How Load VSWR Affects Non-linear Circuits

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If your amplifiers test out fine in the lab but fail QC testing, the testing environment — not the product — is likely at fault.

Consider the following scenario: You're designing and implementing into production a broadband Class C power amplifier. During your design phase, you follow all the rules of science and also dig into your bag of electronic tricks to meet the design specification. Your design is fabricated and tested successfully in the lab. Twenty-five more units are built in the lab and they, too, test out fine.

Confident that both design and production procedures are satisfactory, you begin series production. But when the first units reach RF test, not one meets specification. Yet when you retrieve the units, they test OK in the lab.

What's wrong with these amps? Probably nothing. This scenario, in one form or another, is all too common in the design and manufacture of non linear RF circuitry. The culprit is correlation of test systems. A difference of .5 dB is enough to fail units that are perfectly good, resulting in unnecessary and expensive retesting or even reworking. Still worse, a half dB error will pass units that don't meet specs and never should be shipped.

Such correlation errors will disrupt an even more important function, that of maintaining product continuity. A device built in 1982 should perform the same as an identical model number device built in 1976. Another way of saying this is that a device tested in a 1982 test system should produce the same results when tested in a 1976 system. The key, of course, is RF correlation.

What is RF correlation? Simply put, RF correlation occurs when target error limits are established and adhered to on a continuous basis among two or more testing stations. Such correlation is essential to cost-effect production of non-linear RF and microwave power amplifiers, whose circuits are extremely sensitive to the impedance of their loads, either in test systems or equipment environments. It is easy to compensate for the insertion loss errors in an attenuator, but it is much more difficult to compensate for variations in the input impedance difference between attenuator pads, that is, the load VSWR.

Let's examine RF correlation on both an empirical and theoretical level.

EMPIRICAL APPROACH

The empirical approach is shown in Table 1, where several test circuit loads (consisting of series attenuators, directional couplers and RF switches) were assembled. The insertion loss and input impedance of each load string was measured. Following this, the individual loads were connected to a given test circuit containing a common base microwave power transistor. The power meter used was also a constant.

Table 1 shows insertion loss, insertion loss corrections, indicated RF power, and actual power data of each load string. A maximum error of 0.52 dB was detected with a standard deviation of .19 dB. All these loads had a VSWR less than 1.1:1 at the frequency tested. A VSWR of 1.1:1 is better than the published specifications of commercially available attenuators, directional couplers, and RF switches from most leading manufacturers. A VSWR of 1.5:1 is a typical VSWR specification limit at 1.4 GHz. It must be noted that many users will gladly pay an additional nominal charge for components meeting a tighter VSWR spec.

THEORETICAL APPROACH

The vehicle for the theoretical discussion is the well known expression:

$$P_0 = \frac{(V_{CC} - V_{CESAT})^2}{2R_L}$$

Where: P_0 = Power output
V_{CC} = Collector supply voltage
V_{CESAT} = Collector-Emitter saturation voltage
R_L = Load resistance.

This expression is valid for a narrow range of R_L (10% range maximum). Over a wider range of R_L, significant changes in V_{CESAT} occur as a function of R_L. Output power varies with the square of V_{CESAT}. V_{CESAT} is a very strong function of collector current and transistor die temperature.

The theoretical approach will evaluate the changes in amplifier output power (P_0) for a given change in load resistance (R_L).

For simplicity, let us assume the following hypothetical conditions, which are typical of today's RF power transistors.

Hypothetical conditions:

V_{CC} = 28 V

V_{CESAT} = 1.5 V

P_{OUT} = 50 W

Frequency = 1.0 GHz

Solving for load resistance:

$$R_L = \frac{(V_{CC} - V_{CESAT})^2}{2P_0} = \frac{702.25}{100} = 7.02 \ \Omega$$

Additionally, assume that a simple two-section impedance matching network matches the 7 Ω to 50 Ω. Let this two-section match consist of two λ/4 wave transformers.

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**Table 1. Microwave Load Substitution Study**

The vehicle used for this test was a production test fixture and correlation sample #2 for the TRW MRA1417-6 broadband, high–gain transistor. Measurements were taken at 1400 MHz with input power of 1.1 W.

Load #	Measured Power Level	Circuit Return Loss	Collector Current	Measured Insertion Loss	Calibration Error	Actual Power	Delta from Reference	Load Input Return Loss	Impedance Angle	Real	Imaginary
1	1.1 W	35 db	—	30.03 dB	+ .03 dB	thru	calibration	− 40.2	99.1	49.8	+ 1.0
1	7.7 W	16 db	.51 A	30.03 dB	+ .03 dB	7.75 W	reference	− 40.2	99.1	49.8	+ 1.0
2	7.6 W	15.5 db	.5 A	39.66 dB	− .44 dB	6.87 W	− 30.5	—	− 77.5	50.6	− 3.0
3	7.65 W	15.5 db	.51 A	39.68 dB	− .32 dB	7.10 W	+ .38 db	− 34.1	− 171.5	50.4	− 2.0
4	8.0 W	15.5 db	.51 A	39.8 dB	− .20 dB	7.63 W	− .07 dB	− 34.1	68.1	50.7	− 1.9
5	7.2 W	16 db	.505 A	30.16 dB	+ .16 dB	7.47 W	− .16 db	− 30.1	− 128.0	51.1	− 3.0
6	8.3 W	15.2 db	.51 A	39.78 dB	+ .22 dB	7.89 W	+ .08 db	− 31.7	− 144.6	47.9	− 1.5
7	7.75 W	16.2 db	.505 A	39.73 dB	− .27 dB	7.28 W	− .27 db	− 32.7	11.9	49.0	− 2.4
8	7.78 W	16.8 db	.503 A	39.7 dB	− .30 dB	7.26 W	− .28 db	− 35.4	− 111.9	49.1	− 1.5

Largest Delta after calibration correction is 0.52 dB.
Mean value of the measured power = 7.41 W.
Standard Deviation = .34 W = .19 dB.
NOTE: − 30 dB RETURN LOSS = ρ of 0.03 and VSWR of 1.06:1.

Given the conditions we have hypothesized, the R_L of 7.02 Ω represents the collector load that will yield the best simultaneous satisfaction of device efficiency, device gain, gain transfer characteristics, and saturated power.

For minimum Q, with a 2 section match, the transformation ratio of each section is
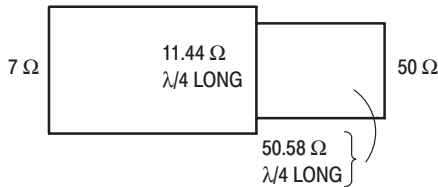
$$\sqrt{\frac{50}{7}} = 2.67.$$

$$Z_0 \text{ 1st section} = \sqrt{(7)(2.67)(7)}$$

$$= 11.44 \ \Omega$$

$$Z_0 \text{ 2nd section} = \sqrt{(7)(2.67)(50)}$$

$$= 30.58 \ \Omega$$

$\lambda/4$ @ 1 GHz = 2.95″ = .075 m

Table 2 shows the transformed impedance at the input of the matching network as a function of various load impedances. Our example utilizes a real-to-real impedance match for convenience. The analysis also is appropriate for an imaginary to real match in that center of the VSWR circle at the input to the matching network will be rotated but won't change in magnitude from the data presented.

CONCLUSION

The data presented in table represents the power variation into a load with a VSWR of 1.1:1 relative to 50 Ω. The result is a power output of 50 W ± 5.3 W 1 ± .435 dB). The total Delta is 10.3 W (.87 dB). This is enough to:

A) Make a good circuit look bad, or . . .

B) Make a bad circuit look good.

This analysis was done for a single frequency. The problem is compounded in a broadband environment by requirements for a good broadband load impedance.

TEST EQUIPMENT ACCURACY

Test equipment manufacturers have produced some very impressive equipment in recent years; however, the accuracy of a well constructed system using the latest equipment available is generally considered to be no better than ± 3%. Considering the number of variables in RF testing and the magnitude of the task faced by the test equipment manufacturers, ±3% is no small achievement. However, ±3% is ±.13 dB. This ±.13 dB added to the ±.435 dB indicated earlier yields a total possible error magnitude of ±.565 dB. This adds up to a total possible error of ± 14% into a load with 1.1:1 VSWR. The output power range of our amplifier is now 50 W ± 7.05 W.

Now we see how bad things can be, a few comments on reality are in order.

The author believes that the correlation target for the test of RF power devices should be ±0.2 dB, which we believe is the optimum tolerance for combining strict quality standards and the need for easy repeatability under series production conditions. If more than an occasional device fails this test, do not assume that the devices are at fault. Instead, first analyze the test circuit and then the test system to determine the reason for the additional error. Some suggestions on how to maintain a ±0.2 dB correlation are shown in Table 3.

The 0.2 dB target is an achievable target in broadband test systems. However, a constant awareness of the test systems capabilities and potential problem areas is mandatory. RF correlation problems will never go away, but they can be made easier to handle.

Table 2. R_L Effects on Output Power

Load Resistance (Ω)	Transformed Load Resistance (Ω)	Output Power (W)	ΔdB	Cumulative ΔdB
45	6.30	55.73		
46	6.44	54.52	.095	.095
47	6.58	53.36	.093	.189
48	6.72	52.25	.091	.280
49	6.86	51.18	.090	.370
50	7.00	50.16	.087	.457
51	7.14	49.18	.086	.543
52	7.28	48.23	.085	.628
53	7.42	47.32	.083	.710
54	7.56	46.45	.081	.791
55	7.70	45.60	.080	.871

Maximum Delta dB vs. VSWR

VSWR	Maximum ΔdB
1.02	.17 (± .085)
1.04	.34 (± .17)
1.06	.51 (± .255)
1.08	.68 (± .34)
1.10	.87 (± .435)

Table 3. Notes

Suggestions to the Maintenance of Correlation

1. Serialize and document all components (attenuators, directional couplers, power meters, detectors, etc.) of the test system. Do not disturb the system once calibration has been performed. Calibrate the system once a month.

2. Require that loads have a calibration return loss ≫ – 35 dB (VSWR) of 1.05:1) in frequency band of interest.

3. Dedicate test systems to specific circuits or specific circuits or products. This is necessary for both correlation and product continuity.

4. The placement of transistors in the test fixtures must be uniform. For instance, flanged transistors should be placed in the test fixtures with the device pushed towards collector load circuitry.

5. Be selective when using cables in test systems. For example, the MIL-C-17 specification for "RG" cable types says that RG-58 can have a characteristic impedance from 48 to 52 Ω (maximum VSWR of 1.04:1) when terminated in a "perfect" 50 Ω load.

6. Be very selective when choosing RF switches. The VSWR of a mechanical switch will vary with time.

7. If possible, terminate the system with a 50 Ω load rather than an attenuator. Load manufacturers need only consider the VSWR of a load. However, for attenuator, tradeoffs must be made between VSWR and frequency response. Measure power and other performance parameters via calibrated directional couplers.

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