Simplified Attenuator and Impedance Transformer Design

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INTRODUCTION

When performing a signal substitution measurement in accordance with a test specification familiar to many ITEM readers, it is required that the signal generator have a 50-ohm output impedance. A 50-ohm signal generator is also needed to check the 6-dB cutoff frequencies of the 50-ohm filters used in establishing the bandwidth of the signal detection system. However, if a 50-ohm generator is not available, the generator output impedance may be changed to 50 ohms using a special resistive attenuator known as a "minimum-loss pad," or the required impedance transformation may be accomplished with a broadband transformer.

Generator output impedance may be changed to 50 ohms using a special resistive attenuator.

When using a 50-ohm signal generator, a common practice is to place a 50-ohm, 6- to 10-dB pad on the output of the generator to stabilize its output impedance. For example, the H-P Model 8444A tracking generator is specified as having a maximum output voltage standing wave ratio (VSWR) of 2.3. A 10-dB, 50-ohm pad placed on the tracking generator output reduces the maximum VSWR to about 1.08. Reducing the excessive signal generator output VSWR is especially important when using the generator as a source for signal substitution measurements or for filter testing so that repeatable and reliable data are obtained.

TEMPEST test engineers should know how to design resistive pads for signal reduction or impedance stabilization and how to design minimum loss pads or transformers for impedance transformation. The resistive pads are especially important because: they give a precisely-controlled attenuation which is virtually independent of frequency (unlike the transformer which is limited to about two or three frequency decades); they have an impedance matching capability; and they have an impedance smoothing property in that a large change in impedance at one side of the pad appears as a much smaller change at the other side of the pad. Although transformers have a limited frequency range, they have the advantage of providing impedance transformation without the loss inherent in the resistive minimum-loss pad.

Although the electronics handbooks include all the necessary design equations for resistive pads, the scope of the presentation is usually so broad that it is difficult to find the appropriate equations that apply to those few applications most likely to be of interest to the TEMPEST test engineer. And when the appropriate (and invariably unfamiliar) equations are found, there is no assurance that the resulting calculated resistor values are correct unless additional calculations are made.

This article will give computer-calculated resistor values of unbalanced-to-ground symmetrical and minimum-loss pads in an easy-to-understand tabular format. The impedance-smoothing effect of pads will be explained and procedures will be discussed for constructing simple broadband impedance matching transformers.

RESISTIVE PAD DESIGN

Resistive pads are commonly used to attenuate signal levels in a transmission line without disturbing the impedance level of the transmission line, or to change the impedance level of the transmission line. In addition to signal attenuation and impedance transformation, resistive pads also have the frequently overlooked capability of impedance smoothing. This will also be discussed in this article.

Although there are several different types of resistive pads, the only two types considered in this article are the unbalanced-to-ground symmetrical equally-terminated pad and the minimum-loss pad. These are the two types the TEMPEST engineer will most likely require. Design information on other pads such as the lattice or bridged-tee is seldom needed. If necessary, information on these pads may be obtained.[1,2]

*See Advertisement on Page 288.

UNBALANCED SYMMETRICAL EQUALLY-TERMINATED PADS

For the unbalanced-to-ground symmetrical equally-terminated pad, there are two possible configurations, and they are known as "Tee" and "Pi" networks (Figures 1A and 1B). The pad impedance level has been selected as 50 ohms as this is the most commonly used impedance level; however, pads for other equally terminated impedance levels can be easily calculated as explained in note (b) of Table 1.

Although the Tee and Pi networks can be designed for the same attenuation level, the computer-calculated resistance values listed in Table 1 are quite different, as seen by comparing the resistance values under the Tee and Pi headings. The Pi network may be more convenient than the Tee when installing the resistors between two BNC connectors in a small aluminum mini-box because the input and output resistors (R4) can be connected from ground to the pins of the BNC connectors, and the series resistor (R3) can be connected between the pins of the connectors. In this case, all connection points are firmly fixed. In comparison, the junction of R1 and R2 in the Tee configuration is supported only by the resistor leads. However, from a performance standpoint, the Tee configuration has a significant advantage over the Pi configuration for attenuation levels greater than about 10 dB. At the higher attenuation levels the Tee resistance values are significantly lower than the Pi values. For example, for a pad attenuation of 20 dB the larger Tee value is 40.9 ohms whereas the larger Pi value is about six times greater. This means that for RF applications the lower resistance value of the Tee network is less likely to be affected by the stray inductance and capacitance of the network.

The attenuation levels listed in Table 1 range from one to 20 dB in increments of one dB, with one exception. Designs for increments smaller than one dB or larger than 20 dB are seldom needed, and when more than 20 dB is needed it can be obtained by cascading two of the listed designs of the same configuration. This will result in a 5-branch resistive network with the total attenuation spread over five branches instead of only three. By using a 5-branch instead of a 3-branch network, the design attenuation is less likely to be affected by the network stray capacitance and inductance. For example, in the Pi-network, the series resistance (R3) in the 20-dB pad is 248 ohms whereas the same resistance in a 30-dB pad is 790

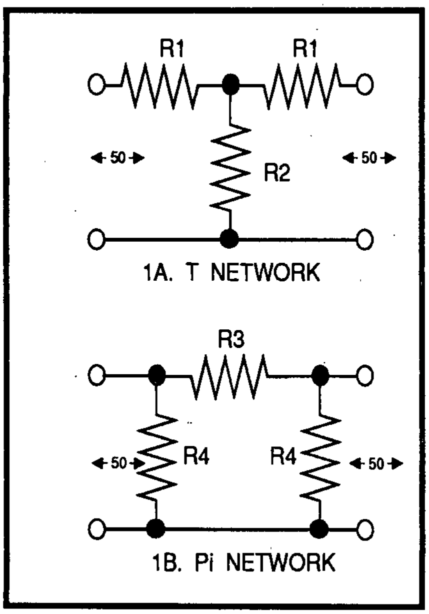

FIGURE 1. *Networks for 50-ohm Unbalanced-to-ground Symmetrical Resistive Pads.*

	T Network		Pi Network			T Network		Pi Network	
ATTN. (dB)	R1 (Ω)	R2 (Ω)	R3 (Ω)	R4 (Ω)	ATTN. (dB)	R1 (Ω)	R2 (Ω)	R3 (Ω)	R4 (Ω)
1.0	2.88	433	5.77	870	11.44	28.9	28.9	86.6	86.6
2.0	5.73	215	11.6	436	12.0	29.9	26.8	93.2	83.5
3.0	8.55	142	17.6	292	13.0	31.7	23.6	106	78.8
4.0	11.3	105	23.8	221	14.0	33.4	20.8	120	74.9
5.0	14.0	82.2	30.4	178	15.0	34.9	18.4	136	71.6
6.0	16.6	66.9	37.4	150	16.0	36.3	16.3	154	68.8
7.0	19.1	55.8	44.8	131	17.0	37.6	14.4	173	66.4
8.0	21.5	47.3	52.8	116	18.0	38.8	12.8	195	64.4
9.0	23.8	40.6	61.6	105	19.0	39.9	11.4	220	62.6
10.0	26.0	35.1	71.2	96.2	20.0	40.9	10.1	248	61.1

How to use the 50-ohm resistive pad design table:

(a) For a 50-ohm impedance level:

1. Select one of the two network configurations shown in Figure 1.
2. From Table 1, read the resistor values corresponding to the desired attenuation and the selected network.

For example, the R1 and R2 values for a 10-dB T network are 26.0 and 35.1 ohms.

(b) For impedance levels other than 50 ohms:

1. Calculate the ratio of the desired impedance relative to 50 ohms.
2. Multiply the tabulated resistor values associated with the desired attenuation by the calculated impedance ratio.

For example, the R1 and R2 values for a 75-ohm, 10-dB T network are:
1.5(26.0) = 39.0 ohms and 1.5(35.1) = 52.7 ohms, respectively.

NOTE: The VSWR smoothing effect of these pads (or any resistive pad) is found from Figure 3. For example, if the 50-ohm output of a signal generator (such as the H-P Model 8444A tracking generator) has an unpadded VSWR of 2.3, a 10-dB pad placed on the generator output will reduce the VSWR at the pad output to about 1.08. Reducing an excessive VSWR of a signal generator is especially important when measuring the response of a filter.

TABLE 1. *Resistor Values for 50-ohm Pads.*

ohms — more than three times greater. At dc, this presents no problem, but at the higher radio frequencies a 790-ohm resistor is much more likely to be affected by the stray capacitance and inductance associated with the resistors. Consequently, to achieve high levels of attenuation it is better to cascade lower attenuation networks having lower values of resistance. This minimizes the effects of inductance and capacitance associated with the resistors.

A design for a non-standard attenuation increment (11.0 to 11.4 dB) is included in Table 1 because of its unique property of requiring three resistors of the same value. For those applications where an integer level of attenuation is not required, this particular design is convenient to assemble because only resistors of one value are needed. A Pi attenuator was assembled on a small piece of one-sided pc board with three 86.6-ohm resistors, two BNC connectors and two ground lugs. An attenuation of 11.4 dB was measured and found to be constant from dc up to 100 MHz with a gradual rise to about 12.2 dB at 500 MHz.

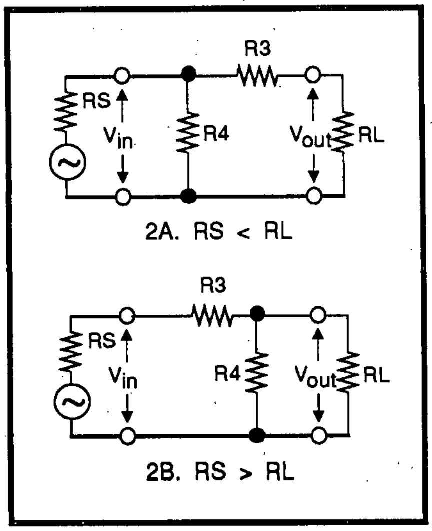

FIGURE 2. Networks for Minimum-loss Matching Pads.

UNBALANCED MINIMUM-LOSS MATCHING PADS

In addition to providing a specific amount of signal attenuation, resistive networks may be used for impedance matching between unequal source and load impedances. For example, a correctly designed minimum-loss pad placed between a 600-ohm signal generator and a 50-ohm load permits the generator to look into its preferred load impedance of 600 ohms while the load sees an apparent source impedance of 50 ohms. This particular pad is designed to provide both the desired matching between different impedance levels and to accomplish the matching with minimum loss.

The minimum-loss pad consists of only two resistors, one series and one shunt resistor. The resistor position relative to the source and load depends on whether the source impedance is less than or greater than the load impedance (Figures 2A and 2B). Table 2 shows the computer-calculated values of minimum-loss matching pads between those different impedance

RS —Ohms—	RL	R3 —Ohms—	R4	Atten. (dB)	Fig. No.	V Drop (dB) [V_{out} re V_{in}]
50	75	43.3	86.6	5.7	2(A)	4.0
50	93	63.2	73.5	7.2	2(A)	4.5
50	125	96.8	64.5	9.0	2(A)	5.0
50	150	122	61.2	10.0	2(A)	5.2
50	300	274	54.8	13.4	2(A)	5.6
50	500	474	52.7	15.8	2(A)	5.8
50	600	574	52.2	16.6	2(A)	5.8
75	50	43.3	86.6	5.7	2(B)	7.5
75	93	40.9	170	4.1	2(A)	3.2
75	125	79.1	119	6.5	2(A)	4.3
75	150	106	106	7.7	2(A)	4.6
75	300	260	86.6	11.4	2(A)	5.4
75	500	461	81.3	13.9	2(A)	5.7
75	600	561	80.2	14.8	2(A)	5.7
93	50	63.2	73.5	7.2	2(B)	9.9
93	75	40.9	170	4.1	2(B)	5.0
93	125	63.2	184	4.8	2(A)	3.6
93	150	92.5	151	6.2	2(A)	4.2
93	300	249	112	10.3	2(A)	5.3
93	500	451	103	12.9	2(A)	5.6
93	600	552	101	13.8	2(A)	5.7
125	50	96.8	64.5	9.0	2(B)	12.9
125	75	79.1	119	6.5	2(B)	8.7
125	93	63.2	184	4.8	2(B)	6.1
125	150	61.2	306	3.8	2(A)	3.0
125	300	229	164	8.7	2(A)	4.9
125	500	433	144	11.4	2(A)	5.4
125	600	534	140	12.3	2(A)	5.5
150	50	122	61.2	10.0	2(B)	14.7
150	75	106	106	7.7	2(B)	10.7
150	93	92.5	151	6.2	2(B)	8.3
150	125	61.2	306	3.8	2(B)	4.6
150	300	212	212	7.7	2(A)	4.6
150	500	418	179	10.5	2(A)	5.3
150	600	520	173	11.4	2(A)	5.4
300	50	274	54.8	13.4	2(B)	21.2
300	75	260	86.6	11.4	2(B)	17.5
300	93	249	112	10.3	2(B)	15.4
300	125	229	164	8.7	2(B)	12.5
300	150	212	212	7.7	2(B)	10.7
300	500	316	474	6.5	2(A)	4.3
300	600	424	424	7.7	2(A)	4.6
500	50	474	52.7	15.8	2(B)	25.8
500	75	461	81.3	13.9	2(B)	22.2
500	93	451	103	12.9	2(B)	20.2
500	125	433	144	11.4	2(B)	17.5
500	150	418	179	10.5	2(B)	15.7
500	300	316	474	6.5	2(B)	8.7
500	600	245	1225	3.8	2(A)	3.0
600	50	574	52.2	16.6	2(B)	27.4
600	75	561	80.2	14.8	2(B)	23.8
600	93	552	101	13.8	2(B)	21.9
600	125	534	140	12.3	2(B)	19.2
600	150	520	173	11.4	2(B)	17.5
600	300	424	424	7.7	2(B)	10.7
600	500	245	1225	3.8	2(B)	4.6

Explanation of how to use minimum-loss matching pads in Table 2:

1. From Table 2, find the values of R3 and R4 corresponding to the source (RS) and load (RL) impedances to be matched.

2. Connect resistors R3 and R4 between the source and load as shown in Figure 2A or 2B, depending on whether RS is smaller or larger than RL. For example, to obtain a match with minimum loss between a 50-ohm source and a 75-ohm load, connect R3 and R4 (43.3 and 86.6 ohms, respectively) between the source and load using Figure 2A as specified in the table listing for the 50/75-ohm combination.

The Atten. parameter in Table 2 is the signal loss that results from using a minimum-loss pad instead of a matching transformer. The VSWR smoothing effect caused by the pad attenuation is found by matching the value in the Atten. (dB) column with the corresponding attenuation curve in Figure 3. Interpolation may be required. For example, a 50/75-ohm, 5.7 dB minimum-loss pad reduces a VSWR of 2.0 to about 1.2. The voltage drop in dB from the pad input to the pad output is given in the V-Drop column of Table 2; however, this is not the same as the pad attenuation.

TABLE 2. Values for Minimum-loss Matching Pads Shown in Figures 2A and 2B.

levels most likely to be needed by the TEMPEST test engineer. To use the table, find the values of R3 and R4 corresponding to the source and load impedances to be matched. Then connect the resistors between the source and load as shown in Figure 2A or 2B, depending on whether RS is less than or greater than RL.

For example, if an H-P 200CD signal generator is to be used to check the response of a 50-ohm filter, the 600/50-ohm minimum-loss pad of Figure 2B with R3 = 574 ohms and R4 = 52 ohms would be installed between the generator and the filter input. The filter output would be terminated with a 50-ohm resistor, and a high-impedance ac voltmeter would be used to measure the output voltage. With the minimum-loss impedance-matching pad installed, both the signal generator and the filter will see their proper design impedance levels and the measured filter response will be accurate and repeatable.

The equations given in Appendix A can be used if a design for a symmetrical or minimum-loss pad is desired for an attenuation level other than those listed in Tables 1 and 2.

The resistor type recommended for constructing the pads discussed in this article is Yageo ® Type MF-25, 1/4-watt deposited metal-film with a tolerance of one percent and a temperature coefficient of 100 ppm/deg. C. Almost any desired resistance value can be obtained within one percent using a single resistor selected from the table of standard resistor values. The Yageo resistors are available from Digi-Key at $0.52 for a single-value bulk package of five resistors. Call Digi-Key at 1-800-344-4539 for a free catalog.

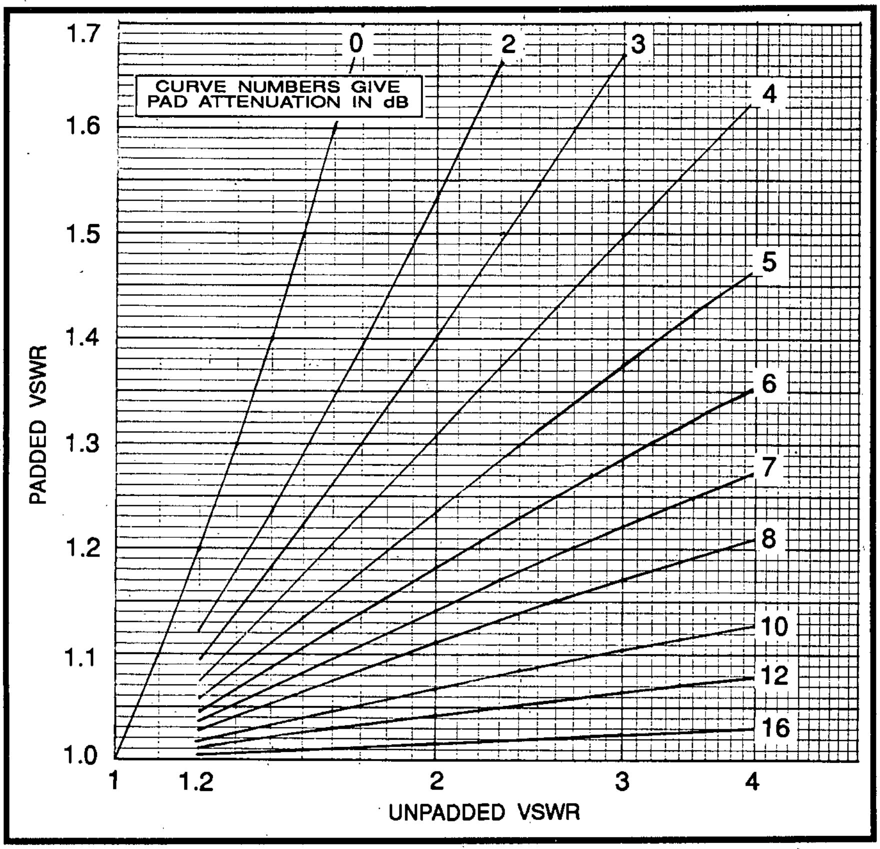

FIGURE 3. *Padded VSWR vs. Unpadded VSWR for Various Attenuation Levels.*

MINIMIZING IMPEDANCE VARIATIONS USING RESISTIVE PADS

Any resistive pad, whether it is designed for attenuation in a specific impedance level or for the matching of two different impedance levels, has the ability to minimize the impedance variations which normally occur in a source or load over a wide frequency range. This impedance "smoothing" property is shared by all resistive pads, irrespective of their type or configuration. The amount of impedance smoothing is determined solely by the pad's insertion loss. Thus, a 3-dB minimum-loss pad has exactly the same amount of impedance smoothing as a tee-pad or any other 3-dB pad. This smoothing effect is bilateral and gives the same result in either direction through the pad.

Impedance variations are usually expressed in terms of VSWR, which is calculated by taking the ratio of the actual impedance to the nominal value, or the reciprocal of this ratio, whichever is greater than one. Thus a VSWR of 2, referred to a 50-ohm reference, may be used to indicate an impedance of either 100 or 25 ohms. For example, if the maximum impedance of a nominal 50-ohm signal source at a particular frequency is specified as 100 ohms, the maximum VSWR is said to be 2. If a pad is placed between the signal source and a load, then the impedance seen at the pad input is called the pad input (or unpadded) VSWR and the impedance seen at the pad output is called the output (or padded) VSWR.

It is generally not necessary to know the precise amount of impedance smoothing and the corresponding VSWR reduction produced by a pad; an estimate of the VSWR reduction will suffice. The family of curves in Figure 3 shows the relationship between input (unpadded) VSWR and output (padded) VSWR for attenuation levels between 1 and 16 dB. For example, if a 6-dB pad is placed between a signal generator having a maximum VSWR of 2.0 over its operating frequency range, the maximum possible VSWR at any frequency will be about 1.18 at the pad output. The family of VSWR smoothing curves was calculated from the equations given in part (C) of the Appendix.

To assure repeatable and reliable signal substitution measurements when performing TEMPEST tests, it is important that the VSWR of the signal source be minimized. This is best accomplished by inserting a pad between the signal source and the load. A generally accepted maximum VSWR at the pad output is 1.20. The amount of pad attenuation required to obtain this level of VSWR may be found as follows. Refer to the technical manual of the signal generator being used and find its maximum output VSWR. This level of VSWR will be the pad input (unpadded) VSWR level. For example, assume the signal generator has a maximum VSWR of 2.0. Using the graph in Figure 3, read the required amount of smoothing pad attenuation at the intersection of a vertical line drawn through 2.0 on the X-axis and a horizontal line drawn through 1.2 on the Y-axis. The attenuation required to obtain a pad output VSWR of 1.20 is between 5 and 6 dB. A standard 6-dB pad will therefore be satisfactory.

Although the previous example was concerned with minimizing signal generator VSWR, it is also important to minimize the input VSWR of the receiver associated with the TEMPEST test detection system. Consequently, if the receiver technical manual specifies that the receiver maximum input VSWR is greater than 1.2, a suitable 50-ohm pad should be placed in front of the receiver input to reduce its input VSWR to an acceptable level. This pad then becomes a part of the detection system, and all level measurements are made with the pad connected to the receiver input.

WIDEBAND TRANSFORMER DESIGN & CONSTRUCTION FOR IMPEDANCE TRANSFORMATION

Although the resistive minimum-loss pad can provide wideband impedance transformation and impedance smoothing with just three inexpensive resistors, it has the disadvantage of high loss when large impedance transformations are required. For example, when using a minimum-loss pad to transform a 600-ohm to a 50-ohm impedance level, the signal loss compared to using a transformer is 16.6 dB (as listed in Table 2 for 600/50 ohms). And when transforming from a 600-ohm to a 150-ohm impedance level, the loss compared to using a transformer is 11.4 dB. Consequently, when an impedance transformation of four-to-one or more is required, the use of a transformer is desirable to minimize excessive signal loss.

IMPEDANCE TRANSFORMER DESIGN

When using a high-permeability ferrite toroidal core, it is relatively simple to design and wind an impedance-matching transformer for signal levels equivalent to less than one-quarter watt. With proper design, the transformer can cover a three-decade frequency range starting as low as 1 kHz. A design procedure will be explained and an example provided showing how a suitable core is selected and wound to provide an impedance reduction from a 600-ohm source. Because dc isolation is not needed between the primary and secondary windings, a tapped single winding will be used because it is simpler to wind than a transformer having isolated primary and secondary windings.

To explain the transformer design procedure, the signal source will be assumed to have the higher impedance level. The parameters that must be known are the impedance level to be transformed and the lowest frequency to be passed. Knowing this, the required inductance of the transformer primary winding can be calculated, the core selected and the number of turns determined.

Assume that a 600-ohm source impedance is to be transformed to appear as a 50-ohm source using a combination of a transformer and a minimum-loss matching pad. The lowest frequency of interest is 6 kHz. The following example illustrates the design procedure.

The first design decision is to choose the inductance of the transformer high-impedance winding, which involves a compromise between efficiency, bandwidth and ease of winding the transformer. For example, if the winding reactance at the lowest operating frequency is made to be ten times the source impedance, the increase in the source current when the transformer is connected across the signal source will be about 0.5 percent, or virtually unnoticeable. Although the efficiency of this transformer will be very good, its high-frequency performance will be limited because of its higher than necessary interwinding capacity. Also, the high number of turns will make the transformer more difficult to wind. On the other hand, if the

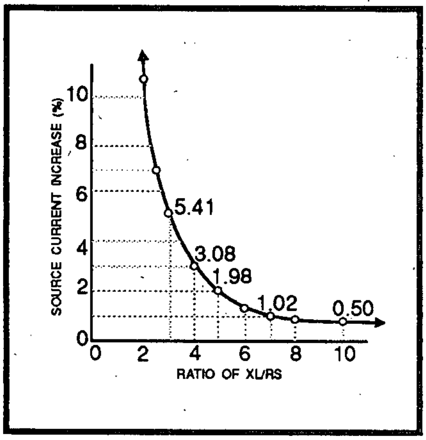

FIGURE 4. *Source Current Increase as a Function of XL/RS Ratio.*

winding reactance is made equal to the source impedance at the same frequency previously used, the transformer will be easier to wind because of the fewer turns. Also, the high-frequency response will be better because of the reduced interwinding capacity, but the efficiency will be unacceptable because the source current will be increased by 41.4 percent! Obviously, the transformer primary winding reactance should be somewhere between one and ten times the source impedance. The ratio between the winding reactance (XL) and the source impedance (RS) should be such that the source current is not increased excessively. If an increase in source current of about three percent is assumed to be acceptable, then an acceptable XL/RS ratio is four.

Figure 4 shows the percentage of source current increase as a function of XL/RS. As shown by the curve in Figure 4, as the XL/RS ratio becomes less than four, the change in the percentage of source current increase is quite significant; however, as the XL/RS ratio becomes greater than five, the percentage change becomes very small. Since the "knee" of the curve appears to be between four and five, four to five is generally accepted as a suitable XL/RS ratio for this type of transformer design. For this particular design example, XL/RS is assumed to be four, and the following calculations will be based on this ratio.

Because 6 kHz is the lowest frequency the transformer is to pass and the transformer reactance at this frequency is four times RS or 4 · 600 ohms = 2400 ohms, we can calculate the inductance of the transformer primary winding.

Lpri = XL/(2pi · F),
= 2400/(6.28 · 6000)
= 0.0637 H or 63.7 mH

From the Magnetics catalog[3], ferrite "J" and "W" materials are considered for use because they are available in a toroidal form, they have a high permeability (5k and 10k, respectively) and they are suitable for broadband transformer applications. Section 13 (Toroids) of the Magnetics catalog shows that toroidal cores are available in outer-diameter sizes ranging from 0.100 to 3.375 inches. A core having an OD, ID and Hgt of 1.000, 0.610 and 0.312 inches (Part 42507-TC) is selected because of its convenient size for handwinding. The J material is selected for a first trial because its inductance of 3,913 mH/1000 turns appears adequate for this application. The complete part number of this Magnetics core is J-42507-TC. (The designation "AL" refers to the inductance of a 1000-turn coil wound on a particular core, and this factor is listed in the manufacturer's catalog.)

The tabulated AL factor of 3,913 mH/1000 turns is converted to 39.13 mH/100 turns and then corrected to 0.8·39.13 = 31.3 mH/100 turns to account for the 20 percent permeability tolerance. This AL correction is made to assure that the actual inductance will not be less than the calculated value.

The required number of turns is calculated from the equation:

$N = 100(L/AL)^{0.5}$
Where
L = 63.7 mH
AL = 31.3 mH
Hence
$N = 100(63.7/31.3)^{0.5}$
$= 100(2.03514)^{0.5}$
$= 100 \cdot 1.4266$
= 143 turns

The exact number of turns is not critical and it can be varied slightly to make the following calculations more convenient. For example, so the 50-ohm tap will be an integral turn, 142 will be used as the total number of turns, and when it must be divisible by three, 144 turns will be used.

Two possible winding configurations can be used for the transformer:

- A single-wire winding of 142 turns with a 50-ohm tap at the 41st turn above the grounded end. Figure 5A shows the schematic diagram of the tapped transformer. The tap position is calculated from the equation:

  Turn number for 50-ohm tap
  $= [142(50/600)^{0.5}]$
  = 40.99
  = 41st turn

- A 48-turn trifilar winding (total turns = 144 turns) with a tap at the junction of the first and second windings above ground. At this position, the tap has an impedance of $600/[(1/3)^2] = 600/9 = 66.7$ ohms. Figure 5B shows the schematic diagram of the trifilar-wound transformer.

The main advantage of the trifilar-wound transformer is that its windings are magnetically closely coupled, thereby minimizing leakage inductance and

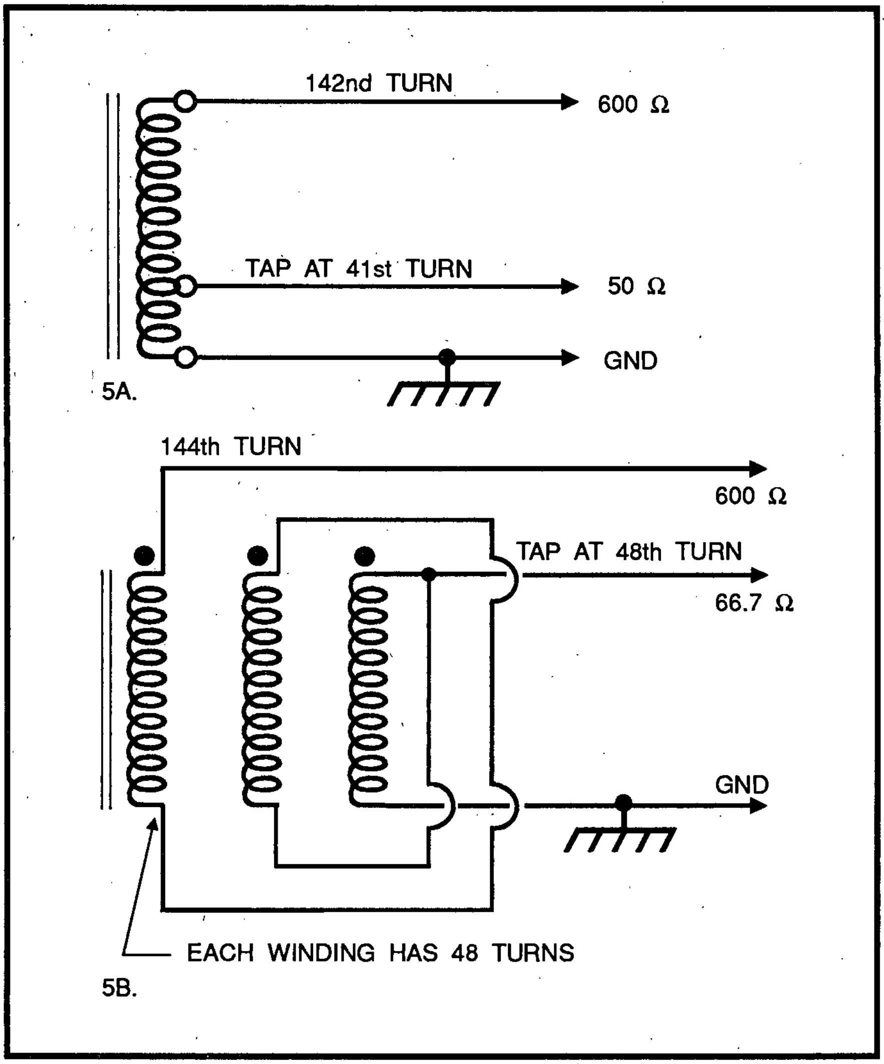

FIGURE 5. *Schematic Diagram of Two Transformer Winding Configurations.*
A. Single-winding transformer with a 50-ohm tap.
B. Trifilar-wound transformer with a 66.7-ohm tap.

maximizing the high-frequency response. In comparison, the single-winding transformer has reduced bandwidth because of its higher leakage inductance due to the poorer coupling between turns. The trifilar-wound transformer will be used in this design example because of its wider frequency response.

Although the trifilar-wound transformer has its tap at 66.7 ohms and not at the desired 50-ohm level, the tap can be easily matched from 66.7 ohms to 50 ohms with a minimum-loss pad having only 4.8-dB loss and with R3 = 33.2 ohms and R4 = 100 ohms. Figure 6 shows the schematic diagram of the trifilar-wound transformer connected to the 66.7/50-ohm minimum-loss pad.

This completes the transformer and pad design necessary to transform a 600-ohm signal source to a 50-ohm level.

TRIFILAR-WOUND TRANSFORMER CONSTRUCTION

Three four-foot lengths of #28 magnet wire are twisted together to make it easier to wind the wires on the toroidal core. The three wires are easily twisted together by clamping one end of the three wires in a table vise while the other end is clamped in a hand-drill chuck. While keeping the four-foot cable taut by pulling on the cable with the hand drill, power is applied to the hand drill until the cable is sufficiently twisted together. About six to eight twists per inch is suggested. While the cable is being twisted, enough tension must be kept on it to prevent any kinks from forming.

After the cable twisting is completed, the cable is removed from the vise and drill chuck and half of the cable is threaded through the toroidal core. All kinks should be removed before beginning the winding of the core. Twenty-four turns are wound on half of the core. Then the winding is finished by using the other half of the cable to wind twenty-four more turns on the other half of the core. The windings are evenly spaced over the whole core with no overlapping of the windings. The start and finish leads of each of the three windings are determined with an ohmeter and marked so the connections can be made according to the schematic diagram in Figure 5B. After the winding connections are completed, the correctness of the connections should be confirmed by applying a 10-kHz signal between the top and bottom leads of the winding. The voltage at the 66.7-ohm tap should be one-third of the voltage applied across the full winding.

After the winding connections are confirmed as being correct, the transformer can be installed in a small metal box with a pair of pin jacks for the input and a BNC connector for the 50-ohm output. The two resistors comprising the 66.7/50-ohm pad are connected between the transformer tap and the BNC connector as shown in Figure 6. Figure 7 is a photograph of the completed transformer/pad.

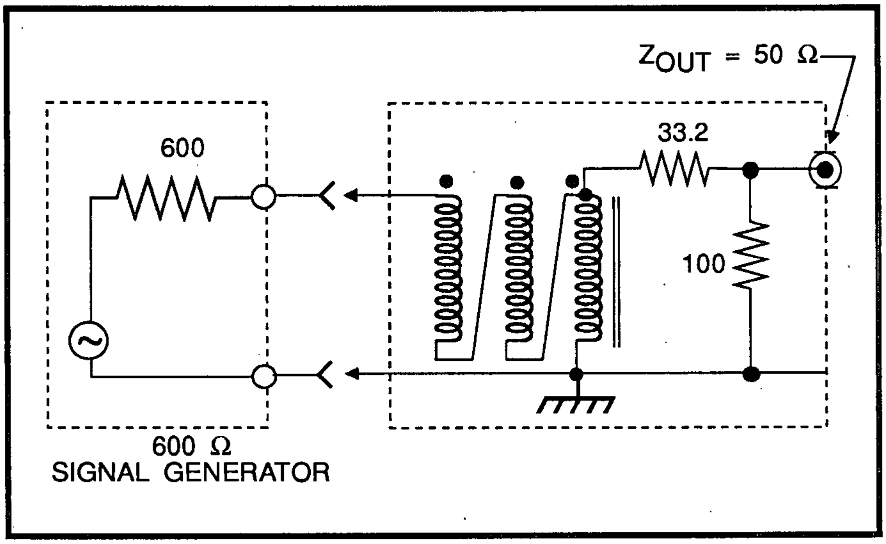

FIGURE 6. *Schematic Diagram of a 600/66.7-ohm Trifilar-wound Transformer and a 66.7/50-ohm Minimum-loss Matching Pad to Give a 50-ohm Output Impedance.*

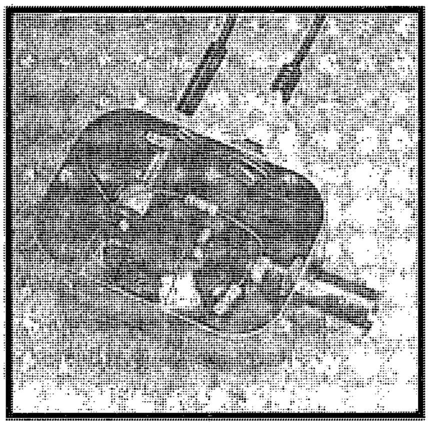

FIGURE 7. *Photograph of the Completed 600/50-ohm Matching Transformer and Minimum-loss Matching Pad Installed in a Metal Box.*

The return loss of the transformer/pad was measured at the BNC connector output with a 600-ohm resistor connected across the transformer input. The return loss was better than 24 dB (equivalent to VSWR = 1.135) over a three-decade span from 3 kHz to 3 MHz. As compared to using only a 600/50-ohm minimum-loss pad on the output of an H-P 200CD signal generator, the transformer/pad gives an additional 11.8 dB of signal voltage.

SUMMARY

The importance of resistive attenuators in TEMPEST testing, both for impedance smoothing and for minimum-loss impedance transformation, was discussed. Computer-calculated tables of 50-ohm Pi and Tee attenuator pads and minimum-loss matching pads were presented, and a family of curves of padded versus unpadded VSWR for various attenuation levels showed how resistive padding can be used to minimize undesirable impedance variations in signal generators and receivers. A procedure for designing a transformer for matching widely different impedance levels was explained, and the construction of a simple trifilar-wound autotransformer and a 4.8-dB minimum-loss matching pad was demonstrated for matching a 600-ohm signal generator to a 50-ohm load. All necessary design equations used in the pad and curve calculations are included in an Appendix. The material in this article will be of interest to all electronics engineers who may occasionally be required to design and construct a resistive attenuator or low-power impedance transformer.

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3. *Ferrite Cores* (15-Section Catalog), Copyright 1991. Magnetics, 900 E. Butler Road, POB 391, Butler PA 16003. Telephone: (412) 282-8282.

APPENDIX

Equations for Symmetrical and Minimum-Loss Matching Pads

(A) Symmetrical Pads:
A = Attenuation (dB)
Z = Impedance (ohms)
$K = 10^{(A/20)}$
$R1 = Z(K - 1)/(K + 1)$
$R2 = Z \cdot 2 \cdot K/(K^2 - 1)$
$R3 = Z(K^2 - 1)/(2 \cdot K)$
$R4 = Z(K + 1)/(K - 1)$
(See Figure 1 for R1-4)

(B) Minimum Loss Matching Pads:
A = Attenuation (dB)
RS = Source Impedance (ohms)
RL = Load Impedance (ohms)
For RS>RL: R = RS/RL
For RL>RS: R = RL/RS
(See Figure 2 for position of RS and RL)
$M = (1 - 1/R)^{0.5}$
$K = [(1 + M)/(1 - M)]^{0.5}$
$X = (K^4 - 1)/[4(K^2)]$
$Y = (K^2 + 1)/(K^2 - 1)$
If RS<RL: $R3 = RS \cdot X$, $R4 = RS \cdot Y$
If RL<RS: $R3 = RL \cdot X$, $R4 = RL \cdot Y$
A = 8.68589*LOGe(K)
V_{drop} (in dB)
$= 8.68589 \cdot LOGe(V_{in}/V_{out})$

(C) VSWR Smoothing curves of Figure 3:
A = Attenuation (dB)
T = Unpadded VSWR
V = Padded (smoothed) VSWR
$K = 10^{(A/20)}$
$X = (K^2 + 1)/(K^2 - 1)$
$V = (1 + T \cdot X)/(T + X)$

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