Chapter 19

On the Nature of the Source of Power in Class B and C RF Amplifiers

Based on data from Terman's *Radio Engineers Handbook, 1943*

Sec 19.1 Introduction

In this chapter we will discuss the nature of the source of power in Class B and C RF amplifiers. As in previous chapters that clarified misconceptions concerning SWR and reflected power, this chapter will be concerned with clarifying misconceptions prevalent among amateurs and professional electrical engineers alike concerning the operation of RF power amplifiers. In attempting to resolve the unfortunate and protracted controversy concerning the conjugate matching theorem in relation to these amplifiers, discussions with many of these people revealed an alarming number of misconceptions concerning the complex relationships of voltage and current that occur in the development of the source of power in these amplifiers, especially in relation to the coupling to their loads. Therefore, the focus of this Chapter will be to highlight and clarify those misconceptions.

However, before discussing amplifier operation, two synonymous terms that play a vital role in amplifier operation need clarification, because they are widely misinterpreted in discussions relating to the source of power. The terms are *maximum available power,* and *all available power*.

Maximum available power, or all available power, is simply the power available for delivery from the source to the load whenever the source is matched to the load. In Class B and C amplifiers it is the power delivered when the loading is adjusted for peak output ***at any given level of drive***. It is ***not*** the absolute maximum power that can be obtained by overdriving, or using excess plate voltage or plate current, as many amateurs and engineers alike have been misled to believe.

Turning now to the discussion of amplifier operation, one misconception is that Class C amplifiers cannot support circuital analysis using general network theorems because of the nonlinearity[1] of the amplifier operation. In clarifying this misconception we will show that, although the input circuit of the pi-network tank circuit in Class C amplifiers is nonlinear, the output circuit to the load is indeed linear, due to energy storage in the tank. Consequently, the linear relationship between voltage and current appearing at

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[1] The use of 'linear' and 'nonlinear' relates to the voltage/current relationship at the output terminals of the amplifier tank circuit, or at the terminals of a network. This usage does not relate to nonlinearity between the input and output of an amplifier that results in generation of distortion products in the output signal.

the output of the tank circuit does indeed support the application of theorems that require circuits to be linear for their application to be valid.

Another misconception concerns the relationship between the output and load resistances of these amplifiers. Because of wild speculations, without verification by ***valid*** measurements, many people believe incorrectly that the output resistance is much greater than the load resistance, and thus proclaim that a conjugate match cannot be obtained between the amplifier and the load. However, when a *linear* source of power is delivering **all** of its available power to the load, there is a conjugate match by axiomatic definition, as explained in the following paragraph. *(Also see the references quoted in Appendix 9.)* An example from Terman is used in clarifying the misconception concerning the relationship between output and load resistances, shown below in Sec 19.3. In addition, data obtained from my own measurements, shown below in Sec 19.8, prove that after the amplifier has been adjusted to deliver all of its available power at any given drive level, the output and load impedances of the amplifier ***are equal*** and thus are conjugates of each other.[2] My measurements have been confirmed by Tom Rauch, W8JI, using identical measurement procedure.

Now to explain two axioms of the Conjugate Matching Theorem that are commonly overlooked, which has resulted in widespread confusion concerning its use. We know that when a load impedance differs from its source impedance, a matching device is required to allow delivery of all the available power from the source to the load. In this condition we say the load is *matched* to the source. The term 'matched' has been used universally for many decades, and in those earlier days the term was used alone. However, when all the power available from the source is delivered to the load, the matching occurs because the source and load impedances are conjugates of each other. Consequently, during the last fifty years, the term '*conjugate* match' gradually came into use synonymously with 'match' to describe the term more accurately. In other words, 'match' and 'conjugate match' in this context are used interchangeably with no difference in meaning. Unfortunately, misinterpretation and misunderstanding of *conjugate* in the newer term has created confusion for many people when a routine impedance match is referred to as a 'conjugate' match. To clarify the confusion, the following two axioms, which follow from the Maximum Power-transfer Theorem, accurately define a conjugate match:

Axiom 1) there is a conjugate match whenever all of the available power from a source or network is being delivered to the load.

Axiom 2) there is a conjugate match if the delivery of power decreases whenever the impedance of either the source or load is changed in either direction.

(Additional axioms and explanations appear in Appendix 9.)

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[2] In addition to the data in Terman's example, I have made measurements that determine the output impedance of RF power amplifiers, which prove the existence of a conjugate match. The data show that when the amplifier is loaded to deliver all of its available power, the output impedance of the amplifier equals the load impedance, thus signifying a **linear** voltage/current relationship at the output of the tank circuit, and thus a **conjugate** match. The description of my measurement procedure, and the resulting data showing the proofs that follow in Sec 19.8.

We now return to clarify the misconception concerning output and load resistances. The term source *resistance R_S* of an RF power amplifier, as is often misused (and confused with R_P) in referring to the source of RF power delivered by Class B and C amplifiers, reveals still another prevalent misconception. This misconception is that the *entire source of power* in these classes of tube-type amplifiers is a *dissipative* resistance. In clarifying this misconception, we will use the example by Terman to demonstrate that the source of RF output power in a Class C amplifier is the combination of *two* resistances; a *non-dissipative* resistance related to the characteristics of the *effective* load line, and a *dissipative* plate resistance R_{PD}. Resistance R_{PD} is not plate resistance **R_P**, as determined from the well-known expression $R_P = \Delta E_P \div \Delta I_P$. From this expression it is evident that R_P is the result of a small change in plate current due only to a change in plate voltage, which is *not* the source of power in RF power amplifiers as is claimed by many who have misinterpreted the expression. The source of power is actually derived by a large change in plate current resulting from a change in ***grid*** *voltage*. This phenomenon will be discussed in more detail later.

One portion of the ***non***-dissipative resistance is the reciprocal of the total conductance from both plate and power supply to the input of the pi-network tank circuit. At that point in the typical amateur pi-net Class B and C amplifier, the load is the tank input. The source is the combination of two parallel conductive paths to the tank: 1) the blocking capacitor in series with the active device, the tube(s)[3]**,** and 2) the same blocking capacitor in series with the RF choke and the voltage of the power supply. These two conductance paths are paralleled at the input of the tank, operating at different, but overlapping times throughout the cycle. The other portion of the non-dissipative resistance is related to the operating load line, which will be discussed in Sec 19.3a.

Plate resistance R_{PD} ***is dissipative***, whose value is determined by the power P_D dissipated as heat by the plate divided by the square of the average DC plate current I_{DC}, the current measured by the DC plate ammeter. Note in Terman's Statement 3 below, that dissipated power P_D is the product of *the instantaneous plate-to-cathode voltage and the instantaneous plate current*. We know that energy is transferred from the plate circuit of the amplifier to the pi-network by periodic pulses of plate current that flow during the conducting portion of the RF cycle. Knowledge of the *non*-dissipative portion of the source resistance will allow you to understand why Class B and C amplifiers can deliver all of their available power into a conjugately matched load with efficiencies greater than 50 percent. This concept is important, because the ability of these amplifiers to be conjugately matched has been incorrectly disputed due to three erroneous assumptions that have caused many amateurs and engineers alike to be misled.

If you experience difficulty appreciating the concept of a *non*-dissipative resistance, please refer to Appendix 10 for a detailed explanation and published ref-

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[3] The material discussed in this chapter pertains only to RF amplifiers used in the Amateur Service with tubes and pi-networks in the output circuit. The material does not necessarily pertain to amplifiers used in various commercial services, or any amplifier using solid-state components.

erences on the subject for clarification.

Sec 19.2 Erroneous Assumptions

The principal reason many people have been misled is because they have incorrectly estimated the amount of the source resistance in the amplifier that is dissipative. This incorrect assumption led them to believe that half the power is dissipated in the source resistance, and thus, as in the *classical generator*, a conjugate match would limit the efficiency to 50 percent. However, this is not true, because, as noted above, the source of the power delivered to the pi-network tank circuit is non-dissipative, except for the dissipative plate resistance R_{PD}. Because dissipative plate resistance R_{PD} is generally less than the load resistance R_L, more power is delivered to the load resistance than that dissipated in the dissipative plate resistance, thus allowing efficiencies greater than 50 percent. The lower dissipative plate resistance occurs because plate current is allowed to flow only when the plate voltage is at the minimum of its sinusoidal swing, as explained in Terman's Statement 7 below. Repeating Terman's Statement 3 for emphasis, dissipated power P_D is the product of *instantaneous* plate-to-cathode voltage and *instantaneous* plate current. (Keep in mind that plate current is zero except during the short conduction time, considerably less than 180 degrees.)

The second erroneous assumption is that the Conjugate Matching and Maximum Power-transfer Theorems don't apply to Class B and C RF amplifiers, because the operation of these amplifiers is nonlinear[1]. This assumption is also incorrect because they have failed to appreciate the isolating action of the vitally important pi-network tank circuit. The pi-network tank is *not* simply an impedance transformer, as many believe, but is also an *energy storage* device. The energy storage capacity of the tank isolates the pulsed nonlinear mode at the input from the smoothed *linear* mode at the output that delivers the nearly perfect sine waves. This widely overlooked and misunderstood concept will be discussed in depth later.

A third erroneous assumption concerns the misuse of the role 'source' resistance 'R_S' plays in the delivery of power to the tank circuit. Because they say the value of R_S is as much as five times greater than load resistance R_L, a condition that violates the Conjugate Matching Theorem, some people, including the ARRL technical staff, assert this is why no conjugate match is possible in systems where the source is an RF power amplifier. However, to obtain R_S they erroneously used the expression $R_P = \Delta E_P \div \Delta I_P$, where R_P **is** greater than R_L. The reason the expression was used erroneously is because, in this expression, I_P varies **only** with variation of plate voltage, not grid voltage, as explained earlier. And because the change in plate current due to a change in plate voltage is small compared to the change in plate current due to a change in grid voltage, R_P and the erroneous 'R_S' are much greater than R_L. The crucial point here is that the source of power is derived from the much larger change in plate current due to the change in ***grid*** voltage, while the effect of the change in plate current due to the change in plate voltage is insignificant in relation to the output impedance of the amplifier. Consequently, as we proceed we will learn that both R_P and

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[1] See page 19-1

'R_S', as perceived by the present *ARRL* technical staff, are totally irrelevant to conjugate matching the output impedance of the amplifier to the impedance of its load, and thus impose no impediment to the conjugate match.

Sec 19.3 Analysis of the Class C Amplifier

The following discussion of the Class C amplifier, which reveals why the portion of the source resistance related to the charactersistics of the load line is non-dissipative, is based on statements appearing in Terman's *Radio Engineers Handbook*, 1943 ed., Page 445, and on Terman's example of Class C amplifier design data appearing on Page 449. Because the arguments presented in Terman's statements are vital to understanding the concept under discussion, I quote them here for convenience: (Parentheses and emphasis mine)

1. The average of the pulses of current flowing to an electrode represents the direct current drawn by that electrode.
2. The power input to the plate electrode of the tube at any instant is the product of plate-supply voltage and instantaneous plate current.
3. The corresponding power (P_D) lost at the plate is the product of instantaneous plate-cathode voltage and instantaneous plate current.
4. The difference between the two quantities obtained from items 2 and 3 represents the useful output at the moment.
5. The average input, output, and loss are obtained by averaging the instantaneous powers.
6. The efficiency is the ratio of average output to average input and is commonly of the order of 60 to 80 percent.
7. The efficiency is high in a Class C amplifier **because current is permitted to flow only when most of the plate-supply voltage is used as voltage drop across the tuned load circuit R_L, and only a small fraction is wasted as voltage drop (across R_{PD}) at the plate electrode of the tube.**

Based on these statements, the discussion and the data in Terman's example that follow explain why the amplifier can deliver power with efficiencies greater than 50 percent while conjugately matched to its load, a condition that is widely disputed because of the incorrect assumptions concerning Class B and C amplifier operation as noted above. The terminology and data in the example are Terman's, but I have added one calculation to Terman's data to emphasize a parameter that is vital to understanding how a conjugate match can exist when the efficiency is greater than 50 percent. That parameter is *dissipative plate resistance* R_{PD}. (As stated earlier, dissipative resistance R_{PD} should not be confused with plate resistance R_P of amplifiers operating in Class A, derived from the expression $R_P = \Delta E_P \div \Delta I_P$.)

It is evident from Terman that the power supplied to the amplifier by the DC power supply goes to *only two places,* the RF power delivered to load resistance R_L at the input of the pi-network, and the power dissipated as heat in dissipative plate resistance R_{PD} (again, not plate resistance R_P, which is *totally irrelevant* to obtaining a conjugate match at the output of Class B and C amplifiers). In other words, the output power equals the DC input power minus the power dissipated in resistance R_{PD}. We will now show why

Data from Terman's example on Page 449 of *Radio Engineers Handbook*

(1) E_b = DC Source Voltage = 1000 v

(2) $E_{min} = E_b - E_L = 1000 - 850 = 150$ v [See Terman, Figs 76(a) & 76(b)]

(3) I_{dc} = DC Plate Current = 75.1 ma = 0.0751 a

(4) $E_L = E_b - E_{min} = 1000 - 150 = 850$ v = Peak Fundamental AC Plate Voltage

(5) I_1 = Peak Fundamental AC Plate Current = 132.7 ma = 0.1327 a

(6) $P_{IN} = E_b \times I_{dc}$ = DC Input Power = $1000 \times 0.0751 = 75.1$ w

(7) $P_{OUT} = \frac{(E_b - E_{min})I_1}{2} = \frac{E_L I_1}{2}$ = Output Power Delivered to $R_L = \frac{(1000 - 150) \times 0.1327}{2} = 56.4$ w

(8) $P_D = P_{IN} - P_{OUT}$ = Power Dissipated in Dissipative Plate Resistance R_{PD} = 18.7 w

(9) $R_{PD} = \frac{P_D}{I_{dc}^2} = \frac{18.7\text{ w}}{0.0751^2\text{a}}$ Dissipative Plate Resistance R_{PD} = 3315.6 ohms

(10) $R_L = \frac{E_b - E_{min}}{I_1} = \frac{E_L}{I_1}$ = Load Resistance = $\frac{850}{0.1327}$ = 6405 ohms (6400 ohms in Terman)

(11) Plate Efficiency = $P_{OUT} \times \frac{100}{P_{IN}} = 56.4 \times \frac{100}{75.1} = 75.1\%$

this two-way division of power occurs. First we calculate the value of R_{PD} from Terman's data, as seen in line (9) in the data above. It is evident that when the DC input power minus the power dissipated in R_{PD} equals the power delivered to resistance R_L at the input of the pi-network, there can be no significant dissipative resistance in the amplifier other than R_{PD}. The antenna effect from the tank circuit is so insignificant that dissipation due to radiation can be disregarded. If there were any significant dissipative resistance in addition to R_{PD}, the power delivered to the load plus the power dissipated in R_{PD} would be less than the DC input power, due to the power that would be dissipated in the additional resistance. This is an impossibility, confirmed by the data in Terman's example, which is in accordance with the Law of Conservation of Energy. Therefore, we shall observe that the example confirms the total power taken from the power supply goes only to 1) the RF power delivered to the load R_L, and 2) to the power dissipated as heat in R_{PD}, thus, proving there is no significant dissipative resistance in the Class C amplifier other than R_{PD}.

Note in line (10) that R_L is determined simply by the ***ratio*** of the fundamental RF AC voltage E_L divided by the fundamental RF AC current I_1, and therefore does not involve dissipation of any power. Thus R_L is a ***non***-dissipative resistance. (For more on non-dissipative resistance see Appendix 10.)

Referring to the data in the example, observe again from line (10) that load resistance R_L at the input of the pi-network tank circuit is determined by the ratio $E_L \div I_1$. This is the Terman equation which, prior to the more-precise Chaffee Fourier Analysis, was used universally to determine the approximate value of the optimum load resistance R_L. (When the Chaffee Analysis is used to determine R_L from a selected load line the value of plate current I_1 is more precise than that obtained when using Terman's equation, consequently requiring fewer empirical adjustments of the amplifier's parameters to obtain the optimum value of R_L.) Load resistance R_L is proportional to the slope of the operating load line that allows all of the available integrated energy contained in the plate-current pulses to be transferred into the pi-network tank circuit. (For additional information concerning the load line see Sec 19.3a below.) Therefore, the pi-network must be designed to provide the equivalent optimum resistance R_L looking into the input for whatever load terminates the output. The current pulses flowing into the network deliver bursts of electrical energy to the network periodically, in the same manner as the spring-loaded escapement mechanism in the pendulum clock delivers mechanical energy periodically to the swing of the pendulum. In a similar manner, after each plate current pulse enters the pi-network tank curcuit, the flywheel effect of the resonant tank circuit stores the electromagnetic energy delivered by the current pulse, and thus maintains a continuous sinusoidal flow of current throughout the tank, in the same manner as the pendulum swings continuously and periodically after each thrust from the escapement mechanism. The continuous swing of the pendulum results from the inertia of the weight at the end of the pendulum, due to the energy stored in the weight. The path inscribed by the motion of the pendulum is a sine wave, the same as at the output of the amplifier. We will continue the discussion of the flywheel effect in the tank circuit with a more in-depth examination later.

Let us now consider the dissipative plate resistance R_{PD}, which provides the evidence that the DC input power to the Class C amplifier goes only to the load R_L and to dissipation as heat in R_{PD}. With this evidence we will show how a conjugate match can exist at the output of the pi-network with efficiencies greater than 50 percent. In accordance with the Conjugate Matching Theorem and the Maximum Power-transfer Theorem, it is well understood that a conjugate match exists whenever all available power from a linear source is being delivered to the load. Further, by definition, R_L is the load resistance at the tank input determined by the characteristics of the load line that permits delivery of all the available power from the source into the tank. This is why R_L is called the *optimum* load resistance. Thus, from the data in Terman's example, which shows that after accounting for the power dissipated in R_{PD}, all the power remaining is the available power, which is delivered to R_L and thence to the load at the output of the pi-network. *Therefore, because all* ***available*** *power is being delivered to the load, we have a conjugate match by definition.* In the following Sec 4 we will show how efficiencies greater than 50 percent are achieved in Class C amplifiers operating into the conjugate match.

Sec 19.3a Examining the Operating Load Line

The finer details of the somewhat trial-and-error method of establishing the operating load line are beyond the scope of this Chapter. However, once established, the load line represents the non-dissipative load resistance R_L appearing at the input of the pi-network tank circuit. The slope of the load line is proportional to the ratio of the continuous fundamental RF voltage and current. When the network is terminated with the correct output load resistance (a resistance equal to the network output resistance as explained in Sec 19.8), the network transforms the output load resistance up to resistance R_L at the network input. Once established (and proven by measurements of network output impedance described in Sec 19.8), the slope of the operating load remains constant with changes in input power levels. Consequently, because R_L represents the slope of the load line, both the fundamental RF voltage-current ratio appearing along the load line and the network output impedance remain constant whatever the power level of the integrated current pulses enter the network. It should be clearly understood that, because the operating load line, and the optimum resistance R_L it represents, are established solely by the *ratio* of the RF voltage and current, the load line and R_L are non-dissipative. As explained earlier, the entire dissipation to heat occurs only in the dissipative plate resistance R_{PD}.

When using the Terman equation to determine load resistance R_L, an approximate load line and average plate current are first estimated from the tube characteristic curves. The corresponding value of R_L is used as a trial value and the output power and efficiency are determined in a trial run. However, several trial runs with different load adjustments are necessary to converge toward the optimum value of R_L that will yield the desired conditions for operation, simply because the first estimation of average plate current is rarely the optimum value.

When the Chaffee Analysis is used to determine R_L in establishing the load line, the average value of plate current I_1 during the conduction period is obtained by first plotting the load line on a graph of constant plate current characteristics of the tube. The load line is then marked off in several increments corresponding to successive angles of conduction of plate current. The plate current at each conduction angle is then found at the intersection of the load line and the constant-current curve. The plate voltage at each conduction angle is also found on the plate voltage line directly below the above stated intersection. The averages of plate current and voltage are then determined using the trapezoidal rule. Load resistance R_L is then determined by dividing the average plate voltage by the average plate current, the Terman equation. Thus the Chaffee method saves time compared to using Terman's equation alone, because the initial value of average plate current is closer to the optimum value than that estimated for use in the Terman equation.

Sec 19.4 Calculation of Efficiency Greater than 50 Percent

To show how efficiencies greater than 50 percent are obtained while the amplifier is conjugately matched, we will dissect the data in the Terman example to discover that load resistance R_L is greater than dissipative plate resistance R_{PD}, thus allowing more power to be delivered to the load than that dissipated in R_{PD}. Referring again to Terman's example in line (10), his calculation of load resistance R_L is 6400 ohms. From line (9) we find R_{PD} is 3315.6 ohms by dividing 18.7 watts dissipated in R_{PD} by the square of 75.1 mA. DC plate current I_{DC} flowing through R_{PD}. Correspondingly, line (7) shows the power delivered to R_L is 56.4 watts, and from line (8), power P_D dissipated in R_{PD} is 18.7 watts. With 56.4 watts delivered to R_L and 18.7 watts dissipated in R_{PD} we have accounted for the total input power, 71.5 watts, shown in line (6). The relative power distribution is 75.1 percent delivered to R_L, and 24.9 percent dissipated in R_{PD}. Earlier we showed that after accounting for the power dissipated in R_{PD}, all the remaining available power is delivered to the load R_L. Thus, this distribution of power clearly demonstrates why a Class C amplifier can deliver more than 50 percent of its input power to the load, because its load resistance R_L (6400 ohms) is greater than its *dissipative* plate resistance R_{PD} (3315.6 ohms). These calculations are in accord with with Terman's Statement 7 that "efficiency is high in the Class C amplifier, because current is permitted to flow only when most of the plate-supply voltage is used as voltage drop across the tuned load circuit R_L, and only a small fraction is wasted across R_{PD} at the plate electrode of the tube." None is dissipated in the non-dissipative resistance related to the characteristics of the load line. As stated earlier, the non-dissipative portion of the source resistance is the reciprocal of the total conductance from both the plate of the tube and the power supply to the input of the pi-network tank circuit. It should be noted however, that we are considering *only the power delivered to the tank*; we are not concerned here with inherent loss in the tank that results in some decrease in the power delivered at the output of the tank.

Sec 19.5 Evidence of Conjugate Match

The example has proven that a conjugate match exists, because all the available power has been delivered to the resistive load R_L, and thence to the load terminating the pi-network, in accordance with Conjugate Matching Axioms 1 and 2 recited in Sec 19.1 and again in Appendix 9. The example has also shown that more power has been delivered to the load than was dissipated, because 54.6 watts were delivered and only 18.7 watts were dissipated. Thus, contrary to the opinion of many who fail to understand this concept, we have shown that conjugate matching to a Class C RF amplifier does not limit its efficiency to 50 percent. The same reasoning applies to amplifiers operating in Class B.[2]

So now you ask, do we have a conjugate match during SSB operation? The answer is yes, but which begs an additional question: Does the output impedance of the amplifier remain constant with SSB modulation, or does it change during the variations of drive and output power corresponding to the voice modulation? My measurements, described below in Sec 19.8, show that the output impedance does not change significantly with voice modulation. This is because, for a given load resistance R_{LOAD}, the operating load line related to the load resistance R_L appearing the input of the tank circuit, and the output resistance R_{OUT}, are established during the tuning and loading procedure when the loading is adjusted to deliver maximum available power. During this procedure maximum available power is that power which is delivered to the load with the drive level set for obtaining the desired output power at the full modulation level. After the load line has been established in this manner it remains constant for all values of drive. I have made extensive measurements, described below in Sec 19.8, which show that once the operating load line is established during this routine procedure, it remains constant during swings of grid voltage during SSB modulation, as long

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[2] See page 19-2

as the plate supply voltage remains constant.

So now we ask, is the conjugate match of such importance that we should be concerned about it? Yes it is, if we are to understand why antenna tuners perform their intended task of matching the complex impedance appearing at the input of a transmission line that is Z_O mismatched to an antenna, while also establishing a conjugate match that overrides the Z_O mismatch at the antenna. **The principles of conjugate matching are fundamental to the matching function performed by the antenna tuner, and are indeed fundamental to all impedance matching obtained with any impedance matching device that allows delivery of all available power from its source!** Additional material pertinent to understanding the matching function performed by the antenna tuner is presented in Chapter 24, “The Conjugate Match and the Z_O Match.”

Sec 19.6 The Vital Role of Energy Storage in the Tank Circuit in Providing Linear Operation at Output

We now return to conduct a close examination of the vitally important flywheel effect of the tank circuit. The energy storage (Q) in the tank produces the flywheel effect that isolates the nonlinear pulsed energy entering the tank at the input from the smoothed energy delivered at the output. As a result of this isolation the energy delivered at the output is a smooth sine wave, with linear voltage/current characteristics that support the theorems generally restricted to linear operation. We know that the widely varying voltage/current relationship at the tank input results in widely varying impedances, which precludes the possibility of a conjugate match at the input of the tank circuit. However, the energy stored in the tank provides *constant impedance at the output* that supports both the Conjugate Matching and the Maximum Power-transfer Theorems.[1]

The acceptance by many engineers and amateurs of the erroneous notion that the output of the RF tank is nonlinear is a reason some readers will have difficulty in appreciating that the output of the RF tank circuit is linear, and can thus support the conjugate match. Valid analogies between different disciplines are often helpful in clarifying difficulties in appreciating certain aspects of a particular discipline. Fortunately, energy storage in the mechanical discipline has a valid and rigorous analogous relationship with energy storage in LC circuitry that makes it appropriate to draw upon a mechanical example to clarify the effect of energy storage in the RF tank circuit. (A further convincing analogy involving water appears later in the Chapter, in which the origin of the term ‘tank circuit’ is revealed.)

The smoothing action of the RF energy stored in the tank circuit is rigorously analogous to the smoothing action of the energy stored in the flywheel in the automobile engine. In the automobile engine the flywheel smooths the pulses of energy delivered to the crankshaft by the thrust of the pistons. As in the tank circuit of the amplifier, the automobile flywheel is an energy storage device, and the smoothing of the energy pulses from the pistons is achieved by the energy stored in the flywheel. In effect, it is the flywheel, in the

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[1] See page 19-1

same manner as the tank delivers energy to its load, that delivers the energy to the transmission. The energy storage capacity required of the flywheel to deliver *smooth* energy to the transmission is determined by the number of piston pulses per revolution of the crankshaft. The greater the number of pistons, the less storage capacity is required to achieve a specified level of smoothness in the energy delivered by the flywheel. The storage capacity of the flywheel is determined by its moment of inertia, and the storage capacity of the tank circuit in the RF amplifier is determined by its Q.

As stated earlier, the tank circuit in the RF amplifier receives two overlapping pulses of energy per cycle. But if the effect of the overlapping pulses were considered to be a single pulse, we would have a condition that is somewhat analogous to an engine having only one cylinder. If we were to assume that the piston in the one-cylinder engine delivers one thrust of energy per revolution, it is evident that a large amount of energy storage is required to enable the crankshaft to deliver a smooth output during the entire rotation of the crankshaft. In this case, a very heavy flywheel is required to deliver a smooth output. This is also the case with the RF tank circuit, which requires a Q of 10 to 12 to yield a smooth sine wave output with an acceptable minimum of harmonic ripple. Because the tank receives only one pulse of energy per cycle, it must store many times the amount of energy in comparison to the amount it passes through, to provide a continuous sine wave output when supplied only with pulses of energy at the input. Thus the energy storage capacity of the tank provides for the smoothed *linear* output to the load circuit despite the *nonlinear* pulsed input, which, for the purpose of analysis, allows the pulsed source and tank to be replaced with an equivalent Thévenin generator whose output impedance equals R_{Lout}. Although no conjugate match exists at the input of the pi-network tank, because of the large variation of impedance in the current pulses, the isolation derived from the flywheel action of the tank thus allows a conjugate match to exist between the output of the tank and its load, a concept which will become clear as we continue.

To further clarify the action, and the effect of the energy storage in the tank that achieves a linear voltage/current relationship at the output of the tank, parts of the following discussion are paraphrased from correspondence with Dr. John Fakan, KB8MU. It should be emphasized here that a conjugate match *can* exist between the output of the RF power amplifier and its load because of the linear voltage/current relationship at the output of the tank resulting from the energy storage in the tank.[1]

The tank circuit stores the energy by passing it back and forth cyclically between the L and C components, and passes only a fraction of that energy to the tank's load on each cycle. Because the amount passed on to the load is such a small fraction of the total stored in the tank, and because even that small amount is restored during the cycle, the tank can be considered to be an *active* source. Because it can be considered as an active source we have no need for interest in what is going on ahead of it in the overall system (so far as what the downstream devices see).

Consider that when designing to get

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[1] See page 19-1

energy from a power supply our concern is only with the characteristics seen at the power supply terminals. Our design does not depend on whether the line-feed to the supply is single-phase or three-phase, 60 Hz or 400 Hz, or even if the power factor is unity or some other value. None of that matters once you know what shows up at the output connections of the supply. For our purposes the actual source of energy is the connection at the output of the supply, and the characteristics at that point will be determined by the components in the filter circuitry.

As a source of sinusoidal energy, our RF amplifiers are no different. The "source" of this energy that will be passed on to our antenna system is the *tank*. The load connected to the output port of the amplifier can only see the voltage swings and the impedance presented by the tank components. A properly designed tank (of any type) will not pass so much energy on each cycle that the relationship between its terminal voltage and current is affected enough to cause non-linearity. Sometime during the cycle even that small amount of energy will be replaced, thus maintaining its operating levels.

Because this "new" source happens to present a linear impedance to its load (the first connection in our antenna system) we need have no concern about nonlinear processes occurring at points upstream of the tank. Once we have a linear active source in the cascade and we do nothing downstream to subsequently cause non-linearities, we can take advantage of those theorems and ideas that depend on the linearity of the network.

My teachings in "Reflections" depend on the linear nature of the energy transfer from the amplifier's output port right on through to the last antenna element. Because the energy to this network is supplied by a linear source (the tank) everything in my teachings can be assured of sound scientific basis. Objections by others, based on non-linearities ahead of the tank are simply not applicable.

The energy pulses supplied to the tank must be sufficient to "refill" the tank's energy store on each cycle. The connection where that energy transfer occurs is the one at the input to the tank. As stated earlier, at that point in the typical amateur pi-net class-C amplifier, the load is the tank input, and the source is the combination of two processes: 1) the blocking capacitor in series with the active device (the tube), and 2) the same blocking capacitor in series with the RF choke and the voltage of the power supply. These two sources are paralleled at the connection, but operate at different, but overlapping times through the cycle.

The load resistance R_L appearing at the input to the tank is determined by the value required to accommodate the energy transfer requirement to provide enough energy per cycle to make up for that being transferred by the tank to its load. Because of the lack of linear or even simple square-wave characteristics of the active device the designs in this region have always been very empirical. Actual experience and a good seat of the pants feel for the significance of active device data sheets have been the main tools for the design of tank circuits. The amount of energy delivered via the action of the active device (the tank) is dependent on a number of things like drive, feedback, supply voltages, etc. They all can play a role in providing for the right amount of energy transfer to allow the tank to function as a linear active source.

If the tank does not receive enough

energy to sustain the power level it has established with its load it will decrease in output accordingly. Malfunctioning of the upstream energy "bucket brigade" can result in linear operation at a lowered level, or in nonlinear operation depending on how well the tank design can handle the changes. The important point is that once conditions allow the tank to operate as a linear active source, everything else in the network downstream of the tank is linear and follows the Conjugate Match Theorem and other linear system theories. Changing the conditions at the input to the pi-net (e.g.: changing drive, feedback, etc.) affect the performance of the tank as a linear source of RF energy. If the tank is supplied with energy pulses having a different integrated average energy than that being supplied to the tank's load, the tank's output characteristics will change to fit the available energy. It will do this by changing its output impedance to whatever value is required so that at the new Conjugate Matching point the voltage-current product will equal the energy rate available. It has no choice since the Conjugate Matching Theorem requires the change in output impedance if it is to continue to be a linear source. Consequently, the load impedance at the output must be changed accordingly to retain the Conjugate Match. If the changes are too extreme it may not be able to accommodate the required impedance change in a linear manner so wave-shape distortion could occur, e.g. flat topping.

The important point is that the design and operation of the circuitry providing energy input to the tank circuit involves a number of issues having to do with protection of the active device, stability, efficiency, etc., as well as the amount of energy transferred to the tank during each cycle. It doesn't matter that the wave shape of the energy pulse is ugly and would be difficult to characterize mathematically because the tank circuit doesn't care.

It is positively uncanny how easy it is for some people to simply ignore experimental evidence staring them right in the face when one of their pet understandings is in jeopardy. Many people concede that amateur Class-C amplifiers typically operate at greater than 50 percent efficiency. They will also agree that it is common to tune for a power peak. They will then wiggle and squirm to avoid agreeing that the tuning process is simply matching the output and load impedances to a common conjugate. Their reason is that the internal "resistance" precludes the higher than 50 percent efficiency. The fact that there are two *independent* definitions for the word *resistance* doesn't seem to matter. They are completely ignoring Definition 2 of the IEEE definitions of 'resistance', the non-dissipative resistance, i.e., the real part of the impedance. To clarify the two independent definitions of resistance, Definition 1 and Definition 2, please refer to Appendix 10 for the IEEE definitions, and an in-depth treatment of the two.

RF power amplifiers are necessarily designed to match to load impedances at or near the characteristic impedance of common coaxial transmission lines. No other design value would make sense. The Conjugate Match Theorem is simple and absolute — when the energy being transferred across any linearly behaving connection cannot be further increased simply by changing the impedance of either source or load a conjugate match exists. And that is commonly the operating condition for amateur Class B and C RF amplifiers. From the tank circuit forward, the behavior is linear, because the voltage and current at the input of the tank are continuous and sinusoidal due to the energy storing ('flywheel'), smoothing action of the tank. There is really no wiggle room for debate.

Sec 19.7 Origin of the term *Tank* Circuit

Let me digress for a moment to say that it is customary for an author of a chapter such as this to have his writing peer-reviewed to uncover possible errors that may have escaped him. Because of the protracted and unfortunate controversy brought about by those who claim that a conjugate match cannot exist in an RF system powered by an RF power amplifier, my engineering credibility as an author has been attacked. Therefore, because this chapter is primarily concerned with presenting a convincing argument that a conjugate match does indeed exist in RF power amplifiers, I have attempted to make sure it contains no conceptual or substantive errors, or invalid statements. Consequently, I requested *several* professional RF engineers with unquestionable credentials and expertise to review and critique this chapter. All reviewers but one found my presentation accurate. This dissenting reviewer flat out rejected the concept that the pi-network tank circuit isolates the pulsed input from the output, and therefore he maintains that the output circuit of the pi-network cannot support or sustain linear operation, thus no conjugate match. Unfortunately, during the nine years of the controversy I discovered that opposition to the application of linear theorems to *any* aspect of RF power amplifier operation is prevalent in the confused mind set of *many* otherwise intelligent and capable engineers. It therefore occurred to me that others also might have similar difficulty in accepting the concept of energy storage in the tank circuit providing isolation between the input and output of the tank that allows linear theorems, such as the Maximum Power-transfer Theorem and the Conjugate Matching Theorem to be valid at the output. I have already presented two examples of the storage of mechanical energy that illustrate the smoothing function of energy storage, which are precisely analogous to energy storage in the tank circuit of the RF power amplifier. In addition, a valid water analogy where the operative word is "tank" in the literal sense might further clarify the issue. I also believe you'll find it interesting to learn how the term *tank* originated as an active description of the LC circuit used in the output coupling of all RF power amplifiers.

Legend has it that in the early days of RF amplifier development the 'water tank' analogy was applied for the very purpose of explaining the energy-storage function of the LC output circuit. It goes like this. A water tank is filled to a specific depth that causes a corresponding pressure applied on the bottom. A hole is made in the bottom with a size that allows one gallon per minute to flow with the specific applied pressure. Water is added at the top of the tank at the rate of one gallon per minute, thus maintaining the original level in the tank as the water flows smoothly out from the bottom. Let's now consider how the water is added at the top. It can be added in spurts, but the water flowing out from the bottom will still flow smoothly without ever knowing the nature of the spurts added at the top. The spurts can be added at a rate of one gallon dumped in every minute, a half gallon twice during the minute, or one-thirtieth of a gallon thirty times per minute, etc. You get the picture. As long as enough water is added to maintain the original level, thus maintaining the same constant pressure at the bottom, the water will continue to flow smoothly from the bottom at the rate of one gallon per minute, regardless of how the water is added at the top. It is the ***energy stored in the tank*** that isolates the intermittent addition of water at the top from the continuous flow at the bottom. If the tank is filled to a higher level (greater depth) the pressure at the bottom is increased, resulting in an increased rate of flow of water at the bottom, in direct proportion to the increase in pressure.

It should be appreciated that the ***fluid impedance*** at the output of the tank (the ratio of the pressure to the flow rate), at which the energy contained in the water flowing from the bottom of the water tank, is established solely by the size of the hole and the height of the water above the hole. The same energy rate can exist with a tall tank and a small outlet hole (high output impedance), or shorter tanks with appropriate larger holes (low output impedance). However, the impedance and linearity of the *input* to the tank is irrelevant as long as it results in maintaining a constant water level. Thus the action at the bottom is linear even though the action at the top is not.

The same is true in the *tank* circuit of the RF amplifier. The impedance at the output of the RF tank is the ratio of the voltage to current at which power is being delivered to the tank's load. The voltage and current appearing at the output of the pi-network tank circuit are analogous to the water pressure at the bottom of the tank (voltage), and the rate of flow of the water (current) out of the tank. As in the water tank, the shape of the current pulses entering the pi-network tank has no effect on the smooth sinusoidal voltage and current appearing at the output. If the average integrated energy of the current pulses entering the tank increases, the voltage and current at the output will increase in a linear relationship. Thus it is shown that the output of a properly designed RF tank circuit is linear, and the theorems associated with linear circuits are applicable.

Sec 19.8 Measuring the Output Resistance of the RF Power Amplifier

Background

I have developed a test setup and procedure based on the standard IEEE load-variation method for measuring the source, or output resistance R_{OUT} of networks, which are described below. Measurements made with this setup and procedure show that output resistance R_{OUT} equals the load resistance R_{LOAD} when the amplifier is initially adjusted to deliver all of its available power to that load, thus proving the existence of a conjugate match. However, before proceeding further it will be helpful in obtaining an appropriate perspective by reviewing some background concerning the issue.

There has never been a problem in determining the correct value of load resistance R_L appearing at the input of the pi-network tank circuit of the RF amplifier. Resistance R_L is routinely calculated using either the Terman equation or the more precise Chaffee analysis to determine the slope and other characteristics of the operating load line, as mentioned earlier. After the network has been adjusted to deliver its intended power into its terminating load, resistance R_L appearing at the input of the network is easily and routinely measured with appropriate impedance measuring equipment with the amplifier powered down.

However, determining the *output* resistance R_{OUT} appearing at the output of the pi-network has been daunting. Wild speculations sans measurements concerning the output resistance abound because of the misunderstandings and incorrect assumptions concerning the actions of the tank circuit as described above in Sec 19.2. The misconception that a conjugate match cannot exist at the output of RF power amplifiers has precluded logical reasoning, that when the amplifier is delivering all its available power there is a conjugate match by definition. Consequently, it has been considered unthinkable that the output source resistance could possibly be equal to the load resistance.

I am not aware of any writings in the professional literature that discuss the measurement of R_{OUT}. A probable reason for this lack of discussion is that knowledgeable people know that R_{OUT} must equal the load resistance when all the available power is being delivered, and it would therefore be redundant to state it. However, one notable speculation concerning the value of R_{OUT} is in the article appearing in the November 1991 issue of *QST* that claims no conjugate match can exist in a system if the source is an RF power amplifier[142]. The author of the article, Warren Bruene, W5OLY, described a test setup in which he thought he was measuring the source resistance, which he calls 'R_S'. However, he presented no proof that what he measured was really the source resistance, or that his test setup could measure source resistance. But because his measurements of what he thought to be source resistance yielded values as much as five times greater than the load resistance, he proclaimed that no conjugate match could exist with RF power amplifiers. It is his proclamation that caused the current technical editors of the *ARRL* to reverse the position of their predecessors, thus igniting the unfortunate and protracted controversy concerning the conjugate match and the RF power amplifier. As a result of that author's persuasion, it is also the current official publicly stated position of the *ARRL* that no conjugate match can exist when an RF power amplifier is the source. So it is now appropriate to describe the test setup and procedure that does yield the correct value of source resistance R_{OUT}, *the value that* ***equals*** *the load resistance.* Consequently, using the standard IEEE load-variation procedure described below, it will be seen that the data resulting from my measurements (also shown below) prove two things: 1) *source* resistance is *not* what the author Bruene was measuring, and 2) my measurements prove the existence of the conjugate match at the output of RF power amplifiers.

It should be noted here that the data obtained from my measurements have been verified by another RF engineer, Tom Rauch, W8JI, who is an RF power amplifier design engineer with Ameritron.

The test setup I developed for measuring the output resistance R_{OUT} of RF power amplifiers is arranged to use the load-variation method of measurement, based on the IEEE expression for measuring the output resistance of networks. The IEEE expression is $R_{OUT} = \Delta E \div \Delta I$, where ΔE and ΔI represent the corresponding change in load voltage and load current, respectively, with a small change in load resistance R_{LOAD} terminating the network. In the measurements described below all values of R_{LOAD}, (R_1 and R_2) are pure resistances, R + *j*0. In these measurements the output load resistance R_{OUT} (R_1) terminating the pi-network is selected and the parameters of the amplifier are then adjusted to obtain delivery of all the available power into that load at a given drive level. Then by varying the load resistance a small amount (to R_2), around a 10 percent change from R_1, and then measuring the difference in load voltage and current, the output resistance is obtained by substituting the differential voltage and current values in the IEEE expression for R_{OUT} shown above.

The equipment used in the measurements consisted of two tube-type transceivers using two parallel 6146 tubes and a pi-network tank circuit in the RF power amplifier. They are a Heathkit HW-100 and a Kenwood TS-830S. A Hewlett-Packard HP-4815A RF Vector Impedance Meter modified for digital readout, along with ESI 250-DA universal impedance bridge, for measuring RF and DC resistances of non-inductive load resistors R_1 and R_2. An HP-8405A Vector Voltmeter modified for digital readout for measuring voltages appearing across load resistors R_1 and R_2, and an HP-410B RF Voltmeter with HP-455A Coaxial Adapter, also modified for digital readout to indicate load voltage. The RF Vector Impedance Meter was used to confirm that the load resistors contained zero reactance. The experiments were conducted at 4.0 MHz.

Procedure

The pi-network output of the amplifier is initially terminated with R_1, then tuned and loaded to deliver a specific maximum available output power with a given level of grid drive. The load voltage E_1 is measured with load R_1, then the load is changed to R_2 and load voltage E_2 is measured. Load currents I_1 and I_2 are then determined by calculation of I = E/R, using the measured values of R and E. Finally, as stated above, $R_{OUT} = \Delta E \div \Delta I$, as shown in the data resulting from the measurements shown in Table 19.1 below.

Amplifier tuned and loaded with drive level set to deliver maximum available power of ≈ 110 watts. All adjustments remain undisturbed thereafter. The data in Table 19.1 was obtained using the Heathkit HW-100.

Table 19.1
Using Standard IEEE Small-Load-Variation Method to Measure Network Output Source Resistance

Load Resistance	Load Voltage	Load Current	Output Resistance	Measured Power Out
51.2	75.9	1.482	52.7	112.5
44.6	70.6	1.583		111.6
	Δ=5.3	Δ=0.101		
51.2	76.9	1.502	51.2	115.5
44.6	71.6	1.605		114.9
	Δ=5.3	Δ=0.1034		
51.2	69.75	1.36	49.4	94.9
46.4	66.29	1.43		94.8
	Δ=3.46	Δ=0.70		
51.2	62.5	1.22	51.7	76.25
46.4	59.4	1.28		76.0
	Δ=3.1	Δ=0.60		
51.2	77.8	1.519	47.8	118.2
46.4	74.1	1.597		118.3
	Δ=3.7	Δ=0.078		
51.2	77.5	1.514	47.4	117.3
47.75	74.9	1.569	**Average**	117.5
	Δ=2.6	Δ=0.0549	**50.3 ohms**	

The reason for the variation, or scatter in measured output resistance and output power seen in the data above was found to be the short-term sag in output power between the measurement of R_1 and R_2. This problem was solved by changing the switching from R_1 to R_2 from manual to coaxial relay, thus reducing the time delay, and by waiting until the sag in power output bottomed out. However, the worst case difference between R_1 load of 51.2 ohms and the R_2 value that yielded R_{OUT} of 47.35 ohms is a mismatch of only 1.081:1, with a reflection coefficient ρ of 0.039, for a conjugate mismatch loss of only 0.0066 dB.

After many more measurements similar to those above, except for adjusting the pi-network for delivery of maximum available power prior to each measurement, I found that with load R_1 now at 51.0 ohms, the measured values of R_{OUT} varied randomly within 11 ohms on either side of the 51.0-ohm load with each measurement, i.e., from 40 ohms to 62 ohms. However, I discovered the variation results from the very small slope of the power output curve near the peak. Using only the analog output-power meter to observe the point at which the power was maximum, I found it impossible to find the true peak in output power where R_{OUT} equals R_1 of 51 ohms, because the characteristics of the matching curve near its peak appear to be more like a 'round-top hill' than a peak. Evidently the adjustment for maximum output requires a method of indicating that provides better resolution than that obtained with the analog output power meter alone. On the other hand, the mismatch between 51 and 40 ohms, and between 51 and 62 ohms, is only 1.28:1, for a voltage reflection coefficient ρ of 0.12, which results in a conjugate mismatch loss of only 0.066 dB at the maximum 11-ohm difference from 51 ohms. Thus it is evident that during routine tuning and loading adjustments using analog meters indicate peak power output, the actual output resistance of the network during the measurements will seldom be *exactly* the value of the load resistance, but the consequence of the small difference is insignificant.

The next step in the procedure yielded the increase in resolution of the data required to find the exact point on the output curve where the output is maximum and R_{OUT} equals the load R_1. After the maximum output that could be obtained by observing the indication on the analog output power meter, R_{OUT} was measured at that point. The pi-network was then re-adjusted in very small increments, measuring R_{OUT} after each readjustment, until R_{OUT} became equal to 51.0 ohms. The increments were so small that although the difference in output power at each increment was indiscernible on the analog power meter, it was clearly indicated by the digital voltmeter. Thus it is shown that the output, or source resistance R_{OUT} of an RF power amplifier is equal to the resistance of the load when the maximum available power of the source is being delivered to the load. It is therefore also evident that a conjugate match exists when the conditions just stated are present.

In addition to measuring R_{OUT} with the load resistance of 51.0 ohms, R_{OUT} was also measured with load resistances of 25 and 16.7 ohms. Using the same technique as described above, R_{OUT} measured 25 ohms when the load resistance was 25 ohms, and, consistent with the measurement pattern already developed, R_{OUT} measured 16 ohms when the load resistance was 16.7 ohms. These measurements indicate that, when the loading is initially adjusted to deliver maximum available power to any value of load resistance within the matching capability of the pi-network, R_{OUT} equals the load resistance.

There is more. So far we have only considered the condition in which the amplifier is delivering its maximum available power in the CW mode. But we would also like to know what happens to output resistance R_{OUT} during SSB modulation after the amplifier is first tuned and loaded to deliver maximum available power with a specific drive level. The measurement data appearing in Table 19.2 below was obtained using the HW-100 transceiver. This data shows that, except for the two caveats stated below, once the operating load line and resistance R_{OUT} are established at tuning and loading, R_{OUT} remains substantially constant over the entire range of drive and output power encountered during SSB modulation. After setting the drive level for the pi-network to deliver maximum available power of 100 watts, and leaving all adjustments except for the level of drive undisturbed thereafter, R_{OUT} was measured at power levels decreasing from 100 watts to 12.5 watts. The changes in output power were obtained by changing the level of drive. This range of power levels, as shown in Table 19.2, corresponds to approximately the same range of output power prevailing during SSB modulation.

However, the two caveats are necessary to explain the changes in R_{OUT} that appear to conflict with the statement above that R_{OUT} is substantially constant. First, and most important, due to imperfect regulation of plate voltage E_P, the increase in E_P as the plate current and output power decrease, causes a small change in the slope of the load line, resulting in an increase in R_{OUT} that would not occur with perfect regulation of E_P. And second, the scatter in the R_{OUT} data results from the measurements being taken prior to the improved setup and method of taking later measurements that yields the more precise data.

As shown in Table 19.2, the maximum value of R_{OUT} is 80 ohms, appearing at the minimum output power level. The conjugate mismatch between the 80-ohms of output source resistance and the 51-ohm load resistance is 1.569, establishing a voltage-reflection coefficient

Table 19.2

Measured Network Output Resistance vs Output Power, HW-100 Transceive

Also see Table 19.3 and Fig 19.1

Output Power Watts	Network Output Resistance Rout Ohms	Plate Voltage Ep	Plate Current Ip, ma.
100.0	48.4	800	270
75.0	58.3	810	240
50.0	57.3	820	190
25.0	74.0	840	140
12.5	80.0	860	110
0.0	NA	890	70

Note increase in network output resistance with increase in plate voltage, due to poor power supply supply regulation as plate current decreases with decrease in output power.

$\rho = 0.2214$, a power-reflection coefficient $\rho^2 = 0.0490$, and thus a transmission coefficient $(1 - \rho^2) = 0.951$, which translates to a conjugate mismatch loss of 0.218 dB. This small amount of loss is insignificant when considering that the purpose of the experiment was to establish proof that a conjugate match exists throughout the range of output power during SSB modulation.

However, the picture is even more optimistic when using the same measurement procedure with the Kenwood TS-830S transceiver. It can be seen from Table 19.3 and Fig 19.1 that the variation in output resistance with this transceiver is much less than with the HW-100 over the entire range of drive and output power. The reason for the nearly constant output resistance with the TS-830S is better plate-voltage-regulation of the power supply. It should be especially noted that in the region of constant output resistance of the network with changes in power level from 102.3 to approximately 25 watts, the constant output resistance indicates a *constant slope* of the loadline with changes in drive and power level, a point that has been in dispute in the absence of appropriate measurements. It is also important to observe that at the 10-watt output level, where the output resistance has increased somewhat due to imperfect voltage regulation (plate voltage increase with decrease in power), the mismatch between the 51.2-ohm load resistance and the 58.6-ohm output resistance is 58.6 ÷ 51.2 = 1.145:1. This small mismatch results in a voltage-reflection coefficient $\rho = 0.0674$, a power-reflection coefficient $\rho^2 = 0.00454$, and thus a transmission coefficient $(1 - \rho^2) = 0.9955$ (99.55 percent), which translates to an insignificant conjugate mismatch loss of only 0.0198 dB with minimum speech level referenced to zero loss at maximum speech level.

Fig 19-1 — Measured Network Output Resistance of Heathkit HW-100 & Kenwood TS-830S vs Output Powe
Power Level Set by Drive Level. See Tables 19.2 & 19.3.

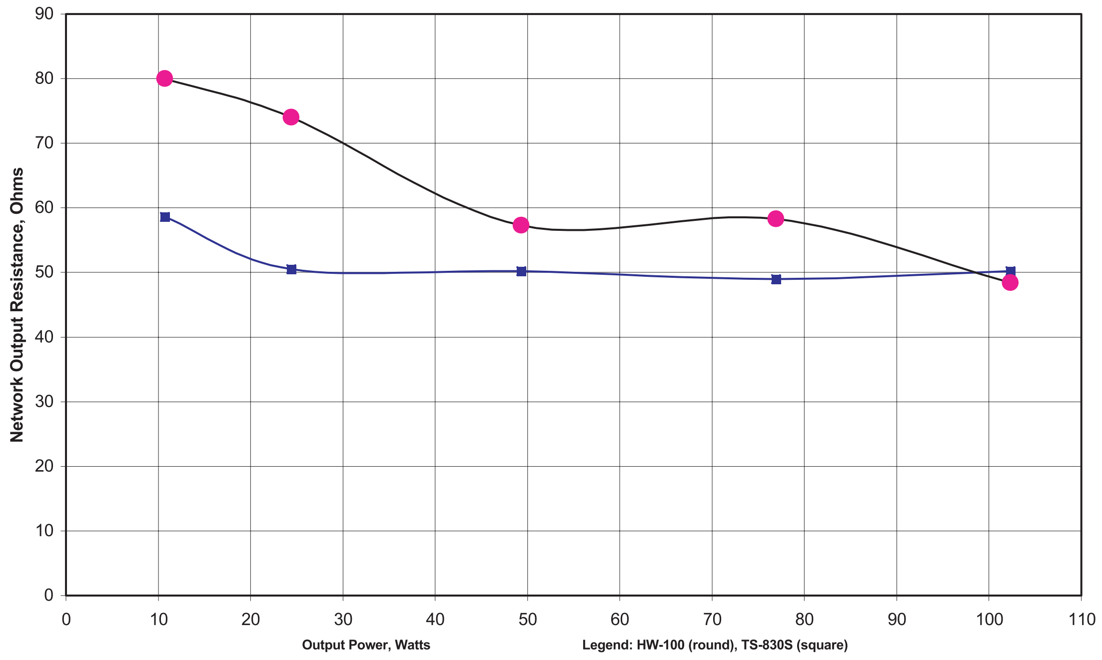


Table 19.3

Measuring Output Resistance of RF Amplifier of TS-830S Transceiver at 4.0 MHz At Various Power Levels Determined by Drive Level With All Other Adjustments Undisturbed

R Out = ΔE / ΔI

See Fig 19.1 and Table 19.2

Nominal Power Out	R Load	E Load	I Load	R Out	Measured Power Out	Ep	Ip ma.	Measured Power In
100 w.	51.2	72.381	1.414	50.2	102.3	790	265	209 w.
	43.5	66.548	1.530		101.8			
		ΔE=5.833	ΔI=0.161					
75 w.	51.2	62.738	1.225	49.0	76.9	790	240	190 w.
	45.3	57.738	1.327		76.6			
		ΔE=5.000	ΔI=0.102					
50 w.	51.2	50.238	0.981	50.2	49.3	810	195	158 w.
	43.5	46.190	1.062		49.1			
		ΔE=4.048	ΔI=0.081					
25 w.	51.2	35.357	0.691	50.5	24.4	810	165	134 w.
	43.5	32.500	0.747		24.3			
		ΔE=2.857	ΔI=0.057					
20 w.	51.2	32.857	0.642					
	43.5	30.119	0.692	54.1	21.1	820	135	111 w.
		ΔE=2.738	ΔI=0.051		20.8			
10 w.	51.2	23.453	0.458	58.6	10.7	825	110	91 w.
	43.5	21.429	0.493		10.6			
		ΔE=2.024	ΔI=0.035					

Except for the lowest levels of speech that would result in output power less than 10 watts during SSB modulation, the data in Tables 19.2 and 19.3 and Fig 19.1 show that the output resistance of the RF amplifier remains sufficiently constant over the normal range of speech levels, ensuring a realistic conjugate match during SSB modulation. Additionally, extrapolation of the data extending the range of output power below 10 watts clearly indicates that further increase in output resistance during the lowest practical levels of speech transmission is insignificant relative to load mismatch. Consequently, a realistic conjugate match exists over the entire range of speech levels.

Before concluding this subject, another way of explaining the action occurring in the amplifier during SSB modulation is that as the average integrated energy of the current pulses entering the tank changes with speech modulation, both the RF voltage and current at the output of the tank change linearly in proportion to the modulation level. Consequently, the ratio of output voltage to output current remains constant during speech modulation. And since the output resistance ROUT is determined by the ratio of current to voltage, the output resistance also remains constant and equal to the load resistance during modulation. Thus all the available power from the source is delivered to its load at all levels of speech, satisfying the condition required for a conjugate match at the junction of the source and load during all levels of SSB modulation.

Sec 19.9 Justifying the IEEE Method for Determining Network Output Resistance

William Sabin, W0IYH, recalled the mathematical expression for the IEEE method in QEX[143]. However, along with Warren Bruene, W5OLY[144], he later backtracked[145, 146, 147], claiming that this method cannot determine the correct output resistance when the network is the output load circuit of an RF power amplifier. Their reasoning is that the non-symmetrical pi-network circuit used in the amplifier does not behave like a perfect impedance transformer (perfect integral mathematical input/output ratio). Therefore, they claim even the small change in load resistance used in the IEEE method does not transform linearly through the network, and thus the input impedance of the network does not change directly with changes in load resistance. Their claim is that the imperfect transformer action of the network corrupts the results of the measurements of network output resistance. However, as I will explain using the data from my measurements appearing in Tables 19.4 and 19.5, and in Fig 19.2, it will become evident that the criticism of Sabin and Bruene is unfounded.

Recall that in the measurements described above to determine the network output resistance, the change in load resistance is **small**, around ±10 percent from the matched load resistance. The change in load must be small to avoid a significant change in the normal operation of the amplifier that would distort the results if the change in load resistance were relatively large. For example, a change in load that would result in a significant change in plate current would change the slope of the load line and the output resistance of the network. On the other hand, for examination and comparison, the data appearing in Table 19.4 and Fig 19.2 show the change in network output resistance (and magnitude of impedance) that results from somewhat larger changes in load resistance. Note that the magnitude of the output impedance changes linearly, but in indirect proportion to the load resistance. However, as seen in Fig 19.2, the output magnitude remains close to the load resistance when the load resistances are close to the value at which the network was adjusted for delivery of all available power. So the questions are why are the changes in output impedance **in**directly proportional to the load resistance? And why does the measured output resistance equal the load resistance when the change in load resistance is small? The answer is in the amount of the resulting change in plate current with change in load, which directly affects the slope of the load line and network output resistance. As we will see, when the change in load is sufficiently small, the change in plate current is also so small that the resulting change in amplifier operation is insignificant in relation to causing error in the measurement of the network output resistance. So let's examine the pertinent changes.

With the matched load (53.1 ohms) the plate current was 260 mA.; 280 mA. with the 27.7-ohm minimum load resistance, (network output impedance Z =

Table 19.4
Pi Network Output Impedance Magnitude Z vs Load Resistance
Kenwood TS-830S at Approximately 100 Watts Output, 4.0 MHz

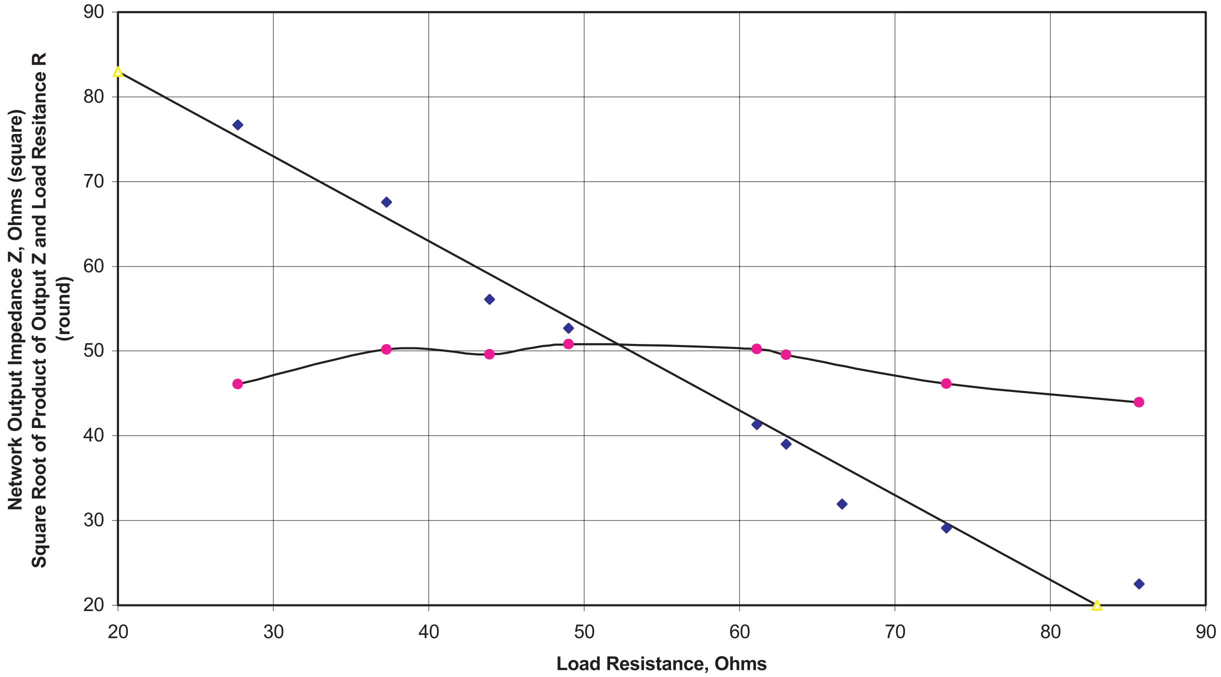
R Load (RL)	Load Mismatch	E Load (EL)	I Load (IL)	Z Out (Zo)	Sqr Root RL x Zo	Power Delivered
53.1		71.0	1.34	76.7		94.9
27.7	1.92:1	46.0	1.66		46.1	76.4
53.1		73.0	1.37	67.6		100.4
37.3	1.42	59.0	1.58		50.2	93.3
53.1		72.0	1.36	56.1		97.6
43.9	1.21	65.0	1.48		49.6	96.2
53.1		75.0	1.41	52.7		105.9
49.0	1.08	72.0	1.47		50.8	105.8
53.1		74.0	1.39	41.35		103.1
61.1	1.15	78.5	1.28		50.25	100.9
53.1		73.0	1.37	39.0		100.4
63.0	1.19	78.2	1.24		49.57	97.1
53.1		74.0	1.39	31.95		103.1
66.6	1.25	80.1	1.20		46.13	96.3
53.1		74.0	1.39	29.1		103.1
73.3	1.38	82.0	1.12		46.13	91.7
53.1		74.5	1.40	22.5		104.5
85.7	1.61	84.0	0.980		43.95	82.3
					Average 48.08	

76.7 ohms), and 210 mA. with the 85.7-ohm maximum load resistance (network output impedance Z = 22.5 ohms). However, when the load was changed from 53.1 to 49.0 ohms to obtain Z_{Out} = 52.7 ohms (see Table 19.4), any change in the 260 ma. of plate current resulting from this small change in load was too small to be discernible on the 0–300 mA. meter.

Observing from Fig 19.2 it is interesting to note that in the range from the load resistance of 37.3 ohms (mismatch 1.42) to 63 ohms (mismatch 1.19), the square root of the product of the network output impedance and load resistance remains close to the value of the load resistance that allows delivery of all the available power (≈ 50 ohms), but begins to decrease with increased load mismatch on either side of the matched condition. It will be shown later that the reactance introduced by the non-symmetrical network while transforming the non-reactive load resistances to the network input are responsible for the decrease as the mismatch increases in either direction away from the resonant condition.

Let’s turn now to Table 19.5 where

Fig 19-2 — Kenwood TS-830S RF Amplifier Pi-Network Output Impedance Z vs Load Resistance. All Available Power of Approx. 100 Watts Delivered Initially to 53.1-Ohm Load. All Adjustments Left Undisturbed During Measurement of Other Load Values. See Table 19.5



my measured data is shown to agree with Sabin's and Bruene's statement that impedance transformation through a nonsymmetrical network is not the same as that through a perfect transformer having a linear ratio of transformation. Although their statement on this point is shown to be true, we will see that the reasoning which they claim renders the IEEE procedure invalid is not correct. Note that except for the 50-ohm load resistance that matches the network, all other purely resistive load resistances transform through the network to obtain reactive impedances at the input. When plotted on a Smith chart the locus of these input impedances form a straight line at an angle of 64° clockwise from the resistive axis, intersecting the axis at the chart center where the impedance is 1350 + *j*0. Still in Table 19.5, note that when the load mismatch is approximately 2:1 on either side of the matched point the angles of the impedances are numerically equal with respect to that at resonance, 32° with the high load resistance and –32° with the low load resistance. However, also note that with the high and low load resistances the magnitudes of the input impedances are 1060 and 1780 ohms, respectively. The differences between the matched input impedance (non-reactive) of 1350 ohms are thus 290 and 430 ohms, respectively. Let's now examine the significance of these **measured** input impedances.

First, the 1780 ohms input impedance obtained with the low-resistance load is 140 ohms further off the resonant value than the 1060 ohms with the high-resistance load, resulting in the higher off-resonance plate current with the low-resistance load than for the high-resistance load with same degree of mismatch (1.92:1 and 2.0:1, respectively).

Second, the measured input impedances resulting from two load resistances of ± 5 ohms relative to 52 ohms were interpolated on the straight-line locus of all the impedances in Table 19.5. At the resulting two equal input mismatches of 1.12:1, the resulting input impedances normalized to 1350 ohms are 0.95 + j0.10 and 1.10 – j0.10, respectively, for real values of 1282.5 + j135 and 1485 – j135 ohms, respectively. With these mismatches of only 1.12:1 on either side of resonance the angle of the mismatched impedances is only ± 6°, and the change from normal amplifier system performance of 1.0 only to 0.9968, (99.68 percent) amounts to a change of only 0.014 dB. Consequently, the small change in amplifier performance under these conditions is insignificant with respect to contributing to error while using the standard IEEE load-variation method in the measurement of network output impedance. Ergo, the Sabin and Bruene criticism of the IEEE method of measuring the output impedance of pi-networks in RF power amplifier operation is unfounded and the method is proved valid.

In conclusion, my measurements and discussion in this Chapter prove that the output of a properly designed RF tank circuit performs with a linear relationship between output voltage and current. Consequently, the theorems associated with linear circuits, such as the Conjugate Matching Theorem and the Maximum-Power Transfer Theorem, are valid and applicable in both the analysis and practical operation of RF power amplifiers performing in both CW and SSB modes.

Table 19.5

Pi-Network Input Impedance vs Non-Reactive Load Resistance

HW-100 Transceiver Initially Resonated With 52.0-Ohm Load at 100 W Output

Network Load Ohms	Mismatch Re 52.0 Ohms	Network Input Z Polar	Network Input Impedance Rectangular (R+jX)
240.0	4.6:1	950@58°	503.4 + j805.6
160.0	3.17	980@48°	655.7 + j728.3
100.0	1.92	1060@32°	898.9 + j561.7
83.0	1.6	1150@20°	1080 + j393.3
52.0	1.0	1350@0°	1350 + j0
41.0	1.22	1580@-14°	1533 - j382.2
34.2	1.52	1630@-18°	1550 - j503.7
26.0	2.0	1780@-32°	1509 - j943.3
20.6	2.52	1900@-41°	1433 - j1245
17.5	2.97	2000@-48°	1338 - j1486