Simulation of a Noise Power Ratio test set and use of it to analyze High Power Amplifier Models in Multicarrier Mode

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Abstract-Noise power ratio (NPR), also known as carrier to inter-modulation noise ratio is an important parameter for analyzing the performance of high power amplifiers in multicarrier mode. In satellites, high power amplifiers are one of the key components in the communication subsystem. All power amplifiers are nonlinear to some degree and if more than one carrier is received by a single amplifier, mixing or intermodulation processes will take place, also the IM analysis becomes complex as the number of carriers are increased in the transmitted signal. In order to analyze intermodulation distortion products, NPR measurement techniques are employed. The objective is to develop a software simulation of such a test set that could analyze the performance of various HPA models in multicarrier mode by measuring the NPR at various back off levels.

***Index Terms*—Noise Power Ratio, Carrier to Intermodulation ratio, Intermodulation Products, Saleh Model, Modified Saleh Model**

I. Introduction

Multicarrier operations are required in satellites to achieve capacity requirements especially when the available bandwidth is limited. Due to the nonlinear behavior of the HPAs, multicarrier transmission generally suffers from IM distortion while HPAs are operating at saturation and also when the number of carriers is increased in the transmitted signal. If a number of carriers are present simultaneously in an amplifier, the operating point must be backed off (BO) to a linear region to reduce the effects of IM distortion. This BO leads to an in-efficient use of the system recourses.

Satellite communication systems often require multicarrier operations, as very high capacity is needed and limited frequency bandwidth is available. Hence, the IM distortions due to the nonlinear behavior of the HPAs have to be analyzed to evaluate the performance of the HPAs in multicarrier mode operations. Also the IM analysis becomes complex when several carriers are present in a non-linear channel, leading to the need of NPR measurements. NPR is an important figure of merit for analyzing the IM distortion performance of HPAs in satellites.

II. NPR Measurement Methodology

The basic methodology adopted for the measurement of PR is to generate a test signal (white noise) representing a multicarrier signal with random amplitude and phase. This test signal is then passed through filters (Band Pass and Notch) to shape the test signal into a specific test signal which is used to excite the high power amplifier model. The IM distortion products produced as a result are analyzed to measure the C/I or the NPR [1].

III. NPR Test Set

The NPR test set comprises of various blocks that represents various modules of the simulator as shown in figure 1.

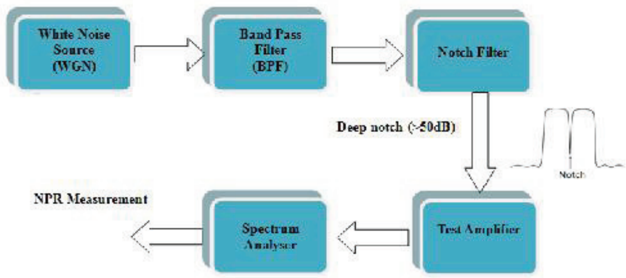

Fig. 1. Block diagram of NPR test set

The white noise source generates white Gaussian noise (WGN) which represents fairly accurate model of a multi-carrier signal. WGN is used because of its property of having an infinite bandwidth in frequency domain which is useful in simulating a multicarrier signal of any bandwidth at any center frequency. Hence we can say that the white noise can be treated as a random signal with a flat power spectral density [2]. This noise signal is then passed through a band pass filter (BPF). The output of the BPF is a square spectral platform of noise, simulating the presence of multicarrier signal with random amplitude and phase. This signal is then passed through a narrow band stop filter to produce a deep notch (typical notch depth > 50dB) [1] at the center of the noise platform as shown in figure 1. After the notch filter, the signal is passed on to the test amplifier model where the nonlinear characteristics of the HPA will produce IMD products, which will then tend to fill in the notch [1]. The output of the HPA model under test is analyzed by taking the fast Fourier transform (FFT) and the measurement of the depth of the notch with respect to the carrier level at the output of the HPA gives the measurement of the NPR. Various NPR values are simulated for a range of input back off (IPBO) and a curve of NPR vs. OPBO is generated. The curves of NPR vs. OPBO obtained from the simulation are compared with the actual NPR data, obtained from Astrium Ltd. via Stephen O'Shaughnessy [3]. The accuracy of the simulator along with the amount of systematic error is determined for every IPBO value and is incorporated in the simulation results.

IV. High Power Amplifier Models

In order to model the amplifier we need to have the amplifier transfer characteristics data. The amplifier performance is described by its output power and input to output phase shift values that are generated using a number of input power values. The measurement values are taken using a single carrier input signal. By having large input back off, the input signal falls in the linear region of the amplifier and by giving small input back off, the signals falls in the saturation region of the amplifier [3].
The AM/AM and AM/PM conversion curve for the linearised TWTA amplifier is taken from Astrium Ltd. via Stephen O'Shaughnessy [3] and is shown in figure 2.

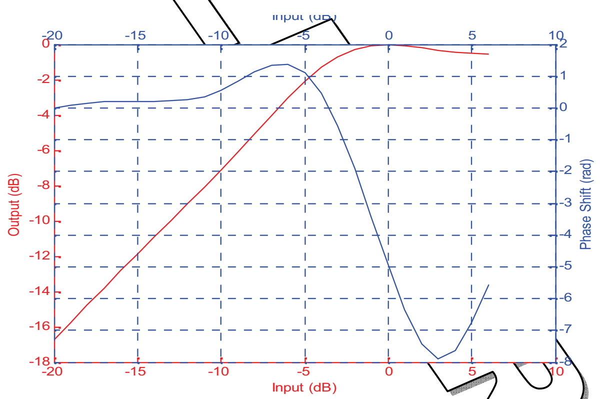

Fig. 2. AM-AM and AM-PM curve for a linearised TWTA

The high power amplifier under test (UT) in the simulator is a behavioral model of the actual HPA. The TWT amplifier has been modeled using the Saleh [4] and modified Saleh [4] model and the results are compared with the actual HPA data. The nonlinear behavior of the HPA is characterized by the two standard functions which define the AM/AM and AM/PM conversions in the Saleh [5] and modified Saleh model [6].
The functions for Saleh model are:

$$g(r) = \frac{\alpha_a r}{1 + \beta_a r^2} \quad (1)$$

$$\phi(r) = \frac{\alpha_\phi r^2}{1 + \beta_\phi r^2} \quad (2)$$

Where, α_a = 1.604555, β_a = 0.630555, α_Φ = -0.08644 and β_Φ = 0.35645. These values are selected according to the amplifier under test.

The functions for modified Saleh model are:

$$g(r) = \frac{ar + br^2}{1 + cr^2 + dr^3} \quad (3)$$

$$\phi(r) = \frac{er^2 + fr^3}{1 + gr + hr^2} \quad (4)$$

Where, a = 1.165445, b = 1.627, c = 1.3734, d = 0.42005, e= 14.145, f= -35.25, g= 56.445 and h= 323.65. These values are selected according to the amplifier under test.

These coefficient values for Saleh and modified Saleh model are generated using the standard minimum mean square error curve fitting equations as given in the Appendix of Saleh [5].

The two equation g(r) and Φ(r) are used to implement the AM/AM and AM/PM conversion curves for Saleh and modified Saleh models. The value of 'r' representing the IPBO and is varied from 5 to -20 dB. The function g(r) provides the corresponding OPBO and the function Φ(r) provides the corresponding value of phase (degrees) change according to the given IPBO.
The AM/AM and AM/PM conversion curves using the Saleh and modified Saleh model are shown in figure 3 and figure 4 respectively.

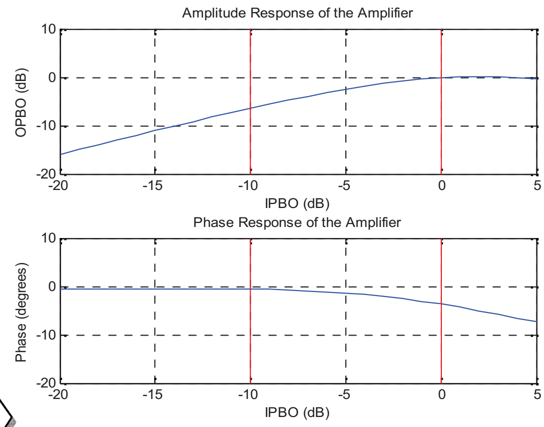

Fig. 3. Saleh model – AM/AM and AM/PM conversion curve

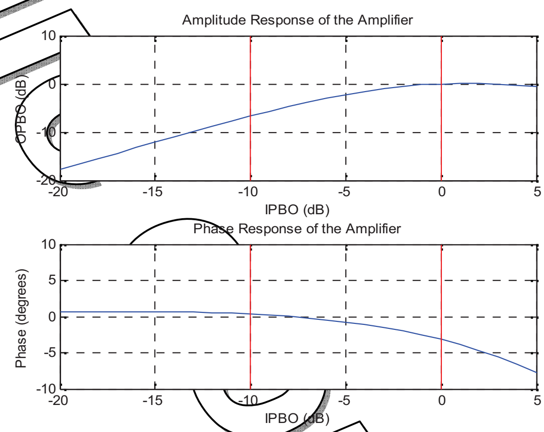

Fig. 4. Modified Saleh model – AM/AM and AM/PM conversion curve

V. NPR Measurement

NPR measurement is achieved by first averaging the carrier power level (dB) and the noise level (dB) of the notch before and after the high power amplifier model and then by taking the difference of these levels. This measured NPR consist of systematic error as well as measurement inaccuracies. These errors are discussed later on and are incorporated in the simulation results. NPR is measured using the Saleh model and modified Saleh model with an input back off of -10dB (Systematic error and the measurement inaccuracy has been considered in the results) and the results are shown in figure 5 and 6 respectively.

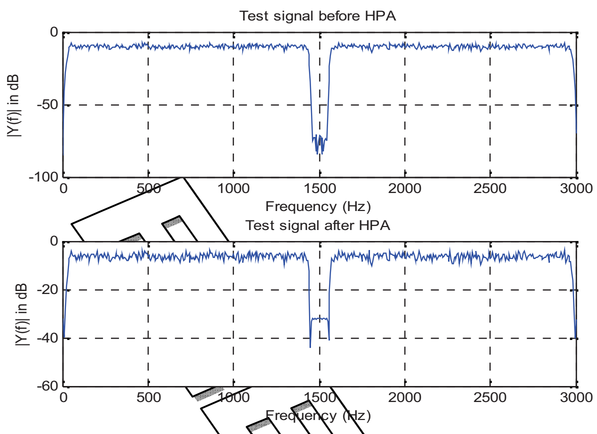

Fig. 5. Test Signal before and after the HPA (Saleh model)

IPBO = -10dB
Number of carrier bin frequencies = 233
Number of noise bin frequencies = 17

- *Before HPA model:*
  Average Carrier Power = -9.8386dB
  Average Noise Power = -72.123dB
  NPR = 62.284dB

- *After HPA model:*
  Average Carrier Power = -6.1741dB
  Average Noise Power = -32.254dB
  NPR = 26.08dB.

Similarly, using modified Saleh model the signal before and after the amplifier model is as follows:

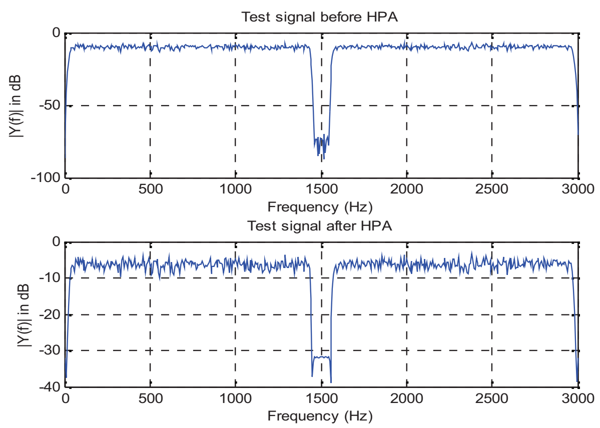

Fig. 6. Test Signal before and after the HPA (Saleh model)

- *Before HPA model:*
  Average Carrier Power = -10.043dB
  Average Noise Power = -72.813dB
  NPR = 62.77dB

- *After HPA model:*
  Average Carrier Power = -6.3803dB
  Average Noise Power = -32.417dB
  NPR = 26.036dB.

VI. SYSTEMATIC ERRORS IN THE MEASURED NPR

These are errors in measurement which lead to the case where the mean of different measurements differs significantly from the actual value. A systematic error is occurred when the measured NPR is close to the test set notch depth. When the bottom of the measured notched is within 10 dB of the test set notch depth, this systematic error is most significant. The error can be corrected with the use of the following correction [7].

$$NPR = 10\log\left(10^{-\left(\frac{NPR_m}{10}\right)} - 10^{-\left(\frac{NPR_t}{10}\right)}\right) \tag{5}$$

Where NPRm is the measured NPR and NPRt is the NPR of the test signal. As NPRm approaches NPRt, measurement precision will be degraded. A correction chart has been produced for finite notch depth = 60dB for modified Saleh model and is shown in figure 7. We can confirm from the figure 7 that as the measured NPR gets close to the test set notch depth, the systematic error becomes significant [1].

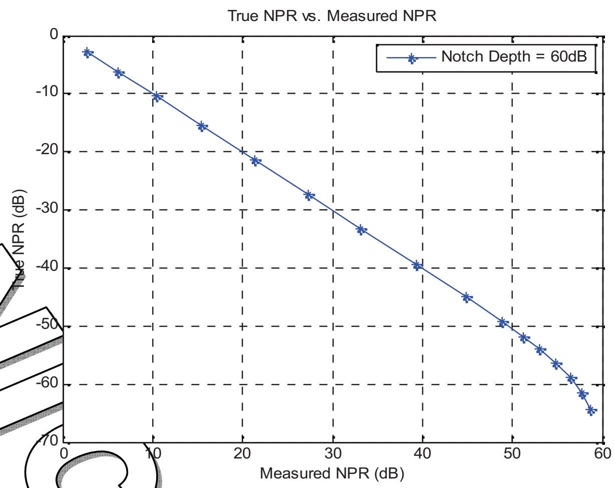

Fig. 7. Correction chart for true NPR for finite notch depth (60dB)

The test signal used in the simulation had a notch depth of around 60dB. The following graphs in figure 8 and figure 9 show the systematic errors with respect to the simulated NPR values for IPBO ranging from 0dB to -20dB for Saleh Model and modified Saleh model respectively. Systematic errors are used to obtain true NPR from the simulated NPR values.

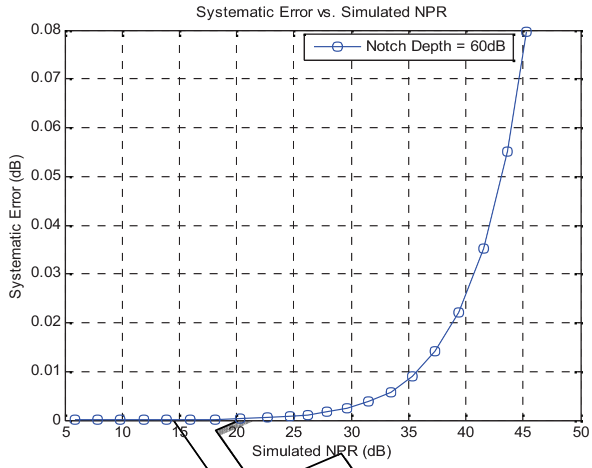

Fig. 8. Systematic Error in simulated NPR (Saleh model)

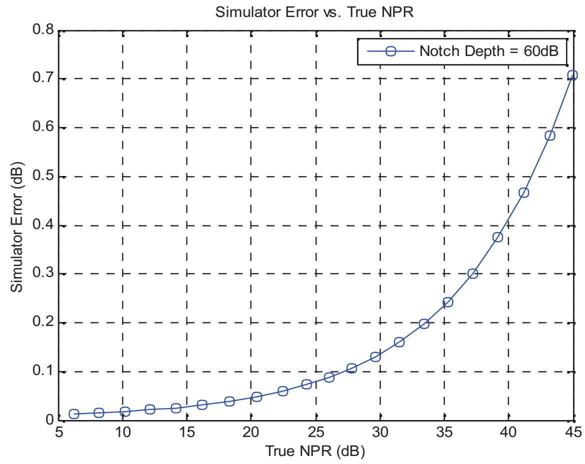

Fig. 10. Simulator Error in True NPR (Saleh model)

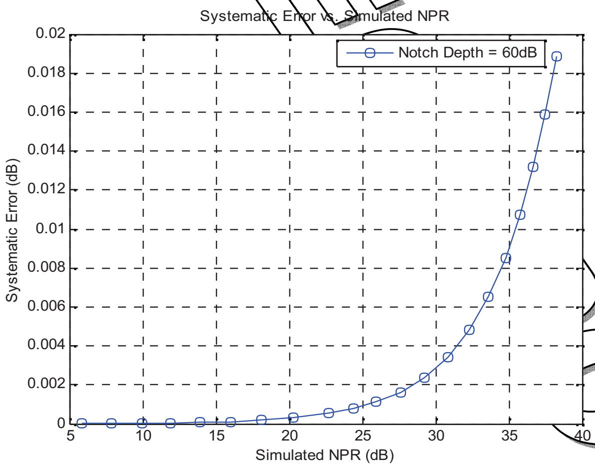

Fig. 9. Systematic Error in simulated NPR (modified Saleh model)

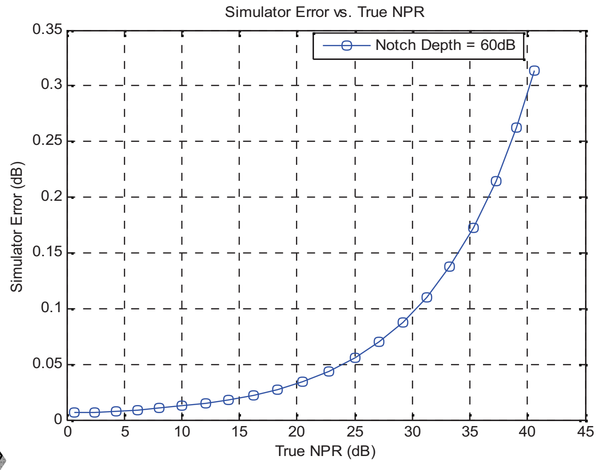

Fig. 11. Simulator Error in True NPR (modified Saleh model)

VII. Simulator Accuracy

Accuracy of the simulator is very important in order to determine the amount of error in the measurements. In order to determine the accuracy of the simulator we first consider that the amplifier is perfect and then we measure the level of notch before and after the amplifier model.

The difference in levels determines the accuracy of the simulation. It can be understood with the help of an example. If the difference in level comes out to be -40dB, we take its linear value i.e. 0.01. It means if the actual input was 1 then the output could be 1.01 or 0.99. By taking the 20log of these values we can obtain the accuracy of the simulation. As in this case the accuracy of the simulation is found out to be ±0.086dB.

The following graphs in figure 10 and figure 11 shows the simulator errors with respect to the true NPR values for IPBO ranging from 0dB to -20dB for Saleh model and modified Saleh model respectively.

VIII. Default Settings

The model proposed by Saleh [5] is a frequency independent nonlinear model of TWT amplifiers [5], so any frequency value can be selected for the simulation. As a default value, the test signal has maximum frequency component of 3 KHz, therefore sampling frequency is taken as twice the maximum frequency component (Nyquist frequency). This value of sampling frequency is user defined and is changed according to the required test signal.

The default FFT size is chosen to be 512. Increasing the number of FFT points beyond 512 only increases the computation time. It is shown in figures 12 and figure 13 that the systematic error and the simulation error do not improve considerably for higher FFT size. Figures 12 and figure 13 have been generated using the Saleh model.

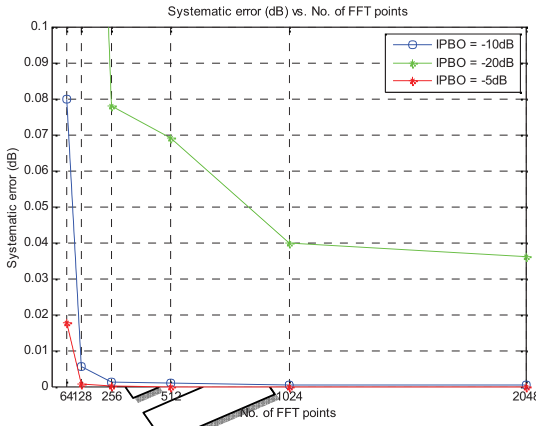

Fig. 12. Systematic error vs. No. of FFT points

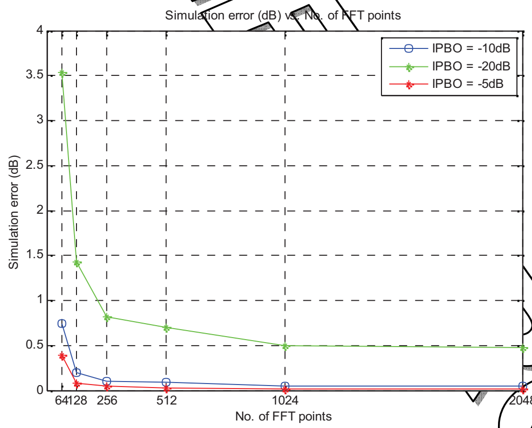

Fig. 13. Simulator error vs. No. of FFT points

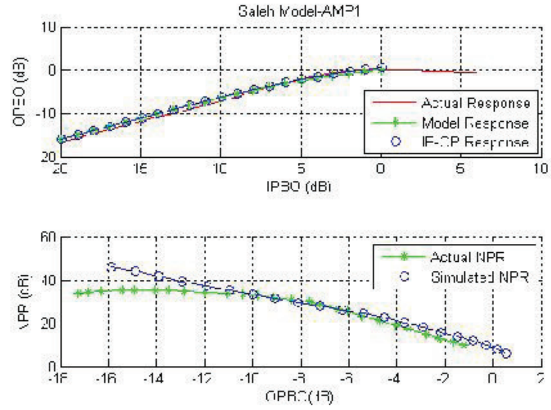

Fig. 14. IP vs. OP and Simulated NPR vs. Actual NPR for Saleh model

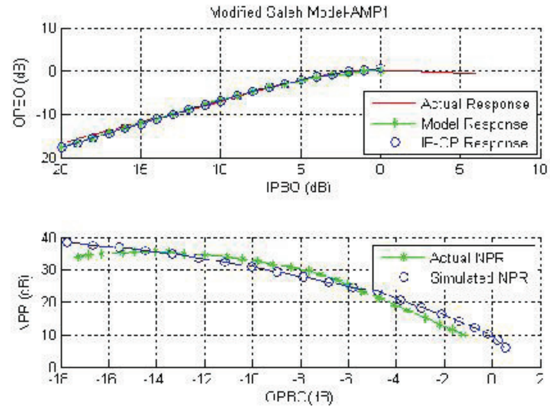

Fig. 15. IP vs. OP and Simulated NPR vs. Actual NPR for modified Saleh model

IX. RESULTS

A. *Amplifier model I/P – O/P responses*

In order to confirm proper functionality of the amplifier model, we need to observe the input (IP) - output (OP) response of the amplifier model under test. The IP (dB) & OP (dB) values are calculated by taking the average value of the carrier bin frequencies before (input) and after (output) the amplifier model. The IP-OP curve generated by varying the input back off (IPBO) represents the amplitude response of the amplifier model. The IP-OP curve for Saleh and modified Saleh models are compared with the actual amplifier response. The IP-OP response closely matches the actual response as shown in figure 14 and figure 15, hence the obtained NPR values are considered to be accurate.

B. *Simulated NPR vs. Actual NPR*

The graphs of simulated NPR vs. actual NPR for the Saleh model and the modified Saleh models are shown in figure 14 and figure 15 respectively.

The simulated NPR values are compared with the actual NPR data provided by Astrium Ltd. The NPR curve for Saleh Model and modified Saleh model are simulated for input back off ranging from -20dB to 0dB and are compared with the actual data. The results are shown in figure 14 and figure 15 respectively.

X. GRAPHICAL USER INTERFACE

The graphical user interface (GUI) developed for the NPR test set is shown in the following figure 16.

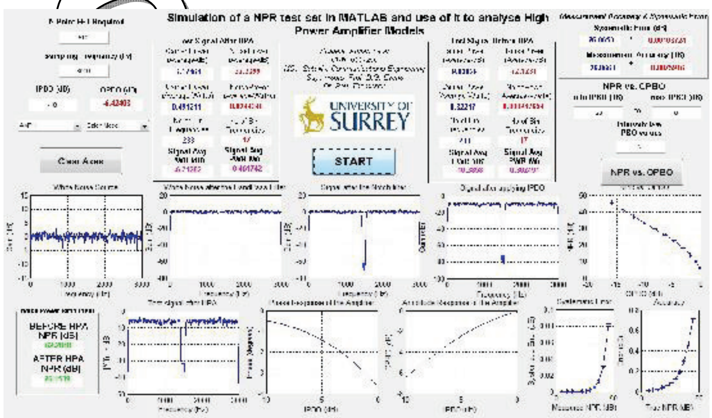

Fig. 16. GUI of NPR test set developed in MATLAB

XI. Conclusion

Computer based simulation techniques can be applied for developing a tool like NPR test set but simulation based approaches can have possibilities of inaccuracies especially while modeling the complex nonlinear components of the system. Hence detailed mathematical modeling is required to have accurate simulations [8].

The GUI for NPR test set has been developed in MATLAB and a TWT high power amplifier is modeled in the simulator using Saleh and modified Saleh behavioral modeling. Any high power amplifier can be modeled using the AM/AM and AM/PM curves available in its data sheet and then by incorporating the modeled amplifier in the test set, the performance of the amplifier model can be evaluated in multicarrier mode.

NPR values are simulated for a range of IPBO and curves of NPR vs. OPBO are generated for both the amplifier models. The NPR curves obtained from the simulation are compared with the actual NPR curves to evaluate the performance of the modeled amplifiers. The simulated NPR results have been found out to be approximately similar to the actual NPR data. Systematic errors and simulator accuracy have also been determined and incorporated in the simulator.

Analyzing the simulated NPR curves, it is concluded that for higher values of IPBO, the value of noise power ratio (NPR) is also large. It is because the greater the IPBO (The amplifier will be operating in the linear region), less IM products will be produced. Likewise, higher IM products will be produced when the amplifier is operating in the nonlinear region i.e. at saturation (In case of low IPBO). Thus, operating the high power amplifier model in the linear region leads to less number of inter-modulation products and the depth of the notch will be less filled and hence the noise level will be low and consequently the carrier to IM noise level will be high and vice versa.

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