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ANALYSIS OF HIGH POWER RF AMPLIFIERS FOR INDUSTRIAL APPLICATIONS

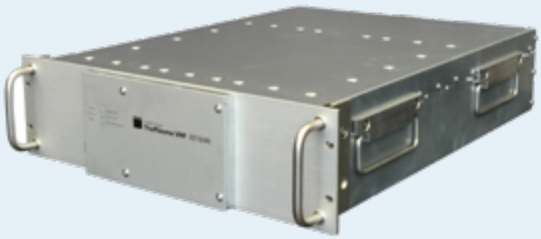

Fig. 1: TruPlasma VHF Series 3000.

Abstract

Based on [1], this paper discusses the effects of power combining structures on the RF and thermal performance of high power RF amplifiers under mismatch conditions. A load pull tuner is used to characterize a power amplifier module of TRUMPF Hüttinger's TruPlasma VHF Series in terms of power and temperature. Based on these measurements, the advantages and disadvantages of in-phase and balanced combining topologies are shown in the context of industrial applications.

I. Introduction

RF generators for industrial applications such as plasma processes or laser excitation provide very high output power level in the kW-range and need to withstand full reflected power for a certain period of time. Historically, these requirements were met only by tube amplifiers or highly derated solid-state amplifiers guaranteeing a stable and robust operation at highly reflective dynamic loads. The recent development of extremely rugged laterally diffused metal oxide semiconductor (LDMOS) power transistors has changed this situation significantly. VSWRs of greater than 65:1 at all phase angles [2,3] can be handled by these power transistors making them the best candidate for a new generation of industrial solid-state RF generators in the VHF frequency range. For the implementation of output power levels far beyond the output power of one basic power device, highly efficient power combiners with excellent power handling capabilities are required.
In this paper, the effects of different combining topologies on the characteristics of the RF LDMOS power amplifier under mismatch are analyzed. The advantages and disadvantages of in-phase and balanced power combiners are presented and the impact on the particular industrial application is discussed.

The organization of this paper is as follows: Section II presents the analysis of a basic power amplifier module concentrating on power and thermal performance for arbitrary load impedances. The different characteristics of in-phase and balanced combining topologies are covered in section III.

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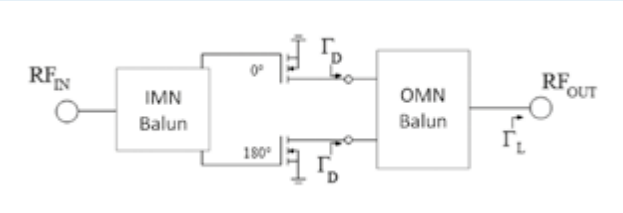

Fig. 2: Block diagram of basic push-pull PA module and definition of drain and load reference planes.

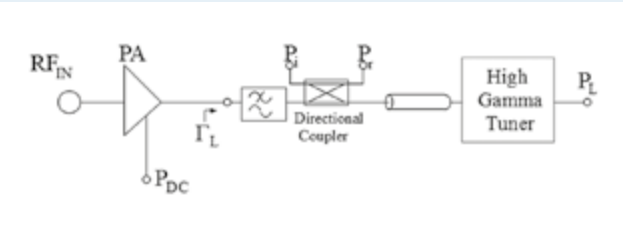

Fig. 3: Block diagram of the measurement setup.

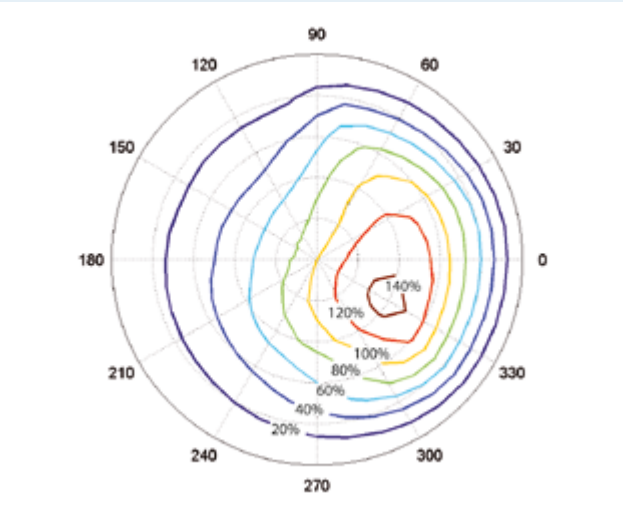

Fig. 4: Measurements of the delivered power over Γ_L normalized to the power delivered into 50 Ω.

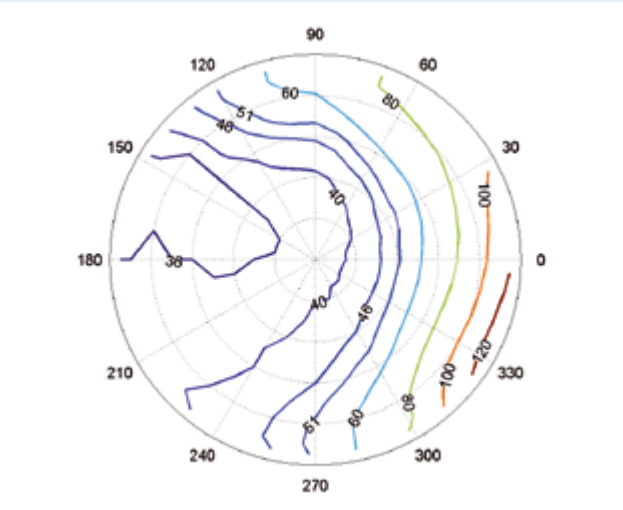

Fig. 5: Measurements of the junction temperature (in °C) over Γ_L (Z_{ref}=50 Ω), Pulsed mode using 10% duty cycle.

II. Analysis of basic PA module

The basic building block of the investigated RF generator is shown in Fig. 2. We will refer to the load impedance as seen by the output of the PA module as Z_L, the load impedance as seen by the drain as Z_D. The output matching network (OMN) is a combination of capacitive and inductive components; it transforms every impedance Z_L bijectively to a drain impedance Z_D.

The measurement setup used for the characterization of the basic PA module is shown in Fig. 3. All higher harmonics are terminated at the output using a low pass filter; the incident power, P_i, and the reflected power, P_r, are measured using a directional coupler, the load power, P_L, is additionally measured using an attenuator at the tuners output port.

The junction temperature is measured using a FLIR A30 infrared camera looking at the transistor without its ceramic case, coated with antireflective paint. As high junction temperatures are expected at full reflection, the tests are conducted at a duty cycle of 10% with a pulse frequency of 1 kHz.

Fig. 4 presents the measured delivered power as a function of Γ_L. It can be clearly seen that the basic PA module has the maximum delivered power at an impedance other than 50 Ω. It can also be observed that the delivered power is highly dependent on the load angle; small changes in load may result in large changes in load power.

When looking at the measurements of the junction temperature in Fig. 5, a possible source of problems can be recognized – the absolute maximum rated junction temperature $T_{J,max}$ is 225°C [2, 3]; with a water temperature of T_{Water}=32°C, that means according to (1) a temperature above about 51°C in pulsed mode with 10% duty cycle corresponds to a thermal overload.

$$T_{J,max,pulsed} = (T_{J,max} - T_{Water}) * 10\% + T_{Water} \qquad (1)$$

To achieve a reasonable lifetime for the LDMOS devices, the junction temperature should be kept below 170°C, corresponding to a junction temperature of 46°C at 10% duty cycle. These values are exceeded in a large portion of the smith chart.

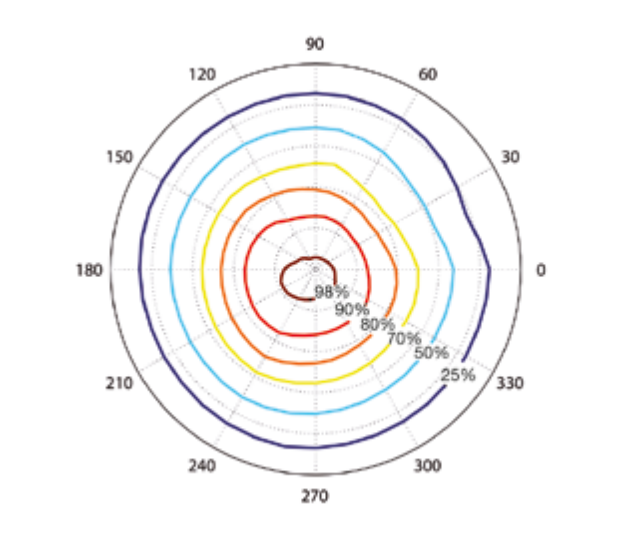

Fig. 6: Load power P_L of the balanced PA over Γ_L normalized to the load power P_L at 50 Ω.

III. Power combining topologies

A RF generator for industrial applications typically needs more power than a single module can deliver, e.g. 50 kW. In this context, the choice of the combining topology plays a very important role.

A. In-phase combining

With an in-phase combining structure, we continue with a network that bijectively maps the load impedance to the drain impedances Z_D. This means that Z_D can attain any value in the smith chart. As the load impedances are mapped from combiner output to the combiner inputs, the peaking of total output power (see Fig. 4) will still be as present as in the single modules albeit in another area.

For LASER applications, such a peaking may be desirable to generate a high voltage for LASER ignition. In this context, the optimum ignition point can be adjusted with the cable length between generator and LASER. Since the load impedances with high junction temperatures correspond to impedances with high incident power, the LDMOS device has to be protected by switching off or reducing the output power at high P_r levels after a certain amount of time.

For plasma applications, a power peaking as shown in Fig. 4 has a significant disadvantage: When deviating from 50 Ω, the delivered power either falls or rises steeply depending on the particular impedance; $|dP_L/dZ|$ is high. Even for small deviations from 50 Ω the available incident power drops very fast at specific load angles $\measuredangle(\Gamma_L)$. This peaking behavior may trigger oscillation effects of the generator/chamber system resulting in an unstable RF power. Hence, a more flat P_L curve would be desirable in order to ensure a stable and reliable plasma.

B. Balanced combining

When combining two PAs with a 3 dB hybrid coupler, e.g. as described in [4], the two PAs are combined 90° out of phase, defined as balanced PA. As the points of minimum and maximum power of a single module are about 90° out of phase as well, the minima and maxima should cancel out. This assumption is confirmed by Fig. 6 illustrating the measured load power of a balanced PA as a function of Γ_L. As expected, high and low powers of each module cancel each other and a flat power distribution is obtained. From matched condition, any load change leads to a uniform decrease in power. Compared to in-phase combining, the gradient $|dP_L/dZ|$ is much smaller. This self-damping characteristic is very advantageous for plasma applications because it helps to eliminate plasma instabilities. Two PAs operating with a 3 dB coupler [4] lead to reproducible and reliable plasma density and stable operation.

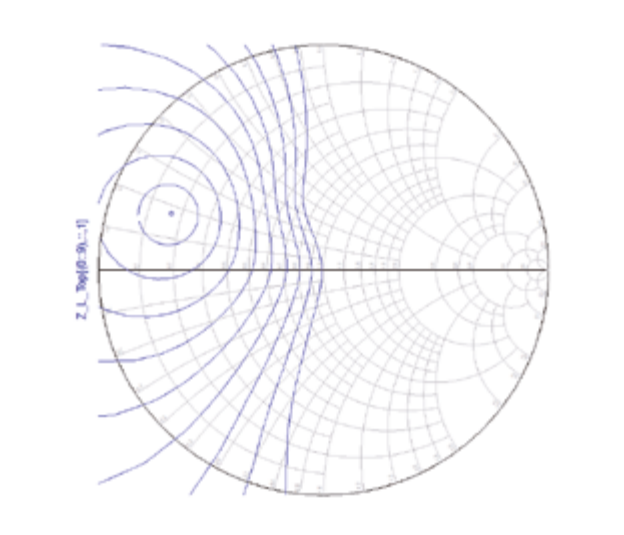

Fig. 7: Load impedance Z_D seen by one LDMOS push-pull pair after sweeping the common load of the balanced PA, $|\Gamma_L| = 0 – 0.9$, $\measuredangle(\Gamma_L) = 0 – 360°$, $Z_{Ref} = 50\ \Omega$.

Another interesting point becomes apparent after taking into account the results in Fig. 7, showing the simulated impedance seen by one LDMOS push-pull pair while sweeping the common load impedance of the balanced PA. In contrast to in-phase combining topologies, the impedance range at the device reference planes is not distributed across the whole smith chart anymore. This effect is used to avoid potentially dangerous impedance areas (e.g. with junctions temperatures above specification) and to increase the robustness of the amplifier. On the other hand, there are areas where Z_D leaves the smith chart and the drain impedance is negative. This effect is caused by active load pulling between both PA modules and has to be carefully considered during the PA design to avoid instabilities. A further advantage of a balanced combining topology is that its output ideally appears like a true 50 Ω source. The hybrid combiner ideally divides the reflected power equally in amplitude but 90° out of phase towards the two amplifer branches; the two amplifers will reflect that power in a way that their power contributions interfere constructively at the absorber resistor port and destructively at the output port of the combiner. That means there are no multiple reflections and ideally no reflected power is returning to the output – a true 50 Ω source.

A disadvantage of the balanced combining is the absorber resistor. It has to be dimensioned large enough to dissipate the power reflected by the amplifiers. That means the resistor needs to be larger than the isolation resistors in common in-phase combiners, which is not only more space-consuming, but also more expensive.

IV. Conclusion

The presented power amplifier measurements show the characterization in mismatch conditions in terms of power and temperature. Possible problems concerning power peaking, asymmetrical power distribution and over temperature of individual modules and combined amplifiers are indentified. It has been shown that in-phase combining and balanced combining structures both have their place.

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[4] TRUMPF Huettinger, Patent US20060197629A1

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