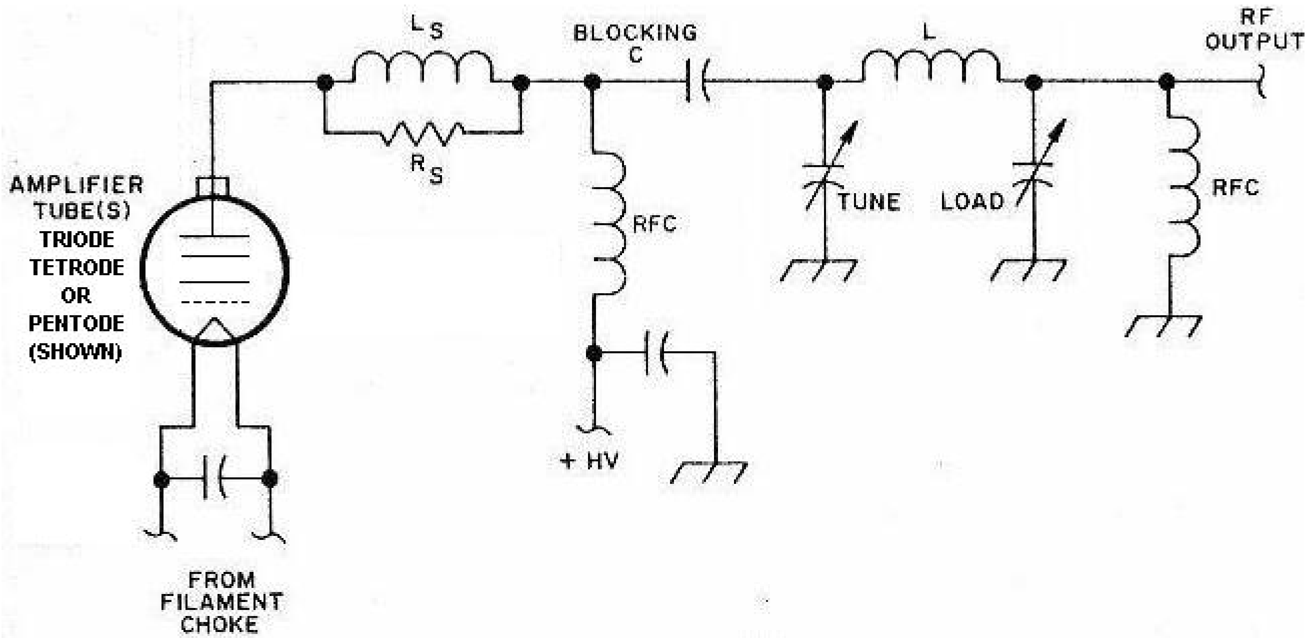
RF Power Amplifier (RFPA) Design Formulas

By Larry E. Gugle K4RFE, RF Design, Manufacture, Test & Service Engineer (Retired)

Designing a 'Output Tank Circuit' For a Power Triode, Tetrode and Pentode Electron Tube



1. **Efficiency in a RF Power Amplifier (RFPA) is a ratio measurement, of how much of the DC Input Power (Pin) from the Source Power Supply (Ps), is usefully applied to the RF Output Power (Po). The more efficient a RF Power Amplifier (RFPA) operates, the cooler it will run, even in high power multi-kilowatt designs. Any loss of efficiency produces heat as a by-product of the energy lost during the conversion of power. *Electron Tube Amplifier Classes of Operational efficiency are*:**

    a. **Class 'A' Amplifier (Linear Region of Operation)**
        i. **Low Efficiency, in RF systems, with a range of 20–30%.**
        ii. **Control Grid (CG) DC bias voltage is set so plate current (Ip) flows the entire 360 degrees of each RF AC input cycle.**

    b. **Class 'AB' Amplifier (Linear Region of Operation)**
        i. **Medium Efficiency, in RF systems, with a range of 30-60%.**
        ii. **Control Grid (CG) DC bias voltage is set so plate current (Ip) flows greater than (>) 180 degrees but less than (<) 360 degrees of each RF AC input cycle.**

1. Subscript '1' (Class AB1), indicates that Control Grid (CG) Current does not flow during any part of the input cycle. 30-45%.
2. Subscript '2' (Class AB2), indicates that Control Grid (CG) Current does flow during some part of the input cycle. 45-60%.

c. Class 'B' Amplifier (Linear Region of Operation)
   i. High Efficiency, in RF systems, with a range of 60-70%.
   ii. Control Grid (CG) DC bias voltage is set so plate current (Ip) is near cutoff, and flows during 180 degrees of each RF AC input cycle.

d. Class 'C' Amplifier (Non-Linear Region of Operation)
   i. Very High Efficiency, in RF systems, with a range of 65-85%.
   ii. Control Grid (CG) DC bias voltage is set so plate current (Ip) flows less than (<) 180 degrees of each RF AC input cycle.

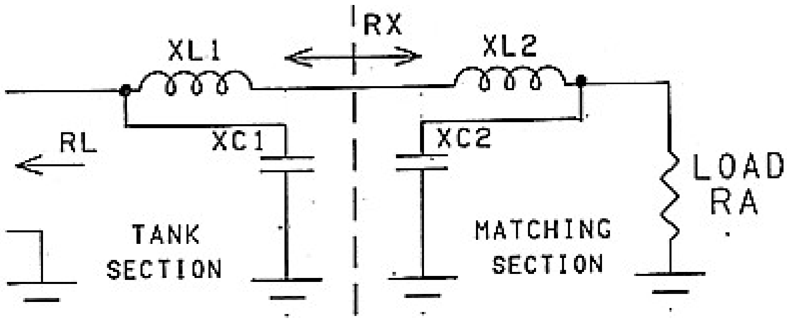
2. The DC Power Input (Pin), is calculated by the formula:
   a. Pin = Plate dissipation in watts ÷ η (% of efficiency)
      1. Plate dissipation in watts is obtained from the Tube Manufactures Data Sheet.
      2. η (% of efficiency) is determined by the Class of Operation. (listed above)

3. The Plate Current (Ip), is calculated by the formula:
   a. Ip = Pin ÷ Ep
      1. Plate Voltage (Ep) 'maximum', for the Tube's class of operation, is obtained from the Tube Manufactures Data Sheet.

4. The Class of Operation uses a 'K' factor for a specific Amplifier design which is:
   a. For Class A Operation it is (1.3 ~ 1.4)
   b. For Class AB Operation it is (1.5 ~ 1.7)
      1. For Class AB1 Operation it is (1.5)
      2. For Class AB2 Operation it is (1.6 ~ 1.7)
   c. For Class B Operation it is (1.8 ~ 1.9)
   d. For Class C Operation it is (2.0)

5. The Plate Load Resistance (R_L), is calculated by the formula:
   a. R_L = Ep ÷ K x Ip
      1. Plate Voltage (Ep) 'maximum' is obtained from the Tube Manufactures Data Sheet.

6. The first section of the 'Pi' configured 'Output Coupling Network', consists of the variable capacitor (C1) capacitive reactance (X_{C1}) and one half of the inductor (L1), and is considered to be the 'Parallel Inductive-Capacitive (LC) Tank Circuit', which sets the correct value of the loaded Quality ('Q'). To reflect the correct value of Load Resistance (R_L) to the amplifier output, a resistance value (R_x) must be presented at the tank circuit output.



('Pi' Configured Output Coupling Network - Split Into Two Sections For Analysis)

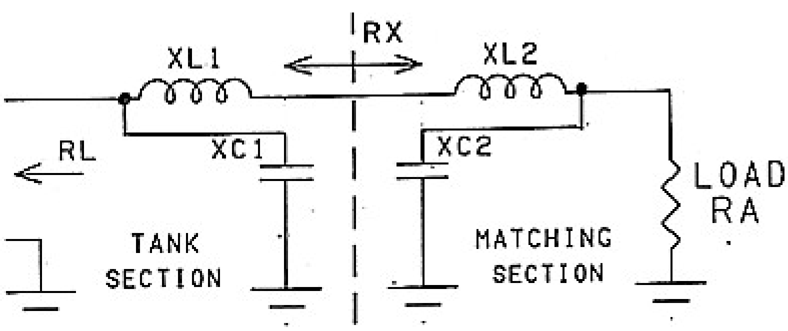
a. **The reactive component (X_{L1}) of the first section of L1, is calculated by the formula:**
    1. **$X_{L1} = R_L \div Q$ (using a optimum 'Q' of 12)**

b. **The reactive component (X_{C1}) of C1, is calculated by the formula:**
    1. **$X_{C1} = X_{L1}$**

c. **The output coupling Tank Circuit Quality (Q), is calculated by the formula:**
    1. **$Q = R_L \div X_{C1}$ or $Q = R_L \div X_{L1}$**

d. **The resistive component (R_x), is calculated by the formula:**
    1. **$R_x = R_L \div (Q^2 + 1)$**

7. **The <u>second section</u> of the 'Pi' configured 'Output Coupling Network', consists of the variable capacitor (C2) capacitive reactance (X_{C2}) and one half of the inductor (L1), and is considered to be the <u>'Parallel Inductive-Capacitive (LC) Tank Circuit'</u>, which matches the value of (R_x), which is normally lower than the characteristic impedance (R_a) of the RF Feed Line connected to the RF Power Amplifier (RFPA) output connector.**



('Pi' Configured Output Coupling Network - Split Into Two Sections For Analysis)

a. **The load characteristic impedance (R_a) is calculated by the formula:**
    1. **R_a = Value from Manufactures RF Feed Line data sheet (normally 50Ω)**

b. **The reactive component (X_{C2}) of C2, is calculated by the formula:**
    1. **$X_{C2} = \sqrt{[(R_x \times R_a^2) \div (R_a - R_x)]}$**

c. **The reactive component (X_{L2}) of the second section of L1 is calculated by the formula:**
    1. **$X_{L2} = (X_{C2} \times R_a^2) \div (R_a^2 + X_{C2}^2)$**

d. **The total reactance (X_L) of L1, is calculated by the formula:**
    1. **$X_L = X_{L1} + X_{L2}$**

8. **The 'Pi' configuration 'Plate' Variable Capacitor (C1), is calculated by the formula:**
    a. **$C1 = 1 \div (2 \times Pi \times f \times X_{C1})$**
        1. **(f) in the formula above should be approximately 500 KHz below the lowest frequency of operation.**

2. Example: for use starting on 160 Meters (1.800 ~ 2.000 MHz), use the frequency of '1.300 MHz' not '1.800 MHz'.

9. The 'Pi' configuration fixed (tapped) 'Inductor' (L1), is calculated by the formula:
   a. $L1 = X_L \div (2 \times Pi \times f)$
      1. (f) in the formula above should be approximately 500 KHz below the lowest frequency of operation.
      2. Example: for use starting on 160 Meters (1.800 ~ 2.000 MHz), use the frequency of '1.300 MHz' not '1.800 MHz'.

10. The 'Pi' configuration 'Load' Variable Capacitor (C2), is calculated by the formula:
   a. $C2 = 1 \div (2 \times Pi \times f \times X_{C2})$
      1. (f) in the formula above should be approximately 500 KHz below the lowest frequency of operation.
      2. Example: for use starting on 160 Meters (1.800 ~ 2.000 MHz), use the frequency of '1.300 MHz' not '1.800 MHz'.

A tuning method of a 'Pi' Output Coupling Networks is suggested as follows:

1. Set the variable Inductor ('L1') near its desired value (set for a suitable loaded 'Q'). If this Inductor is connected to a switch by taps, ensure that the appropriate frequency band is chosen to match the frequency output of the exciter.

2. Set the Load Capacitor ('C2') at about two-thirds (2/3) of its' maximum capacitance value (capacitor stator and rotator plates 2/3 meshed; i.e. setting '3.25' of '0 ~ 10').

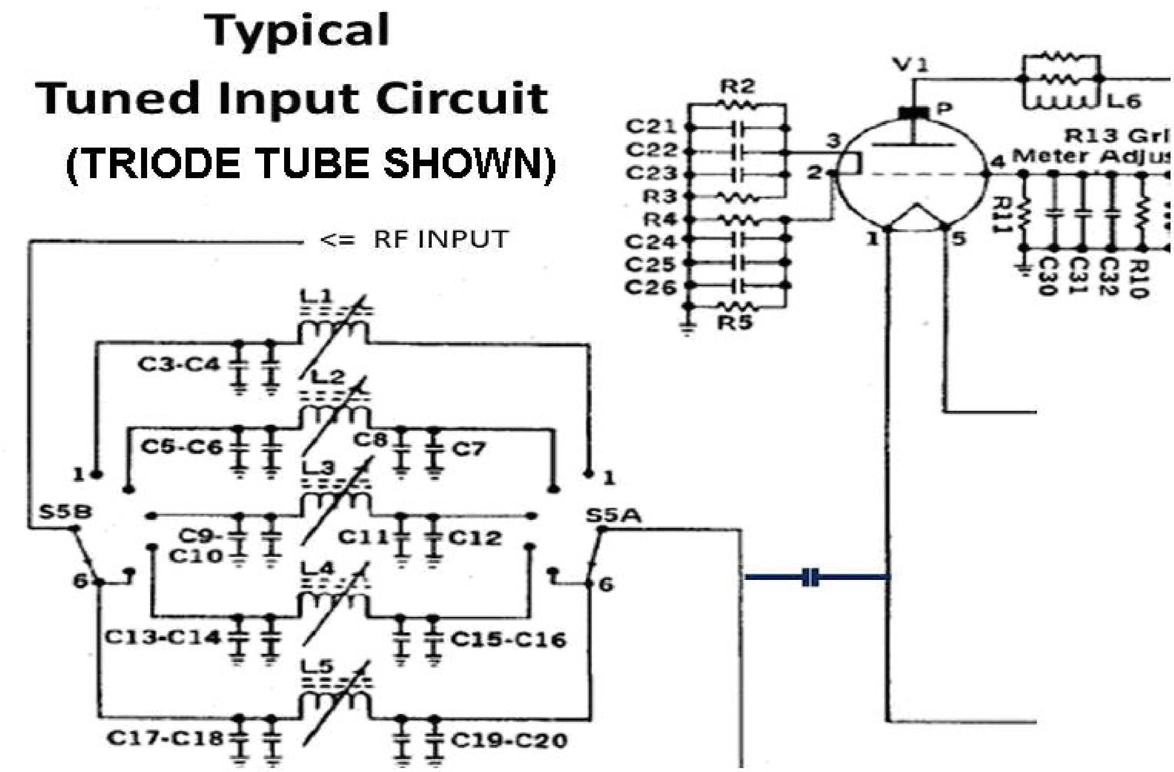
3. Resonate the Plate Tuning Capacitor ('C1') for maximum Output Power by alternatively rotating the capacitor clockwise and counterclockwise until the peak power is obtained.

4. Increase the Load Capacitor ('C2') gradually, by decreasing its' capacitance value (un-mesh the capacitor stator and rotator plates), until the rated Output Power is reached.

5. For each change of Load Capacitor ('C2'), reset resonance with Tuning Capacitor ('C1').

Designing a <u>'Input Tank Circuit'</u> For a Power Triode Electron Tube

Note: The same formulas used to develop the output 'Tank' are used to develop a input 'Tank'.



1. **Electron Tube RF Power Amplifiers (RFPA), using a Power Triode configured in Grounded Grid (GG) Cathode Driven (CD) configuration, do not normally have a Cathode Impedance (Z) that is 50Ω. Because of this an Impedance (Z) Matching Low Pass Filter (LPF) Network configured in a constant 'K', 'Pi' or 'L' is required.**

2. **RF Power Amplifier stages in modern Solid-State Amateur Radio Service Transceivers have a designed Fixed 50Ω Output 'Source' Impedance (Z) and a Fixed Input 'Load' Impedance (Z). This Fixed Impedance (Z) requires a 50Ω 'Load' Impedance (Z) in Transmit Mode and a 50Ω 'Source' Impedance (Z) in Receive Mode for a maximum transfer of RF Power.**

   a. **The RF Coaxial Cable Feed Line 50Ω Characteristic Impedance (Z), connected to the Transceivers RF output connector is the Transceivers first 'Load' Impedance (Z).**

   b. **Then the RF Coaxial Cable Feed Lines 50Ω Characteristic Impedance (Z) becomes the 'Source' Impedance (Z) for the RF Power Amplifier (RFPA) 'Pi' or 'L' configured Low Pass Filter (LPF) input Network 'Load' Impedance (Z).**

c. **The RF Power Amplifier RFPA 'Pi' or 'L' configured Low Pass Filter (LPF) input Network becomes the 'Source' Impedance (Z) for the RF Power Amplifier (RFPA) Electron Tube(s) Cathode 'Load' Impedance (Z).**

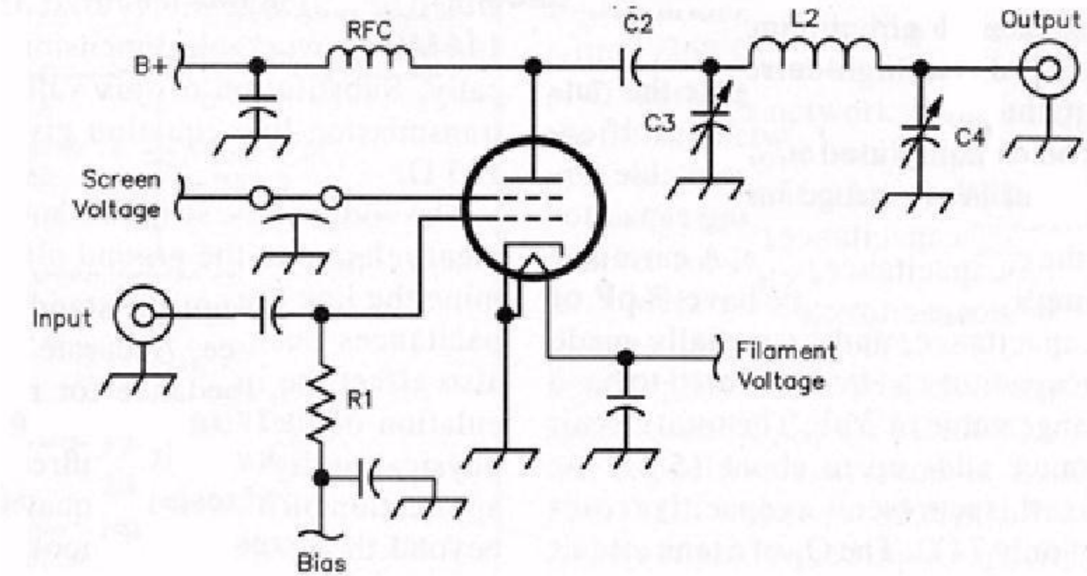
3. **The Tuned-Cathode input circuit coupled by a length of 50Ω Characteristic Impedance (Z) RF Coaxial Cable Feed Line from a Transmitter, is recommended to be designed with a 'Q' of between 'two' (2) and 'four' (4). A simple rule of thumb is that the network circuit capacitances at resonance should be about 20 pF per meter of wavelength for one-to-one impedance transformation.**

4. **Examples of some Power Triode Electron Tube Cathode input Impedance (Z) ohmic (Ω) values:**
   a. **3-500Z**
      i. **One tube = 115Ω**
      ii. **Two tubes in parallel = 57.5Ω**
      iii. **Three tubes in parallel = 38.3Ω**
      iv. **Four tubes in parallel = 28.8Ω**

   b. **572B**
      i. **One tube = 215Ω**
      ii. **Two tubes in parallel = 107.5Ω**
      iii. **Three tubes in parallel = 71.7Ω**
      iv. **Four tubes in parallel = 53.75Ω**

   c. **811A**
      i. **One tube = 320Ω**
      ii. **Two tubes in parallel = 160Ω**
      iii. **Three tubes in parallel = 106.7Ω**
      iv. **Four tubes in parallel = 80Ω**

Designing a <u>'Input Tank Circuit'</u> For a Power Tetrode and Pentode Electron Tube



Input impedance of a Grounded-Cathode (GC) amplifier is high, complex, and also non-linear (decreases at onset of grid current).

A Grid-swamping resistor(50Ω) swamps tube input resistance and reactance, and eliminates effect of input-impedance nonlinearity. As input circuit is broadband, It need not be bandswitched. (R1 is the Grid Swamping Resistor)

Class AB1 (no grid current) most common.

Grounded-cathode amplifier has simple 50Ω resistive input circuit. As input circuit is broadband, it always matches exciter correctly, and need not be bandswitched. Note that lack of tuned input network reduces harmonic suppression, and can allow high RF energy from VHF parasitic oscillations to damage exciter.