A Dynamic Measurement Method for Determining the Output Impedance of an RF Power Amplifier

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***Abstract* ─** Described herein is a novel approach for measuring the output impedance of a radio frequency (RF) power amplifier under actual operating (dynamic) conditions. The procedure involves loading the amplifier with three different values of resistance which are close to the intended load resistance value. Three separate experiments yield load excitation voltages (or powers) which permit direct calculation of the source complex impedance. The precision of determining the source impedance of the amplifier under test is only limited by the known tolerance of load resistance values used and the accuracy of measurements taken. The most important attribute of the technique described is that no requirement exists to alter the operating frequency. Also, the technique is applicable at microwave frequencies.

***Index Terms* ─** Equivalent circuits, impedance measurement, power amplifiers, radio frequency amplifier.

I. INTRODUCTION

A need exists to determine the complex output impedance of an RF power amplifier. The excellent article by Abramovitz [1] gives possible amplifier topologies with predictions of input and output impedances but provides no guidance on experimentally measuring impedances. Other authors [2] describe impedance matching networks for optimizing power transfer and efficiency but do not directly measure the amplifier output impedance. Factually, this reference [2] notes significant discrepancies between simulation and laboratory measurements. Within the microwave bands load pull techniques can characterize amplifier output impedances. Recent articles using slide screw tuners indirectly characterize amplifier output impedance via calculations from reflection coefficients [3]. This method is totally impractical at low frequencies. Such a situation exists for a power supply voltage regulator of the feedback amplifier design. Voltage regulation is a low frequency phenomenon and the output of the regulator may exhibit undesirably high impedance at high frequencies. Serrano-Finetti [4] has suggested varying the regulator load sinusoidally to characterize the system output impedance. This approach addresses only low frequency characteristics.

Classical discussions on amplifier output impedance focus on maximum power transfer [5-7] or suggest measurement methods confined to VHF and frequencies beyond [8]. The study which follows suggests a practical method for characterization of amplifier output impedance. Though experimental results are discussed at VHF, the proposed method is applicable at microwave frequencies as well. A detailed error analysis of the method is also provided.

II. DISCUSSION

Amplifiers may be of narrowband (resonant) or wideband design. A narrowband design will change output power as the operating frequency is altered necessitating “retuning.” By definition, however, a wideband design will not exhibit power output changes with respect to operating frequency changes. In either case, the following measurement procedures and calculations are applicable. Thus, the amplifier’s source impedance can be determined at one frequency or many

Submitted On: Sept. 2, 2011
Accepted On: March 3, 2012

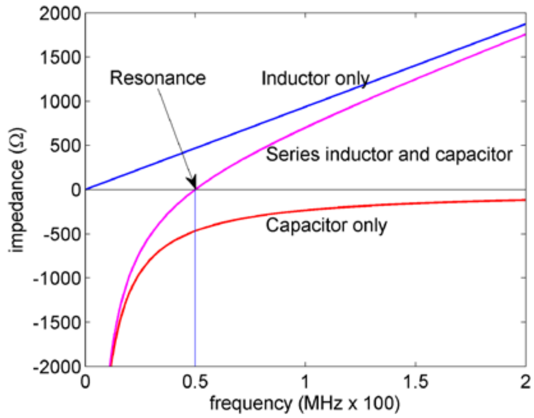

Fig. 1. Series LC reactance vs. frequency.

frequency points. Also, proper modeling allows the technique to be extended through microwave frequencies.

At any single operating frequency the output impedance of an amplifier may be modeled as a Thevenin equivalent circuit: An ideal voltage generator in electrical series with impedance (Z). [6, 9] This impedance, in general, can be complex: that is, $Z=R+jX$ where R is the real (in phase) or resistive component and X is the imaginary (quadrature) or reactive component. Measuring the voltage which appears across a resistor placed at the amplifier output reveals nothing with regard to the amplifier's impedance. However, noting the voltage across a single load does establish a baseline for all measurements to follow. Since Z is complex and possesses two parts (real and imaginary) a minimum of two more experiments (measurements) must be conducted to determine the magnitudes of R and X. For a stable amplifier R will always be positive. However, X may be either negative (capacitively reactive) or positive (inductively reactive). To mitigate the ambiguity of capacitive reactance and inductive reactance a modified version of the baseline measurement will be performed.

The imaginary part of the impedance may be a consequence of multiple reactances of the two different types (capacitive and inductive). Moreover, as system operating frequency is changed the magnitude of impedance may very well vary between peaks and troughs. Temes and LaPatra give an excellent discussion of possible one port impedance characteristics [10].

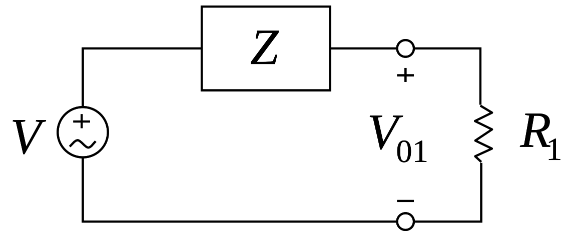

Fig. 2. Thevenin amplifier output model with attached load (R_1).

Irrespective of circuit sophistication, consider an operating amplifier delivering non-zero power to an arbitrary load at a single frequency. The output impedance of this amplifier may be modeled by one of the following: 1) a pure resistance, 2) a resistance in electrical series with an "equivalent" capacitive reactance, or 3) a resistance in electrical series with an "equivalent" inductive reactance. As a numerical illustration consider a 1.49 microHenry inductor in electrical series with a 6.8 picoFarad capacitor. Fig. 1 plots the reactance of the inductor by itself, the reactance of the series combination and the reactance of the capacitor by itself. A plot could also be developed for a parallel connection. However, for the plot presented note that resonance occurs at f=50.0 MHz. Below this frequency the LC combination is capacitively reactive and above this frequency it is inductively reactive. It is only at extreme frequency values (high and low) that the composite LC reactance curve is asymptotic to the individual components reactance curves. In the analysis which follows it is assumed that the system under investigation is linear and time invariant. Further, if the amplifier incorporates a form of automatic gain control (or output leveling) this must be disabled.

III. ANALYSIS

Refer to Fig. 2 which models the amplifier output as a Thevenin equivalent circuit (V in series with Z) with load R_1 connected. The voltage V_{01} is noted across R_1. The load resistance is then changed to a new and different value (R_2). In a similar fashion the voltage drop across this new value of load resistance is noted (V_{02}). Proceeding to a load resistance different from the values of R_1 or R_2 a new load (R_3) is connected to the amplifier. Again, the voltage drop (V_{03}) is noted across R_3. The ordering of resistance values for R_1, R_2 and R_3 (low, medium and high) is unimportant. However, best measurement accuracy is obtained by the widest possible spread of load resistance values. From a practical standpoint, properly designed amplifiers will easily withstand VSWR values of 2.0 or below. Thus, if the intended load is R_0 then other test loads selected might be on the order of 0.5 R_0 and 2.0 R_0. Some test configurations may utilize an instrument which measures power to a load resistance. Laboratory tests performed in the development of this paper used a BIRD model 43 in-line wattmeter. The instrument is useful up to frequencies of 2.3 GHz. At higher frequencies it is possible to develop precision loads monitored by a bolometer. This technique remains to be accomplished. Wideband load resistors used for this investigation were verified via a Hewlett Packard 8510C network analyzer.

In such cases where power to a load resistor is measured, the R.M.S. voltage across the load may be directly calculated by:

$$V_{01}=\sqrt{P_{01}R_1},\ V_{02}=\sqrt{P_{02}R_2},\ V_{03}=\sqrt{P_{03}R_3}.$$

Noting that $Z=R+jX$ we formulate the following:

$$V_{01}=\frac{VR_1}{\sqrt{\left(R+R_1\right)^2+X^2}}\ , \tag{1}$$

$$\left(\frac{VR_1}{V_{01}}\right)^2=\left(R+R_1\right)^2+X^2\ . \tag{2a}$$

Similarly

$$\left(\frac{VR_2}{V_{02}}\right)^2=\left(R+R_2\right)^2+X^2\ , \tag{2b}$$

and

$$\left(\frac{VR_3}{V_{03}}\right)^2=\left(R+R_3\right)^2+X^2\ . \tag{2c}$$

The ratio of these equations is formulated:

$$K_1=\left(\frac{R_1}{V_{01}}\right)^2\left(\frac{V_{02}}{R_2}\right)^2=\frac{\left(R+R_1\right)^2+X^2}{\left(R+R_2\right)^2+X^2}, \tag{3}$$

and

$$K_2=\left(\frac{R_1}{V_{01}}\right)^2\left(\frac{V_{03}}{R_3}\right)^2=\frac{\left(R+R_1\right)^2+X^2}{\left(R+R_3\right)^2+X^2}\ . \tag{4}$$

Equations (3) and (4) may be combined to eliminate X:

$$\begin{aligned}&\left(K_1-K_1K_2\right)\left(R+R_2\right)^2\\&+\left(K_1K_2-K_2\right)\left(R+R_3\right)^2\\&+\left(K_2-K_1\right)\left(R+R_1\right)^2=0.\end{aligned} \tag{5}$$

Let

$$\left(K_2-K_1\right)=A\ , \tag{6}$$

$$\left(K_1-K_1K_2\right)=B\ , \tag{7}$$

$$\left(K_1K_2-K_2\right)=C\ . \tag{8}$$

Then,

$$A\left(R+R_1\right)^2+B\left(R+R_2\right)^2+C\left(R+R_3\right)^2=0\ , \tag{9}$$

or

$$\begin{aligned}&\left(A+B+C\right)R^2+\left(2ARR_1+2BRR_2+2CRR_3\right)\\&+AR_1^{\,2}+BR_2^{\,2}+CR_3^{\,2}=0.\end{aligned}$$

Now, $A+B+C=0$, therefore,

$$R=\frac{-AR_1^{\,2}-BR_2^{\,2}-CR_3^{\,2}}{2\left(AR_1+BR_2+CR_3\right)}\ . \tag{10}$$

Before proceeding to calculate X it is prudent to determine if a reactive component of Z is present. A simple test to determine the presence of X is offered:

Formulate:

$$V_G=V_{01}\left(1+\frac{R}{R_1}\right), \tag{11}$$

$$V_H=V_{02}\left(1+\frac{R}{R_2}\right), \tag{12}$$

$$V_J=V_{03}\left(1+\frac{R}{R_3}\right). \tag{13}$$

If $V_G=V_H=V_J$ no reactance is present and there exists no need to calculate X: $X=0$. When V_G, V_H and V_J are all equal this voltage is the Thevenin open circuit voltage. If, however, V_G, V_H and V_J all differ the calculation of X may be carried forth.

Now, since R is known refer back to either K_1 or K_2 to find X. Using K_1:

$$K_1=\frac{\left(R+R_1\right)^2+X^2}{\left(R+R_2\right)^2+X^2}\ ,$$

or

$$\frac{K_1\left(R+R_2\right)^2-\left(R+R_1\right)^2}{\left(1-K_1\right)}=X^2\ , \tag{14}$$

and

$$\left[\frac{K_1\left(R+R_2\right)^2-\left(R+R_1\right)^2}{\left(1-K_1\right)}\right]^{1/2}=X\ . \quad (15)$$

This last equation gives the magnitude of X. Unfortunately, the sign of the reactance is unknown. The sign of the reactance can be determined by altering the operating frequency. However, the technique put forth promised impedance determination without changing the frequency of operation. This is still possible by adding a reactance in parallel with the test load resistance and observing output voltage effects with the presence or absence of the load reactance.

Either a capacitor or an inductor may be shunted to the load resistance to determine the sign of the source reactance. For example, if the source reactance is positive (inductive) a capacitor (which is not too large in value) shunted across the load resistance will cause the output voltage (and power) to increase. Alternately, if the source reactance is negative (capacitive) an inductor (which is not too small in value) shunted across the load resistance will cause the output voltage (and power) to rise.

If the source reactance is inductive, there is a value of load capacitance (C_{PEAK}) which will cause the load voltage to be a maximum. Similarly, for a capacitive source reactance there is a load inductance (L_{PEAK}) which will result in a maximum load voltage. For testing purposes it is suggested to select either a load capacitor which is smaller than this "peaking" value or an inductor which is larger than this peaking value. This representation avoids ambiguity. That is, if C were too large (or L too small) output voltage would actually decrease. The value of peaking load reactance (capacitive or inductive) may be calculated by treating the generator/load combination as a voltage divider, finding the first derivative of load voltage with respect to load reactance, and setting the derivative to zero. Recognizing that R is the source resistance and X is the source reactance the following occurs:

$$X_{LOAD}=\frac{R^2+X^2}{X}\ . \quad (16)$$

The load capacitance or inductance values shunted across the load resistance, which cause output voltage peaking, may be calculated directly:

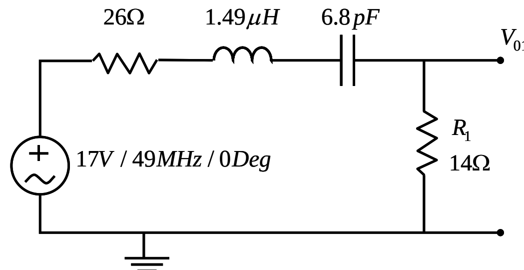

Fig. 3. Thevenin source with complex impedance loaded by resistance R1.

$$C_{PEAK}=\frac{X}{2\pi f\left(R^2+X^2\right)}\ , \quad (17)$$

$$L_{PEAK}=\frac{R^2+X^2}{2\pi fX}\ . \quad (18)$$

IV. DEMONSTRATION FOR COMPLEX SOURCE IMPEDANCE WITH BOTH REACTANCE TYPES

Referring to Fig. 3, the Thevenin source shows a voltage generator of 17 volts R.M.S., a resistance of 26.0 ohms in series with an LC series combination consisting of a 1.49 microHenry inductor and a 6.8 picoFarad capacitor. System operating frequency is set to 49.0 MHz. At this frequency we directly calculate the series reactance of the LC as $-j18.92$ ohms. This Thevenin equivalent circuit is intended to drive a 28.0 ohms load.

The source is respectively loaded with R_1=14 ohms, R_2=28 ohms, and R_3=56 ohms. The following results are recorded:

R (load)	Load Voltage (volts)
R_1=14 ohms	V_{01}=5.38
R_2=28 ohms	V_{02}=8.32
R_3=56 ohms	V_{03}=11.3

Using (3) and (4), one can obtain

$K_1=0.597891129$,

$K_2=0.275722592$.

Then, using (6)-(8)

$A=-0.322168536$,

$B=0.433039037$,

$C=-0.1108705$.

Using (10), R becomes $R=25.36737201\,\Omega$, which checks within 2.433%. Next, one can determine if reactance X is non-zero. Using (11), (12) and (13):

$V_G = 15.128$ volts,

$V_H = 15.865$ volts,

$V_J = 16.419$ volts.

Since the values of V_G, V_H and V_J are different, we proceed to find the magnitude of X as

$X = 19.5094182\ \Omega$,

which checks within 3.11%.

Finally, check sign of reactance: Test load reactances will be used to shunt the load resistance. The load resistance may be any value. Select R_2=28 ohms. Then, using (17) and (18),

$C_{PEAK} = 61.87\, pF$,

$L_{PEAK} = 0.17\,\mu H$.

Recall, without any shunt reactance V_{02}=8.32 volts. On hand, convenient values of C=27 pF and L=0.47 μH are used for testing.

With C connected $V_{LOAD} \cong 7.96$ volts (decreased).

With L connected $V_{LOAD} \cong 8.54$ volts (increased).

The conclusion is that the generator reactance is capacitively reactive. Thus,

$Z \cong R - jX = 25.367 - j19.509\ \Omega$.

It is interesting at this point to compare measured impedance magnitude versus actual impedance magnitude:

$$|Z|_{MEAS} = \sqrt{25.367^2 + 19.509^2} = 32.00\ \Omega\ ,$$

$$|Z|_{ACTUAL} = \sqrt{26^2 + 18.92^2} = 32.155\ \Omega\ .$$

A complete error (sensitivity) analysis is provided in the following section.

V. ERROR ANALYSIS

A. Sensitivity analysis

The impedance of the Thevenin equivalent source of the test case is $Z_{ACTUAL} = 26 - j18.920532\Omega$. The load voltages can be calculated for Z_{ACTUAL}, the measurement resistors of $R_1 = 14\Omega$, $R_2 = 28\Omega$, and $R_3 = 56\Omega$, and the generator voltage of 17V as

$V_{L1} = 5.378635\ V$,

$V_{L2} = 8.318949\ V$,

$V_{L3} = 11.312521\ V$.

Comparing these analytically calculated voltages with the measured voltages, one can find the percentage errors in these measurements as

$$\frac{|V_{L1} - V_{01}|}{V_{L1}} \times 100 = 0.025370,$$

$$\frac{|V_{L2} - V_{02}|}{V_{L2}} \times 100 = 0.012623,$$

$$\frac{|V_{L3} - V_{03}|}{V_{L3}} \times 100 = 0.110683.$$

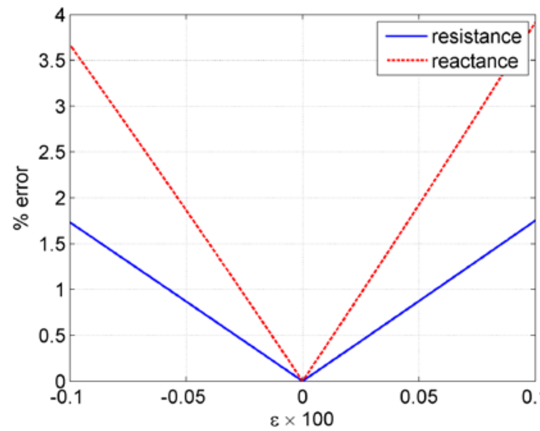

Fig. 4. Error in calculated output impedance when only V_{01} has error.

The resistance and reactance of the output impedance can be calculated using R_1, R_2, R_3, V_{01}, V_{02}, and V_{03}, as described in Sections III and IV, more precisely as

$R = 25.367373\ \Omega$,

$X = 19.509418\ \Omega$.

Compared with the Z_{ACTUAL}, the percentage errors in the calculated values out of the measurements are

$$Error_R = \frac{|R_{ACTUAL} - R|}{R_{ACTUAL}} \times 100 = 2.4332,$$

$$Error_X = \frac{|X_{ACTUAL} - X_M|}{X_{ACTUAL}} \times 100 = 3.1124.$$

This analysis reveals that although the measurement errors in the voltages are very small, the errors in the calculated values of output resistance and reactance are comparatively very large. The calculated values are very sensitive to the measurement errors. Therefore, one should carefully assess the accuracy of the obtained results.

To further analyze the affect of measurement errors on the impedance calculations, the following analysis is performed. First, an error is introduced only to the measured voltage V_{01} such that

$$V_{01} = V_{L1} \times (1+\varepsilon),$$
$$V_{02} = V_{L2},$$
$$V_{03} = V_{L3},$$

where ε is an error term. Then the errors $Error_R$ and $Error_X$ are calculated and plotted versus ε as shown in Fig. 4, which illustrates the extreme sensitivity of the calculations to measurement errors. Similar result can be obtained when error is introduced to only V_{02} or V_{03}.

When the same amount of error is introduced to all three measurements such that

$$V_{01} = V_{L1} \times (1+\varepsilon),$$
$$V_{02} = V_{L2} \times (1+\varepsilon),$$
$$V_{03} = V_{L3} \times (1+\varepsilon),$$

it has been found that the errors, $Error_R$ and $Error_X$, effectively vanish. Therefore, if a measurement system introduces errors to the voltage measurements that are proportional to the measured voltages, then the calculated impedance values are reliable.

B. Optimum choice of measurement resistances

Section III describes a mathematical procedure to calculate unknown output resistance and reactance values of an amplifier through three measurements. Further, we will illustrate that; these values can be obtained through solution of a matrix equation.

Notice that (2) can be rewritten as

$$R_1^2 + 2R_1R + R^2 + X^2 - \frac{R_1^2}{V_{01}^2}V^2 = 0, \quad (19a)$$

$$R_2^2 + 2R_2R + R^2 + X^2 - \frac{R_2^2}{V_{02}^2}V^2 = 0, \quad (19b)$$

$$R_3^2 + 2R_3R + R^2 + X^2 - \frac{R_3^2}{V_{03}^2}V^2 = 0. \quad (19c)$$

One can subtract (19b) from (19a) and (19c) from (19b) and obtain the following equations

$$2(R_1 - R_2)R + \left(\frac{R_2^2}{V_{02}^2} - \frac{R_1^2}{V_{01}^2}\right)V^2 = R_2^2 - R_1^2, \quad (20a)$$

$$2(R_2 - R_3)R + \left(\frac{R_3^2}{V_{03}^2} - \frac{R_2^2}{V_{02}^2}\right)V^2 = R_3^2 - R_2^2. \quad (20b)$$

Equations (20a) and (20b) is a linear set of equations and can be put in the following matrix equation form

$$Ax = y, \quad (21)$$

where

$$A = \begin{bmatrix} \left(\frac{R_2^2}{V_{02}^2} - \frac{R_1^2}{V_{01}^2}\right) & 2(R_1 - R_2) \\ \left(\frac{R_3^2}{V_{03}^2} - \frac{R_2^2}{V_{02}^2}\right) & 2(R_2 - R_3) \end{bmatrix},$$

$$y = \begin{bmatrix} R_2^2 - R_1^2 & R_3^2 - R_2^2 \end{bmatrix}^T,$$

$$x = \begin{bmatrix} V^2 & R \end{bmatrix}^T.$$

Solution of $Ax = y$ yields R and V^2, which then can be used to calculate X.

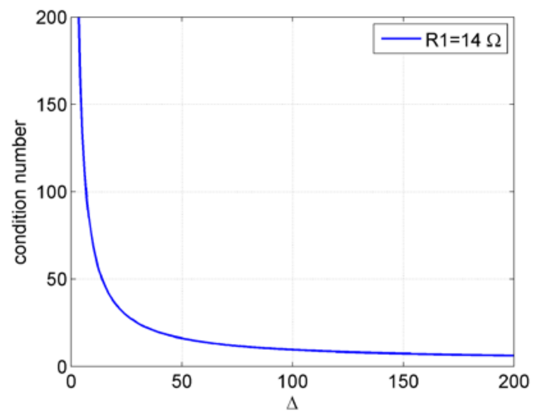

Fig. 5. Variation of condition number as a function of Δ.

A system of equations is considered to be well-conditioned if a small change in the coefficient matrix or a small change in the right hand side results in a small change in the solution vector, while a system of equations is considered to be ill-conditioned if a small change in the coefficient matrix or a small change in the right hand side results in a large change in the solution vector [11]. The condition number of the system described by the example given is calculated using the measurement data in the previous sections as

$Cond(A) = 50.35$. The condition number for a well-conditioned system should be close to unity. The calculated condition number verifies that the system is not well conditioned.

In the above calculation

$$Cond(A) = \|A\| \cdot \|A^{-1}\|,$$

where $\|A\|$ is the row sum norm (also called the uniform matrix norm) of matrix A. Thus,

$$\|A\| = 2(R_3 - R_2) + \left(\frac{R_3^2}{V_{03}^2} - \frac{R_2^2}{V_{02}^2}\right) \qquad (22.a)$$

$$\|A^{-1}\| = \frac{2(R_3 - R_2) + 2(R_2 - R_1)}{2(R_2 - R_3)\left(\frac{R_2^2}{V_{02}^2} - \frac{R_1^2}{V_{01}^2}\right) - 2(R_1 - R_2)\left(\frac{R_3^2}{V_{03}^2} - \frac{R_2^2}{V_{02}^2}\right)}. \qquad (22.b)$$

To simplify the analysis, if we choose equal increments in the measurement resistances such that $(R_2 - R_3) = (R_1 - R_2)$, then the condition number becomes

$$Cond(A) = \frac{\left(4(R_3 - R_2) + 2\left(\frac{R_3^2}{V_{03}^2} - \frac{R_2^2}{V_{02}^2}\right)\right)}{\left(\frac{R_3^2}{V_{03}^2} - \frac{R_2^2}{V_{02}^2}\right) - \left(\frac{R_2^2}{V_{02}^2} - \frac{R_1^2}{V_{01}^2}\right)}. \qquad (23)$$

In this equation, we can replace the measured voltages by the following using (1)

$$V_{01}^2 = V^2 \frac{R_1^2}{(R_1 + R)^2 + X^2},$$

$$V_{02}^2 = V^2 \frac{R^2}{(R_2 + R)^2 + X^2},$$

$$V_{03}^2 = V^2 \frac{R_3^2}{(R_3 + R)^2 + X^2},$$

to obtain the condition number in terms of source voltage and resistances as

$$Cond(A) = \frac{\left(4(R_3 - R_2)V^2 + 2\left((R_3 + R)^2 - (R_2 + R)^2\right)\right)}{\left((R_3 + R)^2 - (R_2 + R)^2\right) - \left((R_2 + R)^2 - (R_1 + R)^2\right)}.$$

If we write $R_2 = R_1 + \Delta, R_3 = R_1 + 2\Delta$, then after some manipulations we can simplify the condition number expression as

$$Cond(A) = \frac{\left(4V^2 + 2(2R_1 + 3\Delta + 2R)\right)}{2\Delta}. \qquad (24)$$

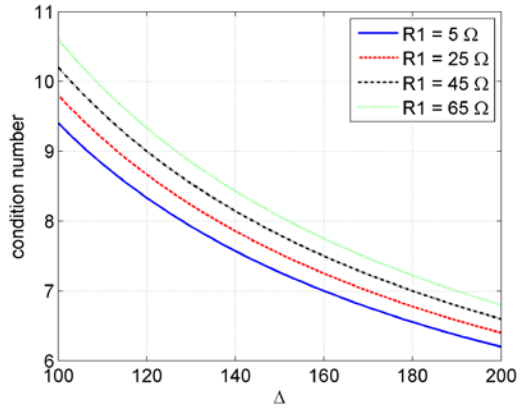

Fig. 6. Condition number vs. Δ for various values of R_1.

This form of condition number expression allows us to analyze what values of resistances would be better to use in the measurements to obtain a system with a smaller condition number. This equation reveals that Δ needs to be large and R_1 needs to be small in order to achieve a well conditioned system. Figures 5 and 6 illustrate the variation of condition number with R_1 and Δ.

While choosing R_1, R_2, and R_3, the main limiting factor would be the maximum allowable VSWR. If R and X can be estimated or are approximately known, they can be used to calculate maximum and minimum allowable measurement resistances. For a given VSWR

$$S = \frac{1 + |\Gamma|}{1 - |\Gamma|}, \qquad (25)$$

where

$$\Gamma = \frac{R_M - R - jX}{R_M + R + jX}. \qquad (26)$$

Here, R_M is the value of the measurement resistance to be determined for approximately known R and X values. Using (25) and (26), one can write

$$|\Gamma|^2 = G = \frac{(S-1)^2}{(S+1)^2} = \frac{(R_M - R)^2 + X^2}{(R_M + R)^2 + X^2}. \qquad (27)$$

Rearranging terms, one can obtain a quadratic equation as

$$R_M^2 + \frac{-2R(1+G)}{(1-G)} R_M + (R^2 + X^2) = 0. \qquad (28)$$

Solution of (28) for R_M leads to

$$R_M = R\frac{S^2+1}{2S} \pm \frac{1}{2}\sqrt{R^2\left(S^2-2+\frac{1}{S^2}\right)-4X^2}, \quad (29)$$

which yields the minimum and maximum allowable values of measurement resistances, i.e. R_1 and R_3, if $R_1<R_2<R_3$.

As a follow-up to the condition number analysis above, one can express (29) as $R_M = R_2 \pm \Delta$, where

$$R_2 = R\frac{S^2+1}{2S}, \quad (30)$$

$$\Delta = \sqrt{R^2\left(S^2-2+\frac{1}{S^2}\right)-4X^2}, \quad (31)$$

and $R_1 = R_2 - \Delta$. When used in (24), The values of Δ, based on (31), and R_1, based on (30) and (31), will yield the minimum condition number, thus the best well-conditioned system, subject to the maximum allowable VSWR in the system, if the measurement resistance values are to be chosen with equal increments of Δ.

VI. CONCLUSION

Proper installation of an RF power amplifier requires knowledge of the amplifier output impedance. With such information, correct load matching is made possible. Matching considerations address power output, efficiency, spurious signal rejection qualities, and possible system longevity. Presented here is a straightforward way to determine the amplifier's output impedance. The method has been checked through operational tests and simulation. Additionally provided is a complete sensitivity analysis for the technique.

ACKNOWLEDGMENT

The authors express sincere gratitude to Mr. William McConnell of Northrop Grumman Corporation, Electronic Systems Division for his support, friendship, and suggestions for this research.

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