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Application Note 9A

Power Efficiency Measurements using the CCMT

This note provides definitions and describes the measurement of RF to DC efficiency using a passive load pull system, such as the CCMT [1]. In particular it explains why Power Added Efficiency cannot be measured when a transistor is mismatched at the input.

Introduction

There are different methods for defining and measuring Transistor Efficiency depending on which RF power at the input of the transistor is taken into consideration.
We use the following definitions:

1- The standard Efficiency (or Transducer Efficiency - **T-Eff**), uses as input power the power *available* at the transistor input.
2- The Power added Efficiency (**PadEff**) uses the power *absorbed* by the transistor as input power.
3- The Collector Efficiency (or **C-Eff**), ignores the input power to the transistor.

Using an automatic pre-calibrated load pull setup allows to measure directly T-Eff and C-Eff for every source and load impedance, but PadEff only if the transistor input port is matched. This is a limitation of load pull systems, which do not use a calibrated reflectometer to detect incident and reflected waves. In practical tests, however, the transistors are often power matched at the source side, in which case our *Transducer Efficiency becomes equal to Power added Efficiency.*

This document describes the definitions, problems, solutions and equipment required to perform these measurements.

Note 1: **C**omputer **C**ontrolled **M**icrowave **T**uner

 June 1996

Efficiency Definitions

RF to DC Efficiency is the ratio of RF power processed by a transistor to the DC power required to bias it. The Efficiency depends on:

- DC bias conditions
- Injected Power
- Load and Source Impedances at the fundamental and the harmonic frequencies.

All these parameters also determine the class of operation of the transistor.

The Efficiency sharply increases with input power when the transistor is biased in class C, but so does the difficulty to measure it accurately, since the contribution of the harmonic components and their loading impedances becomes increasingly important.

The following definitions are used in this document:

Transducer Efficiency
$$T_{eff} = \frac{P_{out.del} - P_{in.av}}{P_{DC}} \quad (1)$$

Power added Efficiency
$$P_{AddEff} = \frac{P_{out.del} - P_{in.del}}{P_{DC}} \quad (2)$$

Collector Efficiency
$$C_{Eff} = \frac{P_{out.del}}{P_{DC}} \quad (3)$$

Total Efficiency
$$Tot - Eff = \frac{P_{out.del}}{P_{DC} + P_{in.del}} \quad (4)$$

Where:
$P_{out.del}$ = Power **delivered** to the Load (tuner) by the transistor
$P_{in.del}$ = Power delivered to (**absorbed** by) the transistor input
$P_{in.av}$ = Power **available** (incident) at the transistor input
P_{dc} = DC power = I1·V1+I2·V2

All relations in the following pages are for the fundamental frequency only. It is in general quite complex to manipulate the harmonic impedances, even though it is easier to terminate them with fixed loads that can be realized "on the fixture" or using a load pull system that can generate harmonic impedances independently [1].

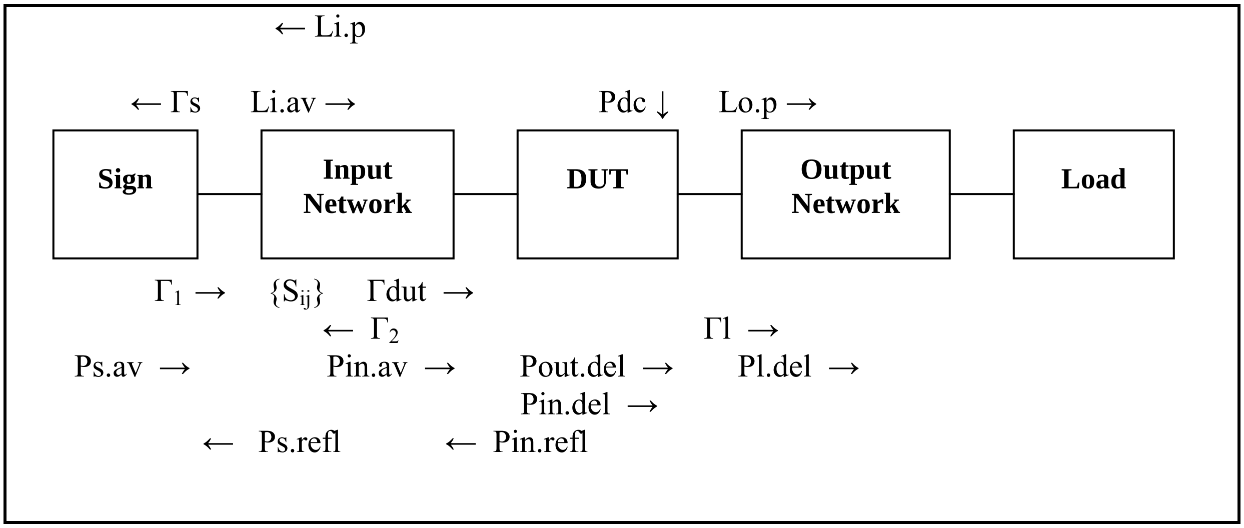

Figure 1: Power and Loss definitions of a tuned transistor

We use two types of **Loss** in order to calculate measured power back to DUT reference plane:

Power Loss

$$Lx.p = \frac{\text{Power delivered to the Network}}{\text{Power delivered to the Load}} = \frac{Ps.del}{Pl.del} \qquad (5)$$

Available Loss

$$Lx.av = \frac{\text{Power available from the Source}}{\text{Power available at the Load}} = \frac{Ps.av}{Pl.av} \qquad (6)$$

x = i: Input, x = o: Output

The available loss of a network depends only on the network's S-parameters and the source reflection factor, whereas the power loss depends only on the S-parameters and the load impedance.

In a Load Pull system, such as the CCMT, the following powers can be measured:

1. Injected power **Ps.av** (measured using a directional coupler).
2. Reflected power at the input of the setup **Ps.refl** (measured at the third port of a circulator, figure 2).
3. Power delivered at the load **Pl.del**.

From those three power measurements we must be able to compute the efficiency value we need.

We use the following relations:

$$Pin.av = \frac{Ps.av}{Li.av} = \frac{P.inc \cdot C}{Li.av} = \text{Available Power at DUT input port}$$

Where C is the coupling factor of the coupler, P.inc is the power measured by the input power meter at the coupler port of the coupler

$$Ps.refl = Ps.av \cdot |\Gamma_1|^2 = \text{Power reflected at the input of the setup}$$

$$= Ps.av \cdot |S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_{DUT}}{1 - \Gamma_{DUT} \cdot S_{22}}|^2 \tag{7}$$

$$Pin.del = Pin.av \cdot \frac{(1-|\Gamma_{DUT}|^2) \cdot (1-|\Gamma_2|^2)}{|1-\Gamma_{DUT} \cdot \Gamma_2|^2} = \text{Power delivered to DUT} \tag{8}$$

$$T-Eff = \frac{Pl.del \cdot Lo.p - \frac{Ps.av}{Li.av}}{P_{DC}} \tag{9}$$

$$PadEff = \frac{Pl.del \cdot Lo.p - \frac{\left(Ps.av / Li.av\right) \cdot (1-|\Gamma_{DUT}|^2) \cdot (1-|\Gamma_2|^2)}{|1-\Gamma_{DUT} \cdot \Gamma_2|^2}}{P_{DC}} \tag{10}$$

$$C-Eff = \frac{Pl.del \cdot Lo.p}{P_{DC}} \tag{11}$$

hereby we use the well known formulas [2], figure 1:

$$\Gamma_1 = S_{11} + \frac{S_{12} \cdot S_{21} \cdot \Gamma_{DUT}}{1 - \Gamma_{DUT} \cdot S_{22}}, \text{ where: } S_{ij} \text{ are S-Parameters of the input tuner.} \tag{12}$$

$$Li.av = \frac{|1-\Gamma_s \cdot S_{11}|^2 \cdot (1-|\Gamma_2|^2)}{|S_{21}|^2 \cdot (1-|L_s|^2)} \quad \text{and} \quad \Gamma_2 = \frac{S_{22} + S_{21} \cdot S_{21} \cdot \Gamma_s}{1 - \Gamma_s \cdot S_{11}} \tag{13}$$

$$Li.p = \frac{|1-L_s \cdot S_{11}|^2 \cdot (1-|\Gamma_s|^2)}{|S_{12}|^2 \cdot (1-|\Gamma_s|^2)} \tag{14}$$

Li.p is the power loss of the input network (tuner) from right to left (DUT is the source and the source of the setup the load (S_{21} in (13) is replaced by S_{12} in (14)).

From equation (10) it becomes obvious that for Power added Efficiency to be measured requires knowledge of the DUT's input reflection factor under large signal conditions.

We are not aware of any simple techniques (except the use of a calibrated reflectometer[1]) that would permit the measurement of Γ_{DUT} under large signal conditions and various source reflection factors, as is the situation in a real load pull setup. This is the reason why PadEff cannot be measured in general.

One might argue that we can measure the power reflected at the input of the tuner (Ps.refl) through a circulator and from this conclude on Γ_{DUT}. However using equation (7) to compute the large signal reflection factor of the DUT, Γ_{DUT} from equation (12) is not going to work, since it includes both amplitude and phase of Γ_{DUT}, but we only have one measurement condition in equation (7)

If, however, the DUT is matched for power at its input port, then Pin.refl (Figure 1) becomes zero and equations (9) and (10) become equal.

This can be achieved in a passive load pull setup when we maximize the overall **transducer gain** by tuning with the input tuner. For the same reason Total Efficiency (equation 4) cannot be measured.

In other words "**a passive system cannot measure the power delivered to a nonlinear DUT, when it is mismatched**". This also makes the measurement of Power Gain of a transistor impossible, using such a system [3], [4].

Important Remark

A commonly made ***wrong assumption*** is that if the input network $\{S_{ij}\}$ tunes the DUT such that the measurable reflected power Ps.refl is zero, then Pin.refl=0 (figure 1). This is only true if the input network (tuner + test fixture) is **lossless**. In a real system this is never the case, however, and in particular not if the tuning ratio (VSWR) is high.

Measurement Setup and Example

The following setup can be used to measure all three types of Efficiency. Depending on the case Power Meter 1 (C-Eff) may not be required. Power meter 3 is only used here for demonstration purpose in order to explain the relation between the different powers flowing through the setup.

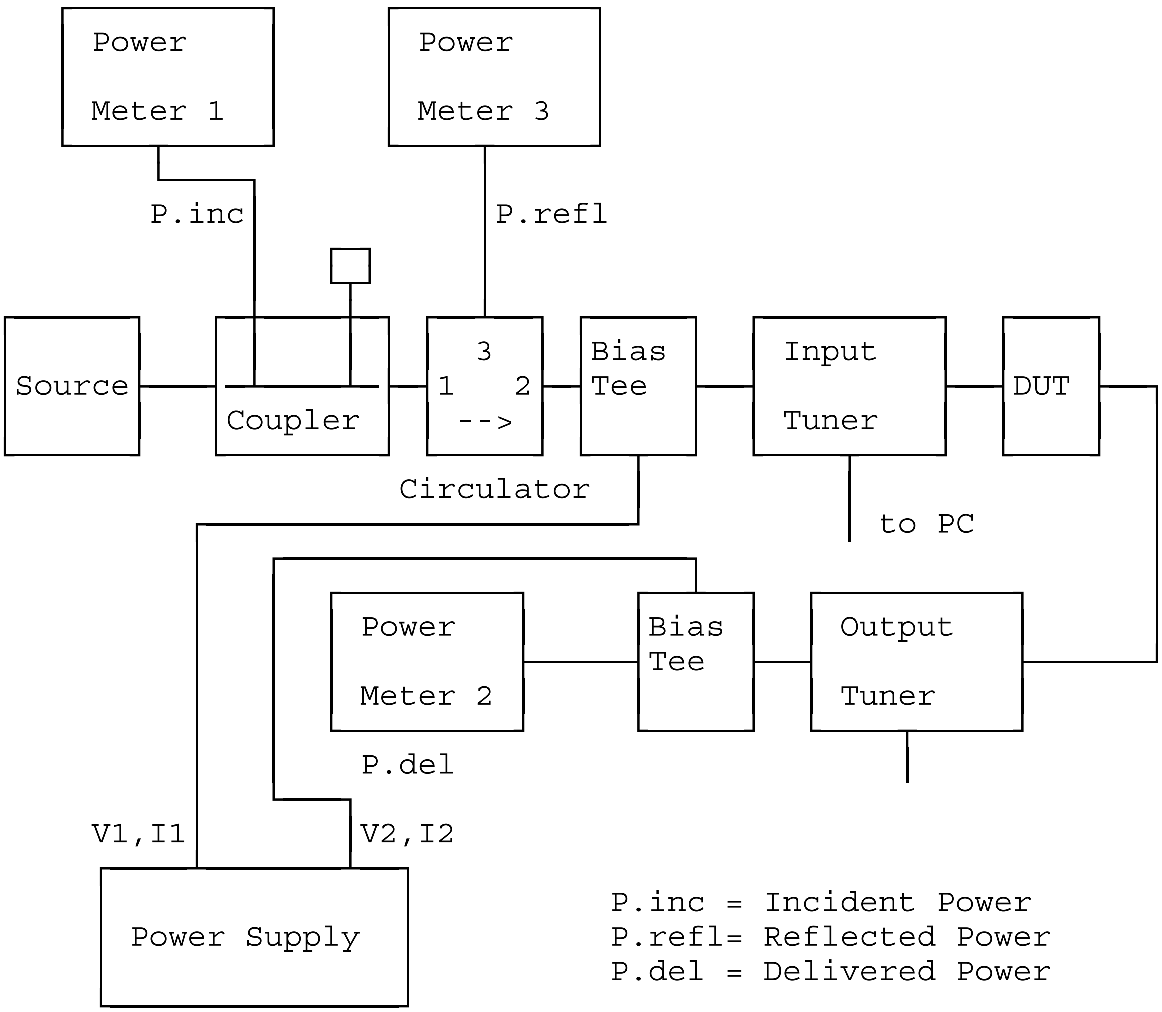

Figure 2: Load Pull setup for measuring Gain, Power and Efficiency

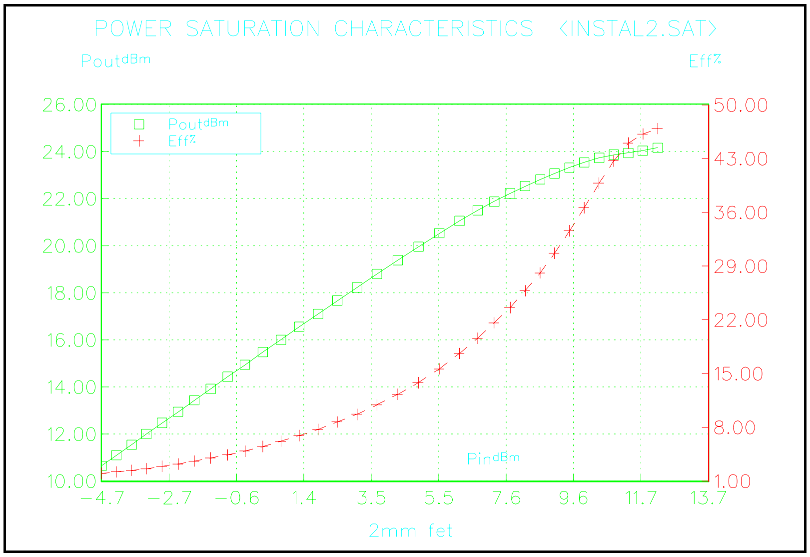

Figure 3: Transducer Efficiency (T-Eff) and Output Power as function of input power. DUT has been matched at the input, so T-Eff = Power added Efficiency.

References

[1] "ALPS, Active Load Pull System..", Product Note 33, Focus Microwaves, page 11.

[2] "Fundamentals of RF and Microwave Noise Figure Measurements", Appl.Note 57-1, Hewlett-Packard, pages 29 and 35.

[3] David Baker, Hughes Aircraft, Missile Systems, private communication, 1994.

[4] Apostolos Samelis, Rockwell International, private communication, 1998.