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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

OUTPUT SYSTEMS OF SIGNAL GENERATORS

● **INTRODUCTION.** Recently, the question of standardizing the output of different models of signal generators has become one of increasing importance. Measurements made using one type of signal generator frequently do not agree with those made with another type. While this lack of agreement does, on occasion, occur at frequencies in the standard broadcast band, the differences are generally much more serious at higher frequencies. The recent extensive use of signal generators at frequencies above the standard broadcast band has brought about this demand for standardization.

The differences in these measurements are generally caused by the differing output impedances of the generators. When a load (usually the input of a receiver) is connected to the signal generator, the voltage appearing at the generator terminals is not the open circuit voltage but is a value determined by the impedances of the generator and load as well as by the indicated open-circuit voltage. Furthermore, the leads connecting the generator and load also affect the voltage actually applied to the device under test. Consequently, the load voltage can be determined from the indicated open-circuit voltage of the generator only if the generator impedance, the load impedance, and the characteristics of the leads are known.

Zero Source Impedance

One approach to this problem is to make these complicating effects negligible, and to a certain extent this situation is achieved at low frequencies. At standard broadcast frequencies and lower, no difficulty is experienced in making the cable con-

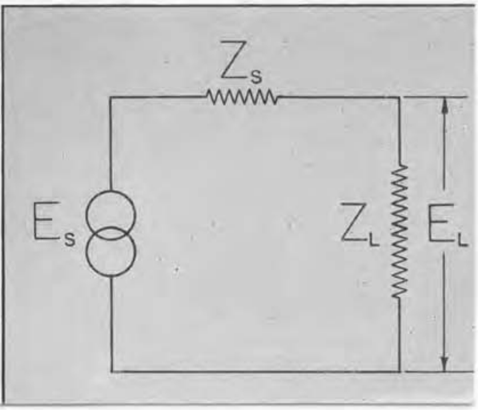

FIGURE 1. A generator of internal voltage E_s and internal impedance Z_s connected to a load Z_L. The load voltage E_L is easily determined by equation (1).

necting the generator and the load so short that there is no appreciable difference between the voltages at the generator end and the load end of the cable. Then, if the voltmeter in the generator is connected to measure the voltage at the generator terminals, this measured voltage is also the voltage applied to the load. If the load impedance is changed, the voltmeter will still read the voltage at the load. Since this arrangement needs no correction of voltage for the effect of load, it can be considered to be a generator with a voltage source of magnitude equal to that indicated on the voltmeter acting in series with a zero source impedance.

Generally, the direct measurement in the signal generator of voltages less than about one-tenth volt is neither convenient nor economically feasible. In order to work down to output voltages of one microvolt and even less, it is customary in low- and medium-frequency generators to insert a low-impedance attenuator between the voltmeter and the output terminals.

Equivalent Source

In order to calculate the effects of the load on the voltage at the terminals of a signal generator using this arrangement of voltage control, it is convenient to use the Thévenin-theorem approach and to represent the generator as a voltage source "behind" — i.e., in series with — an impedance. This equivalent voltage is the open-circuit voltage of the signal generator, and the equivalent impedance is that seen looking into the system with the terminals at which the voltage is measured short-circuited. The signal generator is usually arranged to indicate the value of this equivalent voltage by a combination of the voltmeter reading and the attenuator setting. The equivalent source impedance is generally made as low as is practical, being frequently 10 ohms, or even less. At low and medium frequencies with these low impedances, it is frequently possible to neglect the effect of the load on the output voltage and to assume that the terminal voltage is the open circuit voltage. In any case, it is relatively easy to determine the correction for the load, as indicated in Figure 1, by the formula:

$$E_L = \frac{Z_L}{Z_L + Z_s} E_s = \left(1 - \frac{Z_s}{Z_s + Z_L}\right) E_s \qquad (1)$$

where E_L = Load Voltage
E_s = Source Voltage
Z_L = Load Impedance
Z_s = Source Impedance

When the generator source impedance is small compared to the load impedance, only an approximate value for the load impedance need be used for the calculation of load voltage.

Dummy Antenna

A signal generator with low source impedance, however, is not the complete answer even at low frequencies. For example, the adjustment of a receiver input system to give maximum voltage sensitivity with a low-impedance signal generator will lead to the use of a high ratio transformer at the input with correspondingly high apparent voltage sensitivity. However, the actual sensitivity with a normal antenna will be much less than the measured value. There are several ways of avoiding this discrepancy between measured and actual sensitivities. Fundamentally, it is desirable that the effective source impedance of the generator be essentially the same as that of the energy source with which the device under test is to be used.

One procedure for achieving this condition is to add at the generator output terminals a series impedance of the value necessary to produce the desired source impedance. The standard dummy antenna adopted by the Institute of Radio Engineers for the medium and high frequencies is such a series impedance. Its value has been selected to make the source impedance of the generator approximate that of a representative antenna. An impedance network or a section of special attenuating cable is sometimes used when the simple series arrangement is not practical.

The relatively high impedance of the dummy antenna helps to mask the variations in generator output impedance that are caused by residual reactances. It also aids in isolating the generator from the load to the extent that variations in load impedance do not appreciably affect the voltage indicated by the signal-generator voltmeter. This isolation is particularly helpful when the input impedance of the device under test is to be adjusted during the course of the measurement, since the specified source impedance of the generator is based on maintaining the voltmeter reading constant for varying conditions of load (or at least correcting for the variations of the voltmeter reading).

Loop Antennas

Receivers using loop antennas are usually treated in a manner that makes the loop antenna the source impedance or dummy antenna. In some cases the voltage from the signal generator may be inserted in series with the loop. Then it is important that the generator source impedance be small as compared with the loop antenna resistance. The preferred arrangement uses a small loop antenna connected to the signal generator. This generator loop is so placed as to couple to the receiving loop antenna. In this case the generator output source impedance is usually modified by series resistance to yield a desired field intensity relationship at the receiving loop.[1]

High-Frequency Effects

At frequencies of 5 Mc and higher it is often impractical to make the connection between the signal generator and the device under test so short that its effect on the measurement can be neglected. Then the problem of determining the terminal voltage becomes more involved. This determination can be made in a number of different ways, but it is frequently convenient to associate the connecting cable with the signal generator and then evaluate the characteristics at the load end of the cable in terms of the open-circuit voltage and output impedance. When these characteristics are available, the voltage at the terminals of the load can be determined by the simple relationship of Equation 1, where the end of the cable is taken as the generator terminals.

In order to analyze the different typical conditions that occur as a result of the connecting cable, they can be separated into five specific arrangements, as shown in Figure 2. In each case, the connecting cable is assumed to have negligible loss and be a uniform transmission line of characteristic impedance Z_0 which is a pure real, that is, resistive. Furthermore, the connecting fittings are assumed to be a uniform extension of the line. (For accurate measurements a

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[1] W. O. Swinyard, "Measurement of Loop-Antenna Receivers," *Proc. I.R.E.*, 29, 7, July, 1941.

cable with clip leads should not be used at frequencies above about 5 megacycles. The coaxial fitting at the end of the cable must be connected directly to the chassis of the device under test.) With a properly arranged set-up, these conditions are generally fulfilled for all practical purposes.

Line Matched At Both Ends

The first arrangement, labeled as I in Figure 2, is readily analyzed. The cable is terminated at both ends in a resistance equal to the characteristic impedance of the line. In the first of the two alternative situations, the cable and generator source impedance have been chosen to be alike. In the second alternative, the source impedance of the generator has been increased by the use of a series resistor to a value equal to the characteristic impedance of the line. The output system of the Type 805-C Signal Generator is of this type when used with the termination unit. The situation of a generator source impedance larger than that of the line is not often encountered, but the impedance can be adjusted with a shunt resistor to give a matched condition, in which case correction must be made for the voltage drop of the combination of resistances.

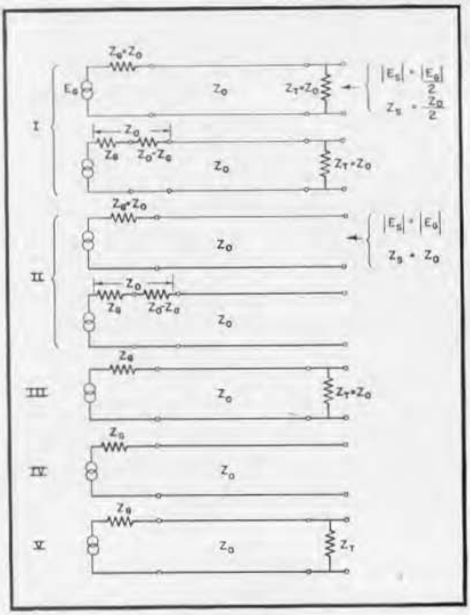


FIGURE 2. Schematic diagrams of four types of generator output systems. Case V is the general case.

The termination at the load end of the cable in this first arrangement matches the line, with the result that the voltage along the line is constant in magnitude but varying in phase. The impedance seen looking into the cable at the generator end is the characteristic impedance of the cable, and the voltage appearing at this end of the cable is one-half the generator voltage. This voltage is then transferred to the other end of the cable without change in magnitude. Therefore, the equivalent source voltage is one-half the generator voltage, or $E_s = E_G/2$. The equivalent source impedance is readily seen to be a parallel combination of a properly terminated line and a resistor equal in value to the characteristic impedance. The effective source impedance is equal to one-half the characteristic impedance, or $Z_s = Z_0/2$. This arrangement gives a source voltage and a source impedance that is independent of frequency, certainly a desirable condition. In actual practice, however, residual reactances in the generator and the termination introduce a dependence on frequency. This behavior is illustrated by the frequency characteristic of the source impedance of the Type 805-C Signal Generator, shown in Figure 3. In this generator the generator impedance is 75 ohms, and the terminating resistor is 75 ohms. The corresponding source impedance is then 37.5 ohms at low frequencies. The residual inductance in the attenuator and shunt capacitance in the termination unit switch cause the deviations at high frequencies from the low-frequency value. For most applications the deviations shown are sufficiently small that no corrections for them need be made.

While there is no standing wave on the connecting cable with no load on the output for arrangement I, any load will alter the condition of proper termination, and a standing wave will exist on the line. This standing wave, however, does not upset the validity of the Thévenin-theorem approach (the use of equivalent source voltage and source impedance).

Line Matched at Generator End

The second arrangement, designated in Figure 2 as II, is probably the most generally useful system. The generator impedance is made equal to the characteristic impedance of the line with the result that the source at the end of the cable is the same as the generator except for a shift in phase of the voltage, that is, $|E_s| = |E_G|$, and $Z_s = Z_0$. That the source impedance is Z_0 can be readily seen from the fact that the line is terminated at the generator end in its characteristic impedance. To show that the magnitude of the open-circuit voltage at the end of the cable is equal to $|E_G|$, compare the power available at this point to the power available at the generator terminals. If there are no losses in the line, the two available powers must be the same. It follows that the open-circuit voltage at either point must have the same magnitude, since the output impedance is the same, and the same power is available. This voltage can, of course, also be derived from the standard transmission-line equations.

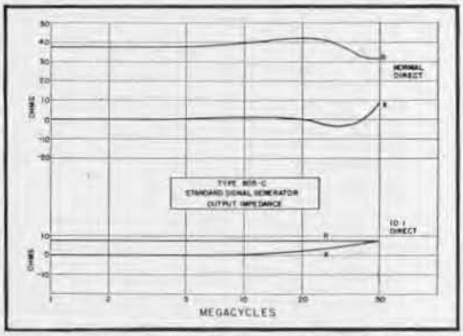


FIGURE 3. Output impedance of TYPE 805-C Standard-Signal Generator as a function of frequency.

This arrangement has a source impedance and output voltage independent of frequency, and it has the advantage over the previous arrangement that, for a given power supplied at the generator terminals, appreciably more power is available at the output terminals than in the previous case. A disadvantage is that it is somewhat more difficult to avoid a noticeable frequency dependence of the equivalent source at high frequencies.

It is interesting, although not essential to the foregoing discussion, to notice that unless the load is matched to the line a marked standing wave will exist on the line. The open-circuit condition is particularly interesting. Then the voltage at the end of the line remains in magnitude always equal to the generator voltage E_G, but the voltage at the input to the line varies from that value to practically zero as the frequency increases from very low frequencies. The zero value of voltage occurs for frequencies at which the transmission line is an odd multiple of a quarter wavelength. At frequencies higher than that for which the line is a quarter wave-length long, in the open circuit condition there will be some point or points along the line at which the voltage will be practically zero. The actual value of this "practically-zero" voltage depends on the losses in the line and will be of the order of one-tenth to one-thousandth of the generator voltage.

The length of line in these first two arrangements does not affect the behavior provided the impedance is properly matched. There is then no need for a cable that is permanently attached to the signal generator if the connectors and cables used form a uniform transmission line of the correct value of characteristic impedance. At ultra-high frequencies and higher, uniformity is particularly important. At these frequencies a succession of even small discontinuities can cause a very serious degradation of the characteristics of a transmission system, and, therefore, connectors and cables specially designed for this frequency region should be used.

Line Matched at Load End

Arrangement III is used in some signal generators. The transmission line is terminated in its characteristic impedance when there is no load on the line, but its characteristic impedance is not equal to the generator impedance. The no-load terminal voltage is given by the simple formula:

$$|E_s| = \left|\frac{Z_0}{Z_0 + Z_G}\right| |E_G|$$

If the generator impedance is a pure resistance, the output voltage is independent of frequency. The frequency characteristic of the source impedance is more complicated, but can be readily derived from the transmission line equations. It can be expressed as

$$Z_s = \frac{Z_0\left(Z_G + jZ_0 \tan\frac{2\pi l}{\lambda}\right)}{(Z_0 + Z_G)\left(1 + j\tan\frac{2\pi l}{\lambda}\right)}$$

where l = length of transmission line
λ = wave-length of signal in transmission medium

The source impedance varies with frequency as can be seen from this equation. If the generator impedance is a pure resistance, the source impedance varies in magnitude as a function of frequency between the extremes $Z_GZ_0/(Z_G + Z_0)$ (the parallel combination of Z_0 and Z_G) when the cable is an integral multiple of a half wave-length long and $Z_0^2/(Z_G + Z_0)$ when the cable is an odd multiple of a quarter wave-length long. At these extremes the source impedance is a pure resistance, while at other frequencies there is a reactive component. The maximum value of reactance occurs when the cable is an odd multiple of an eighth wave-length long. For this condition the source impedance is

$$Z_s = \frac{Z_0}{2} \pm j\frac{Z_0(Z_0 - Z_G)}{2(Z_0 + Z_G)}.$$

Line Unmatched

The next arrangement, IV, yields a source whose impedance and open-circuit voltage both vary with fre-

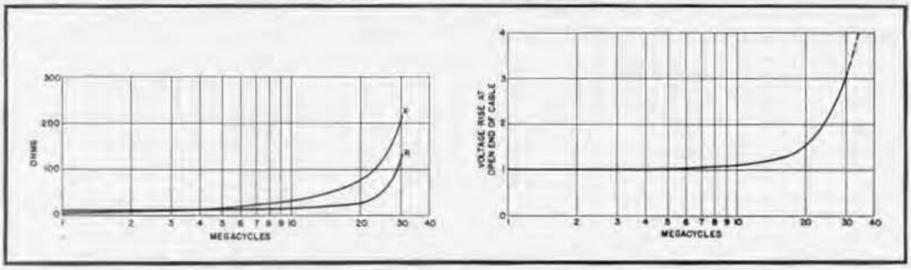


FIGURE 4. Output impedance and voltage of TYPE 605-B Standard-Signal Generator and TYPE 774-R Cable as a function of frequency.

quency. The transmission-line equations show that the equivalent source for this line terminated only at the generator end in a resistance different from the characteristic impedance is

$$Z_s = \frac{Z_0\left(Z_G + jZ_0 \tan \frac{2\pi l}{\lambda}\right)}{Z_0 + jZ_G \tan \frac{2\pi l}{\lambda}}$$

$$E_s = \frac{Z_0 E_G}{Z_0\left(\cos \frac{2\pi l}{\lambda}\right) + jZ_G\left(\sin \frac{2\pi l}{\lambda}\right)}$$

If the generator impedance is real, the source varies between the extremes

$$Z_s = Z_G, \,|E_s| = |E_G|$$

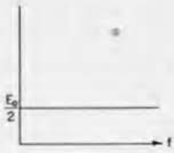
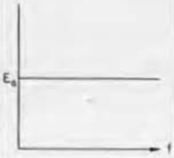
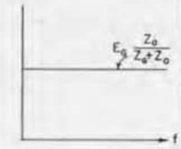
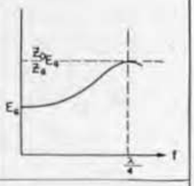
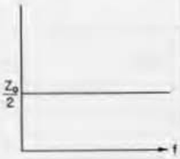
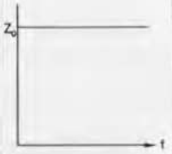
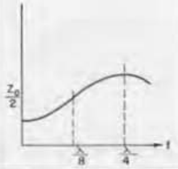
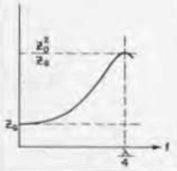
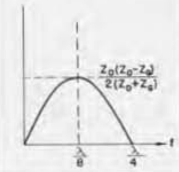
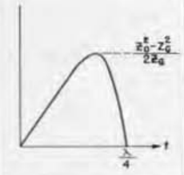
when the transmission line is a multiple of a half wave-length long, and

$$Z_s = \frac{Z_0^2}{Z_G}, \,|E_s| = \frac{Z_0}{Z_G}|E_G|$$

when the transmission line is an odd multiple of a quarter wave-length long. At these extremes the source impedance is a pure resistance, while at other frequencies there is a reactance component.

This arrangement is the one that occurs when the TYPE 605-B Signal Generator is used with a TYPE 774-R coaxial cable. The TYPE 605-B has a 10-ohm attenuator, and the cable impedance is 72 ohms. The measured results for the equivalent source of this combination are shown in Figure 4. The impedance was measured by the TYPE 916-A Radio-Frequency Bridge and the voltage was measured by comparing receiver response with and without the cable. As a

FIGURE 5. Summary of impedance and voltage characteristics of the four types of terminations shown in Figure 2. The relative phase relationships of the voltages are not included, and it is assumed that Z_G is a pure resistance.

	I	II	III	IV
E_s	$\frac{E_G}{2}$	E_G	$E_G \frac{Z_0}{Z_G+Z_0}$	$\frac{Z_0 E_G}{Z_0 \cos\frac{2\pi l}{\lambda} + jZ_G \sin\frac{2\pi l}{\lambda}}$
Z_s	$\frac{Z_0}{2}$	Z_0	$\frac{Z_0(Z_G + jZ_0 \tan\frac{2\pi l}{\lambda})}{(Z_0+Z_G)(1+j \tan\frac{2\pi l}{\lambda})}$	$\frac{Z_0(Z_G+jZ_0 \tan\frac{2\pi l}{\lambda})}{Z_0+jZ_G \tan\frac{2\pi l}{\lambda}}$
E_s vs f				
R_s vs f				
X_s vs f	0	0		

result of departures from the idealized conditions of termination, the equivalent source impedance cannot in general be easily calculated. The actual value of source impedance can be most readily determined by direct measurement with a bridge, for example, the TYPE 916-A Radio-Frequency Bridge.

General Case

The fifth arrangement, labeled in Figure 2 as V, is the general case with terminations at both ends. For this case the equivalent source is

$$E_s = E_G \frac{Z_0 Z_T}{\left(Z_0(Z_G + Z_T)\cos\frac{2\pi l}{\lambda} + j(Z_G Z_T + Z_0^2)\sin\frac{2\pi l}{\lambda}\right)}$$

and

$$\frac{1}{Z_s} = \frac{1}{Z_0}\,\frac{Z_0 + jZ_G\tan\frac{2\pi l}{\lambda}}{Z_G + jZ_0\tan\frac{2\pi l}{\lambda}} + \frac{1}{Z_T}$$

This case is included only to complete the record, since the previous ones are special cases of this general one.

Summary

In order to determine the voltage applied to a device from a signal generator it is necessary to know the load impedance, the characteristics of the connecting cable, and the generator voltage and source impedance. The second and third can be combined to give an equivalent source for the combination. Certain specific characteristics of generator and cable are to be preferred for this equivalent source, notably that in which the generator impedance is equal to the characteristic impedance of the cable. Measurements made with a radio-frequency bridge are the most reliable method of obtaining the necessary impedance values.

— ARNOLD PETERSON

MISCELLANY

● **Among the recent visitors** to our laboratories were the distinguished British physicist, Sir Robert Watson-Watt; Dr. Alfred L. Loomis, of the NDRC; Mr. Johan C. Lagercrantz, our representative in Stockholm, Sweden; and Messrs. Jurg Keller and Jacques Baerlocher-Sarasin, of the firm of Seyffer and Company, Zurich, who represent us in Switzerland.

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