

Neutralization Circuit of 28 MHz RHIC Amplifier

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SUMMARY

It is desirable to increase the power gain of the 28 MHz RHIC power amplifier in order to reduce the required output of the QEI driver. Since the input power consumption of the 4CX150,000E tube circuit is negligible, the main power drain is the 200 ohm loading resistor in the amplifiers input circuit. The purpose of this resistor is to reduce the likelihood of oscillation due to the negative input impedance introduced by the tube internal feedback capacitance (plate to grid). Neutralization is used to overcome this effect. The neutralization circuit will be examined to see if increasing the input loading resistor is feasible.

1.0 Tube Equivalent Circuit

The equivalent circuit for the grounded cathode circuit is given in fig. 2. The input, output and feedback capacitances are taken from the Eimac data sheet.

The plate output loading resistor was determined to be 1500 ohms. See Appendix 1. The inductance of 0.5 nano henrys, was determined by the relationship between load resistance and circuit "Q".

The output circuit used in the simulation was a generator gain of -120 with a source resistance of 1500 ohms. The circuit of figure 2 ignores all filtering circuits in the amplifier

2.0 Negative resistance and neutralization

Due to the tube feedback capacitance there is a possibility of negative resistance looking into the amplifier (See Appendix 2) The miller effect input capacitance is

given by:

$$C_{IN} = C_{GC} + C_{GP} (1 + A \cos \theta)$$

Where C_{GC} = grid to cathode cap., θ = plate load angle and for inductive load

C_{GP} = feedback capacitance

The real part of the unloaded input admittance is given by:

$$\frac{1}{R_{IN}} = \omega C_{GP} (-A \sin \theta)$$

For our case the unload resistance is

$$\frac{Y}{R_{IN}} \cong (2\pi \times 3 \times 10^7)(1 \times 10^{-12})(60)$$

\therefore Or $R_{in} = -88.5$ ohm (note in parallel with 200 ohms)

Since the loading reaction of 200 ohms exceeds this value the designers put in neutralization.

3.0 Neutralization Circuit

The purpose of neutralization is to feedback a current equal and opposite the current due to the tube internal feedback capacitance.

Coaxial lines are configured to feedback this current from a variable capacitor in the output circuit. The signal from the capacitor is feedback via a 50 ohm transmission line. Its center conductor is effectively shorted to a ground plane. Its outer conductor is open however, forcing a current in the shield of the outer conductor. See Figure 3. Thus a second TEM type transmission line in the form of a single wire to ground plan is formed. Midway along this line it is taped into the grid. It then continues to be shorted to the ground plane. Note the shield

of the 50 ohm line is now the effective center conductor of the new transmission line, so there is a 180° reversal seen by the current flowing. This is shown in figure 3B.

T3 forms the inductance to resonator out the input capacitance of the grid T2 delivers the neutralization current to the grid and provides the phase reversal to buck out the tube capacitance current.

A further modification was not to connect the center conductor of the 50 ohm line to the ground plane, but to use a series resonant circuit shunted by a 50 ohm resistor and then connect to the ground plane. This was done to disable the neutralization circuit when off resonance and thus avoid any off frequency responses that the neutralization circuit might introduce.

The length and impedance of the single wire ground plane TEM lines had to be found. Since the tap point to ground appeared to be half way along the length of the shield, Z_0 and the length of T2 and T3 were made equal. Initial value of Z_0 and length were approximated (See Appendix 3).

In the initial PSPICE simulation both feedback capacitors were omitted as well as the T1 and T2. T3 was included and its length and characteristic impedance were adjusted for resonance on the input circuit.

The resulting values were Z_0 equal to 166 ohm with a delay of 0.37 nano seconds.

The fine-tuning of resonance simulated the variable capacitor used in the actual circuit. The result was:

$$370 + 150 = 510 \text{ picofarads}$$

$$\text{range of variable cap } C_{18} = 10 - 1000 \text{ pF}$$

4.0 Simulation

4.1 Effect of tube feedback capacitance

The tube feedback capacitance was added to the PSPICE circuit. The input capacitance was trimmed (line Jennings) for matching input and output resonances.

From figure 4 the effect of the feedback is seen by the glitch in the low Q input circuit. Note the phase of the glitch. The input voltage initially rises and then falls, eventually returning to its normal high bandwidth resonant response.

At this point the input impedance was measured and there was no indication of negative resistance. The input resistor had to be increased from a loading of 200 ohm to over 5000 ohms. The simulated input generator source resistance was also increased from 200 to over 5000 ohms.

4.2 Effect of Neutralization Circuit

The tube feedback capacitor was replaced by the neutralization circuit. The initial capacitance that was used was equal to C_{PG} since its impedances is much lower than the input impedance. It acts, as a fixed current source thus the neutralization capacitance should have a similar value.

The results are shown in figure 6. Again the input capacitance was trimmed to match the input and output resonances.

NOTE: the results are similar but with a 180° shift.

4.3 Adding series resonator, shunt 50 ohm

Without the series resonator there is a single response on the input at around 130 MHz. This changed with various choices of Z_o /line length. There were no off resonances when the 50 ohm resistor was added.

5.0 Conclusion

A workable PSPICE model has been created which should help in the testing phase of the RHIC

amplifier. Tuning of the feedback for neutralization should be eased by knowing the expected input response curves (phase reversal for over neutralized current).

It does not appear that the series resonances device may be of some help in eliminating high frequency responses, but in our simulator these responses were not seen on the output. Since this simulation doesn't depict the true circuit condition, driving source impedance and output loading, it is hard to make a strong case for the true need of the circuit.

It is encouraging to note that there is a good likelihood that the input impedance may be increased and thus improve amplifier gain. A new input matching transformer would be required to achieve this increased gain.

Again the simulation does not duplicate circuit conditions. From the simulation it was not apparent that the circuit would oscillate.

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Appendix 1 – Determine output-loading resistance

A1A. From reference 1 Table 1

$$P_{ADC} = 131.4 \text{ Kilowatts, DC plate power}$$

$$P_{OUT} = 85 \text{ Kilowatts, RF output power}$$

$$I_{DC} = 7.3 \text{ amp, DC plate current}$$

$$I_{A1} = 10.64 \text{ amp, RF fundamental current}$$

From pg 272 reference 2 assuming class B operation

$$I_{PK} = I_{DC} (\pi) = (7.3) (3.1416) = 22.9 \text{ amp}$$

$$I_{A1} = 0.5 I_{PK} = 11.45$$

$$I_{PK} = \text{peak value of half sine wave}$$

This is in disagreement with Ref 1 namely 10.64 amp. We assume class B operation and use

10.64 amp to find I_{DC}

$$I_{DC} = \frac{2(10.64)}{\pi} = 6.8 \text{ amps instead of 7.3 amp.}$$

These currents are close so a value of 10.64 amps is used

$$V_1 = \text{voltage seving} = \frac{2P_{out}}{I_{a1}} = 16 \text{ K volts}$$

Thus plate swings from 18 to 2 kilovolts

$$R_{out} = \frac{V_1}{I_{a1}} = \frac{1600}{10.64} = 1500 \text{ ohm}$$

A1B Plate resistance from tube curve.

Another way to determine the output load is to use the tube curves.

Given a plate seving of 16 kilovolts and a peak current of 21.5 amps the corresponding seving of grid voltage was found to be 260 volts from the EIMAC tube curves.

Using the assumed class B half sine grid current and the load line the values of plate

current for 15 degree increments changes from 0 to 180 degrees grid current, can be determine. Using the formula given on page 28 of reference 3 and page 274 of reference 2 of the values of fundamental current and DC current can be found. This formula uses fourier analysis to determine plat current. EIMAC provides a calculator to determine coefficients (pg 21).

Our results were a d c current of 6.2 amps and fundamental current of 10.1 amps.

From this the plate resistance was determined to be 1584 ohms. Using the grid voltage swing of 260 volts (380-120) the gain was given as 61.5.

We used a plate load resistance of 1500 ohms with a source impedance of 1500 ohms. The equivalent generator used was 120 Eg (2x gain).

See figure

Appendix 2 Negative resistance

The determination of negative resistance is found on page 233 Ref 4. The first step is to find the current feedback.

The voltage across the feedback capacitor is simple the input voltage + minus the output voltage

$$V_{CAP} = E_g - E_p (\theta + 180^\circ)$$

Where θ is load angle (+ if inductive)

$$I_g = j\omega C_{GC} E_{in} + j\omega C_{GP} [E_g - E_p (\theta + 180^\circ)]$$

$$\begin{aligned} Y_{in} &= \frac{I_g}{E_s} = j\omega C_{GC} + j\omega C_{GP} [1 - \frac{E_p}{E_s} (\theta + 180^\circ)] \\ &= j\omega C_{GC} + j\omega C_{GP} [1 + A \cos \theta + \sin \theta] \end{aligned}$$

Where A is gain

Separating real and imaginary

$$\text{Imag} [Y_{in}] = \omega C_{GC} + \omega C_{GP} [1 + A \cos \theta]$$

Thus

$$\text{Input } C = C_{GC} + C_{GP} [1 + A \cos \theta]$$

$$\text{Input } R = \frac{1}{Y_{real}} = - \frac{1}{\omega C_{GP} A \sin \theta}$$

Appendix 3 Approximate Z_o + length

From pg. 49 of reference 5

$$L = 5 \times 10^{-3} \ell \left[2.3 \log \frac{4\ell}{d} - 1 \right] \text{ micro henrys}$$

Where ℓ is length and d is diameter in inches.

For $\ell = 4.5$ in and $d = 0.25$ inches $L \cong 75$ nano henrys (73 nano henrys in Ref 1)

Time delay

$$\text{TIME} = \frac{1}{28 \text{ MHz}} = 3570 \text{ pico seconds or about } 4.19 \text{ inches}$$

From page 590 reference 6

$$Z_o = \frac{138}{\sqrt{\epsilon}} \log_{10} \frac{4h}{d} \quad \epsilon \equiv \text{relative dielectric constant}$$

$$\text{Let } h = 1" \quad d = 0.25 \quad h = \text{height above ground}$$

$$Z_o = 166 \text{ ohms} \quad d = \text{diameter}$$

Set at 550 pico farads ($180 + 370$)

$$X_L = (2 \pi (2.8 \times 10^6)(73 \times 10^{-9})) = 12.85 \text{ ohms}$$

For delay $\cong 35 \text{ E-11}$ have $\lambda \cong .01$ normalized wave

From Smith chart this is .08 ohms

$$L = (.08) (166) = 13.2 \text{ ohms which is close}$$

