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APPROXIMATE MODELS OF THE INVERSE PROBLEM FOR DETECTOR CHARACTERISTIC

Characteristics of semiconductor diodes as power indicators are studied. The rigorous electromagnetic model of the direct problem of average detection current is derived using Shockley ideal diode equation for I-V characteristic with taking into account the influence of a load and a source resistance. This model is used for testing the variety of approaches to the solution of inverse problem of recovering the input power through output voltage. Some of approximate models of the inverse problem for detector characteristic such as Hoer-Roe-Allred's, Potter-Bullock's, Zhaowu-Binchun's, and polynomial model are under consideration. Approximate models of the inverse problem for detector characteristic based on "polynomial" with non-integer power and rational-fractional representation are proposed. The application of continuous fractions for the numerical implementation of the last approach demonstrates its advantages. Maximum errors of approximation for different orders of approximating models and source resistance are calculated. The comparison the new approaches and application of neural networks based on radial functions is carried out.

Keywords: power measurements, nonlinearity correction, rational-fractional approximation, non-integer power, neural networks.

1. Introduction

Semiconductor diodes are widely used in various electronic measuring setups [1-6] as detectors of radiofrequency (RF) and microwave signals. The current-voltage characteristic of a semiconductor diode is well-known [7, 8] and this characteristic provides the solution of the direct problem. But for implementation of majority of measuring schemes the dependence of the power versus voltage depending on diode current is need to be used. This problem can be interpreted as the inverse one. Semiconductor diodes have substantial advantages over thermistors due to lower requirement to signal power level and faster operation [1]. But unrepeatability of the input impedance and deviation of output voltage of detector versus the measuring power from ideal linearity are their disadvantages.

For improvement of the measurement accuracy, a correction of this nonlinearity should be made [2, 9-11]. A flexible method of approximation gives the use of radial basis functions. An artificial neural network, operating with this basis, can effectively approximate functions with arbitrary behavior [12], so there is reason to use this approach. For a comparison of approaches to the solution of the diode inverse problem, in the present paper the algorithm of the rigorous computer simulation of the direct problem of average detection will be proposed. It will be applied to investigation of the maximum errors of proposed models (polynomial, fractional, neural networks on base of radial functions etc.) of the detector inverse problem.

2. Known approximate inverse models of detector characteristics

The simplest procedure of the correction is based on assumption that detector works in the square-law region for low power levels and in linear region for high levels of the RF input power. This fact leads to the following expression of the solution of the detector inverse problem [3]:

$$P = c_1 U + c_2 U^2 , \tag{1}$$

where unknown parameters c_1 and c_2 should be estimated from the procedure of the calibration.

Many experimental and theoretical investigations [7, 8], shows that model with two regions does not give a correct presentation of the detector characteristics especially when the temperature is low and the bias current is small. In the last situations exponential region [7, 8] appears for intermediate level of RF power. But even for normal temperatures and bias currents the accuracy of the simplest model (1) is not satisfactory for a precision measurement even in the two-region situation.

There are many papers devoted procedures of the calibration of detectors and correction their nonlinearity for their use in six-port reflectometers [4-6, 13]. They have used approximate models of higher orders for decreasing errors of the inverse solution beside square-low region. The most popular model is Hoer-Roe-Allred's one [1, 4, 5]. It is proposed in [9] and has form

$$P = c_0 U^{f(U)} , \tag{2}$$

$$f(U) = 1 + c_1 U + \ldots + c_n U^n . \tag{3}$$

Potter-Bullock's model [10] is also widely used [6, 13] and described by expression

$$P = KU \exp\left(\sum_{m=1}^{n} c_m U^m \right). \tag{4}$$

Sometimes Zhaowu-Binchun's model [11] is considered

$$P = KU \exp\left\{ \ln(10) \sum_{m=1}^{n} c_m \left[\ln(U/q + 1) \right]^m \right\}. \tag{5}$$

The use of polynomial model for six-port reflectometers [2] should be also mentioned

$$P = \sum_{m=0}^{M} c_m U^m . \tag{6}$$

All these models supply correct behavior for small value of input RF power and some improvement in the beginning of the transition region. But in the region of linear detection high-order models cannot be useful. In the region of exponential detection, the inverse solution must be close to logarithmic behavior which should not be described by exponential function against polynomials of higher order.

3. Solution of direct problem and comparison of maximum errors for different approximate models

In [7, 8] some numerical and analytical approximate models of the direct problem have been proposed. They have good agreement with experimental data for some particular cases. But their errors cannot be controlled.

In present work for obtaining numerical solution of the direct problem we proposed a computer simulation of a detection process in the static assumption. The simulation is based on Shockley ideal diode equation for I-V characteristic [7]

$$I_D = I_T \left[\exp(U_D / U_T) - 1 \right], \tag{9}$$

where I_D and U_D are the current and the voltage across the diode, I_T is the saturation current, U_T is the effective thermal voltage ($U_T \approx 25$ mV for the room temperature [8]). For average detection source current I_m for given source voltage U_m can be found from equation:

$$I_m = I_T \{\exp[(U_m - I_m R)/U_T] - 1\}, \tag{10}$$

where R is total resistance of the source, the load and linear part of diode.

For some particular cases simple expressions for initial value I_{iv} of I_{m} can be written. For small value of resistance R we have

$$I_{iv} = I_T [\exp(U_m / U_T) - 1]. \tag{11}$$

For small value of source voltage U_m we have

$$I_{iv} = U_m / (R + R_d), \tag{12}$$

where $R_d = U_T / I_T$ is the differential resistance of the ideal diode.

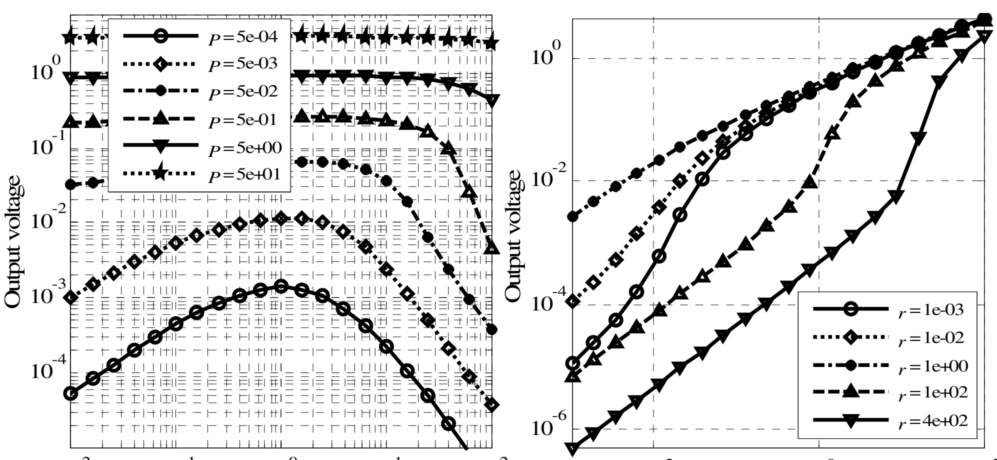
For a large forward value of source voltage U_m we have

$$I_{iv} = U_m / R. \tag{13}$$

For large reverse value of source voltage U_m we have

$$I_{iv} = I_T. \tag{14}$$

By some intellectual efforts higher-order analytical approximations of solution of (10) can be obtained. Numerical solutions of (10) have been found by the Newton method. For meander-shaped signals we need the solution of (10) only for two values of source voltage U_m. For sinusoidal signals we have used 120 values of U_m on the period of the oscillation. The average value of $U_m - I_m R$ is used as output voltage U of average detector. The results of computer simulation of solution of direct problem are shown in Fig. 1.



a b

Fig. 1. Output voltage versus relative resistance of source for different input RF power (a) and versus input RF power for different relative resistance of source (b).

4. Numerical simulation of new approximate inverse models of detector characteristics

An approximation of high order with correct asymptotic behavior for small and large levels of input microwave power can be achieved by application of "polynomial" with non-integer power. For example, we have used following formula:

$$P=\sum_{m=0}^{M} c_m U^{1+\frac{m}{M}} . \tag{7}$$

It is clear, that the non-integer powers of elements in "polynomial" have values in the range from 1 to 2 equidistantly. The step of the power increasing is equal to m/M and depends on the order M of the model. One of the most powerful mean for a solution of the approximation problem is the ratios of polynomials or fractional-rational expressions [14]:

$$P=\frac{\sum_{m=0}^{M} c_m U^m}{\sum_{m=0}^{M+1} d_m U^m} . \tag{8}$$

This model has $2M+1$ degrees of freedom instead of M degrees of freedom for the previous models. The fractional-rational approximation using the interpolation by continued fraction provides rather stable results [14] thus this computational scheme has been applied. An artificial neural network, operating with basis of radial basis functions, has been used for the solution of the inverse problem.

Verification of the applicability of known and proposed approximate models of the inverse problem (determination of the incident microwave power from the voltage at the output of the detector) can be performed using the experimental data or results of computer simulation of rigorous direct models. Maximum relative errors versus relative resistance of source *r* for different orders of approximation *M* are presented in Fig. 2-3.

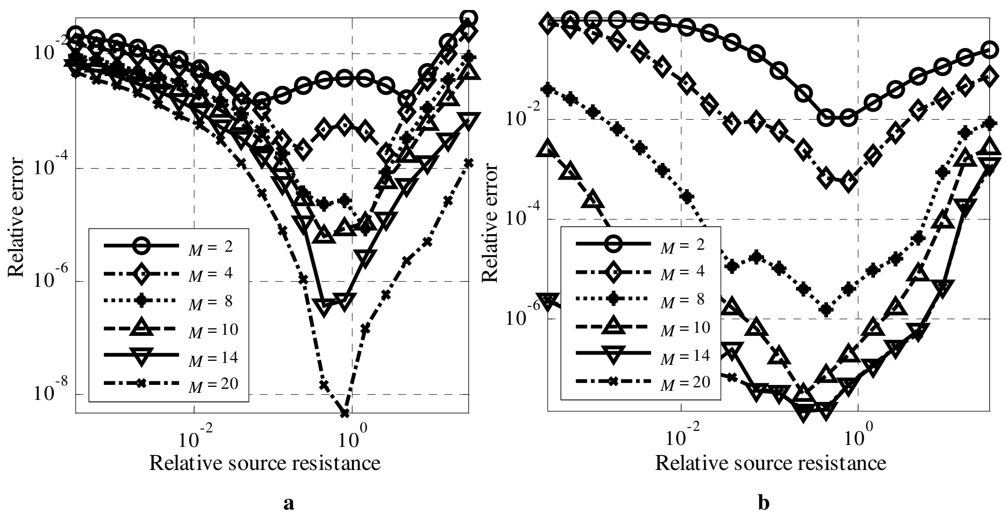
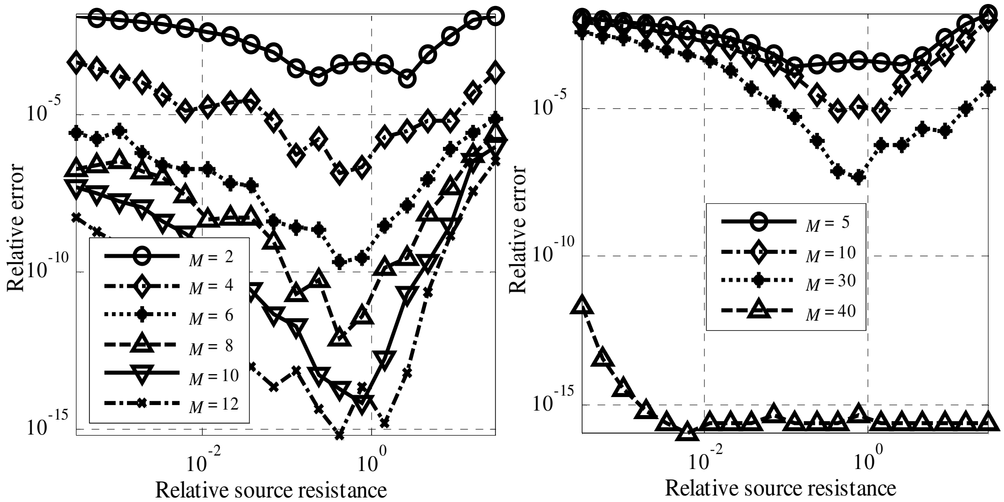


Fig. 2. Maximum relative error versus relative resistance of source for different order *M* of approximating polynomial (a) and polynomial with non-integer power (b).



a **b**

Fig. 3. Maximum relative error versus relative resistance of source for different order *M* of the order of polynomial (a) in fractional-rational expression and neural network (b).

For implementation of the artificial neural network the parameter "spread" has been chosen as the tripled value of M-th part of the range of independent variable variation. The dependence of maximum relative error versus relative resistance of source for polynomial with non-integer power has wider region of minimum with less level than for approximating polynomial for different orders M , for instance M=14. But the fractional-rational approximation using the interpolation by continued fraction for M=6 (the number of degrees of freedom is 13) provides better results. The neural networks have not preferable results in comparison with fractional-rational approximation ones for the case of equivalent numbers of degrees of freedom but for M=40 networks provide more accurate results. A comparison of the best error of approximation by different methods with the maximum orders of the models is presented in Fig. 4.

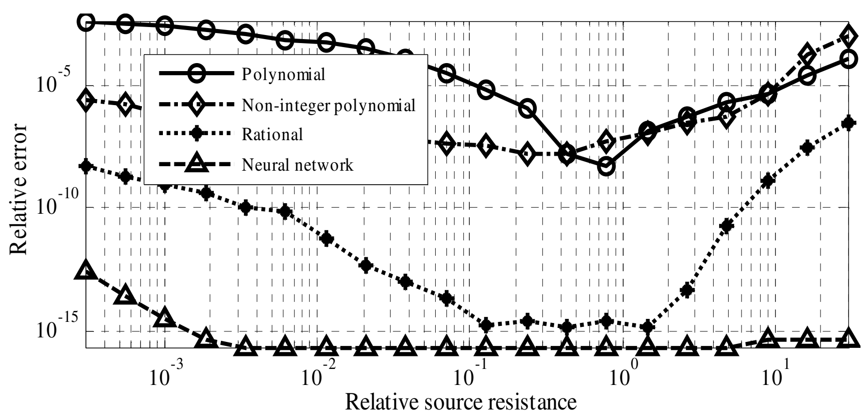


Fig. 4. Maximum relative error versus relative resistance of source for different approximate models.

5. Conclusions

The best results of the inverse problem for semiconductor diode (determination of the incident microwave power from the voltage at the output of the detector) in comparison with traditional approaches are provided by rational approximation based on continued fraction and the neural network on base of approximation with the radial basis function.

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