FEEDBACK Phase to Face

Part III

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Op-amps have gained respect for their high quality and the varied range which covers many applications in the vast field of electronics. Whether the feedback is linear or non-linear, resistive or reactive, op-amps are bound to function in their specified set of rules.

A logarithmic amplifier in Fig. 14 uses the base emitter junction of a transistor in the feedback loop. The principle of operation relies on the logarithmic relationship of the base emitter voltage and the collector current of the transistor. A log amplifier is non-linear so that a large input variation produces only a small output variation.

A number of supporting steps are necessary to ensure that the operation carries on unambiguously. First of all, the characteristics of the transistor must lie in the desired log structure. High frequency compensation is often necessary for which a capacitor of proper value across the feedback device will serve the purpose. To counter the practical possibilities of input polarity reversal, which is very unpleasant for the transistor in the feedback path, a protective diode is inserted here. If all the functional refinements are completed, the feedback element governs the output of the system.

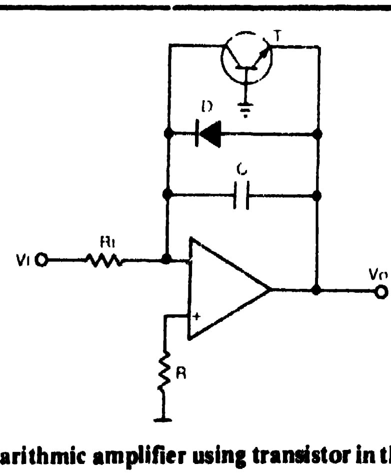

Fig. 14: A logarithmic amplifier using transistor in the feedback loop.

A reactive element in the leading feedback path of an amplifier implies that the system is frequency dependent. A typical example is an integrator or integration amplifier. The output voltage of such an amplifier is inversely proportional to the time constant of the feedback network and directly proportional to the integral of the input voltage.

The circuit in Fig. 15 can be used for a wide frequency range application. The intermediate frequency of the system is set by the values of R and C, while the high frequency range is fixed by the feedback capacitor Cf and R. Resistor R1 provides DC feedback so that the offset voltage cannot continuously charge Cf, thereby leading it into the limiting point. However, R1 may have the effect of limiting the gain of the op-amp at very low frequencies. If the input offset voltage of the op-amp is very low, the non-inverting input can be connected to the ground through a fixed resistance of value close to resistor R.

Recently, there has been an extraordinarily heavy emphasis on CMOS technology due to the availability of complementary P-channel/ N-channel transistors in the monolithic form. For example, 74C04, a CMOS inverter gate, can be used as an amplifier with the help of proper negative feedback. Due to the symmetry of P- and N-channel transistors, negative feedback around the complementary pair develops a self-bias of approximately half the supply voltage. Now the system behaves as if it is biased for class A operation.

Under AC conditions, a positive going input will cause the output to be a negative going variation and vice versa, providing an overall inverse effect. One of the outstanding properties of this arrangement is that it can operate at a very low voltage (3 volts) if the input frequency is below 1 kHz. At about 5V, the frequency range extends to 1 MHz within a possible gain of about 30 dB. The major drawback, of course, is the singing of the output voltage, especially when it approaches the supply level. At present this scheme is used in cases where distortion is not critically significant.

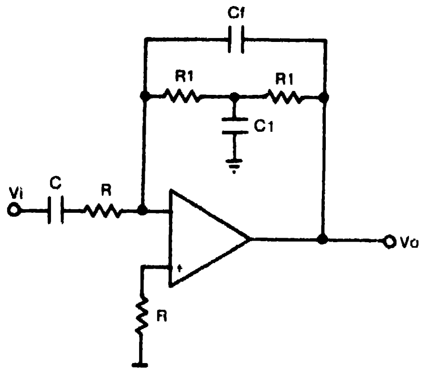

Fig. 15: An integration amplifier can be used for a wide frequency range applications.

Positive feedback

As the system status moves away from the point of normality, deeper into the danger area, there appears a finite possibility that the system will acquire a status of irreversibility. In engineering jargon it is 'catastrophic failure' and in physiological terms it is 'death'. Both these mean a continuous snowballing of excessive parameters leading to a complete loss of function, an obvious result of indiscriminate positive feedback into the system. One should note that in such cases there is no appreciable time lag in feeding back the information within the given frame of reference.

It is interesting to speculate on the role of the factor 'gh' when it lies in between 0 and 1. When it assumes zero value, the system escapes from the burden of feedback of any kind into carefree open loop formation. In this case, the sole authority is 'g', the open loop amplification factor. Any increase in the product 'gh' with identical polarities for both 'g' and 'h' will create a positive feedback. Clearly, the system succumbs to the positive feedback or regeneration by which the closed loop gain shoots up. It reaches infinity or saturation when the product 'gh' equals unity. Some of these properties raise a host of fascinating possibilities.

Frequency selective feedback makes the factor 'h' a function of frequency. Obviously, the signal which is fed back must be in phase (or any integral multiple of 360°) with the input signal to secure regeneration. If the factor 'gh' is close to unity where the close loop gain seemingly assumes infinity, the output of the system will no longer resemble the input signal.

In the strict sense, the system does not require any external input, but it is capable of functioning on its own, replacing the external inputs with the feedback signals. At a frequency decided by the feedback networks, the factor 'gh' falls to zero, forcing the system to go into its open loop set up. This happens at the mid-frequency of the network when the phase angle undergoes 180° phase shift, which together with the presently introduced phase shift of the amplifier makes a total phase shift of 360° and the amplifier output starts tracking in the opposite direction. Hence, even if the frequency of operation of the amplifier is different, it will be forced to operate in and around the frequency of the feedback network.

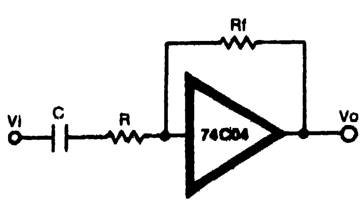

Fig. 16: An amplifier using a CMOS inverter gate with negative feedback.

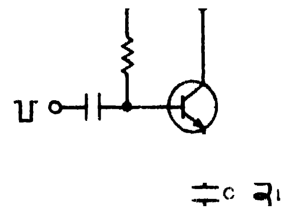

Fig. 17: Shock-excited oscillators for damped sinusoids on excitation.

But things are not as rosy as they appear to be. If the factor 'gh' is less than unity, each succeeding cycle of the feedback from the output will be less than the previous feedback quantum. Eventually, the oscillations will damp or decay and disappear. Shock-excited oscillators, like the one in Fig. 17, provide damped sinusoids on excitation. As soon as a negative voltage is applied to the base, the collapsing magnetic field around the inductor charges the capacitor. However, the oscillations developed because of this decay rapidly due to loss of energy in the resistance.

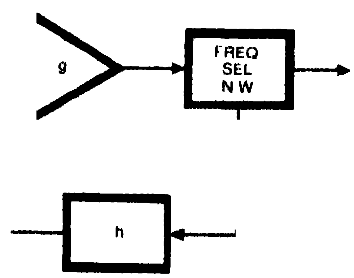

Fig. 18: Block diagram of a Wien bridge configuration.

If the factor 'gh' is greater than unity, the oscillations will tend to grow until a saturated equilibrium state is reached. With the help of specific feedback devices, oscillations like triangular waves, sawtooth waves or waves of other interesting forms can be generated. This is, of course, of inestimable value in digital applications.

The Barkhausen stability criterion, proposed in 1919, lays emphasis on the loop gain of slightly greater than unity for a sustained oscillation. This abstract point of view became more prominent in the later developments. A clearer persperctive emerged mainly by the work of Appleton and Van der Pol in 1926. Starting from relaxation oscillators and multivibrators, a new genre of electronic circuit technology developed in the area of such applications as time base, counters, waveform generators and logical circuits. The main concern was the frequency stability and its range. The principle of harmonic balance introduced by Groszkowski in 1933 led to the development of numerous oscillator circuits bearing the names of their inventors.

Logically, the first problem arising in this field is the one of frequency selective networks which are capable of discriminating frequencies very sharply. A frequency selective feedback path makes the factor 'h' a function of frequency. Several such frequency selective networks are available in the world of electronics.

Wien bridge (sometimes called Wien-Robinson filter) is considered to be one of the most reliable networks to provide a feedback path. It allows one-third of its input voltage to appear at its output. At its mid-frequency or centre frequency (which is the reciprocal of 6.28RC for a symmetrical network), the gain of the loop drops to zero. By selecting proper R and C values it is possible to suppress a predetermined frequency range.

One of the weaknesses, often recited in Wien bridge is that the voltage is not referred to a common ground, rather it is taken from the mid-points of the leading branches as in the case of purely resistive wheatstone bridge.

Another interesting aspect is its phase angle relationship with the input and mid-frequency. Phase angle of its output continues to increase negatively as the increase in its input

Complex Numbers

One question usually asked in high school algebra classes is the root of the equation $x^2 + 1 = 0$. Indeed, it looks simple, but there is a catch in it. It is a fact that there is no real number which can satisfy this equation, rational or irrational. Needless to say, there are a great many practical situations where a system is better explained with such equations. Evidently, a mere collection of rational and irrational numbers would not be efficient enough to establish functional relationships in many systems. What do you make of this grim riddle?

School boys would heave a sigh of relief when you say that the root of the above equation is an imaginary number, another gerund in the mathematical language. By the law of signs, (+k) multiplied by itself is k^2 and so is (-k) multiplied by itself. This is why a number which on multiplying itself gives a negative sign is branded as an imaginary number. Playing with riddles like the one we have just seen, we get a number which when multiplied by itself gives (-1). For us it is easy to grasp the

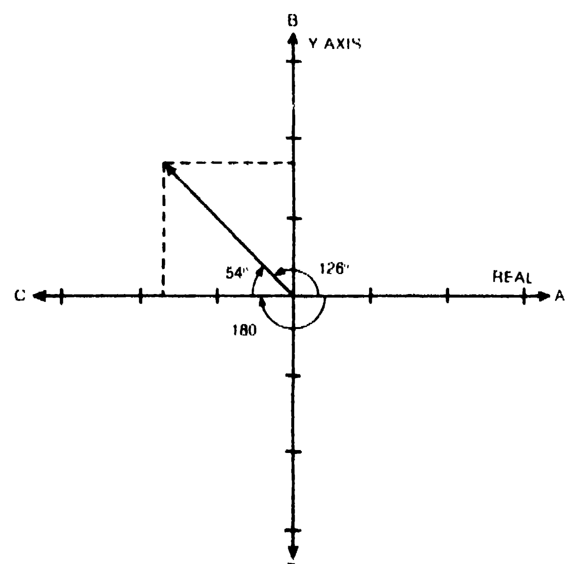

Fig. 1

number with a direction attached to it, such as positive k and negative k or so-called image or back numbers. The mystification of imaginary numbers ends when we are ready to accept the roots of negative numbers as we do in the case of positive numbers.

Assume a semicircle with its diameter passing through the origin of a Cartesian coordinate system. Any perpendicular drawn from a point on the circumference to the diameter will create two right angled triangles within the semicircles. Now, according to elementary geometry, the distance OC equals to the square root of the product OA and OB. If the origin is so situated that the negative side is 5 units and the positive side is 1/5 units, then the height OC equals to the imaginary number, square root of (-1). On the contrary in Euclidian geometry, the sign of OA is ignored and the height OC is expressed only in magnitude.

There is a reflex to identify electrical parameters in terms of pure positive numbers. This ability to ignore what is highly unlikely is a part of our heritage. It is an easy way of concluding the situation quickly and with utmost (never definite) probability. Electricity does a lot of commendable work which is easily perceptible so we do not normally speculate on its intermediate parameters. In fact the function of electronic devices cannot be fully explained in terms of a set of positive real numbers owing to the frequent partnership of real parameters with imaginary numbers.

Euler, an eminent French mathematician who lived centuries ago, introduced the symbol 'i' with a property $i_2 = -1$. This was the auspicious beginning of a new vista of numbers called complex numbers. The versatility of 'i' is so great that it has repeatedly been used by scholars like Gauss, Cauchy, Rieman, Hailton and so on. The accepted outfit of a complex number is (a+ib), where a and b are real numbers. The new born 'i' enjoys a piggyback ride on the coefficient b. Of course, we need not tax our imagination regarding a, the real part of the complex number.

When it comes to electronics, the symbol 'i' would not be a unanimous choice at all, since it has long been recognised as a representation for current. For convenfrequency, until it attains the characteristic mid-frequency. If the input frequency is exactly equal to the mid-frequency of the network, the phase angle undergoes an abrupt reversal from negative 90^{0} to positive 90^{0}, from where it continues to decrease with the increase of the input frequency.

In twin-T filter (sometimes known as double integration selective filter), similar (not identical) characteristics in phase and frequencies are cited. However, because of the common ground for both input and output, twin-T has an edge over the other. The common feature is the increased reliability at low impedance levels.

A symmetrical Wien bridge sinusoidal oscillator is shown in Fig. 20. The resistor-capacitor combination provides a positive frequency selective feedback path around the op-amp, while the resistor 'r' together with an incandescent lamp sustains a negative feedback. The positive feedback is extremely dominant in the circuit operation, since it causes the circuit to oscillate sinusoidally.

The resistor 'r' is normally kept slightly less than twice the resistance of the lamp, so that the closed loop gain is greater than unity. When the amplitude of oscillation increases, the lamp gets heated up, thus increasing its resistance. In the absence of this or a similar arrangement, the system will enter into its non-linear state, introducing distortion. The lamp helps to regulate the amount of negative feedback stabilising the amplitude of the sinusoidal output.

Another protective measure often employed in oscillators is the use of negative feedback. This is highly desirable in op-amps, since in open loop conditions, or when the factor 'gh' approaches unity, the op-amp gain will cause its output

ience, this imaginary number 'i' in mathematics is changed into 'j' the next letter in the alphabetical order though it possesses all the properties of the symbol 'i'. Now, the complex number can be represented as (a+jb), where 'jb' is the imaginary part.

The use of mathematical gerund or operator 'j' in Cartesian coordinate system provides a visual indication of the phase of the potential difference across the reactive and resistive elements. The convention adopted for this is that along OA and OC the positive and negative real parts (which are equivalent to $(-j^2)$ and $(+j^2)$ respectively) are scaled while along OB and OD the operator 'j' takes its positive and negative states respectively. The impedance, current or voltage can now be represented in this complex plane.

It is customary to write a complex number in polar form, as $V = k\angle\phi$, which means that V equals k at an angle of ϕ. If we take $V = a + jb$, then $k^2 = a^2 + b^2$ and $\tan\phi = b/a$.

For example, if $V = -0.9 + 1.2j$, it lies in the second quadrant since its real part is negative and complex part is positive which only the second quadrant can satisfy. Then $V = 1.5\angle126^\circ$. (This is elucidated in this way, $(1.5)^2 = (0.9)^2 + (1.2)^2$, $\tan\phi = 1.2/0.9 = 1.33$ or $\phi=54^\circ$. The angle in the anticlockwise direction is equal to $180^\circ-54^\circ = 126^\circ$ (Fig. 1). Similarly, $Z = 32 + 55.4j$, corresponding to $Z = 64\angle60^\circ$.

According to Euler's theorem, a complex quantity of magnitude 'k' making an angle ϕ with real axis can be expressed in exponential form, as $(ke^{j\phi})$, which is equivalent to $k\angle\phi$. This is very important in the field of electronics because of the simplicity in multiplication and division of the quantities in polar or exponential form. However, addition and subtraction of the polar or exponential forms are extremely tedious. Complex numbers are expressed in rectangular form for the process of addition and subtraction. The quantity $V = a + jb$ in rectangular form is equal to $V\angle\phi=k\angle\phi$ in polar form and $V=ke^{j\phi}$ in exponential form, where $k^2=a^2+b^2$ and $\tan\phi=b/a$.

Now the product of (0+j) with, say, $3\angle60^\circ$ equals to $(1\angle90^\circ)(3\angle60^\circ) = 3\underline{\angle90+60} = 3\angle150^\circ$, while their mutual division gives $3\underline{\angle90-60} = 3\angle30^\circ$. This is the reason why the operator 'j' is often referred to as the operator that rotates a line in the complex plane by 90°.

In LR or CR circuits the voltage and current may not be in league with each other. Their cohabitation is influenced by the frequency of operation. This can be investigated by using a vectorial representation of the total opposition in the network which is a specific combination of resistance (real or in-phase component) and reactance (imaginary or quadrature component).

In LR circuit the total opposition or impedance is $Z=R+jwL$, where w is the angular frequency (6.28 multiplied by the frequency in Hz) and L the inductance in 'henry'. See how the imaginary part takes leave of the circuit at zero frequency or in DC.

For example, a 100-ohm, 100-microhenry circuit operating at a frequency of 100 kHz has an impedance of 118 ohms but offers 636 ohms at 1 MHz and reaches 100

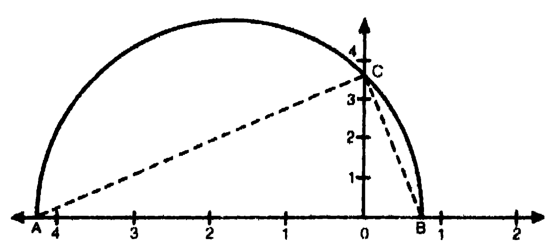

Fig. 2

ohms at zero frequency. This impedance lies in the first quadrant and is equal to $118\angle32^\circ$ while it is $636\angle81^\circ$ at 1 MHz frequency. If we multiply the parameters with current, we get the potential difference across the resistive and the reactive components. This shows that the potential difference across the impedance leads with respect to the real or in-phase components.

In a CR circuit the impedance is similarly defined, which is equal to $Z=R+1/jwC$ or $Z=R-j/wC$. The negative j, here, brings the impedance in the fourth quadrant. For example, a 1k, 0.1 μF circuit operating at 1kHz offers an impedance of $1880\angle328^\circ$, or $1880\angle-32^\circ$. If we multiply the parameters with the current in the circuit, we can see that the voltage lags behind by the same angle with respect to the real or in-phase component.

It is significant in complex representation that the real and complex parts are absolutely independent of each other. Thus the complex number (a+jb) equals to (c+jd) only if a=c and b=d. This is visible in the above example where the parameters were different and possessed the same phase angle in magnitude but were in different directions.

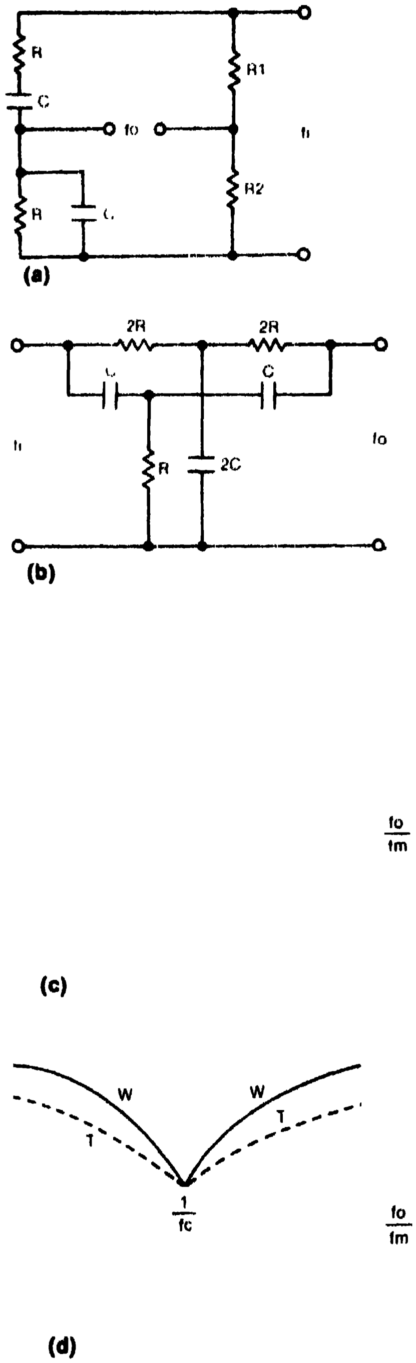

Fig. 19(a): Wien bridge configuration; (b) a twin-T network; (c) phase angle relationship with input and mid-frequency in case of Wien bridge; and (d) the relationship in case of twin-T network between phase and frequencies.

to latch on to the supply voltage level, thereby introducing heavy distortion. A well designed negative feedback around the op-amp fulfilling the requirements of the specific frequency selective network has a tendency to stabilise the amplitude and linearity of the output of the system. This type of oscillator is also called multiple feedback oscillator.

In many systems the manner in which the oscillations

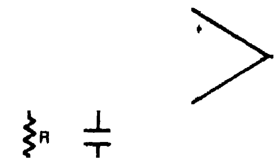

Fig. 20: A symmetrical Wien bridge sinusoidal oscillator.

begin is slightly obscure. The nagging problem in the initial stages of operation is that the positive feedback needs some input to begin with. However, it is easier done than said. Any minute discrepancy in the amplifier symmetry will result in some output which is more than sufficient for the rest of the operations. In most of the cases, it is more difficult to stop the oscillations than to start them, if all other conditions are favourable for oscillations.

Another classic example of multiple feedback oscillator is the twin-T sinusoidal oscillator. Here a double integration technique is employed in the frequency selective feedback path. Behaviour of the twin-T is similar to that of the Wien bridge, except for the common ground facility. The time period of centre frequency is equal to 6.28RC as in the case

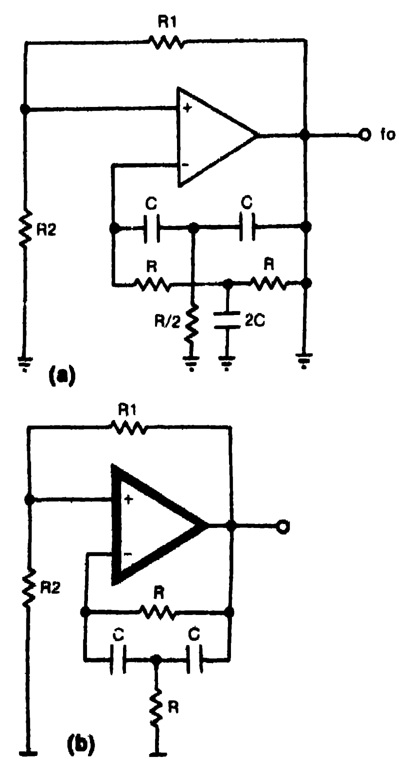

Fig. 21(a): Twin-T sinewave oscillator; (b) sinewave oscillator with single-T feedback network.

of Wien bridge oscillator. When the network is balanced, it acts as a frequency dependent attenuator giving zero output at its centre frequency.

Another striking result which emerges from the architecture of oscillators is the concept of the negative resistance. The live stock operators of the oscillator are lined up so as to project this formidable image. If an inverting amplifier as in Fig. 22 with equal resistors 'r' in the negative feedback path

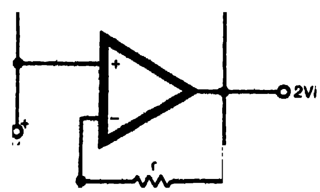

Fig. 22: An inverting amplifier with equal negative feedback resistor.

is considered, the gain of the system is clamped to 2. Now the input voltage Vi will appear as 2Vi at its output. Introducing a resistor R from the output to the input to provide a positive feedback, the input current from the source is virtually divided by R. In other words, resistor R will develop a voltage Vi so as to oppose the input voltage. However, the total voltage from the output to the ground appears as 2Vi.

As far as the source is concerned, the system has a negative resistance equal to R. In principle, the losses in an oscillatory circuit due to heat and radiation, especially at high frequencies, should be minimised. The heat loss or I^2R loss could be reduced to zero or made negative since I is the rms current. This requires that power should be fed to the circuit in some way so that losses due to resistance of the network are overcome.

The phenomenon of synthetic negative resistance is invariably present in a majority of the sinusoidal oscillators and function generators. Negative conductance and resistance are observed under static conditions as well as under dynamic conditions. Since negative resistance circuit elements are always non-linear, the term 'dynamic negative resistance' has greatest significance when defined in terms of the ratio of fundamental components of current and voltage.

A negative variation of conductance implies that a negative increment of current flows in opposition to the positive increment of the voltage that causes it. This means that a negative conductance circuit must always have a power source associated with it. Although various negative resistance effects such as arc discharge, dynatron etc have been known for many years, practical devices simulating negative resistors became available only with solidstate devices and their combinations.

A close inspection of oscillators like Hartly, Colpitts, Clapp, Franklin, Pierce, Meissner, Reinartz, phase-shift etc reveals a similar basic principle of oscillation realised through different means. In all these oscillators, the frequency determining network has stable phase characteristics with a sharply resonant centre frequency. Around the centre frequency there is a rapidly changing frequency response. Freedom from non-linearity, instability, distortion and load variations are the focal points in the selection of an oscillator for a given application from the above mentioned multitude of oscillators.

Although the oscillator circuits described here are designed within the specifications laid down by the theoretical model, they are still unstable for a variety of reasons. Obviously the instability in oscillators is moulded by the reactive elements which may not have a constant phase shift as assumed. By presuming somewhat ideal conditions, one can define the stability factor for an oscillator in terms of its sensitivity to the amplifier phase shift. In a majority of oscillators (one notable exception is the phase-shift oscillator), the stability factor is directly related to the open loop voltage amplification, thus hinting at a further instability due to variations in open loop gain. Supposing that the open loop gain is a constant, one can prove that the stability is maximum for twin-T (0.5g) followed by bridged-T (0.45g and then the Wien bridge oscillator (0.25g).

Voltage regulators with positive feedback are not new. The circuit shown in Fig. 23 is a bistable system with two possible states - Vz the zener voltage and Vd the contact potential of the zener diode. However, the latter state is difficult to acquire, as a result of the presence of positive voltage across the zener due to diode D. When the system is just turned on, the zener voltage is less than Vz and the current through the zener is negligibly small. But very soon rapid regeneration would follow at a rate set by the ratio

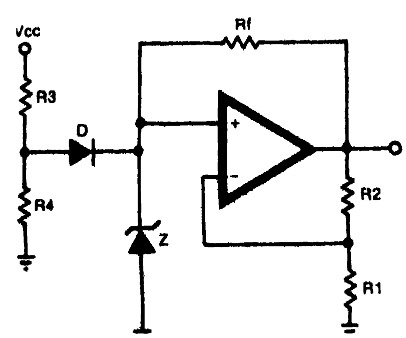

Fig. 23: Voltage regulator with positive feedback.

R2/R1. Moreover, the voltage across the positive feedback resistor is negligible due to the lack of current through the zener, i.e. the output voltage is equal to the voltage across the zener. The process of regeneration stops abruptly, as soon as the zener starts conducting, which provides a reference voltage to the amplifier.

Another modifier of temporal relationship in the positive feedback system might be called 'hysteresis'. The response

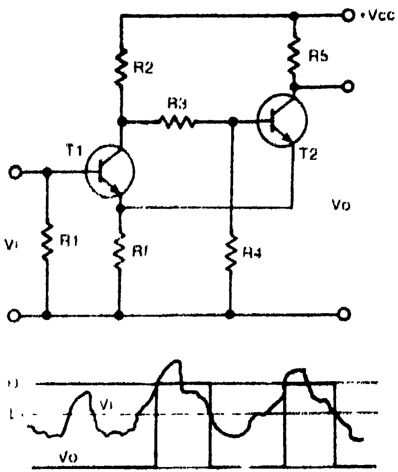

Fig. 24: A basic schmitt trigger configuration.

depends on the direction of change and previous values of the input but not on its rate of change. This corresponds to the hysteresis property found in magnetic materials. Different turn-on and turn-off threshold points in a hysteresis structure leads to a highly predictive action for continuously varying smooth signals. Signal storage due to hysteresis is independent of storage time. In physiological terms it is an 'all or none' response since the signal is either obtained at full amplitude or not at all.

The circuit shown in Fig. 24 is a basic schmitt trigger configuration. Consider the situation when the input to T1 is equal to zero. The forward bias provided by the potential divider R2, R3 and R4 facilitates T2 to conduct. The positive voltage across Rf prevents T1 from conducting while T2 is held slightly below saturation.

When the input voltage is increased to the level of the base voltage of T2, T1 starts conducting. The collector voltage of T1 falls rapidly by the positive feedback between the emitters, ultimately changing the status of both the blocks.

Here, it is a mutual exchange of system status at a much faster rate because status is always away from saturation. Due to hysteresis, the system does not retrace the steps as soon as the input signal crosses the threshold or trip point. A wide range of digital building blocks exploit this property of positive feedback.

Devices like SCR, UJT, triac etc, from the family of high speed switches can be considered as a combination of two or more amplifiers for example, SCR has two transistors interconnected to form a positive feedback pair. Once a signal is applied to the gate (base of the transistor T1) just above the threshold level, an avalanche of regeneration occurs due to the excessive gain of the individual blocks.

(To be concluded)