negative resistance microwave device which he called the BARITT (BARier controlled Injection and Transit Time delay) diode. Capable of operating in the microwave region, the BARITT diode shares the low-noise, low-cost advantages offered by other semiconductor structures of this kind.

Although the physics of these devices is extremely complex, they all depend for their operation on the creation of negative resistance, a phenomena first exploited more than half a century earlier. They are not readily available to the home constructor, but any reference to negative resistance oscillators would have been incomplete without a brief mention being made of them.

Ordinary transistors can, however, be persuaded to operate in this way, and a number of circuits will now be considered.

50kHz OSCILLATOR

It is not too widely known that the emitter/collector structure of some small signal transistors can be made to display a pronounced negative resistance characteristic. A circuit which exploits this is given in Fig.2a, where the emitter/base/collector junctions of an *npn* bipolar transistor are connected across a power supply via load resistor R2 and a voltage divider chain comprising preset VR1 and resistor R1.

The characteristic curve of the semiconductor structure is shown in Fig.2b, and the device can be set around the mid-point by means of VR1. No connection is made to the base (b) of the transistor, and the polarity of the supply voltage has to be reversed (supply positive to the emitter (e) of an *npn* transistor).

The impedance of the semiconductor is low, and it is best suited to maintaining oscillations in a series tuned circuit which has a matching low impedance at resonance. Accordingly, the tuned circuit is formed by capacitor C1 in series with coil L1, and the components specified in Fig.2a can be made to resonate at 50kHz.

The output signal is taken from across the coil via coupling capacitor C2. Oscillation continues to be maintained when the output is fed into an impedance as low as 4·7 kilohms, but signal voltage is reduced and preset VR1 has to be set very precisely.

If possible, the input impedance of the accepting circuit should be at least 100 kilohms and, preferably, 470 kilohms. The value of capacitor C2 should be as low as possible consistent with the delivery of sufficient output.

Output and waveform quality depend, to a considerable extent, on the *L/C* ratio of the tuned circuit. Formulae relating inductance, capacitance and frequency were given in Part One (see also Part Three), and the tuning capacitor values suggested there would ensure good results with this circuit. Electrolytic components can be used to provide the comparatively high values of capacitance required for tuning below 100Hz without there being any perceptible deterioration in performance.

A 50kHz OSCILLATOR

The 50kHz negative resistance oscillator is the simplest and, at the same time, the most unusual oscillator in the series. Illustrated in Fig.2, and relying on the semiconductor junctions within a transistor to create negative resistance, it has something in common with Esaki's tunnel diode.

The circuit will oscillate vigorously from low audio frequencies to more than 100kHz and, when carefully adjusted, will produce a good output waveform. Its characteristic curve (Fig.2b) clearly displays falling voltage with rising current.

100kHz TO 10MHz OSCILLATOR

The two-transistor circuit shown in Fig.3 uses changing bias voltages on a directly-coupled pair of transistors to create the rising current/falling voltage characteristic associated with negative resistance. It will oscillate from low audio frequencies to around 10MHz, and is tolerant of high values of capacitance in the tuned circuit.

Waveform quality is reasonably good provided the controls are set to ensure that the output does not exceed 3V r.m.s. The internal capacitance of the circuit is relatively high, and this will slightly curtail the frequency coverages of the coil and capacitor combinations scheduled in Table 1.

The circuit will oscillate vigorously from the lowest audio frequencies to around 150kHz, but 100kHz should be taken as the upper frequency limit for reliable operation. With a reasonable *L/C* ratio in the tuned circuit, careful adjustment of preset VR1 will produce a perfect sinewave output in the region of 5V r.m.s. Current flow through the device is a little more than 4mA when the circuit is oscillating.

All of the transistors listed in Fig.2a will oscillate reliably up to 100kHz, but the various specimens of BC237 and 2N3707 tried produced the greatest output. Readers who wish to experiment with this circuit will be assured of good results if they start by using one or other of these devices.

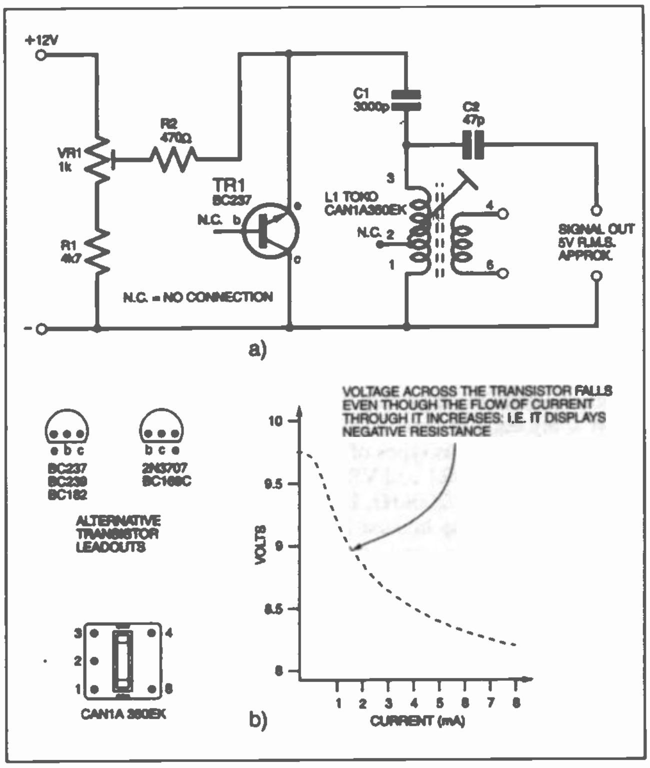


Fig.2a. Circuit diagram for a 50kHz Negative Resistance Oscillator. This circuit exploits the negative resistance characteristic within a transistor. Note that the emitters of npn-*transistors must be connected to supply* positive *for this circuit to function. The current/voltage characteristics of an* npn *transistor connected as shown is given in (b).*

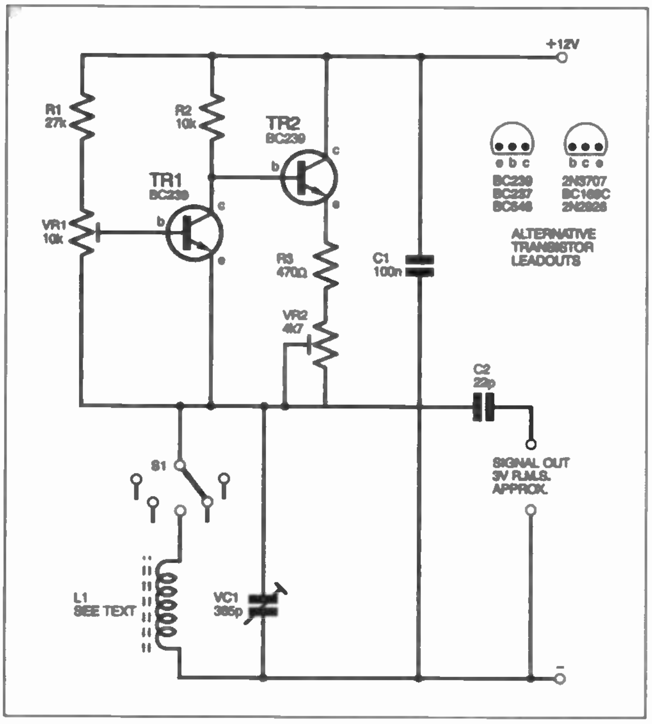


Fig.3. Circuit for a 100kHz to 10MHz negative resistance oscillator.

A number of *pnp* transistors were tried, with the supply polarity reversed, but they could not be persuaded to oscillate.

TWO TRANSISTOR OSCILLATOR

The two transistor combination depicted in Fig.3 is sometimes offered as a tunnel diode substitute. The profile of its characteristic curve is certainly very similar, but the actual operation of the circuit has nothing in common with Esaki's tunnel diode.

When the voltage across the circuit is low, most of the current flows through transistor TR2, and, as voltage increases, so does the flow of current. However, if the supply voltage continues to be increased, a point is reached when transistor TR1 begins to conduct. This transition point is, of course, determined by the setting of TR1's base bias potentiometer VR1.

As the current through TR1 increases, the voltage dropped across its collector load resistor R2 increases. The collector (c) of TR1 is directly coupled to the base (b) of TR2, and the falling voltage reduces the current drawn by the second transistor. The net result is a fall in the current flowing through the circuit, even though the voltage across it is rising; i.e. negative resistance is being created.

When placed in series with a parallel tuned circuit, this two transistor combination will maintain oscillation from audio frequencies up to 10MHz or so. The tuned circuit of Fig.3 is connected on the negative side so that the moving vanes and frame of tuning capacitor VC1 can be grounded. Switch S1 selects inductors, L1, and the output is taken from the "hot" end of the tuned circuit, via capacitor C2.

Earlier comments regarding the input impedance of the accepting circuit apply equally here. Bypass capacitor C1 ensures consistent operation with various types of power supply.

Potentiometers, VR1 and VR2, should be adjusted to get the circuit working at, say, 200kHz, before refining the settings to ensure oscillation across the highest frequency range. They can also be adjusted to produce a good waveform at the expense of output.

This arrangement thrives on relatively high ratios of capacitance to inductance in the tuned circuit (with parallel tuning, this lowers impedance at resonance and increases the Q factor). Capacitors of 2000pF can be wired in parallel with inductors as low as 50μH and the circuit will still oscillate vigorously, with no reduction in output, and the quality of the waveform is improved. This should be kept in mind if the circuit is used as a spot frequency generator.

F.E.T. OSCILLATOR (100kHz to 30MHz)

Although it is claimed that valves possess distinct advantages as the maintaining devices in oscillatory circuits, there are some transistor configurations which valves cannot emulate. One of these is the combining of pairs of transistors of opposite polarity.

An arrangement of this kind is shown in Fig.4, where a complimentary pair of field-effect transistors (f.e.t.s) has been used to create negative resistance. Close scrutiny reveals a variant of the Butler source (originally cathode) coupled oscillator discussed last month.

In Fig.4, f.e.t. TR1 is a source follower and TR2 a grounded gate stage, and the different polarity of the two devices (*npn* and *pnp*) enables the inputs and outputs to be directly connected. This combination results in a "two terminal" device which will maintain oscillation when placed in series with a parallel tuned circuit.

Preset potentiometer VR1 enables the circuit to be set at the midpoint of its negative resistance characteristic. It should be adjusted to ensure that oscillation is maintained at the maximum capacity setting of VC1 on the highest frequency range. The circuit will then perform satisfactorily on all switched ranges.

The internal resistance of the power supply has to be reasonably low or operation becomes erratic on the higher frequency ranges. The value suggested for VR1 should, therefore, be adhered to.

Current changes triggered by the circuit going in and out of oscillation induce voltage changes across VR1, making it difficult to adjust the operating point. Zener diode D1 holds the voltage across the potentiometer constant and makes the setting up process much easier.

If the power supply delivers less than 12V, the value of resistor R1 should be reduced accordingly. With low resistance supplies of 6V or less, R1 and D1 can be dispensed with.

The negative resistance generator (TR1/TR2) is placed in series with the tuned circuit formed by L1 and VC1. The output is taken from the "hot" end of the tuned circuit via capacitor C1, and, again, it should be fed into an impedance of at least 100 kilohms to avoid excessive damping. The power supply is bypassed by capacitor C2.

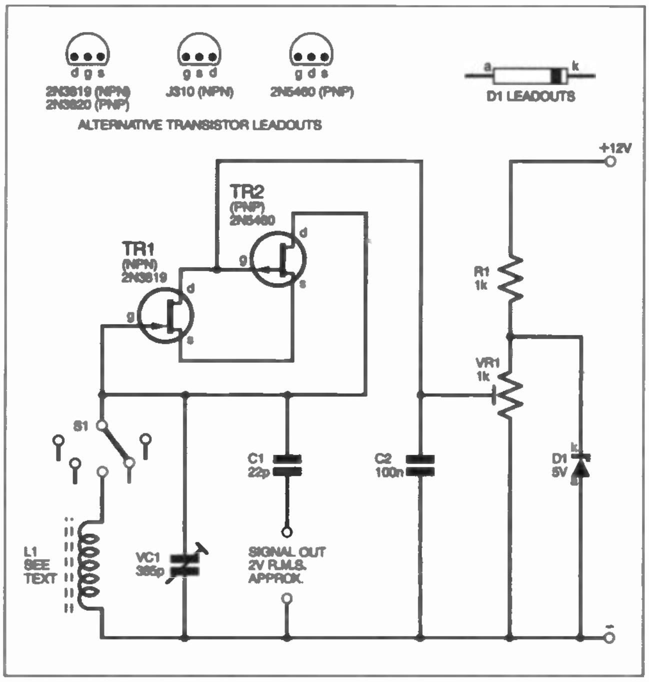


Fig.4. Circuit diagram for a 100kHz to 30MHz negative resistance oscillator using a complimentary pair of f.e.t.s.

TABLE 1:
NEGATIVE RESISTANCE OSCILLATORS

Frequency coverage with Toko coils and a 10pF to 365pF tuning capacitor. (See Fig.4 and Fig 5 for circuit diagrams).

Band	Toko coil L1	Base wiring	Min. Freq. (MHz)	Max.Freq. (MHz)
1	CAN1A350ER	B	0·1	0·25
2	CAN1A350ER	D	0·22	0·64
3	RWR331208N2	A	0·52	1·73
4	154FN8A6438EK	A	1·4	5·4
5	154FN8A6439EK	A	3·8	15·5
6	KXNK3767EK	A	7	30

Notes:
(1) See Fig.6 for details of coil base wiring.
(2) Coverage can be varied, between fairly wide limits, by adjusting the coil ferrite cores.

100kHz TO 30MHz OSCILLATORS

Directly-coupled, complimentary pairs of transistors are used to generate negative resistance in the 100kHz to 30MHz circuits given in Fig.4 and Fig.5.

Bipolar and f.e.t. versions oscillate vigorously, from the lowest audio frequencies to above 50MHz. Biasing arrangements are more complicated with the bipolar transistor circuit, but there are no setting up adjustments.

As with all of the negative resistance oscillators, a single winding, untapped coil will suffice, and this simplifies range switching. The frequency coverages obtained with Toko coils and the specified tuning capacitor are given in Table 1.

Waveform is reasonable, but both circuits display slightly more drift than the oscillators described earlier in the series. They are, however, perfectly suitable for use as simple signal generators.

IN OPERATION

Most combinations of *npn* and *pnp* field-effect transistors should work in this circuit, but only those listed in Fig.4 have been tried. The use of a J310 type ensures reliable oscillation, on the highest frequency range, with the tuning capacitor set at maximum.

Frequency coverage with a 10pF to 365pF tuning capacitor and a range of Toko coils is scheduled in Table 1. Details of the coil base connections are given in Fig.6. Readers who would prefer to wind their own coils should refer to Part One for details.

Signal output is reasonably constant over the various ranges and across the swing of the variable capacitor, but it falls to around 1V r.m.s. at the maximum setting of the capacitor on the highest frequency range. Oscillation is maintained from the lowest audio frequencies to above 60MHz.

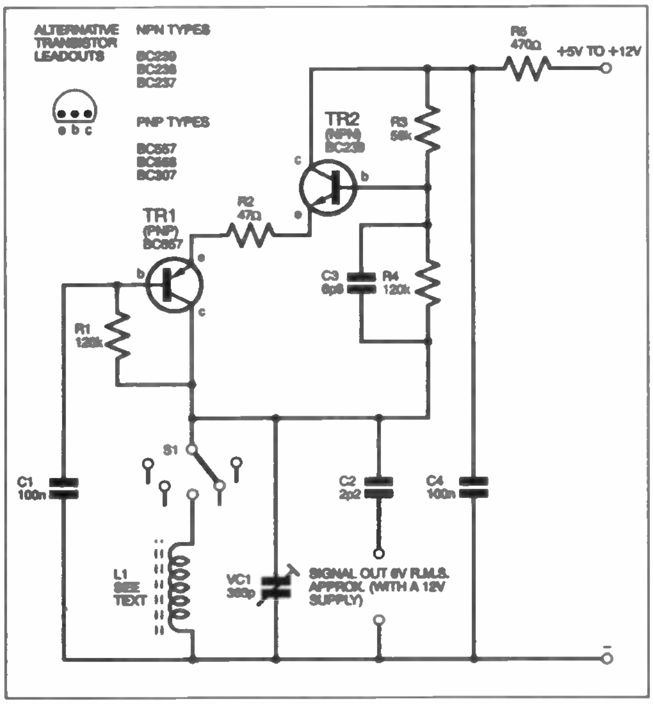


Fig.5. Circuit diagram for a 100kHz to 30MHz negative resistance oscillator using a complimentary pair of bipolar transistors.

If the circuit is to be used exclusively for the generation of low frequencies (100kHz and below), delete the Zener diode and increase VR1 to 4·7 kilohms. At low frequencies, a higher supply voltage and a higher ratio of capacitance to inductance in the tuned circuit ensure a better waveform, and the signal voltage is correspondingly increased.

Above 30MHz, the circuit becomes reluctant to oscillate with high tuning capacitor values, and VC1 should be reduced to 50pF or even 25pF. Leads must be kept as short as possible, and stray capacitance minimised, or the upper frequency limit will be curtailed.

BIPOLAR OSCILLATOR (100kHz to 30MHz)

A bipolar transistor version of the previous circuit is given in Fig.5. Biasing arrangements are more complicated, but the circuit oscillates vigorously and does not require setting up.

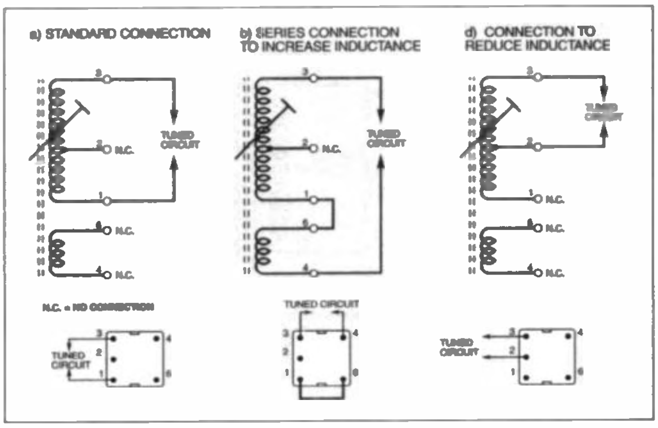


Fig.6. Base connection details for Toko coils.

Base bias is applied to *pnp* transistor TR1 via resistor R1, and voltage divider resistors R3 and R4 fix the bias on the base (b) of *npn* transistor TR2. Capacitor C3 is necessary to ensure adequate feedback at radio frequencies. Low value resistor R2 prevents the circuit behaving erratically. The base of TR1 is grounded by capacitor C1, whilst C4, together with resistor R5, decouples the oscillator from the power supply.

Again, the output is taken from across the tuned circuit, and its r.m.s. value is approximately equal to half the d.c. supply voltage. Output coupling capacitor C2 has been given a very low value in order to attenuate the rather high signal level, which is extremely constant over the swing of the tuning capacitor and the switched ranges.

The circuit has a slightly higher internal capacitance than the f.e.t. version, and this modifies coverage. However, the particulars given in Table 1 still approximate closely to the frequency ranges achievable with the specified variable capacitor. At low frequencies, below 100kHz, operation may become erratic if the ratio of capacitance to inductance in the tuned circuit is low.

Most small signal transistors will work well in this circuit. Those that are known to be suitable are listed in Fig.5.

PERFORMANCE

The field-effect and bipolar transistor versions of the wide range, negative resistance oscillator exhibit slightly greater drift than the conventional feedback oscillators described in earlier instalments of the series. The bipolar version also applies a rough audio modulation to the r.f. output when the circuit is oscillating at high frequencies. Modifying the time constants of the various circuit elements did not cure this.

Both versions of this circuit are vigorous oscillators, capable of delivering a constant output with a reasonably good waveform. They are certainly suitable for use as simple, wide-range signal generators, as audio modulators, or for generating spot frequencies.

MAINS POWER

Readers who lack experience of constructing and commissioning MAINS-POWERED equipment are reminded that the voltages involved can cause DEATH OR SERIOUS INJURY. Anyone who is uncertain about his or her ability to construct or work on equipment of this kind should seek the guidance of an experienced person, use batteries or purchase a commercially produced mains isolated power supply.

PROBLEMS WITH BATTERIES

The current consumed by the transistor circuits included in this series is extremely modest, and well within the capability of small dry batteries. However, the voltage of dry cells varies over quite wide limits, from when they are fresh to the point when they can only just power a circuit.

Voltage reduces imperceptibly, and the unwary can be left wondering why an oscillator won't spring into life when the problem is one of fading batteries. Ageing also effects the internal resistance of dry cells, and this can influence the performance of oscillators, even when bypass capacitors have been provided. There is, therefore, much to recommend a mains power supply unit to the serious experimenter.

LOW-VOLTAGE REGULATED SUPPLY

A circuit diagram for a mains driven Low-Voltage Power Supply, with alternative regulated outputs, is given in Fig.7.

The mains transformer, TR1, primary winding must, of course,

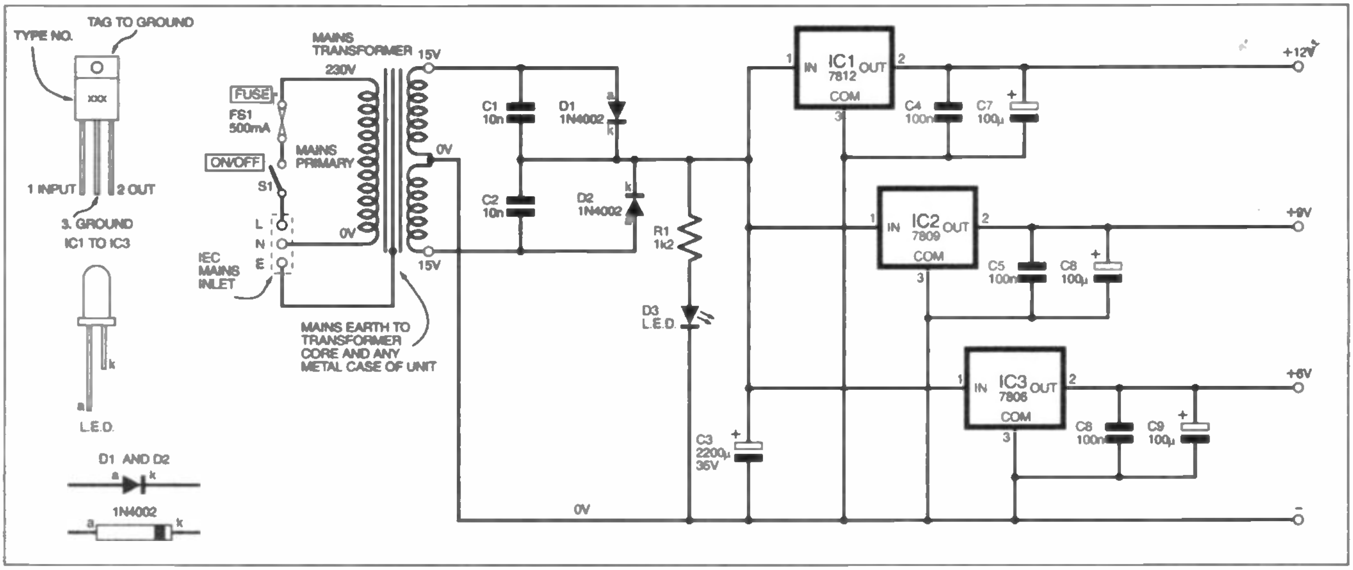


Fig.7. Suggested circuit for a low voltage regulated mains power supply giving outputs of 12V d.c., 9V d.c. and 6V d.c. (Please read warning note, under "Mains Power", given earlier.)

suit the local supply voltage, and the current rating of the secondary winding need be no more than 500mA if the unit is to be used solely for powering the oscillator circuits included in this series. A bench power supply of this kind will, however, be useful for other projects, and a transformer with a 2A or 3A secondary rating would be a sound investment.

The secondary winding output voltages should be 15V-0V-15V for the bi-phase, full-wave rectifier arrangement. This will produce a no-load d.c. voltage across reservoir capacitor C3 of around 21V. Under maximum load, this will fall to approximately 16V, leaving a safety margin above the 15V minimum input required for the 12V regulator, IC1.

An 18V-0V-18V secondary transformer can be used if one is to hand. This will produce an off-load voltage of around 25V, which can exceed the input rating of some 6V regulator i.c.s (this is usually 24V). If an 18V-0V-18V transformer is used, the input to the 6V regulator, IC3, should, therefore, be connected to the output of the 12V regulator, IC1 (i.e., the devices should be connected in tandem) in order to avoid exceeding its input rating.

SAFETY FIRST

The inclusion of a low-current mains fuse, an on-off switch and an IEC mains input chassis plug are good features on equipment of this kind. Mains Earth should be connected to the transformer core and the case of the unit, which should be made of metal. It is best not to connect the mains earth to the output negative rail: electrical interference can be carried into sensitive equipment via the earth wiring.

The specified rectifier diodes D1 and D2 are rated at 1A. If a more powerful unit is contemplated, 3A (1N5402) components must be fitted. Capacitors C1 and C2 are connected across the rectifiers in order to prevent any modulation hum.

The switching action of the diodes will modulate any r.f. current flowing in the circuit at a multiple of the mains frequency, usually 100Hz, and this interference can be picked up by a radio receiver powered by the unit. Modulation hum is tuneable; i.e. it only becomes audible when a signal is tuned in on the receiver. These capacitors should be ceramic components with a minimum working voltage of 50V.

An "on" indicator, comprising an l.e.d., D3, and its dropping resistor R1 is a useful, but not essential, feature.

SMOOTH TALK

The d.c. output from the rectifiers is smoothed by reservoir capacitor C3. An approximate formula for determining the value of power supply reservoir capacitors is:

Value of capacitor in μF = current drain in Amps × 2000.

This formula gives the lower limit of value, and a decent quality power supply should have twice as much reservoir capacitance as this. However, when the supply is regulated, the regulator i.c.s remove much of the ripple which develops under load, and the specified 2200μF will be adequate provided the total current drain does not exceed 1A.

The voltage regulators, IC1 to IC3, are all 1A rated types chosen to deliver dry-battery related voltages. If difficulty is encountered obtaining the 6V and 9V types, 5V and 8V regulators can be substituted without detracting from the versatility of the unit.

If the power supply is to be used to deliver output currents close to the regulator's 1A maximum rating, the i.c.s should be fitted with small heatsinks, especially if an 18V-0V-18V transformer is installed.

Regulator i.c.s produce about 40μV of broadband noise which extends into the r.f. spectrum. The combination of ceramic and electrolytic capacitors connected across each output bypasses this interference to ground.

Outputs regulated in this way have a very low resistance (around 70 milliohms) and a high degree of isolation from one another. This last feature is particularly desirable when powering the different sections of an item of equipment; e.g., an oscillator stage and a buffer stage.

Next month: Crystal controlled oscillators will be considered.