How attenuator pads improve impedance matching

By Harold Kinley, C.E.T.

Unless special precautions are taken, impedance discontinuities can cause severe reflections that can adversely affect a test procedure and circuit operation. Although an attenuator pad injects loss into the system, the loss usually can be overcome. Loss caused by the pad is a small tradeoff for the great improvement in impedance smoothing it provides. In fact, the word "pad" describes the job the attenuator performs—it provides padding at a point in a system or chain where abrupt changes in impedance would otherwise cause a severe reflection.

An analogy is the job performed by the shock absorber on your car. Without it, you would feel every little bump in the road, but with it even the big bumps are reduced to minor ones.

How it works

Figure 1 below shows a signal generator connected to a receiver. It is important for the signal generator to see a proper (50Ω) impedance at its output port. If the load (receiver) presents an impedance other than 50Ω to the generator, the validity of any test procedure might be impaired by reflections on the line. The interconnecting transmission line would become resonant, and the impedance presented to the signal generator would be a complex impedance with inductive or capacitive reactance, depending on the length of the transmission line. In Figure 1, the receiver represents a complex impedance of 30 + *j*40 ohms.

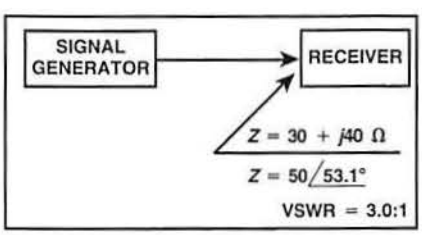

Figure 1. The receiver input presents a complex impedance of (30 + *j*40) ohms to the signal generator. This causes an SWR of 3:1. The complex impedance is also shown in polar form as 50Ω at an angle of 53.1°.

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In Figure 2 below the impedance at the *load* end (point E) is *complex*. That is, it consists of a reactance and a resistance as shown. The complex impedance is represented by the expression 30 + *j*40 ohms.

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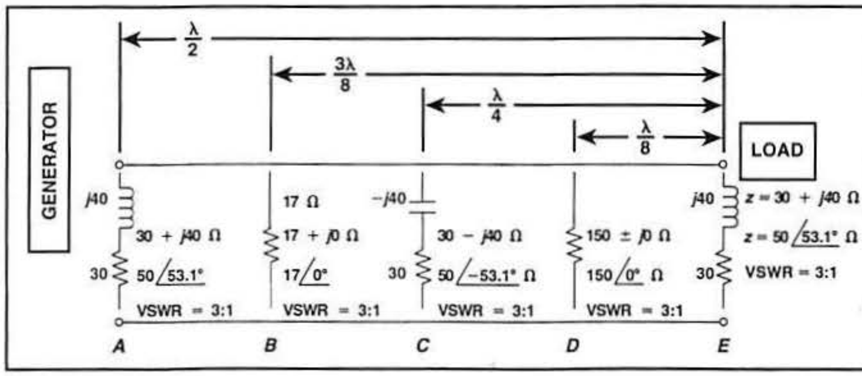


Figure 2. This expands upon the setup in Figure 1. Here, the signal generator is connected to the receiver input via a lossless transmission line that is one-half wavelength (λ/2) long. The VSWR is the same at all points along the transmission line. However, the impedance will vary along the line and will repeat every half-wavelength (λ/2). At two points (λ/8 and 3λ/8) the impedance is purely resistive. However, the pure resistance is still such that the VSWR is still 3:1. This assumes a 50Ω transmission line and 50Ω system impedance.

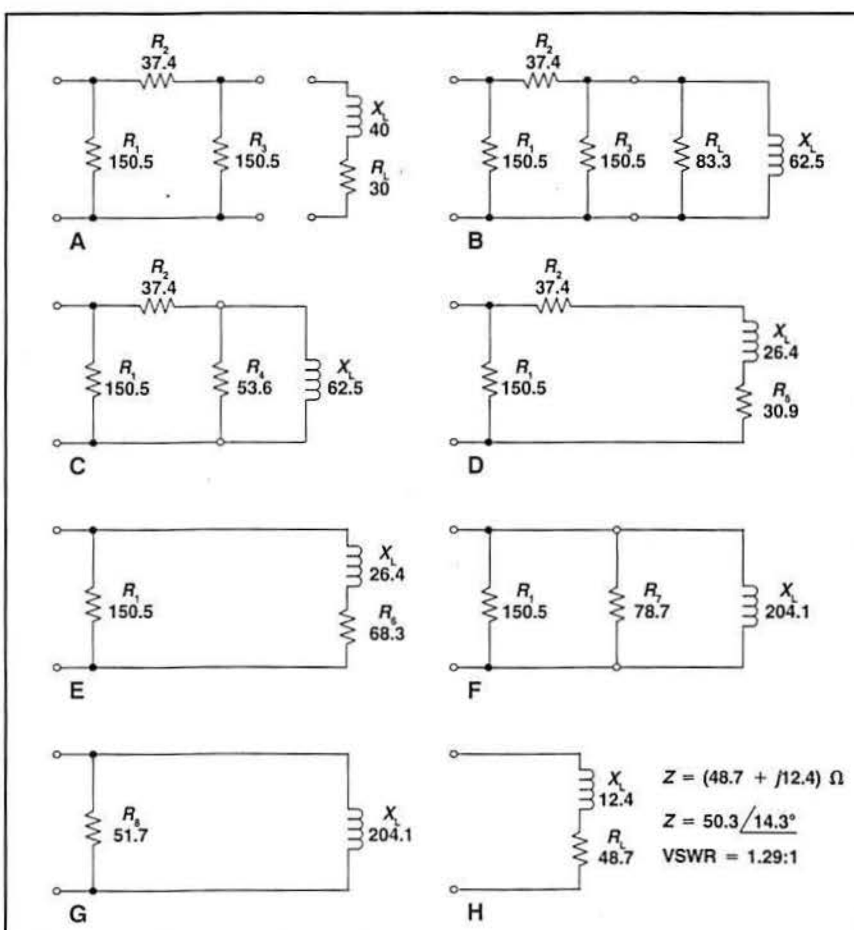


Figure 3. This illustrates through evolution how a 6dB pad transforms the output impedance to the impedance that is "seen" at the pad input. The output impedance, (30 + *j*40) ohms, would cause a VSWR of 3:1. However, looking at the input to the pad, the generator or source would see an impedance of 48.7 + *j*12.4 ohms for a VSWR of 1.29:1.

(continued from page 8)

In polar form, the expression for this impedance would be 50Ω at an angle of 53.1°. The VSWR at this point is 3:1. One-eighth wavelength down the line toward the generator, the impedance is a pure resistance of 150Ω, or 150Ω at an angle of 0°. The impedance at other points along the line is as indicated at the various points. If this line is a lossless line, the VSWR will be the same (3:1) at any point along the line, although the impedance changes.

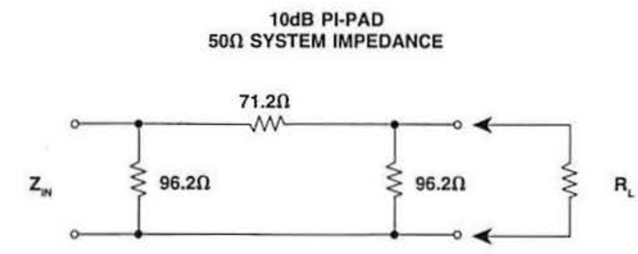
To reduce the mismatch at the generator output, a simple attenuator pad can be placed between the generator output and the load. In Figure 3 on page 8, a 6dB pi-pad is placed between the load impedance (30 + j40 ohms) and the generator. The pi-pad is represented by R_1, R_2 and R_3 in Figure 3A. The complex load impedance is represented by R_L and X_L.

The equivalent impedance presented to the signal generator by the combination of the 6dB pi-pad and the complex load impedance is derived by the process of evolution shown in Figures 3A to 3H.

In Figure 3B, the complex series impedance is converted to the equivalent parallel impedance. Then the parallel combination of R_L and R_3 is replaced by a single resistor, R_4, shown in Figure 3C.

Next, the impedance consisting of R_4 and X_L in Figure 3C is converted to the equivalent series impedance, X_L and R_5 shown in Figure 3D. Then the series combination of R_5 and R_2 are replaced by a single resistor, R_6, in Figure 3E.

The series combination of X_L and R_6 in Figure 3E are replaced by the equivalent parallel combination R_7 and X_L in Figure 3F. Then the combination of R_1 and R_7 in parallel in Figure 3F is replaced by a single resistor, R_8, shown in Figure 3G. Finally, the parallel impedance consisting of R_8 and X_L is replaced by the equivalent series impedance X_L and R_L shown in Figure 3H.



R_L = 100 Z_{IN} = 53.4 OUTPUT VSWR = 2:1 INPUT VSWR = 1.07:1
R_L = 500 Z_{IN} = 58.9 OUTPUT VSWR = 10:1 INPUT VSWR = 1.18:1

Figure 4. This shows how a 10dB pad would reduce the VSWR for a load of 100Ω or 500Ω. The 100Ω load would normally cause a VSWR of 2:1, but the 10dB pad reduces the VSWR to 1.07:1. The 500Ω load would cause a VSWR of 10:1, but the 10dB pad reduces it to 1.18:1 at the input.

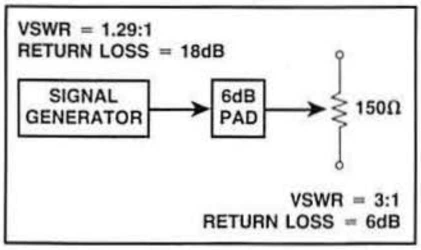


Figure 5. Here, a signal generator is connected to a 150Ω load through a 6dB pad. The VSWR at the load is 3:1 (return loss is 6dB) but is reduced through the pad to a VSWR of 1.29:1 (return loss = 18dB) at the generator output.

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{(30 + j40) - 50}{(30 + j40) + 50} = \frac{-20 + j40}{80 + j40} = \frac{20(-1 + j2)}{20(4 + j2)} = \frac{-1 + j2}{4 + j2};$$

$$\frac{(-1 + j2)(4 - j2)}{(4 + j2)(4 - j2)} = \frac{-4 + j8 + j2 - j^2 4}{16 + j8 - j8 - j^2 4} = \frac{-4 + j10 + 4}{16 + 4} = \frac{j10}{20} = j0.5;$$

$$\Gamma = 0 + j0.5$$

$$\Gamma = \sqrt{0^2 + 0.5^2} = \sqrt{0.5^2} = 0.5$$

$$\text{VSWR} = \frac{1 + \Gamma}{1 - \Gamma} = \frac{1 + 0.5}{1 - 0.5} = \frac{1.5}{0.5} = 3$$

The final impedance represented by X_L and R_L in Figure 3H is 48.7 + j12.4 ohms. In polar form, this is 50.3Ω at an angle of 14.3°. The VSWR at the input to the pi-pad would then be 1.29:1. So the 6dB pi-pad has reduced the load VSWR from 3:1 to a VSWR of 1.29:1 at the generator output.

The greater the attenuation of the pad, the greater will be the reduction of the VSWR at the generator output. For example, Figure 4 on page 46 shows a 10dB pi-pad. Notice how the VSWR at the input to the pad ranges from 1.07:1 to 1.18:1 for a VSWR range of 2:1 to 10:1 at the output. Thus, the pad smoothes the impedance variations between the pad output and pad input.

Return loss

If the impedance mismatch were to be represented in terms of return loss, the return loss for a VSWR of 3:1 would be about 6dB.

Figure 5 to the left shows a signal generator connected to a 150Ω resistive load through a 6dB pad. Assuming no losses in the connecting lines, the return loss at the output of the 6dB pad is 6dB. The return loss at the input to the 6dB pad (signal generator output) is 18dB. This pattern of loss can be generalized into the following statement: The return loss at the input to a pad is equal to the return loss at the output of the pad plus twice the attenuation of the pad. In this case, the return loss at the input to the pad is $6 + 2(6) = 18$dB.

Calculating VSWR

It is simple to calculate the VSWR when only a pure load resistance is involved. However, when the load impedance contains reactance, it is not quite so simple. To find the VSWR, we first need to know the reflection coefficient for a given complex impedance. (See box on page 48.) The reflection coefficient is represented by the Greek letter Γ. Z_L represents the load impedance in complex form, and Z_0 represents the system impedance (50Ω in our case). The equation is simplified by factoring and multiplying both the numerator and the denominator by the conjugate of the denominator. Then the equation is reduced to $\Gamma = j0.5$, or in complex form, $0 + j0.5$.

Next, Γ is found by finding the square root of the sum of the squares of the real and imaginary parts. Thus, $\Gamma = 0.5$. Substituting Γ into the formula for VSWR yields a VSWR of 3:1.

Summing up

As stated, the greater the pad attenuation, the better the match at the generator (pad input). Figure 6 to the right shows how various pads reduce the input VSWR with wide variations in output VSWR. Although pads can be built from ordinary resistors, the result may not be usable at higher frequencies. Pads used at higher frequencies are made of specially constructed resistors. The examples given here are for theoretically perfect pads. Practical pads will not deliver the ideal results. Even so, padding certainly helps to minimize the effects of impedance mismatches and measurement errors that might otherwise result.

An excellent aid in calculating VSWR from complex impedance and other transmission line calculations is the *Transmission Line Calculator*. It was invented by the late inventor of the Smith Chart, Phillip H. Smith. It is available from Analog Instruments, P.O. Box 808, New Providence, NJ 07974. Phone/fax (908) 464-4214.

A program for determining the resistance for various pads (e.g., L-pad T-pad, pi-pad and H-pad) is available from the author for $10 plus $2.50 for shipping and handling. A program for calculating SWR, including complex impedance, is available for $10 plus $2.50 for shipping and handling. Both are available on single diskette for $15 plus $2.50 for shipping and handling. The programs run under MS-DOS on an IBM-compatible PC. Specify 3.5" or 5.25" floppy diskette.

A circular converter that converts among units for transmission loss, reflection coefficient, percentage reflected power, return loss and VSWR is also available from the author for $5 plus $1.50 for shipping and handling.

You may write the author at 204 Tanglewylde Drive, Spartanburg, SC 29301-2949. *Stay tuned!*

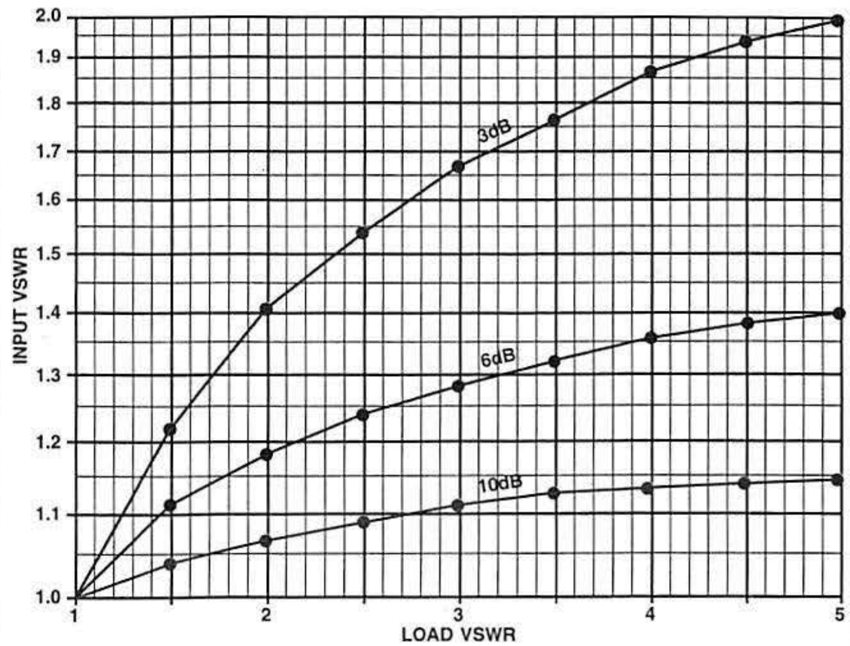


Figure 6. This graph shows how pads of 3dB, 6dB and 10dB reduce the VSWR. Note that the higher the loss of the pad, the greater the reduction in VSWR.