A Procedure To Evaluate The Output VSWR of High Power Amplifiers

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Abstract: In this paper a procedure for evaluating the output VSWR of high power amplifiers is introduced and discussed. Essentially, the procedure is based on the comparison between readings of the forward power measured on a directional coupler in different conditions (short circuit and matched load). The error induced by the non-ideal directivity of the directional coupler is evaluated and requirements on the minimum directivity necessary for evaluating a VSWR better than 2.0:1 are shown. Some experimental results are shown, regarding the comparison between two commercial amplifiers with relatively low power (30 W, 10 kHz - 1 GHz).

INTRODUCTION

The subject of this paper is a test procedure for measuring the output voltage standing wave ratio (VSWR) of RF power amplifiers. The output VSWR of RF power amplifiers is an important parameter in any application in which the load VSWR is substantially different from unity. In this case, an amplifier VSWR different from unity enhances standing wave patterns in the cables interconnecting the amplifier output and the load. This may cause some direct effects, such as a derating of power handling of the cable, and the occurrence of system self-coupling and oscillations which may cause possible troubles to the whole measuring system.

In EMC applications, for which the load connected to the cable (antenna or other device) can be very far from ideal, a high power amplifier output VSWR can lead to difficulties in determining the amplifier power, as will be illustrated.

Standards for immunity testing (e.g. [1], [2]) normally specify, during tests, that the forward power needs to be monitored as a primary feedback parameter. The value of the feedback parameter is normally evaluated in a calibration set-up, i.e. in absence of the EUT and monitoring the actual parameter which needs to be established during tests (i.e. electric field for radiated immunity [1], voltage at the output of a coupling/decoupling network, CDN, for conducted immunity [2]).

If the output VSWR of the RF amplifier is sufficiently high, it happens that multiple reflections occur, enhancing the standing wave pattern, and most importantly these multiple reflections vary the forward power amplitude. This situation typically occurs for wideband antennas near to the band edges, as well as for CDNs during calibration due to the 150/50 Ohm output couplers (see [2] for details).

By a relatively straightforward analysis using transmission line theory (see e.g. [3]) it turns out that two main mechanisms may occur:

1. As a consequence of the load mismatch, the effective forward power delivered by an amplifier may be substantially lower than the value specified for a matched load.

2. In case of immunity tests, the presence of the equipment under test (EUT) during the test may influence the ability of the amplifier to deliver the forward power recorded during calibration; this is particularly true for conducted immunity tests (2)

The technique proposed to evaluate the output VSWR of amplifiers is based on the comparison among measurements of the forward power delivered by an amplifier on a matched load, open circuit and short circuit.

The main error source for the procedure is the non-ideal directivity of the directional coupler, which may affect considerably the measurement especially for the open and short circuit tests. Requirements on the maximum allowable directivity are derived.

The test procedure is then applied to two commercial RF amplifiers, with test results quite similar.

The procedure, in the cases analyzed, is self-consistent and leads to reasonable test results.

TRANSMISSION LINE ANALYSIS

As a reference, the ideal set-up outlined in figure 1 is considered.

The nominal output power of amplifiers for EMC tests is normally specified as the full forward power delivered on ideal load (50 Ohm). We define the voltage incident in this situation on the ideal load as $V_{LO}^+$. In the presence of an arbitrary load $Z_L$, due to multiple reflections between loads and the amplifier output impedance $Z_A$, the forward power (without varying the generator voltage $E$) becomes $V_L^+$. By standard transmission line computations (see e.g. [3]), it is possible to calculate the following quantity:

$$\frac{V_L^+}{V_{LO}^+} = \frac{1}{1 + P_A \cdot P_L \cdot e^{2 \lambda M}}$$

(1)

By considering the worst cases for phase, the maximum amplitude variation in the presence of a non-ideal load can be computed as follows:

$$\frac{1}{2} \frac{(S_A + 1)(S_L + 1)}{S_A \cdot S_L + 1} \leq \frac{V_L^+}{V_{LO}^+} \leq \frac{1}{2} \frac{(S_A + 1)(S_L + 1)}{S_A + S_L}$$

(2)

where $S_A$ is the amplifier output VSWR, $S_L$ is the load VSWR.
The quantity $\frac{V_I^+}{V_L^+}$ measures the difference between the forward power measured on the actual load and the forward power measured in the same conditions measured on an ideal load.

An example of the results of the previous formula is shown in Figure 2, for the case of an amplifier with output VSWR 2:1. It is evident from the figure that, in order to deliver a specified forward power in presence of a load with VSWR equal to 2:1 (absolutely usual) the amplifier power needs to be increased by 23%, while if the load VSWR is 4:1 the power needs to be increased by 44%. These differences are not trivial, and may have strong cost implications for test systems with high power amplifiers.

From the previous observations, it becomes quite clear the requirement expressed in standard [2] for a 1.2:1 output VSWR of the test amplifier.

$$\rho_A = |\rho_A| \cdot e^{j\phi} \quad \rho_L$$

**Figure 1 - Transmission line idealization of the problem**

Taking the worst case between the minimum and maximum value, the surface graph reported in Figure 3 describes the maximum forward power deviation as a function of both the amplifier and load VSWR.

**Figure 3 - Worst case forward power variation for non-ideal load**

During real tests, the presence of the EUT can perturb the set-up and lead to differences in reflected power level (towards the amplifier), especially when the transducer (antenna or CDN) exhibits a high VSWR. In this situation, if a sufficient power level margin is not taken for the RF amplifier, reproducing the forward power measured during calibration can be impossible.

On the basis of the previous considerations, it is evident the need for forward power feedback as stated in the standards and the total inadequacy of controlling the signal generator power alone during EMC immunity tests.

Direct measurements of the amplifier output VSWR using a standard instrument (i.e. network analyzer) directly connected to the amplifier output can be performed only at low amplifier power levels, and are potentially dangerous for the instrument. Protection of the instrument with attenuators results in an increasing loss of dynamics for the measurement.

The test procedure here presented is based on the comparison of readings of the amplifier forward output power (through a directional coupler) on matched load, open circuit and short circuit.

For computations, if $P_{OC}^+$ is the open circuit ($Z_L = \infty$ Ohm) forward power measured at the directional coupler output, $P_{SC}^+$ is the short circuit ($Z_L = 0$ Ohm) forward power measured at the directional coupler output, $P_{50}^+$ is the matched ($Z_L = 50$ Ohm) forward power measured at the directional coupler output, then we define the following quantities:

$$\alpha = \frac{P_{OC}^+}{P_{50}^+} = \frac{1}{1 + |\rho_A|^2 - 2 \cdot |\rho_A| \cdot \cos(\phi - 2 \cdot \beta \cdot I)} \quad (3a)$$

$$\beta = \frac{P_{SC}^+}{P_{50}^+} = \frac{1}{1 + |\rho_A|^2 + 2 \cdot |\rho_A| \cdot \cos(\phi - 2 \cdot \beta \cdot I)} \quad (3b)$$

**Figure 2 - Forward power variation for non-ideal load**
It should be noted that the in the worst case assumption separated phases have been considered for the directivity in open and short circuit measurements. In case the phase can be considered equal, the uncertainties might be probably lower.

**EXPERIMENTAL RESULTS**

The test results presented in this section are based on measurements performed using the following test instruments:

- Spectrum analyzer HP 8594C with tracking generator
- Two-directional coupler Werlatone C2630
- RF generator HP 8648C
- RF amplifiers under test (AUTs) Kalmus 747LC and IFI SMX50, both with frequency range 10 kHz-1 GHz and 50 W nominal output power.

As discussed in the previous section, one of the most significant parameters affecting the accuracy of output VSWR measurements according to the proposed test procedure is the directional coupler directivity.

![Amplifier output VSWR](image.png)

The load on which the directional coupler was terminated was alternatively matched, open, short circuit. An indication of the coupler directivity, assuming that the open, short and load are ideal, can be found by evaluating the difference between the forward power measured in presence of the matched load and that in presence of the mismatched load. It should be pointed out that a true coupler directivity evaluation should be based on measurements with a load with arbitrary phase, when the test instrumentation at disposal allows only simple scalar measurements. What was found is that in the frequency range 150 kHz - 30 MHz the maximum difference between the readings ranges from -0.29 to +0.19 dB. As a consequence, the directivity in that range is about 30 dB. Above 30 MHz, the difference was in the range from -0.65 to +0.67 dB (about 22 dB directivity), hence the measurement was performed only at a reduced set of frequencies (130 MHz, 270 MHz, 435 MHz, 600 MHz).

**Figure 4 - Influence of directivity on the VSWR estimate**

From the previous expressions, it is possible to retrieve the square of the modulus of the reflection coefficient $|\rho_A|^2$:

$$|\rho_A|^2 = \frac{1}{2} \left( \frac{1}{\alpha} + \frac{1}{\beta} - 2 \right)$$

(4)

From the previous equation, it is evident that for a meaningful result the condition $\frac{1}{\alpha} + \frac{1}{\beta} \geq 2$ should be satisfied; this can be interpreted as a consistency condition for the procedure.

The influence of directivity on the results from the test procedure can be described as follows. If the coupler has directivity (in linear amplitude units) equal to $d$, the true measured values at the directional coupler forward port in open or short circuit lead to the following result for the (power) reflection coefficient:

$$|\rho_A|^2 = \frac{1}{2} \left( \frac{1}{\alpha} + \frac{1}{\beta} - 2 \right)$$

(5)

where the apex $d$ denotes the estimated value in presence of a non-ideal directional coupler, $\phi_{oc}$ and $\phi_{sc}$ indicate the phase of the additive contribution representing the non-ideal directivity.

Taking worst cases for the phases, the maximum variation of the estimated value is:

$$\frac{|\rho_A|^2 - d \cdot (d + 2)}{(d + 1)^2} \leq |\rho_A|^2 \leq \frac{|\rho_A|^2 - d \cdot (d - 2)}{(d - 1)^2}$$

(6)

The effect of non-ideal directivity is shown in figure 4 for the evaluation of a 2:1 output VSWR. It turns out that a coupler directivity of 30 dB allows measuring a VSWR from 1.5 to 2.5:1 in place of the nominal 2:1. This kind of accuracy is practically achievable.
MHz, 765 MHz, 900 MHz). At the reported frequencies the estimated directivity is in the range of -40 dB.

Figure 5 reports some test results of two commercial amplifiers with similar specifications (50 W nominal output power, dual band, 10 kHz - 1 GHz). The forward power during testing was about 25% of the rated output power. The test results indicate a similar performance, with worst case output VSWR at the low frequency end (150 kHz) then reducing at higher frequencies.

When considering the 1.2:1 output VSWR requirement of IEC 61000-4-6 [2] it is quite evident that the use of the two tested amplifiers would require an 6-7 dB output attenuator. The attenuation value is indeed generally suggested by the amplifier manufacturers.

CONCLUSION

A test procedure to evaluate the output VSWR of high power amplifiers has been introduced and experimentally applied to two commercial power amplifiers.

The test procedure did yield to repeatable results and did allow the evaluation of low VSWR values.

The main advantage of the test procedure is that it can be applied to the case in which the amplifier is delivering substantial percentages of the rated output power.

The main limitations in the test procedure are the following:

- The test results depend quite critically on the directional coupler directivity.
- For a complete testing, the amplifier should be able to deliver full power on open or short circuit. In any case, the upper output power limit depend on the amplifier protections built in.
- The test results depend critically on the accuracy of the measurement of the output of the directional coupler, and the needed accuracy increases for low VSWR values to be detected.

A further improvement of the presented test results would be using a power meter to detect with better accuracy the directional coupler readings. It should be noted, however, that in this case the power amplifier should operate in linear region with very low harmonics level, which otherwise would substantially affect the measurement results.

REFERENCES

[1] IEC 61000-4-3 Ed. 1: 1995, Electromagnetic compatibility (EMC) - Part 4: Testing and measuring techniques - Section 3: Radiated, radio frequency, electromagnetic field immunity test
