"ON THE FLY" PA DESIGN WITH THE R&S NMDG ZVxPLUS

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Abstract

In cooperation with NMDG [1], world-wide recognized expert in nonlinear network analysis, R&S offers the ZVxPlus add-on kit on top of the high performance R&S ZVA or ZVT vector network analysers. This kit extends the network analysers to accurately characterise nonlinear RF and HF components in the time and frequency domain.

The article shows how engineers can gain complete insight in their components to optimise their performance factors using such a measurement system. With the combination of a vector network analyser and the proper tuning techniques, amplifier designers can now, on the fly, visualise the behaviour of their circuits, optimise their performance based on time-domain measurements and study the impact of changing terminations, caused by, for example, antenna mismatch.

Introduction

Nowadays, Power Amplifier (PA) designers mainly use load-pull systems to extract specifications like Output Power, Inter Modulation Distortion (IMD), Power Added Efficiency (PAE) or Adjacent Channel Power Ratio (ACPR) under different source and load impedance conditions (Figure 1). Such a system [2], based on passive or active tuners, has several drawbacks: preparing the setup with the tuners is time-consuming and cumbersome, while the tuning process is slow due to the power meters which are typically used and the precise movement of the passive tuners. Furthermore, the broadband power measurements do not give full insight in the component. For example, besides the guidance from the component datasheet, one is not sure that the amplifier is operating exactly in the desired class.

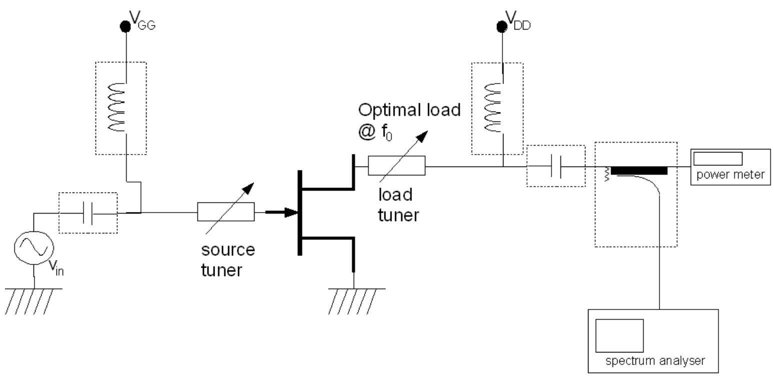


Figure 1: Classical Source and Load Pull Measurement Setup

To overcome these drawbacks and to speed up amplifier characterisation one can use a Large-Signal Network Analyser (LSNA) (Figure 2). The ZVxPlus [3] is an implementation of such a LSNA. It is a hardware and software kit, extending the high performance R&S ZVA or ZVT vector network analysers (VNA) to accurately characterise nonlinear RF and HF components in the time and frequency domain.

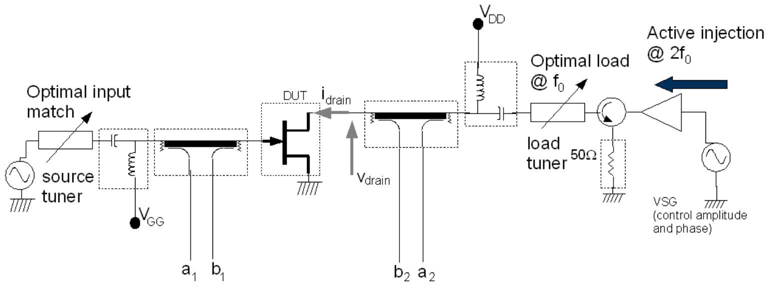


Figure 2: Source and Load Pull Measurement Setup with a LSNA

Presently, calibration of a classic load-pull system requires off-line characterisation of all parts of the measurement setup, typically using a VNA, including pre-characterisation of a tuner for a limited set of impedances. With the alternative LSNA solution, such a calibration is simplified, as the different parts of the setup are calibrated in-situ.

Using such a measurement system, engineers can now gain complete insight in their components to optimise their performance factors.

In the first paragraph, an introduction on the theory of amplifier design is given. Using a simplified model of the component, different classes of operation such as class A, AB, B or C are described.

Next, the ZVxPlus system and its calibration are described.

Finally, thanks to the combination of the ZVxPlus and the proper tuning techniques, it is demonstrated how amplifier designers can now, on the fly, visualise the behaviour of their circuits, optimise their performance based on time-domain measurements and study the impact of changing terminations.

Power Amplifier design in theory

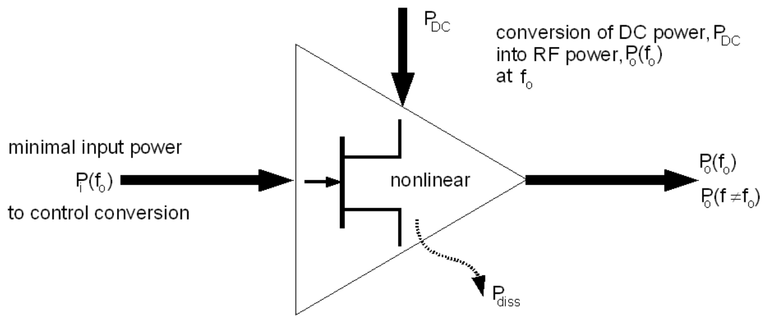


Figure 3: Power budget of an amplifier

A power amplifier is a circuit for converting DC input power P_{DC} into a significant amount of RF output power P_O, using a small input power P_i to control the conversion (Figure 3).

Linearity is a critical factor in PA design, especially when the amplifier is used to boost a signal, modulated in amplitude and phase. Indeed, nonlinearities result in imperfections of the amplified signal, such as distortion. The linearity of RF PAs is typically characterised by IMD, ACPR and error vector magnitude (EVM).

Efficiency is also a main driver of modern power amplifier designs. It characterises how well the DC input power P_{DC} is converted in RF output power P_O, avoiding dissipation of power P_{DISS} through heating of the circuit. Different definitions of efficiency are commonly used.

The overall efficiency can be expressed as:

$$\eta(\%)=100.\frac{P_0(f_0)}{P_i(f_0)+P_{DC}} \tag{1}$$

The power-added efficiency (PAE) gives a reasonable indication of PA performance when gain is high. It is expressed as:

$$PAE(\%)=100.\frac{P_0(f_0)-P_i(f_0)}{P_{DC}} \tag{2}$$

Power amplifiers are typically designated in different classes of operation, e.g. class A, AB, B, or C. All classes use various nonlinear and wave-shaping techniques, i.e. voltage and current waveforms [4].

A typical visualisation tool is the so called dynamic load line display, plotting the output current waveform versus the output voltage waveform on top of the pre-characterised DC current versus voltage curves (Figure 4).

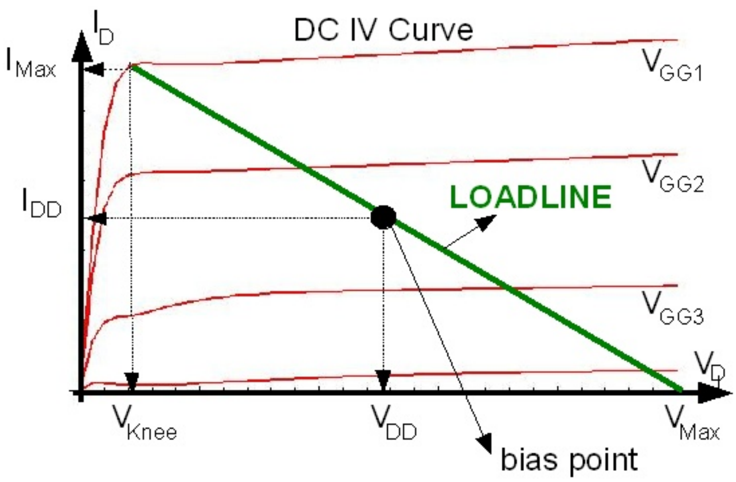


Figure 4: Concept of dynamic load line

The waveform shape of the output current is typically described using the conduction angle α. This angle, expressed in radians or degrees, represents the proportion of the RF cycle for which the device is active.

Class A

In class A, the DC bias current is large enough that the device remains at all times in the active region and acts as a current source, controlled by the input drive. This results in sinusoidal waveform shape for both output voltage and current ($\alpha = 2\pi$ rad). An ideal amplifier in class A is inherently linear. In reality, the nonlinearities depend on the shape of the transconductance, specially around pinch off and saturation. As both positive and negative excursions of the drive affect output current, the amplifier in class A has the highest gain. However, the efficiency of such a amplifier is low (ideally 50%). In consequence, power amplifiers in class A are typically used in applications requiring low power, high linearity, high gain, and broadband operation.

Class B

The input bias of a power amplifier in class B is set at the threshold of conduction so that the DC bias current is (ideally) zero. The device is then active half of the time and the output current waveform is a half sinusoid ($\alpha = \pi$ rad). As such class B introduces distortion of the signal, resulting in less linearity. The efficiency of a class-B amplifier can ideally reaches 78.5%, considering the proper harmonic terminations as explained later in this article. Class B design is typically used in a push-pull configuration so that the two output current add together to produce a sine-wave output.

Class AB

Class AB describes design of power amplifiers in between class A and class B. The input bias is set so that the device is active for more than half the time ($\pi < \alpha < 2\pi$ rad). Class AB sacrifices some efficiency over class B in favour of linearity. As such efficiency is in between 50% and 78.5%.

Class C

In class C design, the input is biased below threshold so that the device is active for less than half the RF cycle ($\alpha < \pi$ rad). Linearity is lost, but efficiency is increased. The efficiency can be theoretically increased towards 100% by decreasing the conduction angle towards zero. However, this results in a decrease of output power towards zero.

Table 1 gives a review of these different classes of operation in terms of theoretical voltage and current waveforms, dynamic load-lines and corresponding factors.

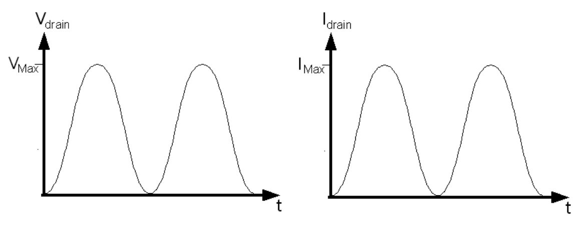
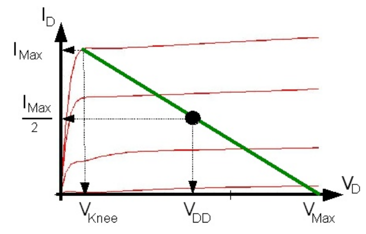
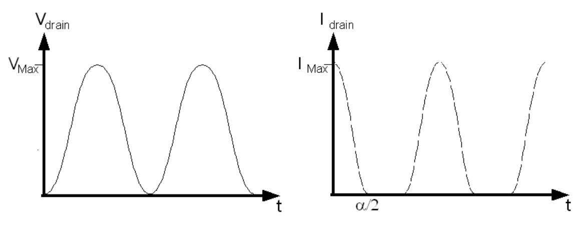
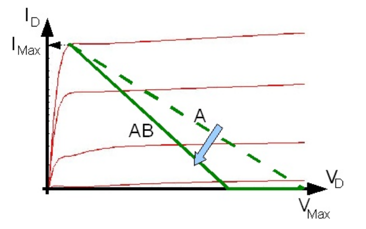
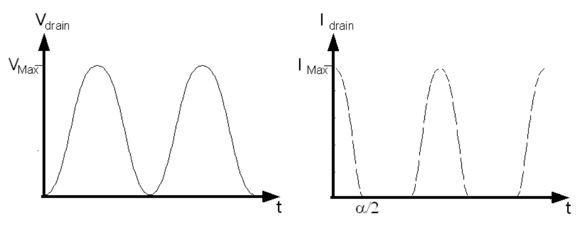
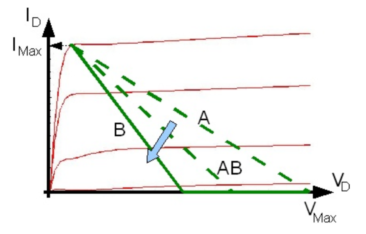
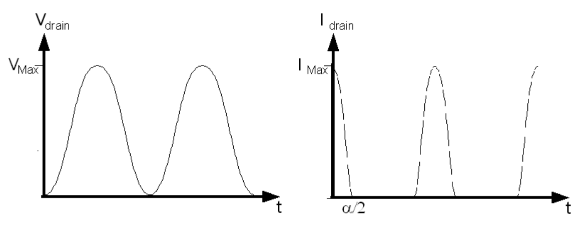
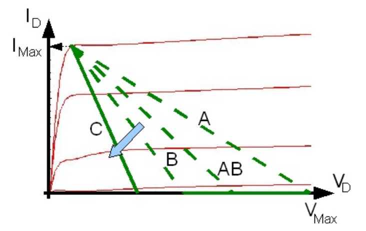
Class of operation	Theoretical Waveform	Dynamic load lines	Remarks
Class A			$\alpha = 2\pi$ rad Linearity: excellent $\eta = 50\%$
Class AB			$2\pi < \alpha < \pi$ rad Linearity: between A and B $50\% < \eta < 78.5\%$
Class B			$\alpha = \pi$ rad Linearity: moderate $\eta = 78.5\%$
Class C			$\pi < \alpha < 0$ rad Linearity: poor $\eta > 78.5\%$

Table 1: Comparison of theoretical behaviour of different amplifier classes of operation

Optimal fundamental and harmonic load impedances

RF transistors are characterised by breakdown voltages and saturated output currents. The combination of the resultant maximum output voltage V_{MAX} and current I_{MAX} (see Figure 4) dictates an optimum load impedance Z_L for delivery of maximum power (Figure 5). This optimal load impedance results in output RF voltage and current excursions from near zero to nearly maximum rated values.

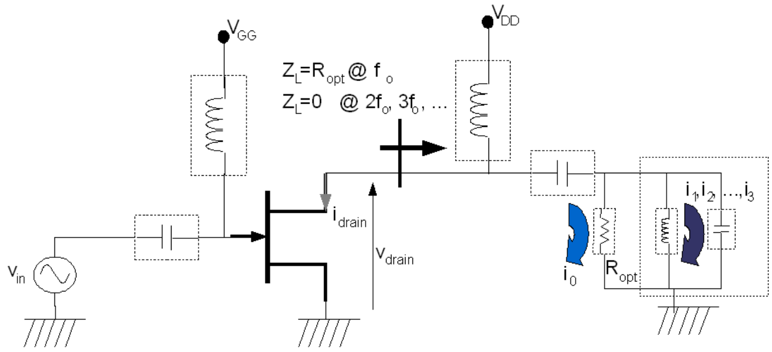


Figure 5: Component load termination

For an ideal power amplifier, i.e. for a component without extrinsic parasitics and no output capacitance, the optimal fundamental load impedance is a simple resistance R_{opt} which can be expressed as:

$$R_{opt} = \frac{V_{MAX} - V_{Knee}}{I_{MAX}} \tag{3}$$

where V_{Knee} is the knee voltage, i.e. the minimum output voltage to “turn-on” the device (see Figure 4).

A proper PA design in class A, AB, B or C requires that any harmonic component in the output current is shortened to ground, avoiding generation of harmonics in the output voltage (Figure 5). For other classes of operation, one typically requires high reflection factors at harmonics.

The ZVxPlus and its calibration

The linear behaviour of RF/HF components like filters, interconnects and transistors under small-signal operation is completely characterised by S-parameters, measured using a VNA. Over time, VNAs evolved from single-ended two-port instruments to multi-port instruments to handle differential linear devices.

Triggered by the growing need for better insight in the nonlinear behaviour of components, VNA manufacturers are adding some “nonlinear” features to some of their models. These features include AM-to-AM, AM-to-PM, harmonic and intermodulation power measurements and mixer characterisation. Unfortunately, these features characterise the nonlinear behaviour only partially.

Complete harmonic characterisation of high-frequency components becomes possible thanks to the ZVxPlus. Extending the capabilities of a VNA, the ZVxPlus accurately measures the amplitude and phase of the incident and reflected waves at the ports of the device under test (DUT), both at the fundamental and harmonics. Amongst others, it is very suitable to characterise diodes, transistors, power amplifiers, multipliers, dividers and fast switching devices.

The ZVxPlus kit consists of a synchroniser, enabling the reconstruction of time waveforms; a harmonic phase reference, supporting the required phase calibration and an easy-to-use software for nonlinear HF component characterisation, supporting system configuration, absolute calibration and measurement. Figure 6 shows respectively a standard block diagram of the ZVxPlus on top of a R&S 4-port ZVA or ZVT and a picture of the system on a R&S 4-port ZVA24.

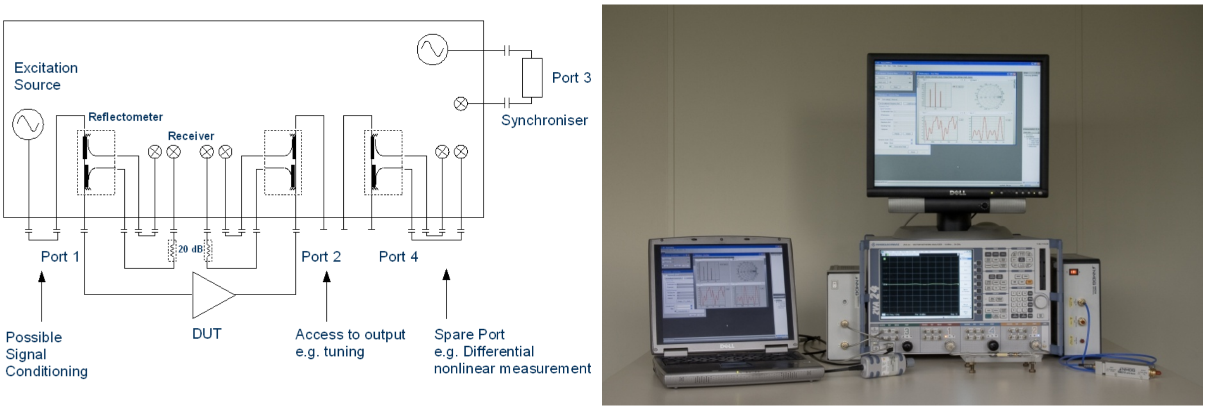


Figure 6: Block diagram and picture of the ZVxPlus

The calibration of such a system requires several steps. First, a VNA-like relative calibration is required using a regular calibration kit. Unlike VNA relative measurements, one needs here to capture the complete information (in amplitude and phase, at both fundamental and harmonics) of the incident and reflected waves. Two more steps are then required. A power calibration using a power meter and sensor is performed at fundamental and harmonics to take into account the loss of the system. Next, the system contains a harmonic phase reference (HPR) [5], which is a unique device that enables the broadband harmonic phase calibration of the system, in order to compensate for the system phase distortion.

As soon as the reference planes are defined using the above calibration, one can (re)-configure the stimuli at input and output of the system without recalibration. One can then study the DUT behaviour in realistic conditions with a single device connection. Furthermore, using passive tuner technology or using fundamental and/or harmonic active tuning techniques, it is even possible to study the behaviour of the component in a non-50 Ohm environment.

PA design in practice using the ZVxPlus solution

It is possible to perform measurements in a non-50 Ohm environment by combining the ZVxPlus with tuning technology. Due to the access to the input and output port, fundamental passive and harmonic active tuning is possible (Figure 6). Once the system is calibrated, one can modify the setup at these ports without invalidating the calibration.

In this section, the design and measurement of a power amplifier in different classes of operation, i.e. class A, AB and B, are performed. The device under test is a commercially available high efficiency heterojunction power FET [6], mounted on a coplanar PCB.

The ZVxPlus system is set up as illustrated on Figure 7. A R&S 4-port ZVA24 is used as VNA. A passive tuner is connected to the accessible output port termination to control the impedance at fundamental frequency f_0. Moreover, a vector signal generator (VSG), combined with an amplifier, is connected via a circulator to the output of the tuner to synthesize actively an impedance at one of the harmonics. For example, by injecting a signal at $2f_0$ with proper power and phase, it is possible to emulate different impedances at 2^{nd} harmonic.

The system has been calibrated for a 1GHz fundamental frequency and up to 10 harmonics at the PCB connector reference planes. Furthermore, proper de-embedding techniques are used to take into account the effect of the PCB board and the parasitics introduced by the package of the device, resulting in measurement of voltages and currents at almost intrinsic level of the device.

The DUT is biased through the internal bias tees of the ZVA and a DC IV characterisation has been performed using the following sweep plan: gate voltage Vg from -1.8V to -0.6V by step of 0.1V and drain voltage from 0V to 7V by step of 0.2V. The resulting DC IV characteristics show up a maximum current I_{MAX} of about 160mA and a knee voltage V_{Knee} of about 0.5V.This corresponds to an optimum resistance R_{opt} of 40 Ohm (equation 3).

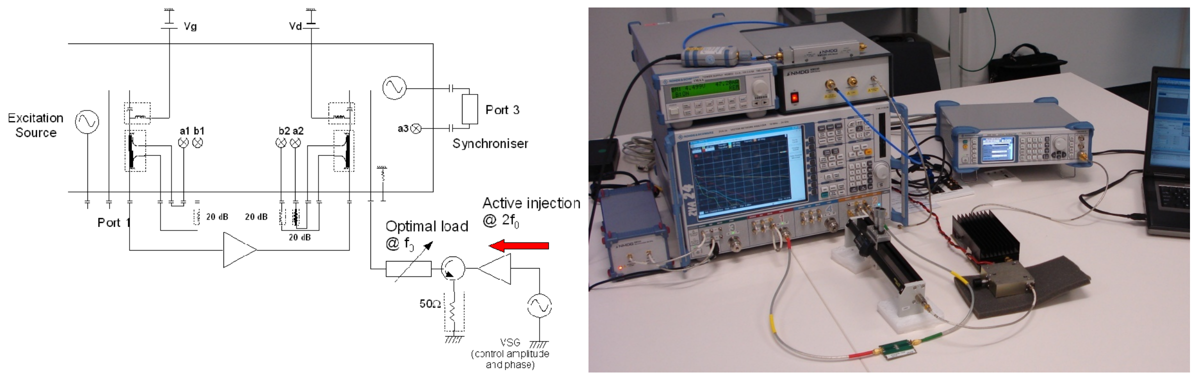


Figure 7: Block Diagram and picture of measurement system: ZVxPlus combined with passive tuner and active injection to control respectively fundamental and 2^{nd} harmonic load impedances.

The described measurement system is then used to set the device successively in class A, AB and B.

For class A design, the DUT is biased with a drain voltage of 3.75V ($0.5*(V_{MAX}-V_{Knee})$) and the gate voltage is selected at -0.8V to obtain a drain quiescent current of about 80mA ($0.5*I_{MAX}$). A 1GHz -1dBm CW signal is applied at input of the device. The passive tuner is positioned to present the optimum resistance R_{opt} as fundamental load impedance at DUT output. Figure 8 shows the resulting drain voltage and current waveforms, output fundamental reflection factor presented to the device and the dynamic load-line on top of the DC IV characteristics. One can see that both voltage and current are sine-wave signals going from about 0 to nearly their respective maximum rated values. A PAE of about 43% is measured in these conditions, close to the theoretical 50% value.

For class AB design, the gate voltage is reduced to obtain a quiescent drain current of about 40mA. The input signal is increased to 3dBm. While the passive tuner is still presenting the optimum resistance R_{opt}, the VSG is used to set the second harmonic load impedance close to a short. Figure 9 shows the corresponding drain voltage and current waveforms, and associated dynamic load-line. While the drain voltage is almost a sine-wave signal, the drain current waveform is clipped for less than half of the RF cycle corresponding to a conduction angle in between π and 2π. A PAE of about 67% is measured in these conditions, in accordance with the theory explained in previous section.

Finally, for class B design, the gate voltage is set close to the threshold voltage. The input signal is further increased to 6dBm. While no modification of the passive tuner is required, one needs to boost and change the phase of the signal injected by the VSG to present a short at 2nd harmonic. Indeed, the 2nd harmonic generated by the DUT at output has changed. Figure 10 shows the resulting drain voltage and current waveforms and associated dynamic load-line. Once again, the voltage waveform is close to a sinusoid, while the current is clipped for half of the RF cycle (conduction angle of π). A PAE of about 74% is measured in these conditions, close to the theoretical 78.5% value.

By using more sophisticated tuning techniques [7], these approaches with the ZVxPlus can be extended to more complicated classes of operation, such as class F.

Conclusions

In this article, the R&S NMDG ZVxPlus measurement system, enabling accurate measurements of the amplitude and phase of the voltages and currents at the ports of a device under test, both at the fundamental and harmonics, has been presented. It has been demonstrated that with such a system, amplifier designers can now, on the fly, visualise the behaviour of their circuits, optimise their performance based on shaping-waves techniques and study the impact of changing terminations.

Thanks to the ZVxPlus it is now possible to match transistors at both fundamental and harmonics to optimise their performance based on instantaneous feedback provided by the voltage and current waveform measurements. The observed waveforms can immediately be compared with the optimal waveforms, described in the textbooks for different modes of operation of amplifiers. Such a solution will surely open new domains and applications.

References

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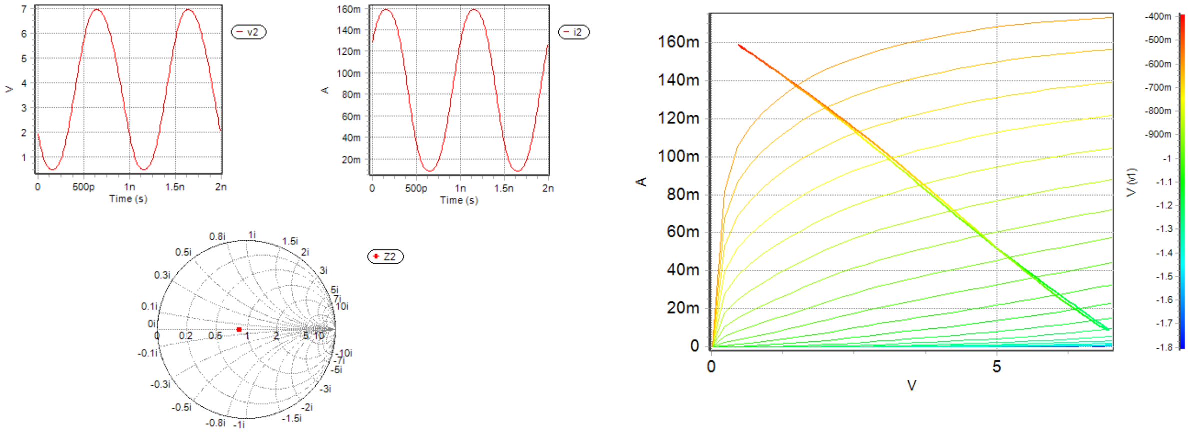

Figure 8: Device in class A PAE:43%

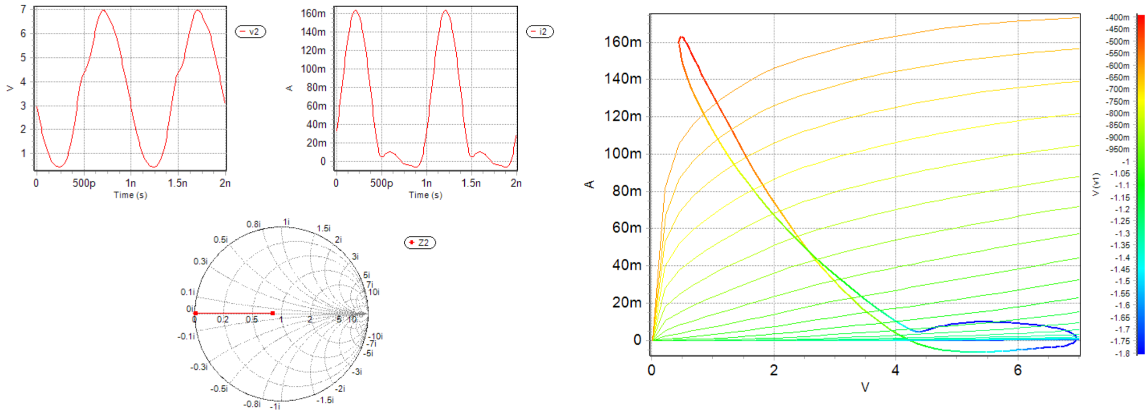

Figure 9: Device in class AB PAE:67%

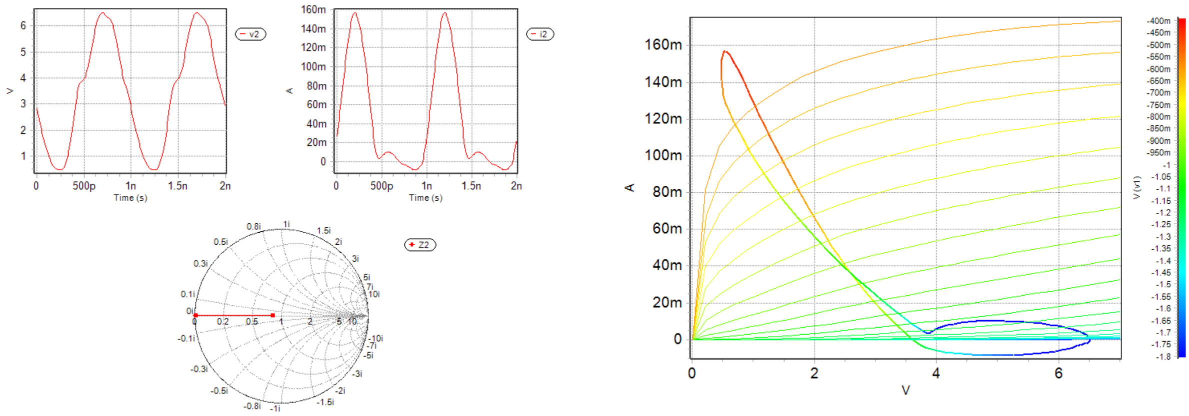

Figure 10: Device in class B PAE:74%