1

Basic Concepts of Oscillators

1.1 INTRODUCTION

1.1.1 Definition of an Oscillator

An oscillator is a device for producing ac power, the output frequency of which is determined by the characteristics of the device. In Fig. 1.1, the input power P_i at frequency f_i is fed to the device which delivers output power P_o at frequency f_o. If f_o is not correlated to f_i, then the device is an oscillator. Usually P_i is high-quality dc power, but that is not a necessary condition. A *harmonic* oscillator is an oscillator producing quasi-sine-wave oscillation, the frequency of which is mainly determined by two types of energy storage elements, such as inductors or capacitors or equivalent; for example, crystal resonators. It is interesting to note that the sine wave does not necessarily have to be present at the oscillator output terminals, but it does exist somewhere within the oscillator and may be either a voltage or current.

In order to realize harmonic oscillations, the following are required:

1. An active element producing amplification.
2. Positive feedback leading to negative resistance.
3. A frequency selective network which mainly determines the oscillation frequency.
4. A nonlinearity, which is hereafter called "limiting" to maintain the oscillation amplitude in stable equilibrium.

Very often items 2 and 3 are performed by the same components.

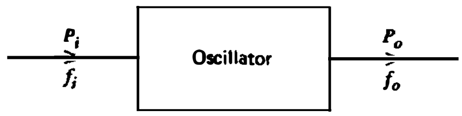

Figure 1.1 Block diagram of an oscillator.

1.1.2 Classification of Oscillators

The oscillators treated in this book have one common characteristic: good frequency stability; but otherwise there are many ways in which they can be classified, for example

1. By frequency range.
2. By power output range.
3. By function; for example, the frequency can be readily modulated or shifted by an externally applied voltage.
4. By the number of active devices; for example, single transistor where the same transistor provides the amplification and the limiting.
5. By the manner its frequency is stabilized for the changes in environment; for example, oven controlled.
6. By the manner of limiting; for example, self-limiting, automatic level control.
7. By the degree of frequency stability; for example, moderate, high.

There are additional classifications, too numerous to mention. For further classifications, see Section 1.5.

To facilitate the classification process, a system of abbreviations has been gradually devised. Some of these abbreviations are:

O	oscillator
X	crystal
LC	inductor capacitor
VC	voltage controlled
TC	temperature-compensated
OC	oven controlled
ALC	automatic level controlled

These basic abbreviations may be combined to form a new abbreviation, for example, ALCTCVCXO would be an automatic-level-controlled temperature-compensated voltage-controlled crystal oscillator.

1.1.3 Crystal Oscillators Discussed in This Book

Detailed discussions are given of oscillators in the frequency range from 0.8 to 200 MHz. Crystal oscillators below this frequency range are rarely used because of the availability of inexpensive, low-power, miniature frequency dividers. However, Chapter 13 will include schematic diagrams of lower-frequency crystal oscillators.

1.1.4 Names of Oscillator Circuits

During the history of oscillator circuit development, names have been given to various circuits; the names were usually the name of the person who originated the circuit, such a Pierce oscillator, Hartley oscillator, and so on. At other times, the name is a part description of the circuit; for example, tuned plate, tuned grid oscillator. In this book, names have also been given to the various circuits described, and great effort has been expended to keep these names consistent with history. However, during the course of time, the names have become somewhat obscured and varied, so that there may be readers who may dispute the choice of name. Of course, the writer makes no claims as to the accuracy of the names and apologizes in advance for any errors he may have made either by commission or omission.

1.2 SUMMARY OF NETWORK THEORY

1.2.1 Two-Terminal Immittance

This subsection states without proof the various forms in which immittance may be expressed and the relationships existing between the different forms. For further information and proofs, one may consult any book on circuit theory of which the number is legion. The notation is standard and universal and will therefore only be explained briefly in the List of Symbols at the end of the book.

1.2.1.1 Basic Definitions and Relations

Rectangular notation:

$$Z = R + jX \tag{1.1}$$

Polar notation:

$$Z = |Z|e^{j\theta} \quad \text{or} \quad |Z|\angle\theta \tag{1.2}$$

where

$$R = |Z|\cos\theta, \qquad X = |Z|\sin\theta \tag{1.3}$$

$$|Z| = \sqrt{X^2 + R^2} \tag{1.4}$$

$$Y = \frac{1}{Z} = G + jB \tag{1.5}$$

1.2.1.2 Derived Relationships

From Eqs. (1.2), (1.3), and (1.5),

$$Y = \frac{e^{-j\theta}}{|Z|} = |Y|e^{-j\theta} \tag{1.6}$$

$$G = \quad \text{———} \tag{1.7}$$

and from Eq. (1.3)

$$G \tag{1.8}$$

From Eq. (1.8), and by defini

$$Q_Z = \left|\frac{X}{R}\right| = \left|\frac{B}{G}\right| \tag{1.9}$$

Figure 1.2 shows the schematic diagram of Z and Y in the rectangular form. The schematic diagram for the polar form does not exist, as it is a mathematical concept.

1.2.1.3 Approximations of Eq. (1.8)

When $Q_Z \geqq 5$,

$$|Z|^2 \approx X^2 \tag{1.4a}$$

and Eq. (1.8) becoı

$$G \approx \frac{R}{X^2}, \qquad -\frac{1}{} \tag{1.8a}$$

1.2.1.4 Some Alternate Specialized Forms

Some calculations are more easily made in alternate representations of Z and Y and some immittance-measuring instruments present their data in these forms.

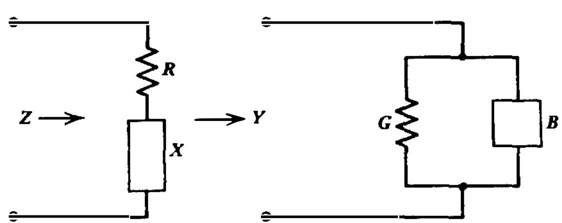

Figure 1.2 Schematic representation of Z and Y.

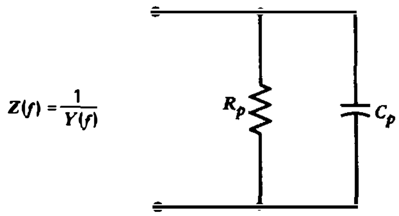

Figure 1.3 Alternate representation of $Z(f)$ for RX meter.

Figure 1.3 shows the data form of the H.P. 250 RX meter. In this figure,

$$R_p = \frac{1}{G} \tag{1.10}$$

$$C_p = \frac{B(10)^6}{2\pi f} \tag{1.11}$$

Figure 1.4 shows the data form of the Wayne–Kerr 100 admittance bridge. The symbols in this figure have already been defined in Eqs. (1.7) and (1.11).

In addition, the very popular Q meter presents its data in Q_Z and C_p.

The H.P. 4815 and 4193 Vector Impedance Meters present their data in $|Z|$ and θ.

The General Radio 1606 Radio Frequency bridge presents its data as R and X.

The General Radio 1402 UHF Admittance Meter, which is useful down to 40 MHz, presents its data in G and B.

1.2.1.5 The $Z = R + \underline{X}$ Representation

The writer in using the $Z = R + jX$ form in long complicated calculations involving multiplication and division of complex immittances found that he made many errors of sign caused by the relationship $j^2 = -1$, and extensive periods of time were expended in correcting the errors. The $Z = R + \underline{X}$ representation was therefore formulated.

All calculations are performed using the $Z = R + \underline{X}$ form and all signs are $+$. Thus no error of sign can be made. At the very end, the $Z = R + \underline{X}$ form is

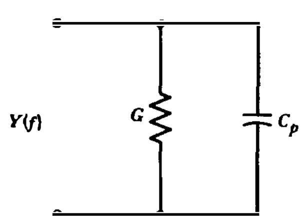

Figure 1.4 Alternate representation of $Y(f)$ for Wayne–Kerr admittance meter.

transformed into the $R + jX$ form, using the following operational rules:

$$\underline{X} = jX \tag{1.12}$$

$$\underline{X}_A \underline{X}_B = -X_A X_B \tag{1.13}$$

$$\frac{\underline{X}_A}{\underline{X}_B} = \frac{X_A}{X_B} \tag{1.14}$$

It should be noted that X_n includes its sign. Thus,

$$3 - jA = 3 + \underline{A}$$

as a special case,

$$\underline{X}^2 = -|X|^2 \tag{1.15}$$

In performing the calculations, care must be taken that values of R and $\underline{X}$ are not added in the sense that apples cannot be added to pears. Also, the sign of X_n must be taken into account.

1.2.1.6 Practical Realizable Tuned Load Values

In many ideal oscillators, the power output increases directly with the value of the transistor-tuned load resistance R_L. Obviously, as higher and higher values of R_L are approached, they become physically unrealizable, primarily due to the frequency of operation, so upper limits to this value, depending upon the frequency of operation, must be set.

The relationship that was developed over long experience is

$$R_L = \frac{10{,}000}{\sqrt{f}} \tag{1.16}$$

(R_L in Ω, f in MHz). This is based on the fact that at 100 MHz, a reasonable circuit capacity is 15 pF and for an operating Q of 10, $R_L = 1000\ \Omega$. Similarly for 1 MHz, a reasonable minimum circuit capacity is 150 pF and for $Q = 10$, $R_L = 10{,}000$. Equation (1.16) is thus derived.

1.2.1.7 Maximum Realizable Resistor Values

Occasionally, it is required to use a resistor which is as purely resistive as possible and as high a value as possible. See Fig. 1.5.

The relationship developed is

$$R_{\max} = 32{,}000/f \tag{1.17}$$

(R in Ω, f in MHz). This is based on the fact that, in a small good noninductive

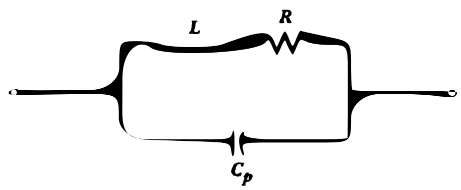

Figure 1.5 Equivalent circuit of a resistor.

high-value resistor, L can be neglected and $C_p \approx \frac{1}{2}$ pF. If a good resistor is defined as $X_{C_p} \geqq 10R$, then Eq. (1.17) results.

1.2.2 Two-Port Linear Network Parameters

Any linear network possessing input and output ports can be represented as in Fig. 1.6. By a linear network is meant:

1 A network composed of passive elements whose values are independent of signal amplitude; or
2 A network composed of active and passive components whose values may be considered independent of small excursions about the mean currents and voltages but are strong functions of the total mean voltages and currents. In this case, the linear relationships apply to the excursions only. This is often called the small-signal network model. Obviously, the model changes when the mean values change.

In oscillators, condition 2 is not valid because the steady-state excursions are not small, but the theory is useful because it will predict whether the oscillator will start, for the excursions approach zero at the starting point.

1.2.2.1 y Parameters

If the relationships between the ports' currents and voltages are written as

$$I_1 = y_{11}V_1 + y_{12}V_2 \tag{1.18}$$

$$I_2 = y_{21}V_1 + y_{22}V_2 \tag{1.19}$$

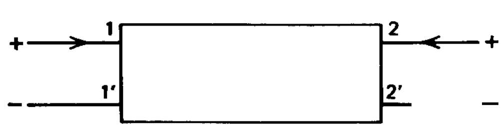

Figure 1.6 Two-port network.

then

$$y_{11} = \left.\frac{I_1}{V_1}\right|_{V_2=0}$$

$$y_{12} = \left.\frac{I_1}{V_2}\right|_{V_1=0}$$

$$y_{21} = \left.\frac{I_2}{V_1}\right|_{V_2=0}$$

$$y_{22} = \left.\frac{I_2}{V_2}\right|_{V_1=0} \tag{1.20}$$

where $V_2 = 0$ means that the output port is short-circuited and $V_1 = 0$ means that the input port is short-circuited.

1.2.2.2 z Parameters

The network relationships are

$$V_1 = z_{11}I_1 + z_{12}I_2 \tag{1.21}$$

$$V_2 = z_{21}I_1 + z_{22}I_2 \tag{1.22}$$

and

$$z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0}$$

$$z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0}$$

$$z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0}$$

$$z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0} \tag{1.23}$$

where $I_2 = 0$ means that the output port is open-circuited and $I_1 = 0$ means that the input port is open-circuited.

1.2.2.3 h Parameters

The network relationships are

$$V_1 = h_{11}I_1 + h_{12}V_2 \tag{1.24}$$

$$I_2 = h_{21}I_1 + h_{22}V_2 \tag{1.25}$$

where

$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$

$$h_{21} = \left.\frac{I_2}{I_1}\right|_{V_2=0}$$

$$h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$$

$$h_{22} = \left.\frac{I_2}{V_2}\right|_{I_1=0} \tag{1.26}$$

It will be noted that h_{11} is an impedance, h_{21} and h_{12} are dimensionless, and h_{22} is an admittance. Also, some of the parameters are obtained under short-circuited conditions, while others are obtained under open-circuited conditions. For these reasons, the parameters are called hybrid.

1.2.2.4 Some Relationships in Network Parameters

1. In all three types, $(\ )_{21} = (\ )_{12}$ for passive networks.
2. For y parameters, as shown in Fig. 1.7, the parameters of composite network Y_c created when connecting networks Y_2 and Y_b in parallel are

$$y_{mnc} = y_{mna} + y_{mnb} \tag{1.27}$$

where m and n are 1 or 2

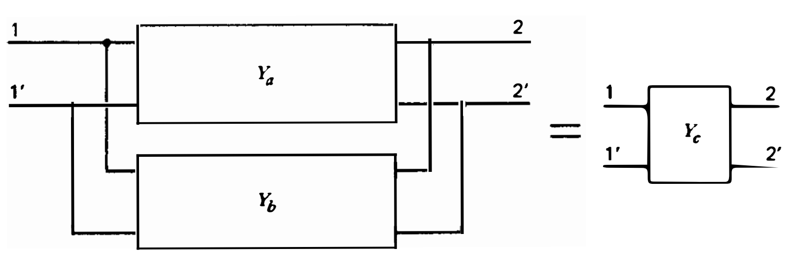

Figure 1.7 Y networks in parallel.

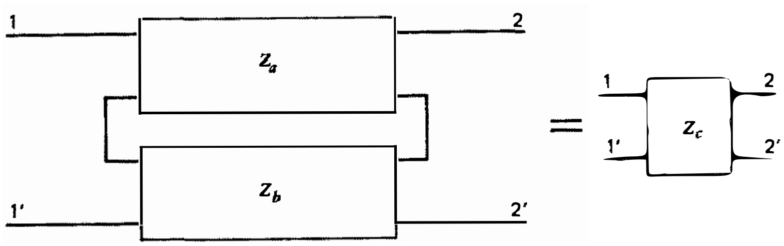

Figure 1.8 Z networks in series.

3 For z parameters, as shown in Fig. 1.8, the parameters of composite network Z_c created when connecting network Z_a and Z_b in series are

$$z_{mnc} = z_{mna} + z_{mnb} \tag{1.28}$$

1.2.2.5 Some Important Relationships in Y Networks

1 For two networks connected in cascade, as shown in Fig. 1.9,

$$y_{11c} = y_{11a} - \frac{y_{12a}y_{21a}}{y_{22a} + y_{11b}} \tag{1.29}$$

$$y_{22c} = y_{22b} - \frac{y_{12b}y_{21b}}{y_{22b} + y_{11b}} \tag{1.30}$$

$$y_{21c} = -\frac{y_{21a}y_{21b}}{y_{22a} + y_{11b}} \tag{1.31}$$

$$y_{12c} = -\frac{y_{12a}y_{12b}}{y_{22a} + y_{11b}} \tag{1.32}$$

2 For a Y network terminated as shown in Fig. 1.10

$$Y_{\text{in}} = y_{11} - \frac{y_{12}y_{21}}{y_{22} + Y_L} \tag{1.33}$$

$$Z_{\text{in}} = \frac{y_{22} + Y_L}{\Delta y + y_{11}Y_L} \tag{1.34}$$

$$Y_{\text{out}} = y_{22} - \frac{y_{12}y_{21}}{y_{11} + Y_S} \tag{1.35}$$

$$Z_{\text{out}} = \frac{y_{11} + Y_S}{\Delta y + y_{22}Y_S} \tag{1.36}$$

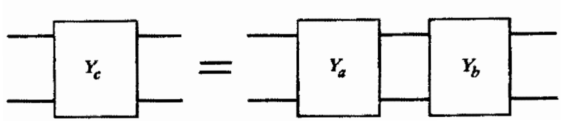

Figure 1.9 Y networks in cascade.

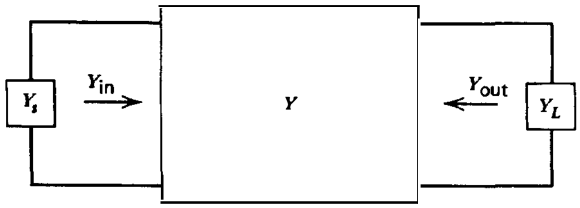

Figure 1.10 Terminated Y ne

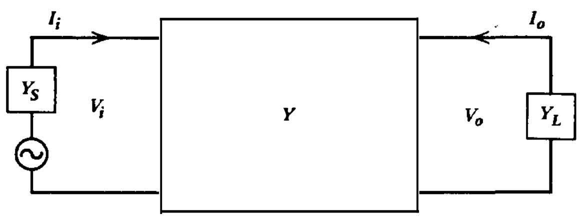

Figure 1.11 Y network fed by generator.

3 For a Y network connected to a generator as shown in Fig. 1.11

$$\frac{V_o}{V_i} = A_V = \frac{-y_{21}}{y_{22} + Y_L} \tag{1.37}$$

$$\frac{I_o}{I_i} = A_I = \frac{-y_{21}Y_L}{\Delta y + y_{11}y_{21}} \tag{1.38}$$

where

$$\Delta y = y_{11}y_{22} - y_{12}y_{21} \tag{1.39}$$

4 Incorporation of the termination into the network, as shown in Fig. 1.12, yields

$$y_{12a} = y_{12b}, \qquad y_{21a} = y_{21b} \tag{1.40}$$

$$y_{11b} = y_{11a} + Y_S \tag{1.41}$$

$$y_{22b} = y_{11a} + Y_L \tag{1.42}$$

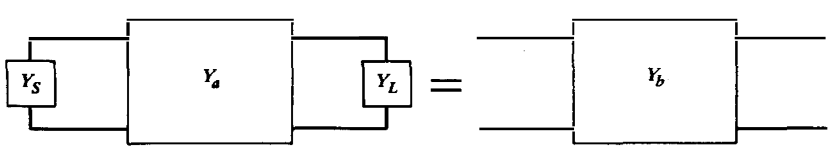

Figure 1.12 Incorporation of the terminations into the network.

Equations (1.40) through (1.42) are important in that they apply equally well to nonlinear networks since the amplitudes of the signals are not changed when the terminations are incorporated into the network. This incorporation will be useful in the analysis of real oscillators.

1.2.2.6 Nonlinear Two-Port Networks

It is possible to configure similar networks for nonlinear two-ports, in which the I, V, Y, Z terms are the effective fundamental components. However, none of the theory presented for linear networks applies, with the exception of item 4 in Section 1.2.2.5.

An interesting and very practical case often found in oscillators occurs when Y_a in Fig. 1.7 is a passive network and Y_b is an active network. Then, Y_c can be considered equal to $Y_a + Y_b$, provided that care is taken to ensure that the voltages and currents in Y_b are equal to those in the active components of Y_c.

1.2.2.7 Transformations between Y and Z Networks

1.2.2.7.1 z to y

$$y_{11} = \frac{z_{22}}{\Delta z}, \qquad y_{12} = \frac{-z_{12}}{\Delta z}, \qquad y_{21} = \frac{-z_{21}}{\Delta z}, \qquad y_{22} = \frac{z_{11}}{\Delta z} \tag{1.43}$$

where

$$\Delta z = z_{11}z_{22} - z_{11}z_{21} \tag{1.44}$$

1.2.2.7.2 y to z

$$z_{11} = \frac{y_{22}}{\Delta y}, \qquad z_{12} = \frac{-y_{12}}{\Delta y}, \qquad z_{21} = \frac{-y_{21}}{\Delta y}, \qquad z_{22} = \frac{y_{11}}{\Delta y} \tag{1.45}$$

where

$$\Delta y = y_{11}y_{22} - y_{12}y_{21} \tag{1.46}$$

1.2.2.8 Final Remarks on Two-Port Networks

The y parameters will prove to be the most useful type in oscillator analysis and design. For an excellent exposition on how these parameters are applied in oscillator analysis, see Ref. 1.1. For further information on the derivation and application of two-port networks in general circuit design, see Refs. 1.2 and 1.3.

1.3 BASIC CONFIGURATIONS OF OSCILLATORS

In considering basic configurations of oscillators, it is convenient to set up oscillator models. There are two different popular models, which upon deeper

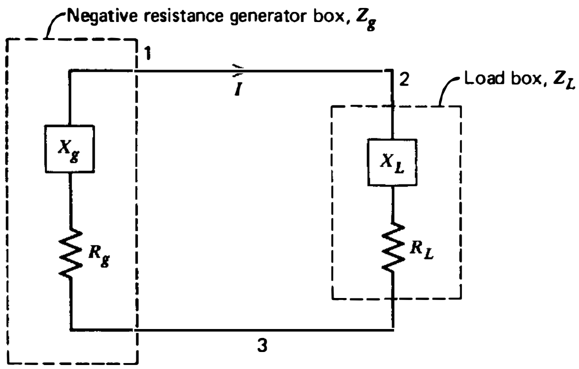

Figure 1.13 Negative resistance model of oscillator.

examination, turn out to be the identical model for 3-terminal active devices. Both models are valid for nonlinear circuits (if it is kept in mind that the model component values change when the signal amplitudes are changed).

1.3.1 The Negative Resistance / Conductance Models

Figure 1.13 shows an oscillator negative resistance model. R_g is a negative resistance, the absolute value of which decreases as the signal amplitude increases. Initially at small amplitudes, $R_g > R_L$. As the amplitude increases, R_g decreases until $R_g = R_L$. The oscillator is then at equilibrium and assumes the frequency of operation at which $X_g + X_L = 0$. Thus, the following is true at equilibrium:

$$R_g = -R_L \tag{1.47}$$

$$X_g = -X_L \tag{1.48}$$

Figure 1.14 shows the dual version of the model of Fig. 1.13. In this figure, G_g is a negative conductance, the absolute value of which decreases as the

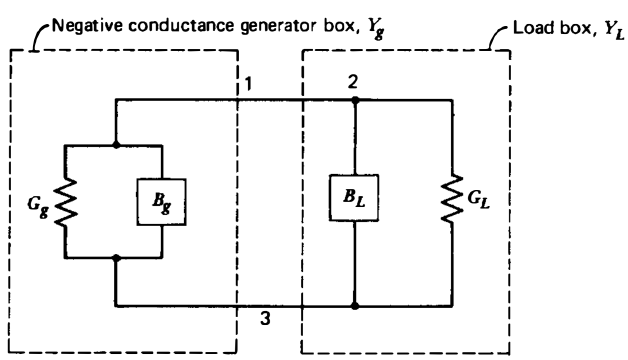

Figure 1.14 Negative conductance model of oscillator.

signal amplitude increases. When G_g reaches G_L, the oscillator is at equilibrium and assumes the frequency at which $B_g + B_L = 0$ so that the equations at equilibrium become

$$G_g = -B_L \tag{1.49}$$

$$B_g = -B_L \tag{1.50}$$

Both models are equally correct and the choice of models depends only upon which model is more suitable in the calculations for the particular application.

A very interesting and important point is that in a given oscillator, no matter what components are allocated to the g and L boxes, the values of the real and imaginary immittance components change but Eqs. (1.47) through (1.50) will always be satisfied by those values.

The models are remarkably simple and they directly provide sufficient information to design oscillators including the amplitude values, provided that the behavior of Z_g or Y_g is known. They are very useful in analysis, experimental verification, and in analysis combined with experimental verification.

At this point, only the negative conductance model will be used but it is to be remembered that anything done with this model can be duplicated in a dual sense with the negative resistance model.

Some interesting applications of the model are presented:

Consider a particular operating oscillator. The g and L boxes are configured in any manner except that all the active devices are in the g box. The operating frequency f is measured. The two boxes are then separated (disconnected) and Y_L is measured at f. Y_g can be computed from Eqs. (1.49) and (1.50).

Furthermore, when f is measured, the current I going into Y_L is also measured. G_L is then varied and for each value of G_L, f and I are measured. From these data, curves of Y_g versus I, G_L, and frequency, which can be used in oscillator design and analysis, can be plotted. The same can be done for variations in B_L.

Some special configurations of g and L boxes are now considered.

1 The passive components which have maximum values of dB/df are placed in the L box and the remaining components in the g box. Again Eqs. (1.49) and (1.50) are valid. By definition, in this arrangement, the g box is called the "llator" and the L box the "osci." Obviously, when the two boxes are connected an "oscillator" is created. This particular arrangement will be used for important analyses in Chapter 17.
2 Another configuration which appears trivial, but in reality is very important, is where all the components are put into the g box. Then from Eqs. (1.49) and (1.50), $Y_g = 0$ (see Fig. 1.15a).
3 Now consider the two-port Y network in Fig. 1.15b. If a voltage exists across terminals 1 and 1′, then by definition, the network is an oscillator since there is no input signal but only output signals. The oscillator load

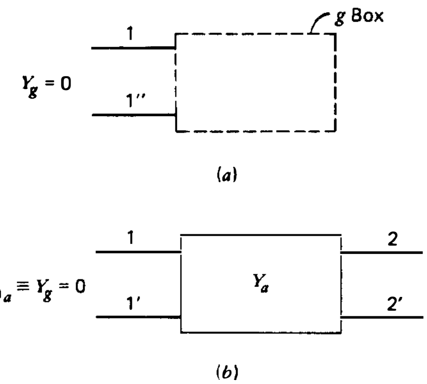

Figure 1.15 Two-port oscillator representation. (*a*) Negative conductance model where all components are in *g* box. (*b*) Two-port network equivalent of the *g* box.

normally connected to port 2 has been incorporated into the network as demonstrated in Fig. 1.12 and Eq. (1.42). (Note that as explained in Section 1.2.2.6, this is valid for nonlinear circuits.)

Obviously the network Y_a is the same as the g box in Fig. 1.15*a* and, therefore,

$$Y_{\text{in}_a} = Y_g = 0 \tag{1.51}$$

Since $Y_{\text{in}_a} = 0$ and $Y_{L_a} = 0$, it follows from Eq. (1.33) that

$$0 = y_{11a} - \frac{y_{12a}y_{21a}}{y_{22a}} \tag{1.52}$$

or

$$0 = y_{11a}y_{22a} - y_{12a}y_{21a} \tag{1.53}$$

or from Eq. (1.39)

$$0 = \Delta y_a \tag{1.54}$$

where Δy_a is called the determinant of network Y_a.

Equation (1.54) is important because it states the conditions necessary for oscillation for a Y_a type of network. This equation will be used later in the section on oscillator design.

1.3.2 The Feedback Oscillator Model

Figure 1.16*a* shows one form of a feedback oscillator model called the *y* model. In this model, A is an amplifier of variable gain, $|A|\angle\theta_A$ and β is the feedback network and has the transfer function $|\beta|\angle\theta_\beta$. Both A and β are strong

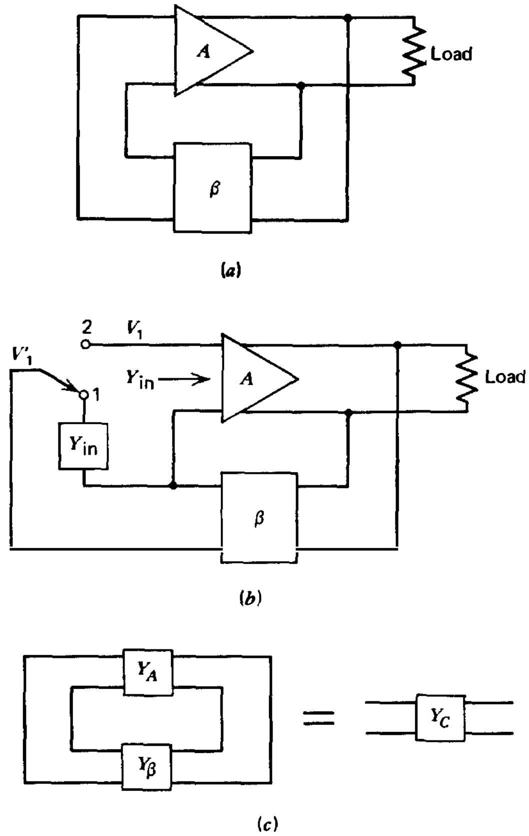

Figure 1.16 Oscillator feedback model. (a) Basic model. (b) Model for calculating A_L. (c) Transformation of (a) into two-port network Y_c.

functions of the operating frequency f. In general $\partial\theta_\beta/\partial f$ is very large in stable oscillators.

Figure 1.16b shows the setup for calculating the open loop gain

$$A_L = \frac{V_1'}{V_1} = A\beta$$

when the switch is in position 1.

When $|A_{L_0}| > 1$ and $\theta_{A_{L_0}} \approx 0$ or $2\pi n$, where n is an integer, the system will oscillate when the switch is transferred to position 2 since V_1' is then the same as V_1. The loop is closed and

$$A\beta = 1 \tag{1.55}$$

$$\theta_A + \theta_\beta = 0 \quad \text{or} \quad 2\pi n \tag{1.56}$$

where n is an integer or in rectangular coordinates at oscillation,

$$\mathrm{Re}(A\beta) = 1 \tag{1.57}$$

$$\mathrm{Im}(A\beta) = 0 \tag{1.58}$$

Equation (1.55) and its derived forms are very often known as the Barkhausen or Nyquist criterion. The reduction of $(A\beta)$ that occurs is called the limiting process.

It has been found convenient to make A_{L_0} the small-signal value which, of course, is always larger, in practical oscillators, than the large-signal value.

If the load is incorporated into the amplifier and the combined load and amplifier shown as Y_A (see Fig. 1.16*c*), the β network now becomes Y_β. Y_β and Y_A then combine into Y_C as given by Eq. (1.27) which is now the same as Y_a in Fig. 1.15*b*. Thus, this model has been converted into the negative conductance model.

Two models which appear different (but are really equivalent) have been developed. The choice of model depends only upon which is more suitable for the calculations and the particular application.

1.4 OSCILLATOR DESCRIPTION AND SPECIFICATIONS

1.4.1 Introduction

The word "oscillator" is ambiguous since it has two recognized meanings:

1. The complete device into which is fed the dc power and out of which comes the desired frequency at the desired power and impedance level. This device is denoted by *oscillator*.
2. That part of the *oscillator*, denoted by oscillator, which generates the desired frequency. It is usually followed by buffer and/or final amplifiers, means of temperature stabilization or compensation, voltage regulation, and so on.

1.4.2 Characteristics of the *Oscillator* versus the Oscillator

The additional circuitry may improve the overall performance in some characteristics and deteriorate the performance in other characteristics. Examples are:

1. Power level increased.
2. Impedance level transformed from the oscillator optimum load impedance to the desired load impedance.

3 The temperature stabilization means will improve the performance under variable ambient temperatures.
4 The short-term stability of the *oscillator* will be deteriorated but the long-term stability will not be affected.
5 The isolation, meaning the effect of change of load impedance upon the frequency, will be improved.

1.4.3 *Oscillator* Specifications

This book is mainly concerned with the design of the oscillator but the user rarely orders an oscillator. He does order *oscillators*!! In doing so, he must prepare specifications which must be satisfied by the *oscillator*. In this connection, it should be noted that the tendency is to overspecify since usually it is much easier to play safe by overspecifying than to exert the efforts required to determine the minimum performance required for the application. For most components, overspecification is often employed to compensate for the gradual deterioration in performance that takes place with time. However, the *oscillator* performance usually improves with operating time, except for catastrophic failures, so the overspecification is not required.

In writing specifications, the following must be considered and included if necessary for the particular application:

1 Output frequency.
2 Short-term stability in the frequency and/or time domain (see Section 1.7).
3 Long-term aging performance.
4 Variation of frequency with load (isolation).
5 Variation of frequency with power supply voltage.
6 Variation of frequency with temperature
7 Frequency settability, coarse and fine.
8 Setting resolution.
9 Minimum number of years for which the *oscillator* may be reset to f, the specification frequency.
10 Frequency stabilization time; for example, 10^{-8} 15 min after turn-on; 10^{-9} 2 hr after turn-on, and so on.
11 Frequency repeatability; for example, 10^{-9} in 8 hr after turn-on, after a turn-off for 48 hr with respect to the frequency before turn-off.
12 Output power into the specified load impedance.
13 Output wave shape and harmonic distortion characteristics. In this connection, it should be noted that the distortion requirement is very often overspecified as many systems fed by the *oscillator* will generate the harmonics anyway.

14 Output spurious signals. (Note: a spurious signal is a signal of frequency not related to f.) Typical spurious signals are power line frequency sidebands. (Also see Sections 18.2 and 18.3.)

15 Signal-to-noise ratio in a specified bandwidth, usually 30 kHz, excluding spurious signals.

16 Power supply power and voltage available for the *oscillator* stating the characteristics of the voltage; for example, 12 V $\pm$ 1%, 10 mV peak-to-peak ripple.

17 Maximum power consumption of the *oscillator* under different environmental and/or operating conditions.

18 Environmental conditions such as temperature, humidity, vibration, shock, acceleration, and nuclear radiation. These conditions must be specified for operating, storage, and/or survival.

19 Dimensions and configuration.

The above demonstrates that the task of writing a proper set of specifications for the *oscillator* requires much effort and substantial analysis of the system requirements.

1.5 OSCILLATOR CIRCUIT CLASSIFICATION

Because the field of oscillator design has such a long history, there are many circuit configurations and many different forms of classification. The choice of which configuration to use in a particular application can only be made after these configurations have been discussed in detail and, therefore, is treated in Chapter 12.

However, an attempt will now be made to create a system of classification as the process of classification will give some insight into the ramifications of oscillator design.

1 Classification by circuit name. This is only important historically and serves the function of identifying the particular circuit; for example, Colpitts oscillator, tuned plate, tuned base oscillator, and so on.

2 Classification by order of stability (e.g., high-, medium-, and low-stability oscillators).

3 Classification by power output (e.g., high, medium and low power). Usually, the higher the power the lower the stability, but there are some exceptions as will be shown later in the discussions on particular circuit configurations.

4 Classification by frequency region (e.g., low, medium, and high frequency).

5 Classification by the type of circuit element(s) which largely determine the frequency (e.g., LC, Crystal).

6 If the element is a crystal—is it used near series resonance or far from series resonance in its inductive region?

7 The type of limiting used (e.g., self-limiting, diode-limiting, ALC limiting, auxiliary transistor(s) limiting). In general, the circuits which have auxiliary devices or circuits for limiting purposes have higher stability.

8 By the ratio, η, of the power output, P_o, to the power dissipated in the main frequency determining element(s), usually called the *drive power*, P_3 or P_x in a crystal oscillator. In general, for a given circuit and a given power output, the stability is lower as η increases. In many circuits, $\eta \ll 1$.

9 Classification by the magnitude of the drive power. In general, the lower the drive power the higher the long-term stability. However, the optimum short-term stability exists at a considerably higher P_x. Thus, one has to compromise on the values of P_x in accordance with the desired performance.

10 Classification by the number of active devices in the circuit (e.g., single transistor, where the one transistor performs both the limiting and signal generating functions. This type of circuit is by far the most popular by reason of its economy. Because of the transistor's dual function, it is also the most difficult to design on a scientific basis. However, when properly designed, it is capable of remarkably good performance. The design algorithms and much of the detailed circuit analysis presented in this book are for this type of circuit.)

11 Classification by which element of the signal generating transistor is at "ground" potential (e.g., grounded emitter, grounded base, etc.).

It is certain that the reader after completing this book will be able to state additional categories of classification but the above is a representative sampling of the many different types of classification.

1.6 REFERENCES

This book could not have been written without the predecessor literature on oscillators, especially Ref. 1.1 and Refs. 1.4 to 1.10.

It is mandatory to have a working knowledge of the subjects listed below in order to fully understand the material in Chapters 13 through 17. These subjects are not included in this book because there is already readily available a very extensive and satisfactory literature. References 1.11 through 1.15 are cited to assist those readers who wish to increase their expertise in these subjects, which are:

1 Characterizations of frequency stability in both the time and frequency domains.
2 Translation of frequency domain stability data into time domain stability data and vice versa.
3 Oscillator noise models.
4 The theory and practice of the measurement of frequency and frequency stability in both the time and frequency domains.