Chapter 7

My Antenna Tuner Really Does Tune My Antenna

(Adapted from *QST*, August 1976)

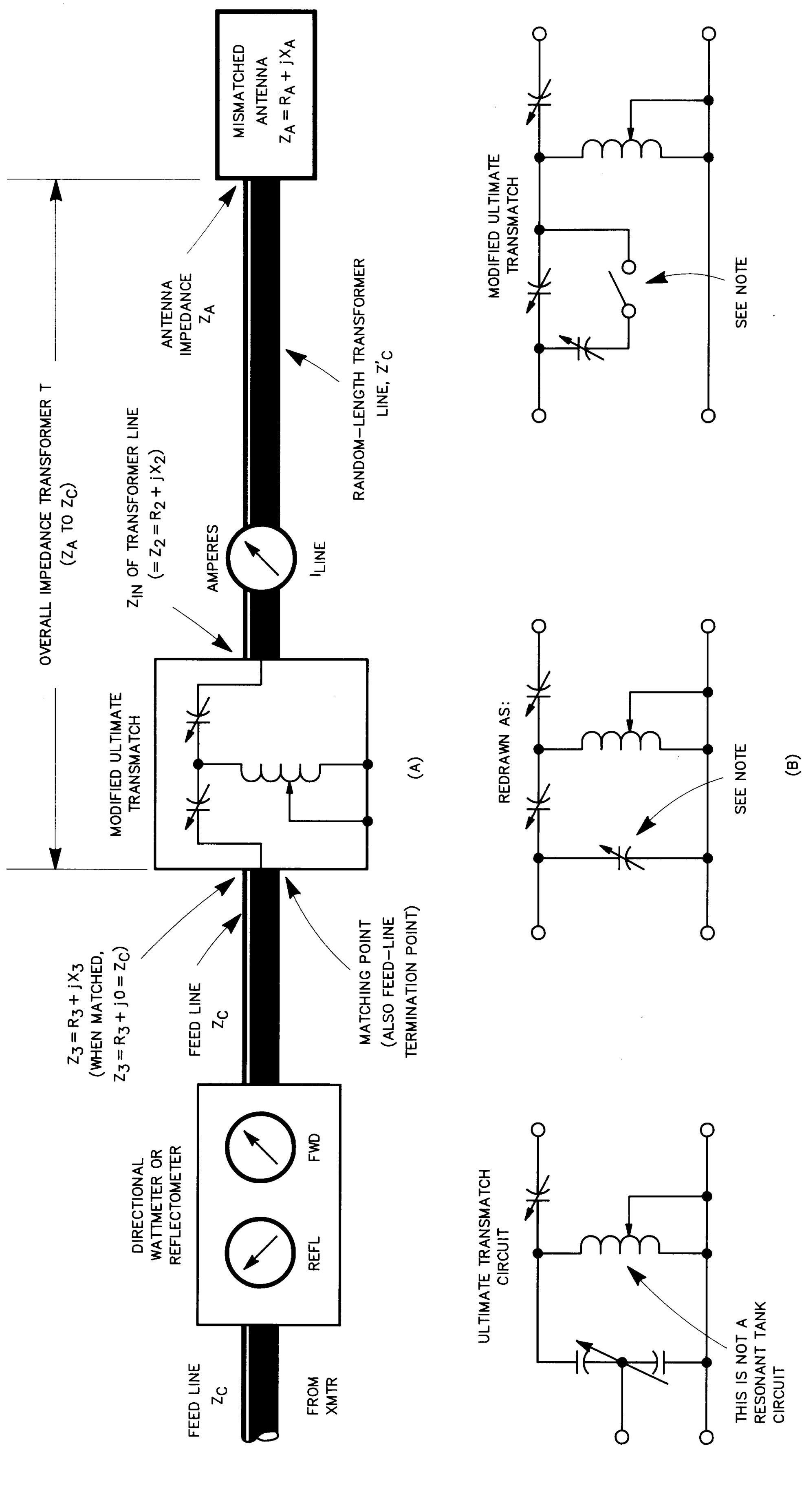
Sec 7.1 Introduction

Chapter 4 discusses conjugate matching and introduces the concept of wave interference as the basis for the mechanics of the matching. I used the transmission-line stub form of matching for the example because of the ease in describing the generation of the waves and the wave actions involved in the matching process. Chapters 5 and 6 discuss some of the reasons why many have been plagued with myths concerning mismatch and SWR, myths that have prevented an enlightened use of impedance matching in our daily operating procedures concerning antennas and transmission lines. In those chapters I also explained power loss caused by line attenuation, and presented both graphic and mathematical means for determining the additional loss resulting from SWR on the feed line. An additional detailed discussion of the conjugate match may be found in Chapter 19. This chapter focuses on the use of line-matching networks formed with adjustable capacitors and inductors instead of stubs made from sections of transmission line. Here I show that the wave actions in both of these forms of matching are identical. I will also explain in detail how transmitters are matched to mismatched feed lines with an external matching network as shown in Fig 7-1, or by using the pi-network tank in the transmitter shown in Fig 7-2. But first let's examine one last reason why so many have been reluctant to operate with an SWR greater than 1:1.

The principle that maximum efficiency is obtained when a feed line is perfectly matched to an antenna — no reflections on the feed line, and a 1:1 SWR — is so well known it hardly needs repeating. Even so, it is recited in practically every good textbook on the subject. So it is important to appreciate that this book makes no statement which violates that principle, nor suggests any disagreement with it. The misconceptions to be clarified concerning lost reflected power stem simply from overuse, or misuse, of the perfect-match principle in its practical applications.

Ironically, textbooks may be a bit responsible for this misuse. While extolling the virtues of the perfect match, many authors fail to explain how much (or how little) one loses when the load is mismatched to the line, if compensated with a conjugate match at the line input. Those authors generally present the case for the ideal impedance match of the load in terms of single-frequency operation, and practically ignore the unique, multi-frequency operations of the radio amateur. We have frequency *bands*, not single, specific frequencies — and we want to operate anywhere within those bands.

Because the antenna impedance changes as we change frequency, relax-



OVERALL IMPEDANCE TRANSFORMER T
(ZA TO ZC)
MISMATCHED
ANTENNA
ZA = RA + jXA
ANTENNA
IMPEDANCE
ZA
RANDOM-LENGTH TRANSFORMER
LINE, Z'C
ZIN OF TRANSFORMER LINE
(= Z2 = R2 + jX2)
AMPERES
ILINE
MODIFIED ULTIMATE
TRANSMATCH
(A)
Z3 = R3 + jX3
(WHEN MATCHED,
Z3 = R3 + j0 = ZC)
FEED LINE
ZC
MATCHING POINT
(ALSO FEED-LINE
TERMINATION POINT)
DIRECTIONAL
WATTMETER OR
REFLECTOMETER
REFL
FWD
FEED LINE
ZC
FROM
XMTR
MODIFIED ULTIMATE
TRANSMATCH
SEE NOTE
REDRAWN AS:
SEE NOTE
(B)
ULTIMATE TRANSMATCH
CIRCUIT
THIS IS NOT A
RESONANT TANK
CIRCUIT

Fig 7-1 — Impedance matching with a matching network external to the transmitter. The impedance of the feed line, Z_C, is usually 50 or 75 ohms in most amateur applications, but the impedance of the transformer line, Z'_C, may be any value, and may be of open-wire or coaxial type. The matching network at A is a simple "T" network, Lew McCoy's Ultimate Transmatch less the shunt capacitor *(Ref 41)*, as shown at B. NOTE: In the redrawn circuit at B (center) the shunt input capacitor is not needed to obtain a match, and the capacitor range may be increased by reconnecting as shown at the right. The story of how this change came about and why commercial present-day antenna tuners now use the simple "T" network, is told in Chapter 14, Sec 14.4.

ation of any feed-line-to-antenna matching restriction is necessary if we are to enjoy such operating freedom. Although many engineering textbooks discuss loss versus load mismatch, few texts discuss multi-frequency antenna-matching situations where line-input matching usually exists. Consequently, an overly rigorous application of the perfect-load matching principle has unwittingly been thrust upon us by dozens of misleading statements appearing in various amateur journals. Add to this a prevalent misconception of pi-network loading principles. Result? The "lost reflected power" syndrome and the mania for low SWR. Thus, providing guidance for the amateur concerning match quality and efficiency in his multi frequency operation is the primary purpose of this writing.

For example, Fig 6-1 is a graph that plots transmission loss in dB versus SWR for various values of line attenuation. The graph shows that maximum efficiency is indeed obtained with a perfect match. On the other hand, it also provides dramatic evidence that when using low-loss feed line that is matched at the line input, the difference between having either a perfect load match or a moderately high SWR is insignificant in terms of power transferred to the antenna. In other words, through the use of line-input matching, the antenna accepts the maximum available power from the transmitter, even when the feed line and antenna are mismatched, and with the antenna off resonance. Matching at the input terminals of the feed line allows us to tolerate this load mismatch because the reflection loss caused by the mismatch is compensated by the *reflection gain* provided by the input match. Consequently, the transmitter is properly coupled to its desired load impedance and the reflected power is conserved. It is *system resonance* that underlies these intrinsic characteristics of input matching involving the principles of the conjugate match. And *system resonance* compensates for the effect of the off-resonant condition of the antenna as we move around within a given frequency band.

For the myth believer who is still unconvinced of the wondrous compensating powers of conjugate line-input matching, let me quote Everitt on the Maximum Power-Transfer Theorem from classical network theory *(Ref 17, p 49; Ref 69)*. The application to feed-line antenna matching is indicated in parentheses: "The maximum power will be absorbed by one network (the antenna) from another (the feed line) joined to it at two terminals, when the impedance of the receiving network (the antenna) is varied, if the impedances of the two networks at the junction are conjugates of each other." Everitt then presents the proof of the theorem.

The expressions in Eqs 6-1 and 6-2, which are plotted in Fig 6-1, illustrate this theorem for the case where a feed line is the sending network. These expressions show that when the networks are conju-

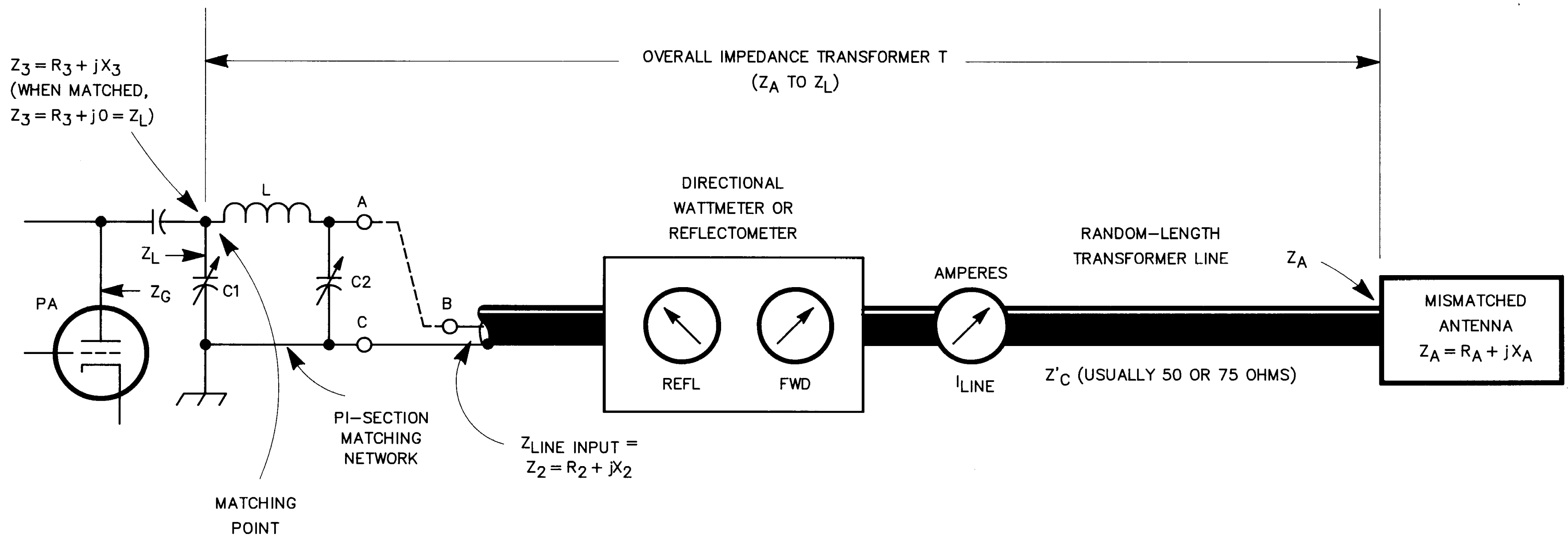


Fig 7-2 — Impedance matching with the final-amplifier tank circuit of the transmitter. Z_L is defined as the optimum load impedance of the amplifier — the impedance into which it delivers its maximum available power.

gately matched, meaning when the transmitter is tuned to the line, (1) there is no loss at the terminals joining the networks, (2) there is no loss in the sending network, the feed line, when that network attenuation is zero, and (3) if the sending network has attenuation other than zero, the transmission loss results only from the line attenuation. For further discussion on the theorem, I invite you to review Chapters 2, 4, 5, and 19.

The way that conjugate matching and reflection gain are achieved is illustrated in Chapter 4, using the stub form of matching to develop the understanding of the wave action. The stub form was used for the illustration because it is easy to visualize. But since it's not a practical form to use where we make frequent changes in frequency, let's see how conjugate matching is performed using devices, which are easily adjusted to perform at any desired frequency. Such devices are the transmatch, a T network, L, pi, and other types of networks. I will show that these devices can perform the matching function at the *input* of a feed line, and that the feed line can be of *any* length instead of requiring it to be $\lambda/2$. I will also show how, in some instances, the transmitter tank circuit itself performs matching at the input of the feed line.

Sec 7.2 Matching at the Line Input

At this point you may ask, "Why match at the *input* of the feed line?" The answer is that without matching at the input, we have very little operating flexibility relative to changing frequency within a band. In the absence of a line-matching network we are restricted to operating in a narrow portion of a band (especially on 80 meters) unless effective measures for broad-banding the antenna itself have been taken. We are restricted because, as we deviate from the resonant frequency of the antenna, the resulting increase in the impedance mismatch between the feed line and the antenna is transferred back to the input of the feed line as an increased mismatch between the transmitter and the feed line. As a result, the load impedance seen by the transmitter varies beyond acceptable limits; the transmitter fails to load properly, and it can be damaged by overloading or by arc-overs caused by underloading.

These phenomena (plus an unawareness of the remarkable performance capabilities of line-input matching) are largely responsible for the traditional low-SWR mania. On the other hand, simple impedance matching at the input of the feed line provides stupendous improvement in operating flexibility; the matching network compensates for the impedance changes at the line input terminals, and provides the correct load impedance for the transmitter at whatever frequency we select within an entire band. The correct load impedance for the transmitter is obtained by simply adjusting the network, conveniently located at the operating position.

So the next question is, "Why not broadband the antenna and avoid having to retune a matching device when changing frequency?" The answer is that we can, but only to a limited degree. This is because, for example, broad-banding techniques which would permit coupling the average amateur transmitter directly into the feed line over the entire 80-meter band (with no adjustments other than retuning the transmitter) are not practical in the average amateur situation. This includes the coaxial dipole (sometimes called a Double-Bazooka) which, contrary to prevalent opinion, fails to deliver a reasonable improvement in bandwidth over that of a simple dipole when it is fed with the usual 50-ohm feed line[1]. While the above statement may appear a bit incredible, I wrote a revealing analysis of that antenna and published it in *Ham Radio Magazine (Ref 62)*. (A condensed version of that analysis appears here as Chapter 18.) However, there is a recent development worthy of your attention. In my analysis I presented information concerning the use of a feed line having an impedance Z_C higher than the usual 50 or 75 ohms (such as 144 ohms) for increasing the bandwidth with stubs in the coaxial dipole. Using my analysis, Frank Witt, AI1H, engineered a novel transmission-line impedance transformer that achieves the required effect of increasing the feed-line impedance. With Witt's transformer, the 2:1 SWR bandwidth of an 80-meter coaxial-stub dipole extends well beyond the range of 3.5 to 4.0 MHz *(Refs 122, 123 and 124)*. Witt has presented a practical way of broad-banding the dipole that deserves serious attention.

An explanation of how either a final tank network or an external line-matching network performs conjugate matching from the viewpoint of reflections is really a continuation of Chapter 4. However, to dramatize both the availability and the advantages of matching at the input of the feed line, we digressed in Chapters 5 and 6 to highlight some of the wrong and right reasons for using low SWR. These reasons show that, in the mania for obtaining low SWR on the feed line, we have often put misplaced emphasis on matching at the wrong end of the line. As stated earlier, the principles of wave reflection found in stub matching are the same as in other matching schemes, such as series λ/4 transformers, L, T, pi networks, etc. As some of the concepts I discuss here were presented in detail in Chapter 4, you may wish to refer to them again.

Sec 7.3 The Intermediate Role of the λ/4 Transformer

How many amateurs remember the Johnson Q Match? And how many have used a λ/4 section of 70-ohm transmission line to match a 100-ohm resistive load to a 50-ohm feed line? Both are examples of series λ/4 line transformers. In addition to requiring an electrical length of 90°, impedance matching is accomplished in these transmission-line transformers because of a specific relationship between their characteristic impedance Z_C, their input impedance Z_I, and their output load impedance Z_L. To perform the matching, the ratio of Z_C to Z_I must be the inverse of the ratio Z_C to Z_L, that is

$$\frac{Z_I}{Z_C} = \frac{Z_C}{Z_L} \qquad \text{(Eq 7-1)}$$

In other words, the impedance required of the transformer is the geometric mean value of the two impedances being matched, stated simply by the well-known expression

$$Z_C = \sqrt{Z_I \times Z_L} \qquad \text{(Eq 7-2)}$$

Both the impedance and the length of the λ/4 line transformer play important roles in clarifying the principles underlying all forms of line-matching networks. Since these roles are not generally well understood, let's examine them.

Chapter 4 shows that reflections play a necessary role in impedance-matching operations. We saw that impedance matching is obtained by canceling the reflections from a load mismatch by wave interference. The interference is set up by new, separate reflections generated by a separate mismatch introduced at a desired matching point. The mismatch introduced at the matching point is tailored to complement the load mismatch, so that the new reflection has the same magnitude and opposite phase (at the matching point) as the reflection generated by the load mismatch. The reflection generated by this complementary mismatch is called either a complementary, or a canceling reflection. In stub matching, the complementary mismatch is introduced by the stub. While investigating complementary reflections generated by stubs, we observed the wave action through which the λ/4 transformer performs the matching (see Table 4-1 and Fig 4-2D).

In Chapter 4 we analyzed the effects of using various stub and transformer lengths to match a resistive load to various feed lines having different values of impedance. We found that when the feed-line impedance is equal to Z_I (relative to transformer impedance Z_C and load impedance Z_L in Eqs 7-1 and 7-2), the transformer length became 90°, and the stub length became zero. In this case the complementary reflection is generated by the mismatch appearing at the junction of the feed line and the input of the transformer. This mismatch results from the abrupt change in impedance (Z_I to Z_C) encountered by the forward wave as it propagates out of the feed line (Z_I) and into the transformer (Z_C). This mismatch is complementary to the resistive load mismatch in magnitude because the ratio between the feed line and transformer impedances (Z_I/Z_C) is the inverse of that appearing between the transformer and the load impedances (Z_C/Z_L), as in Eq 7-1. Thus, the reflections generated by both the load mismatch and the transformer-input mismatch are equal in magnitude (as required to obtain perfect cancellation), because both mismatches are equal in magnitude.

Because the input and output mismatches are physically separated by 90° (the electrical length of the transformer), they are also complementary in relation to the phase of the reflections appearing at the matching point (also required for cancellation). This is because the wave reflected by the input mismatch has zero distance to travel relative to the matching point, but the 90° length of the transformer results in a travel of 180° for the wave reflected by the load mismatch — 90° from the input to the load, plus the 90° return trip. Thus, the load-reflected wave arrives at the matching point with a 180° phase difference relative to the input-reflected wave. We now have two complementary reflected waves — equal in magnitude but opposite in phase at the matching point. Consequently the two waves mutually cancel, resulting in total re-reflection of both waves into the transformer to propagate in the forward direction, as explained in the final paragraphs of Chapter 4. The voltage and current components of both re-reflected waves are in phase with their corresponding components of the source wave. Hence, an impedance match appears at the input terminals of the transformer, all of the power reflected from the load mismatch which reaches the input of the transformer is again on its way to the load, and no reflected wave appears on the feed line[2].

This λ/4 line-transformer matching action deserves serious study. Why? Because it provides an intermediate step in understanding how matching can be achieved at the input of a line transformer of *any random length*, and which may have *any impedance* for its terminating load, such as the complex impedance $Z_A = R_A + jX_A$ of a mismatched, off-resonance antenna. And this line transformer is none other than the feed line so many strive to operate with no reflections by simply restricting its *load* to a matched, resonant antenna!

Sec 7.4 Input Line-Matching Networks

Now let's examine external line-matching networks from the viewpoint of matching impedances with reflections. Referring to Fig 4-2D, we replace the 90° transformer (T) with the combination of an adjustable matching network and a line of *random* length to connect the mismatched load (antenna) to the network. This arrangement is shown in Fig 7-1A. The line connecting the matching network to the antenna will now be called the *transformer line*. The line connecting the transmitter to the matching network is the *feed line,* as in Chapter 4. The matching point is defined as the junction of the feed line and the input of the network.

In a manner which is explained later, the transformer line (which can have *any* value of impedance Z'_C) transforms the complex antenna impedance $Z_A = R_A + jX_A$, to a second impedance $Z_2 = R_2 + jX_2$ at the input of the transformer line. The network then transforms Z_2 to a third impedance $Z_3 = R_3 + jX_3$ at the matching point (the network input). When the network is correctly adjusted, Z_3 is a pure resistance R_3, equal to the feed-line impedance Z_C. In mathematical terms, $Z_3 = R_3 + j0 = Z_C$. Thus, the antenna impedance Z_A is matched to the feed-line impedance Z_C, which is a proper load for the transmitter (*Ref 17, p 243; Ref 69*). Without the matching network, the transmitter load would be impedance Z_2, which could deviate far beyond the range of matching capability for most transmitters. However, by adding the network, we obtain the impedance match by simply adjusting the network to transform R_2 to equal the feed-line impedance Z_C at the matching point, and to cancel any reactance X_2 appearing at the input of the transformer-line to zero at the matching point.

Let's now examine more closely the transformation of impedance Z_2, that which appears at the input of the transformer line. The variations of resistance R_2 and reactance X_2 of impedance Z_2 are dependent on three different factors: the antenna impedance Z_A, and both the length and the impedance Z'_C of the transformer line. From Chapter 4 we know that, for given antenna and transformer-line impedances, a length of line can be found that will make $R_2 = Z_C$, but will also yield reactance X_2. The reactance X_2 requires canceling to obtain a match, for example with a stub, as shown in Fig 4-2A or 4-2B. Another length of line can be found that will make X_2 become zero, but now R_2 will not equal Z_C (still no match). *There is no line length that will yield* $Z_2 = R_2 + j0 = Z_C$, *unless* Z_A *equals* Z'_C.

This situation illustrates the typical endless cat-and-mouse game we play in trying to load the transmitter by changing line lengths. An elegant solution to this problem would be a line of *variable* length, plus a device for dumping the unwanted reactance. So how can we possibly solve the problem using a fixed, random-length line? Because, as we now discover, the line-matching network is the star performer! We know from elementary transmission-line theory that a transmission line is made up of an infinite number of tiny, distributed, series inductances and shunt capacitances. So it should not be surprising that we can adjust the *electrical* length of a line of a given *physical* length by adding lumped inductances or capacitances. Indeed, by a selection and adjustment of reactances arranged in an appropriate L, T, or pi configuration, we can simulate a line having *any desired electrical length* without specifying any physical length whatever! (*See Refs 8 through 13; 19, p 115; 21; 22; 24; 30; 31; 41; 61 and 63.*)

When a matching network is adjusted to obtain a match between the antenna and feed-line input impedances, it performs the following two feats. First, it creates the effect of stretching the *electrical* length of the transformer line to make it reach the matching point, so that resistance R_2 at the input of the *physical* transformer line is transformed to $R_3 = Z_C$. And second, it introduces reactance $-X_3$ to cancel reactance $+X_3$ of the *stretched*-transformer line appearing at the matching point, in the same manner as a stub would perform in stub matching.

The introduction of reactance $-X_3$ at the matching point provides the complementary mismatch which generates the canceling reflection having equal magnitude and opposite phase relative to the reflected wave arriving at the matching point from the mismatched antenna. The matching network has thus provided the proper *overall* transformer length to obtain both the required transformation of the resistance component from R_A to R_3, and a canceling-phase relation between the load-reflected wave and the canceling reflected wave provided by the complementary mismatch of reactance $-X_3$. Consequently, the network has also transformed a dream into reality by conjuring up the elegant variable-length line and a means for dumping the unwanted reactance.

An ideal arrangement for observing the action while performing the tuning adjustments of the network includes an RF ammeter in the transformer line to indicate line current (a meter in each conductor if using a balanced, two-wire line), and a dual-meter reflectometer or wattmeter to indicate forward and reflected power simultaneously in the feed line. It is important that the reflectometer be adjusted initially to indicate zero reflected power with the feed line terminated in a pure resistance equal to the feed-line impedance. The tuning adjustments are complete when we obtain maximum current in the transformer line simultaneously with maximum forward and zero reflected power in the feed line. Of course, because of standing waves on the transformer line, we will obtain different values of line current depending on where along the line the ammeter is inserted. However, our only interest is in seeing *changes in relative current* to indicate when maximum network output occurs during the tuning adjustments. Hence, neither the absolute line current, nor where the meter is inserted, is important.

The simultaneous indication of maximum current in the transformer line and zero reflected power in the feed line is meaningful. This condition denotes four significant factors for comparing the wave actions involved in impedance matching with a line-matching network versus matching with the $\lambda/4$ line transformer described earlier. First, proper network adjustment establishes the complementary mismatch between the feed-line termination and the input of the network, which produces the canceling reflection at the matching point. Second, the canceling reflection at the matching point is equal in magnitude and opposite in phase relative to the load-mismatch reflection. Third, the canceling reflection and the load-mismatch reflection cancel each other at the matching point. Consequently, a purely resistive impedance equal to the feed-line impedance Z_C appears at the input terminals of the network, while reflections and a standing wave remain on the transformer line. And fourth, observing the transformer-line current rising to maximum while the reflected power in the feed line drops to zero provides visual evidence that the power reflected from the load mismatch is indeed re-reflected by the complementary mismatch at the matching point.

Incidentally, it is a good practice to have an ammeter permanently connected in the transformer line. Here's why. If your matching network effectively comprises more than one L section, you can generally obtain a match (zero reflected power in the feed line) with several different combinations of network L and C tuning. However, minimum network loss (which corresponds to highest maximum transformer-line current) usually occurs while using the maximum C and minimum L at which a match can be obtained. Monitoring the transformer-line current during tune-up lets you select the L-C combination that yields the highest output line current. To ensure quick resetability of the network, and to minimize on-the-air tune-up time, L and C settings for the best combination should be logged whenever the network is tuned to a new frequency. The transmitter should be tuned initially into a dummy load, then the network tuned into the antenna *using the lowest power* at which the reflectometer provides a satisfactory indication.

Sec 7.5 Pi-Network Tank-Circuit Line Matching

Let's now examine the case where the final amplifier tank circuit of Fig 7-2 performs the line-matching function. To differentiate from the external network, I will call this network the *tank network.* Comparing Figs 7-1 and 7-2, we see that, in general, the transformations of impedance from Z_A to Z_3 are identical whether using the tank network or the external network. The principal difference is the range of the transformation that can be performed by the two networks. With the external network, impedance Z_2 is transformed to a value Z_3, matching the feed-line impedance Z_C. When the tank network is used alone, as shown in Fig 7-2, impedance Z_2 is transformed to directly match the load impedance Z_L of the final amplifier of the transmitter.

Now a requirement for an amplifier (tube or transistor) to deliver its maximum available power into a load (the loaded tank circuit) is for it to see an impedance which we call the *optimum load impedance*, Z_L. In practice, impedance Z_L is usually resistive, so that $Z_L = R_L + j0$. Thus, the amplifier is properly loaded when it sees impedance $Z_3 = R_L + j0$ (which is $R_3 + j0$) looking into the tank network. The amplifier is underloaded with R_3 *greater* than R_L,overloaded with R_3 less than R_L, and it will have higher than normal dissipation if Z_3 contains any reactance X_3.

When using the tank network alone to perform the matching, as in Fig 7-2, the impedance value of Z_3 is determined by two factors: the impedance value of Z_2 loading the network, and the impedance transformation ratio of the network. The transformation ratio is somewhat variable (using the tuning and loading capacitors, C_1 and C_2), thus providing a range of impedance-matching capability. The matching range allows impedance Z_2 to be any value which the network can transform to the impedance $Z_3 = R_L + j0$ by adjusting the tuning and loading controls. Additional details on this point appear in Chapter 13.

Now we can summarize the principal operating conditions involving transformation of antenna impedances to the optimum load impedance for the output amplifier.

Case 1

The antenna impedance $Z_A = R_A + j0$ (resonant) is matched to the transformer line, and the tank network is used alone — no external matcher, Fig 7-2. Here, antenna impedance Z_A equals the impedance of the transformer line, Z'_C, the SWR on the line is 1:1, and impedance Z_2 is equal to the line impedance. If the transformer-line impedance Z'_C is the commonly used 50-ohm, then the tank network yields the proper amplifier load $R_S + j0$ with the same tank adjustment settings as obtained when tuning up with a 50-ohm dummy load.

Case 2

The antenna is operated somewhat off resonance. Its impedance, $Z_A = R + jX_A$, yields a mismatch to the transformer line so as to transform Z_A to an impedance Z_2 that is within the matching range of the tank network (for transformation to $Z_3 = R_L + j0$). Again, the tank network is used solo.

Case 3

The antenna is operated off resonance, beyond the matching range of the tank network. Here, the tank network is used in conjunction with an external network, as in Fig 7-1. An impedance $Z_3 = R_L + j0$ cannot be obtained with the tank network alone, and the amplifier would be either underloaded, overloaded, or reactively loaded. We remedy this situation by inserting an external line-matching network, which transforms impedance Z_2 to an impedance Z_3 that is within the range the tank network can transform to $R_L + j0$.

Case 1 needs no comment, so let's refer to Fig 7-2 and examine the action in the tank network as it performs the matching function under the conditions of Case 2. As described in Chapter 4, wave interference establishes an open circuit to reflected waves at the matching point. This interference exists between the wave reflected by the mismatched termination on the line and the wave generated by the complementary mismatch at the matching point in the matching network. Recall that the open circuit so established causes total re-reflection of the reflected wave returning toward the generator.

In the tank network, the open circuit to the reflected wave is established at the tank-network input terminals, fed by the plate of the amplifier tube. Consequently, waves reflected from a mismatched antenna, those causing impedance Z_2 to deviate from Z'_C, enter the tank network at its output terminals and become totally re-reflected on arrival at the open-circuited input of the tank[2]. When the network is tuned to resonance, voltage and current components of the reflected wave are re-reflected in phase with the corresponding source-wave components emanating from the amplifier tube. Thus, the amplifier sees a resistive load $Z_3 = R_3 + j0 = Z_L$ at the input to the tank circuit, and the reflected power reaching the input adds to the power from the amplifier. This is why a directional wattmeter indicates a higher forward power than the amplifier is actually delivering when reflections are present on the transformer line.

Optimum amplifier loading is obtained by adjusting the capacitance of the loading-control capacitor C_2 to the value that causes the network to transform R_2 to $R_3 = R_L$. When R_2 changes, following a change in antenna impedance Z_A, C_2 can then be varied to modify the network transformation ratio. This transforms the new value of R_2 to $R_3 = R_L$. The plate tuning capacitor, C_1, is then readjusted to return the network to resonance and we again have optimum amplifier loading. The range of R_2 values which can be transformed to $R_3 = R_L$ by varying C_2 is determined by the design parameters of the network (*Refs 4, 63 and 64*).

Now, what happens when the line-input impedance Z_2 that loads the network contains reactance X_2? This reactance shifts the available range of capacitance provided by the loading-control capacitor, C_2. This shift occurs because reactance X_2 appears in parallel with the reactance of the loading capacitor. Consequently, for proper setting of the loading capacitor where $X_2 = 0$, a capacitive X_2 increases the effective capacitance C_2 (decreasing loading), while an inductive X_2 decreases C_2 (and increases loading). Thus, to obtain a proper loading when X_2 is present, the setting of the loading-control capacitor must be shifted from the $X_2 = 0$ position to compensate for the additional line reactance X_2. If R_2 is within the matching range of the tank network, proper loading will be attainable. This is true as long as X_2 doesn't exceed the value which the loading-control capacitor range can accommodate to maintain the value of C_2 required to transform R_2 to $R_3 = R_L$.

If the line reactance X_2 is too large for the loading capacitor to compensate, we have the conditions described in Case 3. However, there are simple remedies for this condition if R_2 is within matching range of the tank network, but X_2 is not. Here we can simply add a compensating reactance in series with the RF output (between points A and B in Fig 7-2). The added reactance may either cancel the line reactance X_2, or merely bring it within the range the tank network can handle. On the other hand, if the resistance component R_{2P} of the equivalent parallel circuit of impedance Z_2 is within the matching range, the compensating reactance should be added in parallel across the RF output between points A and C.

Whether the compensating reactance should be capacitive or inductive can be determined experimentally by trying first one kind or the other to see whether loading is improved or worsened. The correct kind and value of compensating reactance has been found when proper loading can be obtained with a convenient setting of the loading-control capacitor. An excellent discussion of this subject by Grammer appears in *Ref 4, Part 3*. When using this matching technique with the tank network alone, an adjustment of the length of the transformer line can be of great assistance in obtaining values of impedance Z_2 which are most favorable to the matching range of the network. This subject of impedance transformation versus line length is discussed in Chapter 11.

When operating under the conditions of Case 2 (Fig 7-2), tuning up into a dummy load requires special care; it can be troublesome since the actual load Z_2 at the input of the transformer line often differs widely from that of the dummy load. If the tank network is first tuned into the dummy load and then switched to the transformer line-input impedance Z_2, the tank network must be *retuned* to the new impedance Z_2! Failure to retune to the actual operating impedance Z_2 after tuning up into the dummy load results in an improper load impedance Z_3 for the amplifier — it is no longer $Z_3 = R_L + j0$ because the loading of the tank network has changed. Without retuning, the amplifier is then either underloaded, overloaded or reactively loaded.

In addition to the possibility of damaging the amplifier if operated in this mistuned condition, you also have less power available! Because of this mistuning, the amplifier *delivers less power* by the amount of the reflection loss resulting from the line mismatch. This power reduction is as shown in Fig 6-1, on the curve labeled *Reflection Loss Without Conjugate Match* and at the appropriate SWR ordinate. For example, if the line SWR is 3:1, the amplifier output will drop by 25% while it sees the improper load. On the other hand, retuning the network to the actual operating impedance Z_2 establishes a match to the line-input that restores the proper amplifier load impedance $R_L + j0$ and the amplifier again delivers its maximum available power. For additional discussion on this point refer to Chapter 6, Sec 6.3, and Chapter 19.

"But," you ask, "how do we determine when proper loading is obtained, or that impedance Z_2 is within the matching range of the network?" The answer is by simply completing a normal tuning and loading operation in which you obtain the same plate current, plate-current dip, and screen current readings that you do with the dummy load. However, tuning- and loading-control settings, and the relative power (output voltage) will generally differ from those obtained with the dummy load, depending on how much Z_2 differs from 50 ohms. If normal plate current (and dip) cannot be obtained with any setting of the loading capacitor, Z_2 is outside the matching range of the tank network, and we have conditions as defined in Case 3. If proper loading cannot be obtained with the simple series- or parallel-reactance compensating technique described earlier in this section, then an external network is required. However, I want to emphasize that *any* value of $Z_2 = R_2 + jX_2$ can be transformed to a suitable value for loading the tank network by selecting the proper network configuration (*Refs 19, p 115; 30 and 61*).

The range of impedances Z_2 that the tank network will transform to the value equal to the load impedance $Z_L = R_L + j0$ of the amplifier raises an interesting point concerning the tuning procedure for the external network. The usual practice is to tune the tank network with the dummy load, and then switch in the external network and antenna and tune for zero reflected power in the feed line (not the transformer line). This procedure should be followed if there is a filter in the feed line. However, in the absence of a filter, it is necessary to adjust the external network only for a line-input impedance Z_3 which brings it within the matching range of the tank network. This can be a time-saving feature when changing frequencies during contest operation! If both tank and external networks are adjusted for optimum match at midrange of the intended frequency excursions, in most cases only the tank network needs retuning with changes in frequency. This is true providing the frequency excursions are within the range in which the external network yields a load impedance that the tank network can transform to $R_L + j0$.

1 The broad-banding effect of the coaxial dipole has been widely thought to be accomplished by the shunting of the short-circuited coaxial stubs across the antenna terminals to cancel the off-resonance dipole reactance that appears as the frequency deviates from the resonant frequency. However, a computer analysis performed by Frank Witt, AI1H, has shown that the broad-banding was actually obtained by the resistive conduction loss in the dielectric of the coaxial line. Also see Chapter 18. Footnote appears p3 line 6.