RF Power Amplifier (RFPA) Tune and Load Impedance Matching

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A RFPA using a Power 'Triode', 'Tetrode' or 'Pentode' Electron Tube operated in, Grounded-Grid (GG), Cathode Driven (CD) configuration, the single most important meter to indicate proper operation is the *'Control Grid Current Meter'*! *Control grid current* is far more important than anything else with the output power being second.

A RFPA using a Power 'Tetrode' Electron Tube operated in, Grounded-Cathode (GC), Grid Driven (GD) configuration, the single most important meter to indicate proper operation is the *'Screen Grid Current Meter'*! *Screen grid current* is far more important than anything else with control grid current second and the output power being third.

A RFPA using a Power 'Pentode' Electron Tube operated in, Grounded-Cathode (GC), Grid Driven (GD) configuration, the *single most important meter* to indicate proper operation is the *'Screen Grid Current Meter'*! *Screen grid current* is far more important than anything else with control grid current second and the output power being third.

Note: If you have little or no experience tuning an RF Power Amplifier using the Control Grid (CG) current meter for a Triode or the Screen Grid (SG) current meter for a Tetrode and Pentode, you should use an RF Power Meter (RF Wattmeter) to ensure proper tuning.

Basic Operational Theory

A RFPA using an Electron Tube, has a certain optimum available voltage swing, and it has limited current available. It is important that the load impedance (Z_L) presented to the Electron tube's output matches the optimum values of available RF voltage and current.

When the manual controls of a Tank Circuit are adjusted in a RF Power Amplifier (RFPA), they are set or adjusted so the Source Impedance (Zs) is matched to the Load Impedance (Z_L) present at the output. *There is a 'Pi' configured Low Pass Filter (LPF) Tank Circuit Network consisting of a combination of three components. First there is a Capacitor, 'C1' shunted to ground after the Tube Plate. Second there is an inductor, 'L1' in series with the Tube Plate after the shunted 'C1'. Third there is a Capacitor 'C2' shunted to ground after the series 'L1' and before the Amplifier output 50 Ohm connector.*

1. *First Tune 'C1' and adjust it to match the Tube Plate Source Impedance (Zs) to the 'C1' / 'L1' combination Load Impedance (Z_L).*

2. *Second Tune 'C2' and adjust it to match the 'L1' / 'C2' combination Source Impedance (Zs) to the connected Coaxial Cable 50 Ohm Characteristic Load Impedance (Z_L).*

3. In the 'Classical AC Generator', the condition required for a maximum absorption of power delivered to a Load from a Source, is that the Load Impedance (Z_L) equal the Source Impedance (Zs) of the AC Generator. This condition is called a 'conjugate match'.

    a. The term '*conjugate match*' means that if in one direction from a junction the impedance (Z) is R + jX, then in the opposite direction the impedance (Z) is R – jX.

4. There is a crucial difference between a 'Classical AC Generator' and the Output Coupling 'Tank' Circuit of a real-word RF Power Amplifier (RFPA). Because of the complex nature of various relationships between voltages and currents in an RFPA, during normal operation the internal Source Impedance (Zs) of the amplifier, is almost never equal to its optimum Load Impedance (Z_L).

    a. Therefore because of the different values of impedance existing between the source and the load when we complete a matching operation, we do not have a true 'Conjugate Match'. when an RFPA is coupled to a IMN and then to an Antenna RF Feed Line, the IMN is matched to the optimum Load Impedance (Z_L) of the RFPA, but it is conjugately mismatched to the Source Impedance (Zs).

There are two destructive things, ***'Heat'*** *and* ***'Arcing'***, that can happen when you **mistune an RF Power Amplifier**. **Heat** is always a ***time function*** that depends on the thermal mass of the thing being heated and how much heat is being applied. **Arcing** is an ***instantaneous problem***. *Arcing can destroy things in fractions of a second!* **Here's what happens when we tune**:

1. **'*Over-Coupled'*** means that there is ***'Too Little' Loading Capacitance'* (Capacitor is *'To far 'Un-meshed')*** which causes ***'To Low a Load Impedance',*** to be presented to the Electron Tube. This will cause the ***current to be 'Excessive' and the 'Efficiency' suffers.***

    a. **This can cause 'Heat'.** Heat is a long-term problem that takes a finite time to cause damage. It is generally NOT instantaneous damage, although a tubes Anode can be overheated to the point of damage in a matter of 15 - 30 seconds in some cases.

    b. **One good thing about over-coupling is screen or control grid current is reduced**, and this protects the most sensitive and easily damaged parts of Electron tubes. Another advantage in a tube RFPA is **linearity generally is a bit better with slight over-coupling. There is slightly less buckshot/splatter and distortion**.

2. ***'Under-Coupled'*** means that there is ***'Too Much' loading capacitance' (Capacitor is 'To Far 'Meshed')*** which causes ***'To High a Load Impedance',*** to be presented to the Electron Tube. This will cause the ***current to be 'Reduced' and the 'Voltage' will be too High.***

    a. **This can cause 'Arcing'.** Voltage breakdown of components are possible and It is the worse case scenario because severe damage can be instantly caused and damage can be instantaneous even with very slight over-voltage.

    b. Under-coupling, or having the loading capacitor closed too far meshed for the load impedance and/or drive power, increases grid current and buckshot/ splatter and distortion. **It creates a very hard form of non-linearity where the device switches into non-linearity very quickly, and the sharp transition into non-linearity or gain reduction creates a very wide bandwidth splatter**.

    c. Efficiency is normally very good; heat is reduced or remains in a normal range for the level of output power produced. Voltage can increase well above the supply voltage limits, up to several times the DC supply voltage in extreme cases. Worse yet, once an arc starts, it causes a dielectric failure. The dielectric failure destroys insulation, creates sharp points or surface irregularities that reduce voltage breakdown, or the arc ionizes air or creates a plasma. All of this works to sustain the arc even after voltage is reduced to safe levels.

3. **If there is any coupling error it should be slightly over-coupled (capacitor unmeshed) in the RFPA output device. It is better to see a little too much Anode, current than too much voltage at a reduced supply current**. ***We also do not want excessive grid current in Electron tubes.***

4. **For the above reasons, almost all "pre-tuned" Solid State RF Power Amplifiers are over-coupled to the load.** They are actually optimized for a higher than normal load impedance by slightly over-coupling the output devices to the load.

Signs of Under-Coupling

When the output load capacitor is too far meshed which is too much capacitance, especially at high drive power levels the amplifier will be under-coupled. ***Under-coupling is the very worse thing to do to any amplifier because failures can occur in a matter of seconds! There are several signs of under-coupling*** in a Grounded-Grid (GG), Cathode Driven (CD) Triode, Tetrode and Pentode RF Power Amplifier, or a Grounded-Cathode (GC), Grid-Driven (GD) Tetrode and Pentode RF Power Amplifier. Watch for the following closely:

1. When the drive power, using a steady carrier, is slowly increased, the grid current (either control grid or screen grid) will at some drive level suddenly rapidly increase. The sudden rapid grid current increase will be disproportionate to the Anode current or drive power increase!

2. *DO NOT* go past the point where grid current starts to rapidly increase with small changes in drive power level.

3. Be especially watchful of disproportionately high grid currents compared to Anode currents or drive power, or a rapid increase in grid current with a modest increase in drive power. Too much grid current is a clear sign you have the loading control too far meshed or closed.

Improper and Proper Loading of Amplifier and the Most Common Tuning Errors

1. ***The most common amplifier tuning and loading error is adjusting an amplifier at a low or reduced exciter drive power as the final amplifier-tuning step***.

    a. ***ALWAYS load and tune an RF Power Amplifier 'Tank Circuit' using the maximum exciter drive power that the RF Power Amplifier can safely handle on it's input*.**

    b. Then was it is tuned appropriately, reduce the exciter drive to rated, safe, or desired operating power levels!

        i. This ensures minimum voltage and current in the 'Tank Circuit' and maximum possible linearity (best signal quality).

2. ***NEVER load, tune, peak, or dip an RF Power Amplifier at a reduced exciter drive power, and then attempt to operate or attempt to suddenly apply full drive power!***

    a. ***When a 'Tank Circuit' is loaded and tuned at a reduced exciter drive level, we are establishing that power level as the absolute ceiling for the drive and output power.***

    b. Final loading at reduced exciter drive, results in the loading control too far meshed. This will cause severe under coupling! This can cause arcing, splatter, and excessive grid current.

3. ***Ideally (if possible) we should make the final tuning and loading adjustments at or near maximum exciter drive power***.

    a. **Load the amplifier to maximum obtainable output at full transmitter drive without exceeding amplifier short term overload ratings.**

    b. **After that, advance the loading control very slightly beyond that point (towards less capacitance).**

    c. At least with the loading control too far open, you will not cause an arc, blow out of a band switch, or damage a tube grid. You have slightly more time for mistakes and corrections when the loading capacitor is too far open, than too far closed.

    d. If you are going to make a mistake, make the mistake by having the loading control too far open or unmeshed, not too far closed or meshed!

4. **High grid current is a strong indicator of excessively light loading in amplifiers, which is almost always a sign of a loading control that is too far meshed or closed for the amount of drive power. This is hard to see on SSBSC-AM, and best viewed on CW.**

5. **It is assumed your transmitter's RF Power Amplifier stages output power does not exceed the input drive power limits of your amplifier. If your transmitter has significantly more drive power output than your amplifier can accept, you should turn down the RF drive control if there is one or add an attenuator between the exciter output and the amplifier input to reduce the drive.**

6. There is very little difference between excessive drive power, antenna system faults or failures, or grossly improper adjustment of loading. All can be equally bad and are equally harmful to component life. Improper tank adjustment, antenna system failures, and excessive drive either creates splatter (and in extreme cases cause key clicks) on adjacent frequencies, or they cause excessive heat in the output devices or components in the system. Regardless of the reason for them, amplifiers are damaged by excessive **tank voltages** or **device currents** caused by improper adjustments that prevent proper energy transfer to a load. In some cases, particularly on the lower end of the lowest frequency bands, proper loading cannot be achieved.

7. Some amplifiers drive too easy, so we should always pay attention to factory instructions and avoid exceeding factory amplifier tuning current limits, especially for control and screen grids. Grid current is especially important to watch because grids often do not have sufficient thermal mass to absorb large overloads even for short time periods. Excessive grid current in metal oxide cathode tubes (ceramic tubes with indirectly heated filaments) like the 3CX800A7 and 3CX1500A7/8877 can damage tubes in less than a few seconds; whereas most Anodes will tolerate severe overloads for 15 seconds and longer. It is better to let the large Anode in a tube take the brunt of any mistuning heat, which means with any mistake it will be better to over-couple or have the load control capacitance slightly lower than optimum.

SWR or Reflected Power Myth:

It is claimed that reflected power burns up as heat in the RF Power Amplifier stage. This is not true at all.

The only effect reflected power has is it changes the loadline of the output device. This can either increase PA device RF voltage swing, or it can increase PA device current. If the voltage increases heat generally is reduced, but the PA can arc. If the load mismatch is of a phase angle that increases current, PA device heating increases because conduction angle and peak current increases.

In one case heat increases, in the other heat decreases. ***An SWR mismatch only requires the matching network be readjusted to restore the proper loadline at the output device*****.** In an adjustable Pi or Pi-L Network system the only effect of SWR is in current in the inductor(s) and voltage across the loading capacitor, so long as the network can be adjusted to properly load the output device. In other words if you can retune the network and don't exceed voltage breakdown of the loading capacitor, your amplifier is very likely OK for any SWR.

Exciter Transients or ALC Power Overshoot

Many transmitters have ALC-overshoot issues. The ALC or power overshoot problem worsens as output power is reduced below maximum. There are exceptions and some transmitters have a drive control and a power control that functions in all modes. Backing the drive control off so ALC is barely registering assures there is no ALC power overshoot. On the other hand some transmitters, no matter how they are adjusted, will overshoot beyond the factory rated power levels. These transmitters can trigger arcs in amplifiers and are generally rough on components.

Maximum available carrier drive power might not result in sufficient drive for tuning. This is especially true when an exciter has transients or power overshoot from marginal ALC response.

Transients or overshoot appear on the leading edge of the RF envelope, on the leading edge of speech or CW transmissions. ***This is the time when the transmitter is going from zero power towards full power. Since the ALC circuit has no stored voltage at this moment, the exciter runs full throttle for an instant.*** **Most power meters miss this effect. Once the ALC comes up, the hang time of the ALC will hold the exciter gain back. Transients and/or overshoot will generally disappear.**

Transients and overshoot, being of short duration and infrequently occurring, make it impossible to tune correctly at maximum drive. With transients or ALC overshoot, it is impossible to tune your amplifier properly by simply tuning for maximum output with a carrier, a tuning-pulser, a whistle, or normal speech. We cannot just tune for maximum output and expect the amplifier to be properly loaded when the exciter has leading edge ALC transients!

Let's assume the exciter is rated to deliver 100 watts, but has momentary peaks or transients of 160 watts while the ALC or power control loop "takes hold". Power surges of 160 watts, too short to register on normal power meters, occur at the start of every transmission. Of course, if we don't run the exciter wide open and reduce power to 50 watts the problem actually gets ***worse***! In this example the transient peak would still reach nearly to the same 160 watts, but the amplifier would be tuned for 50 watts drive! This is bad news for splatter and for components in the amplifier.

This is why the maximum power setting of the exciter should generally be used while tuning. If the exciter has far too much drive for the amplifier, we need an attenuator or an amplifier better matched to the exciter.

The loading control should always be advanced a reasonable amount further open then the actual maximum output power setting. This will allow the amplifier tank system to handle transients without arcing or component failure.

Easy Drive RF Power Amplifiers

Some hobbyists and manufacturers specify a "very low drive" as an advantage, claiming it offers "cleaner signals". Nothing is further from the truth.

Exciters almost always provide the best IMD performance when operated at a time-averaged peak power, a reasonable amount below full output, rather than very low levels. At low power levels, exciter performance is dominated by crossover distortion. This is where bias non-linearity or device input threshold induces distortion. The ALC system also adds cutoff bias to early stages. This bias increases distortion in ALC controlled stages. At very high levels, gain compression or negative bias shift becomes an issue. Exciters typically do best when operated in the area of 60-80% of rated power.

Worse yet, low drive amplifiers are especially susceptible to damage from exciter overshoot or transient problems. Transients and overshoot peak power remains almost the same level regardless of exciter power control settings. As exciter operating power levels are reduced, the percent of power overshoot becomes worse.

The most undesirable situations are those where exciter power greatly exceeds (by more than twice) an amplifier's normal drive power limit. Not only does this reduce system IMD performance, amplifier drive transients are aggravated. Amplifiers should be designed or selected to match the exciter's maximum power output, or an external attenuator used to bring the amplifier's drive requirement up to the exciter's full power level.

Amplifiers Without Enough Loading Capacitance

Some amplifiers do not have enough Plate tuning and/or Load Coupling capacitance. The Plate Tuning or Load Coupling controls are all the way at maximum (capacitor fully meshed) for maximum output power, making it impossible to "peak" the output. Opening the Load (Antenna) Coupling capacitor up more just reduces the output power, no matter what the drive level. **This is over-coupling that cannot be corrected**. **Several things can cause it**:

1. **The loading capacitance is inadequate through bad or improper design**. This is common on the lower end of the lower bands in some amplifiers. For example the Kenwood TL-922 and TL-922A (which works better in the old Japanese segment of 160 meters, above 1900 kHz). Other amplifiers that have poor tuning range on 160 and 80 meters are the original Ameritron AL-80, the Dentron Clipperton-L, and several Amp Supply amplifiers.

    a. **The solution to correct this type of problem is to add more capacitance in parallel with the ‘Plate Tune’ and/or ‘Load Coupling’ Air Variable or Vacuum Variable Capacitors to extend their range.**
    b. **Use ‘door-knob’ style "padding" capacitors of appropriate voltage rating to do this.**

2. The output power level you are tuning at is lower than the design target. **As power is decreased, the maximum-power-output loading capacitance setting always increases**. In other words as drive is reduced and we re-tune, the output power "peaks" with more and more loading capacitance.

3. **A padding capacitor has opened up or does not have sufficient capacitance on lower bands.**

4. **A tank inductor has shorted between turns or does not have enough turns.** (Common in Dentron amplifiers on lower bands, where loaded Q is often 20 or more.)

5. Antenna system impedance at the amplifier is too low, or is slightly inductive rather than being resistive or capacitive.