RF POWER AMPLIFIERS - TANK CIRCUITS & OUTPUT COUPLING

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The output tuning and coupling of the final RF amplifier is an important part of the transmitter. It is designed to load the amplifier for optimum power output with a minimum of harmonic content. Here are a few notes on its design.

(The article was first published in Amateur Radio, May 1988. Unfortunately in the publishing process, errors were made in several formulae, one diagram was incorrectly redrawn and some of the text was corrupted. The article is submitted here again, but in its correct form.)

Updated with further corrections to text - Sept. 8, 2007

INTRODUCTION

To obtain high efficiency, final RF power amplifiers for single sideband operation are normally operated in Class AB or Class B and those for CW or FM operated in Class C.

In coupling a tuned RF power amplifier to its load (the antenna or antenna feed line), two requirements must be satisfied:

1. The correct load resistance, which will enable the amplifier to deliver its rated power, must be presented to its output.

2. The loaded Q factor must be carefully selected. Plate current in a class AB, B, or C amplifier does not flow for the complete period of an AC cycle and the waveform is maintained by the inertia of the tuned circuit. Too low a Q causes waveform distortion and increased generation of harmonics. As Q is increased, circulating current in the tank circuit is also increased and if made too high, it causes excessive IR power loss in the circuit. A loaded Q of 12 is considered optimum although values between four and 20 might have to be tolerated over the tuning range of a multiband amplifier.

RF amplifiers can also be operated in a wideband or untuned mode and for this method of operation, a low pass filter is required in the output circuit to reduce harmonics generated by the waveform distortion.

In the following paragraphs, a simple design procedure will be discussed, firstly for the tuned amplifier and then in turn for the wideband untuned amplifier.

LOAD RESISTANCE

For valve RF power amplifiers operating at power levels suitable for amateur use, load resistances (R_L) in the region of 1000 to 7000 ohms are typical. The ARRL Handbook provides the following approximation for valve RF amplifiers:

Class A: $R_L = E_b/1.3I_b$

Class B: $R_L = E_b/1.51E_b$

Class C: $R_L = E_b/2I_b$

where E_b = Plate voltage and I_b = Plate current (Amps)

For the valve power amplifier, the required load resistance is normally much higher than the transmission line impedance (typically 50 ohms). By comparison, the transistor power amplifier with low supply voltage requires a load resistance much lower than the transmission line impedance. Neglecting bottoming voltage, the load resistance of a single ended transistor amplifier is calculated from the following:

$R_L = E_{bb}^2/2P_o$ ....(a)

where E_{bb} = Supply voltage and P_o = Power output (watts)

For a 13.5 volt supply (typically used in a mobile vehicle) and output powers between 10 and 100 watts, R_L varies between 9.5 and 0.7 ohm.

For a 100volt supply (such as might be used with a MOSFET amplifier) and output powers between 10 and 100 watts, R_L varies between 500 and 50 ohm.

There could be some confusion in applying the expressions to sideband transmission where both the power output and plate current swings with speech modulation. In this case, P_o should be taken as the maximum RMS power delivered, (or PEP power) and plate current should be taken as peak DC current swing.

BASIC TANK CIRCUIT

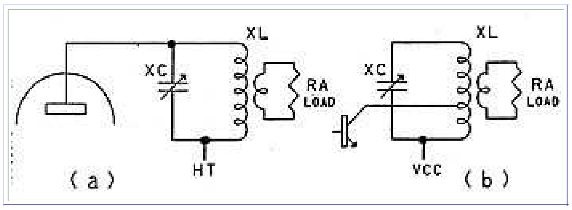

Figure 1: Basic Tank Circuit.

To set the required loaded Q factor in the basic coupling circuit of Figure 1a, the tuning capacitor and inductor in the tank circuit must be selected for the correct reactance at the frequency of operation. Reactances (X_C and X_L) are calculated as follows.

$X_L = X_C = R_L/Q$

where Q = loaded Q (say 12)

Capacitance and inductance are calculated then using the usual formulae:

$C = 10^6/(2\pi f X_L)$ pF ....(b)

and $L = X_L/(2\pi f)$ μH ....(c)

where f = frequency in MHz

The number of turns (N_p) on the primary of the output transformer is set by the inductance calculated. Where the secondary is tightly coupled to the primary, such as in a multifilar wound toroidal transformer, the secondary turns (N_s) are calculated as follows:

$N_s = N_p\sqrt{(R_a/R_L)}$ ....(d)

where R_a = Antenna or transmission line load resistance.

When using such a transformer, there is no provision for loading adjustment except for connection of different combinations of multi-filar windings (if such a means is available). Hence, the coupling transformer must be carefully selected to ensure that the secondary load resistance R_a (say 50 ohms) reflects the required amplifier load resistance at the primary.

With an air wound coupling transformer, the coupling coefficient is lower and more secondary turns than that given by the previous formula, are required. The degree of coupling can be adjusted by either taps on the the coils or by varying the spacing between primary and secondary. Adjustment is usually carried out by initially resonating the tank circuit with the secondary loosely coupled and then gradually increasing coupling and re-resonating until the rated loaded power amplifier current is achieved.

Resonance is indicated by a pronounced dip in plate (or collector) current. (If the off-resonance current is too low to achieve the rated loaded current when dipped, the amplifier may have insufficient input drive power). A variable tuning capacitor is usually fitted in the tank circuit and a tuning procedure could be to initially set the capacitor value near that calculated to give the correct loaded Q, then adjust the inductor taps for near resonance and finally fine tune with the capacitor.

The circuit of Figure 1a, as it stands, is somewhat impractical for transistor use, particularly where a low voltage supply is used. The reason for this is that, for low voltage, R_L is low and X_c is equal to this value divided by Q with the resultant calculated capacitance being extremely large. The situation can be improved by tapping down the collector connection on the inductor as shown in Figure lb. For example, if a tap were selected at a quarter of the turns, the value of R reflected across the whole tuned circuit would be increased to a value of four squared times that of R_L. For a low voltage supply, the calculated capacitance might still be quite high at lower frequencies. However, where a fairly high supply voltage is used (as could apply in the MOSFET amplifier), the figure 1b circuit could well enable a practical small value of capacitance to be used.

THE PI COUPLER

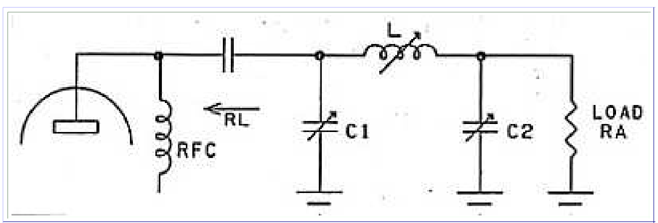

Figure 2: PI Coupling Network.

The Pi coupling network (Figure 2) is a suitable coupling system where it is necessary to reflect, to the output of a power amplifier, a high resistance load from a lower impedance transmission line. It is ideal for coupling a valve power amplifier, normally requiring a high resistance load matched to a low impedance line.

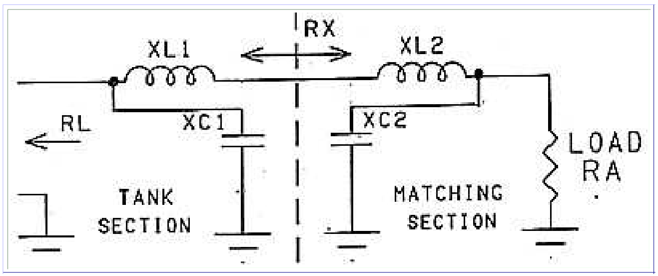

Figure 3: PI Network split into two sections for analysis.

To examine this network, we divide the network into two sections (Figure 3), splitting the inductor (L) into two parts, L1 and L2. The first section can be considered to be the tank circuit which sets the correct value of loaded Q. To reflect the correct value of R_L to the amplifier output, a resistance value of R_X must be presented at the tank circuit output. The two reactive components and R_X, are calculated as follows:

$X_{L1} = R_L/Q$

$X_{C1} = X_{L1}$

$R_X = R_L/(Q^2 +1)$

where Q = loaded Q (say 12)

The value of R_X is normally lower than 50 ohms and the purpose of the second section is to match this resistance to the transmission line impedance (R_a). Making use of formulae described in references 1 and 2, we calculate the reactive components in the second section as follows:

$X_{C2} = \sqrt{[(R_X R_a^2) \div (R_a - R_X)]}$

$X_{L2} = (X_{C2} R_a^2) \div (R_a^2 + X_{C2}^2)$

Putting the two sections together, a single inductive reactance (X_L) is formed by the sum of X_{L1} and X_{L2}. The components Ll, Cl and C2 are calculated from their reactances, as before, from the formulae (b) and (c).

The Pi coupling system is often considered desirable because its formation makes up a low pass filter which attenuates the harmonic cornponents.

In the preceding discussion, the transmission line load has been considered as resistive, however, the three components in the network are normally made adjustable and can be used to also correct for reactance in the line load.

A tuning method for the Pi coupler is suggested as follows:

1. Preset the inductor near its desired value (hopefully set for a suitable loaded Q).

2. With C2 set for maximum value, resonate the plate circuit using C1.

3. Increase the loading gradually, by decreasing C2, until the rated input power is reached. (For each change of C2, reset resonance with C1).

THE T NETWORK

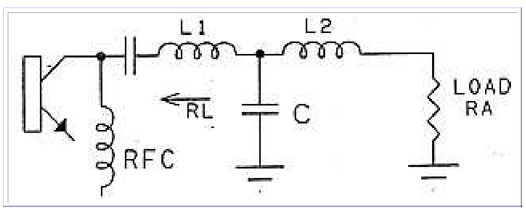

Figure 4: 'T' Coupling Network.

For the transistor RF power amplifier, where the amplifier load (R_L) is low compared to the transmission line impedance, the T network (Figure 4) is more suitable.

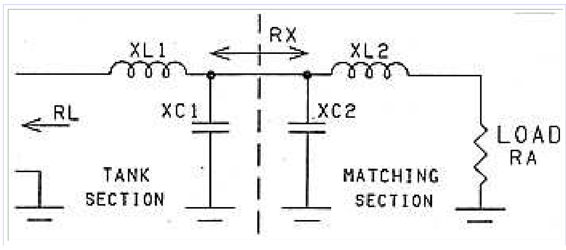
XL1
RX
XL2
RL
XC1
XC2
LOAD
RA
TANK
SECTION
MATCHING
SECTION

Figure 5: 'T' Network split into two sections for analysis.

Again we split the network into a tank section and a matching section with capacitor C split into two parts C1 and C2 (refer Figure 5). In this case, Rx is made greater than R_L and calculation, for the tank section, is as follows:

$X_{L1} = R_L Q$

$X_{C1} = X_{L1}$

$R_x = R_L(Q^2 + 1)$

For the transistor power amplifier, Rx also works out greater than Ra and, in the matching section, we again use the formulae from references 1 and 2, to calculate the reactive components as follows:

$X_{L2} = \sqrt{[(R_x - R_a)R_a]}$

$X_{C2} = X_{L2} + R_a^2/X_{L2}$

Putting the two sections together, the reactance (X_C) of capacitor C, is the parallel result of X_{C1} and X_{C2}, i.e.

$X_C = X_{C1}X_{C2}/(X_{C1} + X_{C2})$

The components Ll, L2 and C are calculated from their reactances, as before, from the formulae (b) and (c).

As stated earlier, the load resistance (R_L) for a transistor is normally quite low and certainly less than the transmission line impedance (typically 50 ohms). However, using power MosFET transistors, the supply voltage is often much higher than that used with bipolar transistors and for low power stages of the MosFET type, the load resistance might turn out to be greater than 50 ohms. For this case the Pi network might be more suitable than the T network. To make the decision, work out the value of R_L first. If R_L is greater than the line impedance, use the Pi network. If it is less than the line impedance, use the T network.

UNTUNED OR BROADBAND AMPLIFIER

Instead of using a tank circuit, transistor RF power amplifiers of today are often coupled to the antenna transmission line via untuned broadband transformers. Harmonics of the operational frequency components are reduced by feeding the output via a low pass filter which has a cut off frequency some 20 to 30 percent above the operating frequency (refer Figure 6).

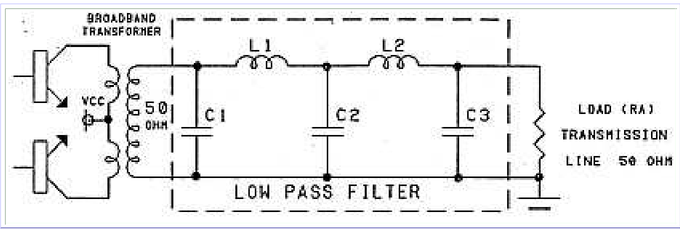

Figure 6: Broadband Coupling with Low Pass Filter

If the amplifier is to work in a linear made for single sideband operation and a high efficiency is to be achieved, it must work in class AB or class B where amplifier current flows for less than the whole AC cycle. In the opinion of the writer, a broadband linear RF amplifier, operating in class AB or class B, should be given the same design considerations as a similar class of audio amplifier, that is, it should operate push-pull to maintain continuity of amplifier current flow for the whole AC cycle. (It is a different case to the single ended tuned amplifier which has the inertia provided by a tank circuit to maintain a good waveform).

Notwithstanding what has been said in the previous paragraph, circuits are published for single ended broadband linear amplifiers which rely on a following low pass filter to remove the harmonic components generated. However, in these, one must question the level of additional components, within the filter passband, which might be generated by intermodulation between the various sideband components passing through the amplifier. Another point is that second harmonic components are those nearest to the fundamental frequency and the least attenuated by the slope of the low pass filter. Push pull operation helps by balancing out these particular harmonics.

A few words can be said about the load resistance of a push pull transistor amplifier. Formula (a) was previously given for the single ended stage. If the amplifier works push pull class B, each transistor works on half a cycle and the load resistance across one half of the output transformer should be the same as formula (a). The load resistance (R_{cc}) across the complete winding is four times this, i.e.:

$R_{cc} = 2E_{bb}^2/P_o$

For push pull class A, each transistor shares half the power over the full cycle and each should see a load resistance, at its own half of the transformer primary, twice that of formula (a). The load resistance across the complete wind is four times that of the half winding, i.e.:

$R_{cc} = 4E_{bb}^2/P_o$

For class AB, one must judge whether operation is closest to class A or class B.

The coupling transformer should be tightly coupled with multi-filar type windings and a ferrite core. The primary reactance, at the lowest operating frequency, should be a number of times larger than the primary load resistance (R_L). Turns ratio (T) is calculated from:

$T = \sqrt{(R_a/R_L)}$

The design of the low pass filter can take many forms depending on the type of filter and the ripple specified in the passband. The following is presented for the design of a 50 ohm 0.1 dB ripple Chebychev filter as applied in Figure 6:

$Ll = L2 = 12.38/f_c$ μH

$Cl = C3 = 4142/f_c$ pf

$C2 = 7134/f_c$ pf

where f_c = the cutoff frequency in MHz

With f_c equal to 25 percent above the operating frequency, the filter should attenuate the second harmonic of the operating frequency by about 35 dB and the third harmonic by about 55 dB. To achieve a satisfactory filter response, aim for a high Q in the inductors and avoid capacitors with high loss resistance such as found in ceramic capacitors.

SUMMARY

Design procedures for various methods of coupling RF power amplifiers to the transmission line have been described. Coupling systems described are divided into those which are tuned and those which are untuned and broadband.

For the tuned systems, you may choose to use a simple tuned tank circuit or take advantage of the harmonic reducing characteristics of the Pi or T network. Where the transmission line impedance is less than the load impedance required to be reflected to the amplifier (such as for the valve amplifier), use the Pi network. Where it is greater (such as with the bipolar transistor amplifier), use the T network.

For the untuned wideband system using an RF power amplifier operating in class AB, B, or C, a low pass filter must be included to reduce harmonics radiated.

REFERENCES

1. LLOYD BUTLER, VK5BR. Loading up on 1.8 MHz. Amateur Radio December 1985.

2. LLOYD BUTLER, VK5BR. An Approach to Antenna Tuning. Amateur Radio June 1987.

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