## Chapter 2

# Countdown for a Journey from Mythology to Reality

(Adapted from *QST*, June 1973)

### Sec 2.1 Introduction

In Chapter 1 we saw that obtaining a low SWR is relatively unimportant for an efficient transfer of power when line attenuation is low. Four steps to assist in understanding the operation of transmission lines with reflections due to a mismatched termination were presented. In addition, the concept of matching the complex impedance appearing at the input of a transmission line with reflections was introduced, based on the principles of conjugate matching. One of the articles of the Conjugate Match Theorem is that a conjugate match exists whenever all of the available power from the source is being delivered to the load. *(Ref 137, IEEE.)* In the following paragraphs we will discuss some of the basic principles involving efficient transfer of power in a system comprising a source, and a transmission line terminated in a mismatch.

A conjugate match exists throughout the entire system, and all the available power will be delivered by the source, when the output impedance of the source is made equal to the resistive component of the line-input impedance, and when all reactance components in the source and line-input impedances are canceled to zero by a matching network, which can be either the pi-network tank circuit or a separate matching network such as an antenna tuner. In this condition the entire *system* is resonant, including the output circuitry of the amplifier. All available power from the source enters the line, and reflections from any terminating mismatch or other line discontinuities are compensated by a complementary reflection, which cancels the original reflection at the matching point in the matching device. Such a reflection is obtained by introducing a non-dissipative mismatch at the match point. This non-dissipative mismatch is one which, if placed in the system by itself, would produce the same magnitude of reflection, or SWR, as is produced by the mismatched line termination. The result is a precise and total re-reflection of the arriving reflected wave. Andrew Alford makes an elegant presentation of this concept *(Ref 39, pp 10-15, Also see Ref 136)*.

Although this sounds very complicated, the entire set of conditions is automatically fulfilled simply by completing a correct tuning and loading procedure. It matters not whether a transmitter having sufficient matching range feeds the line directly, or whether an external matching network (antenna tuner) is used where additional range is required. If the transmitter, or source generator is now replaced by a passive impedance equal to its source impedance (equal to its optimum load resistance), the line can be opened at any point. Then, from this open point, and looking in either direction, one will see the conjugate of the impedance seen in the opposite direction—whatever R + *j*X value is seen in one direction, R – *j*X is seen in the other.

Contrary to what many believe, it is not true that when a transmitter delivers power into a line with reflections, a returning reflected wave sees an internal generator resistance as a dissipative load. Nor is the reflected wave converted to heat and lost, while at the same time damaging the final amplifier. When a matched RF power amplifier is actively supplying power when the reflected wave returns, the reflected wave encounters total re-reflection at the match point appearing at the input terminals of the pi-network tank circuit, and the reflected power is entirely conserved because it never sees the source *impedance* of the amplifier as a dissipative terminating load, but not because the source impedance *is non-dissipative*. (Incidentally, the source impedance of the RF power amplifier is non-dissipative, as will be explained in detail in Chapter 19. The concept of a non-dissipative impedance is one of the most misunderstood concepts in electrical engineering today.) This is because the source and reflected voltages and currents superpose, or add (in phase) at the match point, just as if the reflected power had been supplied by a separate generator in series with the source. The phasor sum of their voltages yields a net current flow which is always in the forward direction. The reflected power thus adds to the source power, deriving reflection gain which compensates for the reflection loss suffered at the mismatched termination. More details on the reflection phenomenon are presented in later chapters.

## Sec 2.2 Line Losses

All power reflected from a mismatched line termination that reaches the source is re-reflected and returned to the load, as part of the forward or incident wave. The only reflected power lost is that from line attenuation during its return to the source and once again during its return to the load. The higher the line attenuation, the less reflected power reaches the source to add to the forward power. Thus, the lower the line attenuation, the higher the allowable SWR for a given loss because of SWR. No reflected power is lost in a lossless line, no matter how high the SWR, because it all ultimately arrives at the load. This is why open-wire line functions so efficiently as a tuned line with any reasonable mismatch value—its attenuation is almost negligible. Since the attenuation is higher in coax, the attenuation imposes lower limits on the mismatch, and may require calculation of the loss penalty for a given SWR. Line attenuation and SWR must both be quite high to incur any substantial additional loss over and above the matched-line loss. The additional loss due to SWR and line attenuation may be determined graphically from Figs 1-1 and 6-1, or calculated using Eq 6-1.

Coax has higher RF losses than open wire at HF for two reasons:

1) It has a lower impedance, causing higher current flow at lower voltage for the same power. This results in higher $R^2$ loss for the same effective conductor size. (Electric power distribution lines minimize $I^2R$ loss by using high voltage and low current). Skin effect also increases the loss with rising frequency because of decreased effective conductor size.

2) The increased amount of dielectric material separating the conductors in coaxial line (air vs solid dielectric) is also a substantial contributor to the attenuation loss factor. The attenuation increases with frequency, especially at VHF and UHF. (The attenuation due to resistance R in

the conductors increases as the square-root of frequency, and the attenuation due to conductance G of the dielectric increases directly with frequency.) Hence, it is understandable why RG-8, especially the foam type with its larger center conductor *(Ref 23)* allows higher SWR (thus more bandwidth) than RG-58 for the same additional loss penalty. And for any cable, the shorter it is, the less loss is added for a given SWR.

A fifth step in improving your understanding of the reflected-power problem is to view the situation objectively, asking yourself, "Have I fallen prey to any of the erroneous teachings? Can I spot the wrong info when I hear it discussed? Do I understand the principles well enough to convince others of the correct version if the opportunity arises?" Several pertinent short statements follow which may be used as self-test material. They highlight and summarize many reflection-related concepts known to be generally confusing to many amateurs. In the interest of brevity they are not intended to be completely self-explanatory, but sufficient material for obtaining a complete understanding of each point appears later, or is available from references in the bibliography. Support for nearly every statement can be found in *The ARRL Antenna Book* alone.

## Sec 2.3 True or False?

1) Reflected power does not represent lost power except for an increase in line attenuation over and above the matched-line attenuation. In a lossless line, no power is lost because of reflection. Only when the matched-line attenuation and SWR are both high is there significant power lost from reflection. On all HF bands with low-loss coax, the reflected power loss is generally insignificant, though at VHF it becomes significant, and at UHF it is of extreme importance.

2) Reflected power does not flow back into the transmitter and cause dissipation and other damage. Damage blamed on reflections is really caused by improper output-coupling adjustment — not by SWR. Tube overheating is caused by either or both overcoupling and reactive (mistuned) loading. Tank-coil heating and arc-overs result from a rise in loaded Q caused by undercoupling. With some manipulation, proper output coupling indicated by a normal resonant plate-current dip at the correct loading level can be attained no matter how high the SWR. The transmitter doesn't "see" an SWR at all — only an impedance resulting from reflections giving rise to the SWR. And the impedances are matchable without concern for the SWR. This is one of the most important issues contributing to the confusion.

3) Any effort to reduce an SWR of 2:1 on any coaxial line is completely wasted from the standpoint of any significant increase in power transfer. See Figs 1-1 and 6-1.

4) A low SWR is not proof of a good-quality antenna system or an indication that it is working efficiently. On the contrary, lower than normal SWR values exhibited over a frequency range by a dipole or a vertical over ground is a clue to trouble in the form of undesired loss resistance. Such resistance can be from poor connections, poor ground system, lossy cable, etc.

5) The radiator of an antenna system need not be of a self-resonant length for maximum resonant current flow, the feed line need not be of any particular length, and a substantial mismatch at the junction of the line and the antenna does not prevent the radiator from absorbing all of the power available at the junction *(Ref 3, Part III, p 20; Ref 24)*.

6) If a suitable matching network can-

cels all the reactance developed by a nonresonant-length radiator and a random-length feed line which is mismatched at the antenna feed point, the antenna system is resonant, the mismatch effect is canceled, maximum current flows in the radiator, and all the power available at the feed point is absorbed by the radiator.

7) The majority of tower radiators used in the standard AM broadcast band (from 540 to 1600 kHz) are of heights which are not resonant lengths at the frequency of operation.

8) The SWR on the transmission line between the antenna and a matching network at the input to the line is determined *only* by the mismatch conditions at the load, and is not changed or "brought down" by the matching network. "Low SWR" obtained by using the device indicates only the mismatch remaining between the input impedance of the network and the impedance of the line from the transmitter.

9) Adjusting the matching network, or antenna tuner, for maximum line current creates a perfect mirror termination for the reflected wave, causing it to be totally re-reflected on arrival at the input end of the line. The tuner provides the proper reactance to cancel the equal but opposite reactance between the source and reflected wave at the input. This causes the reflected wave to add *in phase* to the source wave to derive the total incident, or forward power, which is the sum of the source and reflected power.

10) Total re-reflection of the reflected power at the line input is the reason for its not being dissipated in the transmitter, and why it is conserved, rather than lost.

11) With a good antenna tuner and a well-constructed open-wire feeder, a 130-foot center-fed dipole does not radiate significantly more power on 80 meters than one 80 feet long for the same power fed from the *transmitter (Ref 3, Part III, p 20; Ref 7, pp 50 and 124 or pp 41 and 42 in reprint version; Ref 10; Ref 21)*.

12) A dipole cut to be self-resonant at 3.75 MHz and fed with either RG-8, RG-213, RG214, or RG-11 coax does not radiate significantly more on 3.75 MHz than on 3.5 or 4.0 MHz with any feeder length up to 150 or 200 feet.

13) With a 3.75-MHz dipole, the SWR on a 50-ohm feed line rises to around 6.5 at 3.5 MHz, and around 5.0 at 4.0 MHz, thus utilizing the coax as a tuned feeder, but with *insignificant* loss in radiated power across the entire 80-meter band.

14) With the use of a transmatch or a simple L network at the line input, proper coupling between the transmitter and the tuned-coax feeder can be attained over the entire 80-meter band *with any random coax length*.

15) From the standpoint of line loss because of SWR resulting from the change in quality of the impedance match between the line and antenna, changing the height of the dipole above ground or lowering the ends of a horizontal dipole to make an inverted-V dipole has an *insignificant* effect on the amount of power it absorbs from the transmitter.

16) As a tuned line at 4.0 MHz, RG-8 can handle 700 watts CW *continuously* within ratings, at an SWR of 5:1. With the duty cycle of SSB, it is far below maximum ratings at 2 kW PEP. With a 100-foot length, the *total* attenuation with a 5:1 SWR is just 0.78 dB (0.46 dB due to the SWR), which results in an insignificant loss of power in terms of received signal strength.

17) If the line length is critical in order to satisfy a particular matching condition, the same input impedance can be obtained with any length of line, shorter

or longer, by adding a simple L network of only two components: either two capacitors, two inductors, or one of each, determined by the specific impedance change required of it. This statement is pertinent to coiled-up coax in mobiles *(Ref 19, pp 118-128; Ref 24; Ref 30, p 48; Ref 31.)*

18) High SWR in a coaxial transmission line caused by a severe load mismatch does not produce antenna currents on the line, nor does it cause the line to radiate *(Ref 2, p 101; Ref 32. See also Chapter 20, Sec. 20.3, for the answer.)*

19) High SWR in an open-wire line at HF caused by a severe load mismatch does not produce antenna currents on the line, nor cause the line to radiate if the feed currents in each wire are balanced, and if the spacing is small at the wavelength of operation (also true at VHF if sharp bends are avoided *(Ref 2, pp 101, 106. See also Chapter 20, Sec. 20.3, for the answer.)*

20) Both coax and open-wire feed lines may radiate *(Ref 32)*, though not at a significant level, by reradiating energy coupled into the line from the antenna because of asymmetrical positioning with respect to the antenna. The energy coupled from the antenna results in antenna currents flowing on the *outside* of the outer coax conductor, or *in-phase* (common mode )currents flowing on the wires of the open-wire line. But this condition has no relation to the level of the SWR on the line in either case *(Ref 2, pp 101, 106. See also Chapter 20, Sec. 20.3, for the answer.)*

21) SWR indicators need not be placed at the junction of the feed line and the antenna to obtain a more accurate measurement. Within its own accuracy limits, the indicator reads the SWR wherever it is located in the line. The SWR at any other point on the line may be determined by a simple calculation involving only the SWR at the point of measurement, the line attenuation per unit length, and the distance from the measured point to the point where the SWR is desired. In any case, the primary reason for using the SWR indicator is to assist in proper loading of the transmitter.

22) The SWR in a feed line cannot be changed, adjusted or controlled in any practical manner by varying or adjusing the line length *(Ref 7, p 51)*. (Also see Chapter 21.)

23) If SWR readings change significantly when moving the SWR bridge a few feet one way or the other in the line, it indicates either “antenna” current flowing on the *outside* of the coax, or else an unreliable instrument, or both, or even a reliable bridge incorrectly adjusted to the line impedance, but it is not because the SWR is varying with line length. Some writers insist the bridge must be placed at a 1/2–λ interval from the load to obtain a correct reading. This is *incorrect*. All readings are invalid if they change significantly along the line, even though they may repeat at λ/2 intervals *(Ref 2, pp 101, 106, and 132, Also see Chapter 21.)*

24) Any reactance added to an already resonant (resistive) load of any value for the purpose of compensation to reduce the reflection on the line feeding the load will, instead, only increase or worsen the reflection. It is for this reason, although contrary to the teaching of several writers, that the lowest feed-line SWR occurs at the self-resonant frequency of the radiating element it feeds, completely independent of feed-line length. Any measurements which contradict this indicate that either the measuring equipment or the technique (or both) are in error.

25) Of the several types of dipoles such as the thin wire, folded, fan, sleeve, trap, or coaxial, none radiates more field

than another, providing each has insignificant ohmic losses and is fed the same amount of power *(Ref 3, Part III).*

26) If coax at least the size of RG-8 is used in mobile installations (80 through 10 meters), any matching required to load the transmitter may be done at the input end of the coax without significant power loss compared to matching at the antenna terminals, and with improvement in operating bandwidth.

27) With center-loaded mobile whips of equal size having no matching arrangement at the input terminals, the best radiating efficiency is obtained on models having the lowest measured terminal resistance (highest resonant SWR, model for model). Models having lowest SWR are wasting power in the loading coil, because of either a low value of coil Q or excessive distributed coil capacitance, or both. *(See Chapter 6 for more details.)*

28) The resonant frequency of an antenna cannot be determined by probing the input terminals of a feed line for resonance with a grid-dip oscillator or a noise bridge that has no capability for measuring reactance. Resonances measured at the feed-line input are resonances of the combination of the antenna and the feed line, not the resonance of the antenna alone. A change in length of the feed line results in a different resonant frequency of the combination for every different length of feed line. A $\lambda/2$ feed line is not the answer, because, since the resonant frequency of the antenna is unknown, the frequency at which the feed line should be $\lambda/2$ is also unknown. If the feed line is $\lambda/2$ at some frequency other than the resonant frequency of the antenna, the resonant frequency measured at the input of the feed line will be different than that of either the antenna or the feed line.

## Sec 2.4 How Did You Do?

Did you mark all of the statements correctly? You did if you marked each one TRUE. Yes, *all* of the above statements are true. These examples have been centered around 80-meter operation because bandwidth and dipole length on this band present the maximum SWR problem. Of all the amateur bands, 80 m has the largest bandwidth, 13.3% of center frequency, as compared to 4.2% on 40 m, 2.5% on 20 m, 2.1% on 15 m, and 5.9% on 10 m. Having the longest wavelength (excepting 160 m, of course), 80 m poses the greatest problem with respect to physical construction of radiating systems on existing real estate. Some antenna sites just won't permit an entire $\lambda/2$ on 80 m. So these examples should have a special interest if you wish to work 80 meters but are forced to use a short antenna. Since the bandwidth and antenna-length problem are really one and the same, the 80-meter examples have maximum practical value. But practices recommended at the 80-meter level are also valid on the higher frequencies. Interestingly enough, as we go to the higher bands, the line losses increase but the percentage bandwidth of the amateur bands decreases. This means inherently lower maximum SWR values will be obtained during frequency excursions from the design center to the ends of the band.