UNIVERSITY “POLITEHNICA” OF BUCHAREST

Doctoral School Electrical Engineering

Frequency modelling and analysis of circuits with nonlinear passive components

DOCTORAL THESIS SUMMARY

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CONTENT OF THE TESIS

CHAPTER 1 INTRODUTION

The continue evolution of technologies containing integrated circuits (ICs) has allowed the processing of large volumes of data in the digital domain, at high speeds and low power consumption. The efforts of IC manufacturers to replace analog and digital functions in applications with and without semiconductors have proven extremely difficult in the field of radio frequency (RF) and especially in the field of filtering unwanted signals for the radio communication interface of mobile devices.

Radiofrequency filtering using CMOS technology and their integration into compact structures is possible, but it has the disadvantage that it has much more nonlinearities than in the case of independent radio frequency filter structures.

In practice, successful attempts have been made to integrate passive radio frequency filters into Si-based chip structures, but in terms of mass production, this is of no interest to manufacturers, due to the complexity of multi-band and multi-standard applications. for mobile radio devices.

These passive filters used in the radio interface of mobile communication devices exhibit nonlinear behaviour in terms of radio signal generation. This nonlinear behaviour can have various influences on the operation of mobile radio devices, as will be presented below.

The effects of the non-linearity of the radio frequency filters (amplitude-frequency and the intermodulation effect) were studied in Chapter 2 where two new models of fast simulation were developed using the parameters S of the BAW filters (Bulk Acoustic wave).

In chapter 3 the intermodulation effect, the amplitude-frequency effect and the second harmonic were analyzed by making measurements at different powers of the received signals.

Chapter 4 deals with the influence of passive components in energy networks, highlighting the effects generated by them. At the same time, a new simulation model for energy networks in the field of frequency is proposed.

CHAPTER 2 BEHAVIORAL MODELS FOR BAW POWER FILTERS WITH EXCITING UNI – TON

2.1 A NEW BEHAVIORAL MODEL OF POWER BAW FILTERS FOR FREQUENCY ANALYSIS WITH UNI-TON EXCITES

Power BAW resonators are weak nonlinear circuit components, and their behavioural models contain linear and weak nonlinear circuit elements. The latter have polynomial nonlinearities for which terms of order greater than one have coefficients whose values are much lower than 1. Such an example is shown in Fig. 2.4 where the coefficients are assigned to each nonlinear circuit element in the ADS simulator by the parameter "coeffs = list ()".

The behavioural model proposed in Fig. 2.4 for a BAW power filter, with two ports was made as follows:

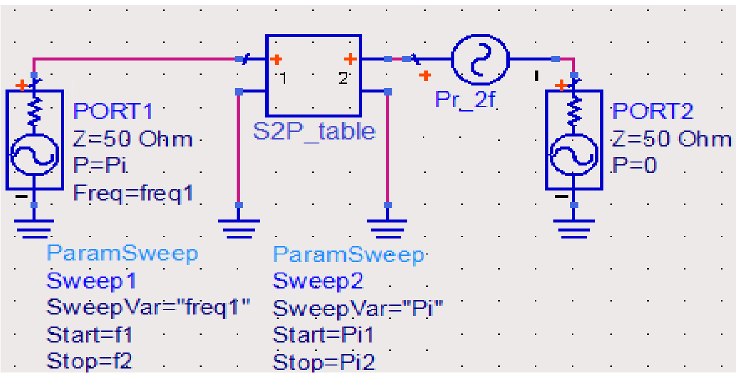

Fig.2.4. Behavioural two-port model for a power BAW resonator

The frequency characteristics of parameters S11, S12, S21 and S22 were measured for frequencies f1 and the input powers Pi with the values of interest. The measured data were stored in table S1

The frequency characteristic of the output power on the second harmonic generated by the frequency excitation1 was measured. The obtained results were stored in the table Pr.

Behavioural analysis of the 2-port BAW resonator based on the above model consists of : calculation of the frequency response of the model f1 having the incident power P1i (the analysis is of type AC using the parameters S obtained from the linear interpolation of the data in table S1) and calculation of the frequency characteristic of the power reflected at the output on frequency 2f using linear interpolation of the measured data from table Pr.

2.1.2. Simulation of BAW power filters

The accuracy of the proposed simulation model was verified by simulating a bandpass filter consisting of three resonators with known dimensions. (Fig. 2.5). [19]

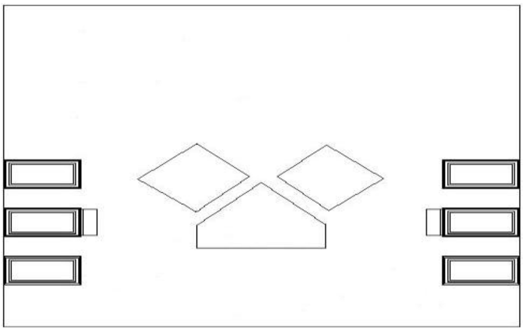

Fig.2.5. Cross section through a BAW filter with 3 resonators

This filter contains two identical apodized series resonators S1 and S2 having the area of 32000m^2, with resonant frequencies fs=2.1344E+9 Hz, fp=2.2035E+9Hz, quality factor approximately Qs=426.4 and a parallel resonator P having the area 44000 **μm^2,** resonance frequencies f_s=2.069E+9Hz, f_p=2.1344E+9Hz and quality factor at f_s Q_s=320 (Fig. 2.6).

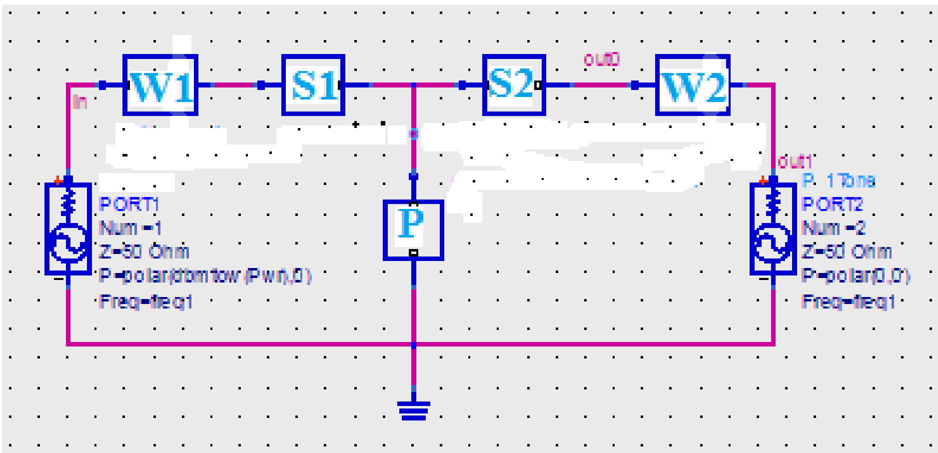

Fig.2 6. Simplified equivalent scheme of the BAW filter with 3 resonators

With circuits W1 and W2 the connections to the test equipment are simulated (see Fig. 2.1.) having the following values for simulation:

W1 : R= 104.9 mΩ, L= 0.7412 nH, C= 31.86 fF,

W2 : R= 96.8 mΩ, L= 0.645 nH C= 29.44 fF

Following the simulation using the model proposed above, highlight that the amplitude - frequency effect is weak, and the measurements made are similar to the simulated values

(Fig. 2.7). In this case, the errors given by the model are negligible compared to the measurements made.

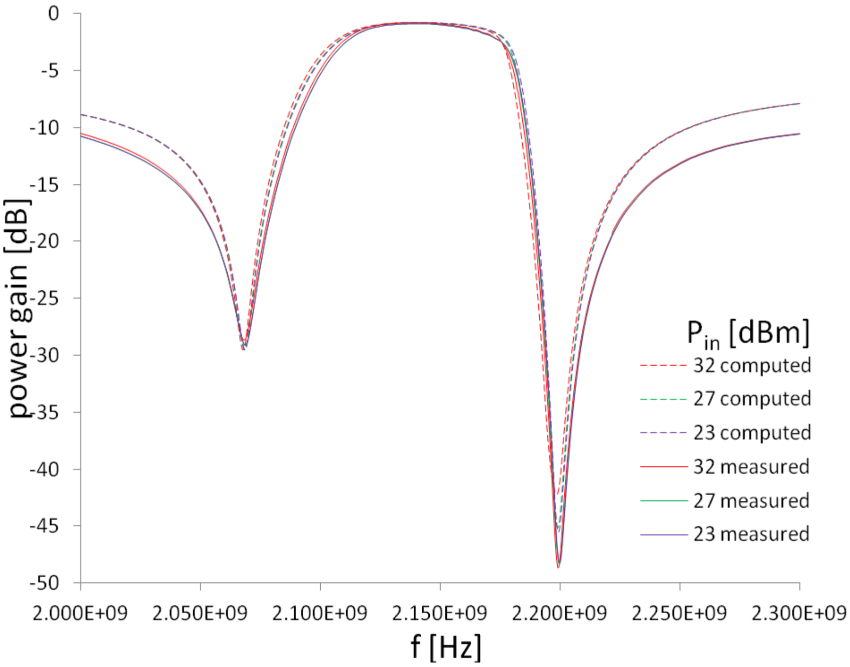

Fig.2.7. Amplitude effect - frequency – measured values versus simulated values

The measured values on the basis of which the above graph was drawn up are set out in the annex in table number 2.1. of the thesis.

It is noted that for the amplitude-frequency effect, the nonlinear circuit model in [23] delivers very good results compared to experimental data. Not the same thing happens with the power frequency feature reflected on the output on the second harmonic of the arousal.

The second harmonic frequency characteristic (2f) reflected at the filter output is shown in Fig. 2.8 .

Two incident power values were chosen for the simulation, with 27 dbm and 32 dbm respectively, which were interpolated with the characteristic for the third incident power of 29 dBm.

Using the nonlinear circuit elements model in [10] and comparing the results with the measurements made, a good approximation is found in the filter pass band. For frequencies of values higher than this band, this circuit pattern does not yield satisfactory results.

To correct this effect, we propose a model to interpolate from a set of measured frequency characteristics of the second harmonic output power. It is noted that the result obtained in this way is much closer to the family of experimental characteristics (red curve in Fig. 2.8).

A similar algorithm can also apply to the family of characteristics that illustrate the amplitude-frequency effect.

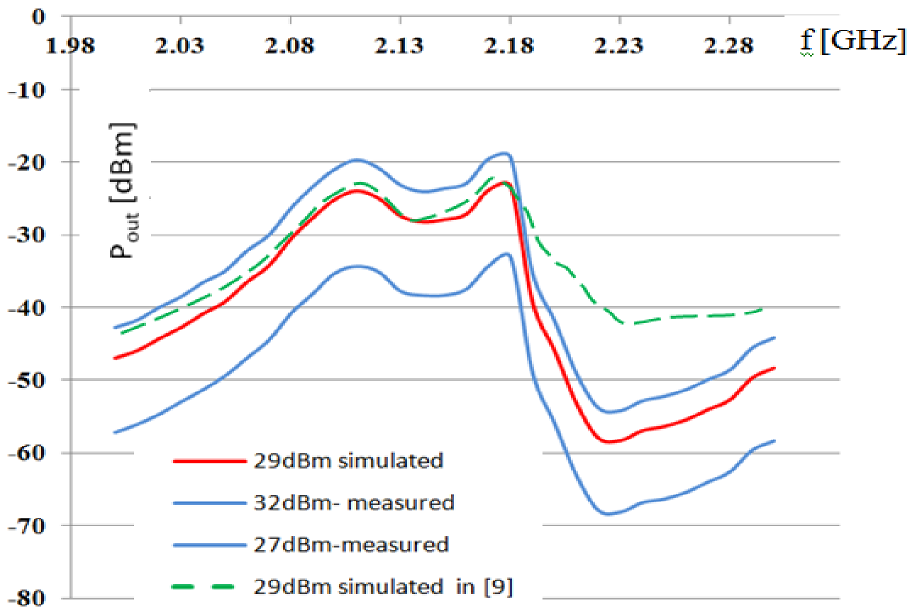

Fig.2.8 Frequency feature for the harmonic of the second power reflected the output of the POWER BAW filter.

This model exploits the poorly nonlinear properties of BAW power resonators, using s parameters that depend on the incident strength of the filter to simulate the response on the fundamental frequency, including the amplitude-frequency effect. The second harmonic of the power reflected at the filter output is represented as a separate source connected to the filter output, the parameters of which are calculated according to the input frequency and the incident input power.

This type of model, based on a set of measurements made at different frequencies and varying levels of power, could solve in a simple way the problem of frequency characteristics of intermodulation products that occur in the case of multiple tone excitations. [25]

2.1.3. Description of the implementation of the method of simulation of POWER BAW filters

Based on data in the files with parameters S, the linear interpolation method is used:

$$P(x) = f(x_0) + \frac{f(x_1) - f(x_0)}{x_1 - x_0} * (x - x_0)$$

The ADS programming environment supports scripts in the form of text-editable files that can then be interpreted by ADS. The language in which ads instructions are written is similar to the commands of the C programming language, some functions being defined in the same way, others having their own syntax. After obtaining files with S parameters, the "Interpolare.ael" file opens where the instructions at the top of the file will be followed.

The interpolation result is automatically displayed in a new open window automatically (Fig. 2.12)

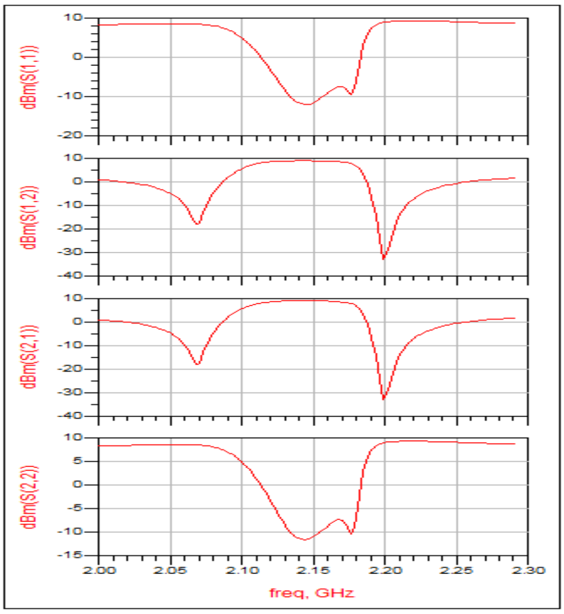

Fig.2.12 Graphic result of simulation interpolation with parameters S

The model thus created can reproduce amplitude effects – frequency and intermodulation for a wide range of incident input powers.[29]

2.2. COMPENSATION OF THE INFLUENCE OF CONNECTION WIRES FOR BEHAVIORAL PATTERNS OF SOME BAW POWER FILTERS.

The simulation model for removing connections to POWER BAW filters was made based on measurements performed on a filter pass tape whose characteristics are described in the thesis.

The simulation circuit model consists of a "T" filter in which: W1 and W2 are filter connections with test equipment, S1 (serial resonator), S2 (serial resonator), P (parallel resonator)(Fig. 2.13).

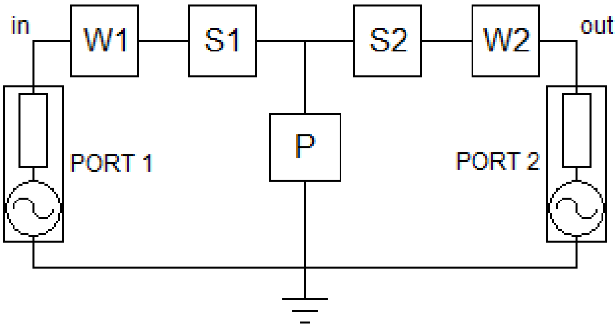

Fig.2.13. The simulation model for a "T" filter with connections Modelling each connection between the test equipment and the filter consists of an RLC circuit Fig. 2.14

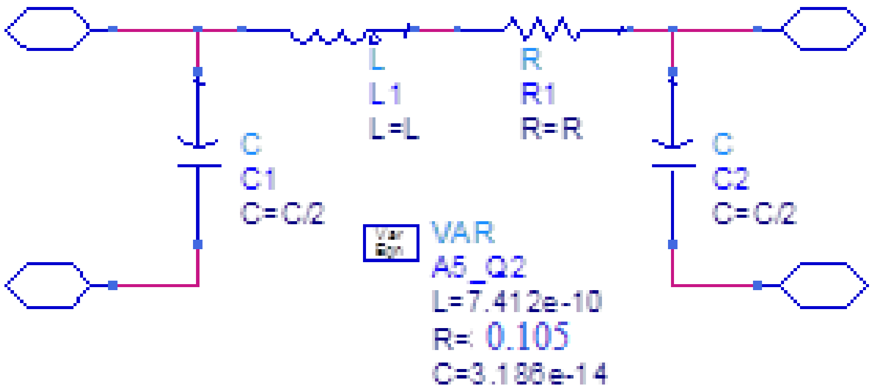

Fig.2.14 Equivalent model of connections to the BAW filter

For resonator modelling, the resonator model with nonlinear circuit elements presented in head 2.1 was used. (Fig. 2.15) of the thesis.

The behavioural model shown in Fig. 2.13 is described in the ADS (Advanced Design System) program.

The behavioural model of the parallel resonator is composed of the same nonlinear circuit elements but with different parameters from the series: R_m, L_m, C_m, and C_0,: R_m=168845 Ω, L_m=31.43e-9 H, C_m=188.3e-15 F, C_0=3.1e-12F

Connecting the W1 and T circuits and connecting the T-circuit with W2 is a cascading one, so any Parameter S of the assembly is the product of the corresponding S parameters of the two components. Since the impedance resonators series and parallel to high value Q have significant frequency dependence, unlike W1, the condition of adaptation between W1 and filter T is not met and the T filter S21 parameter cannot be extracted using property above.

The source connected to PORT 1 in Fig. 2.13 gives a constant incident power for all frequencies. Its power can be changed in small increments by adjusting the power of the source connected to PORT1.

Example: Fig. 2.16 represents variations in the incident power at the input port so that when the power is entered in the T filter, the power is constant with a value of 24 dBm.

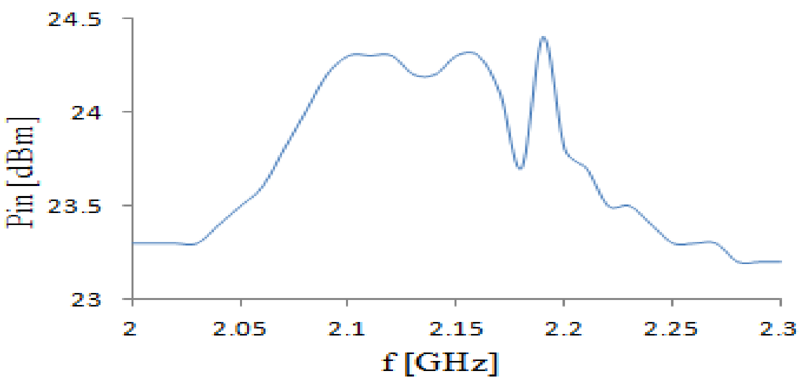

Fig.2.16 The power charged by the source so that at Port 1 there is a power of 24dBm (constant).

To validate the working method, the second harmonic frequency feature of the power reflected at the output port was used.

Calculation of the reflected power at the output of the T filter, using only the behavioural model for the T filter, behavioural model that is powered by a constant signal source of 24 dBm.

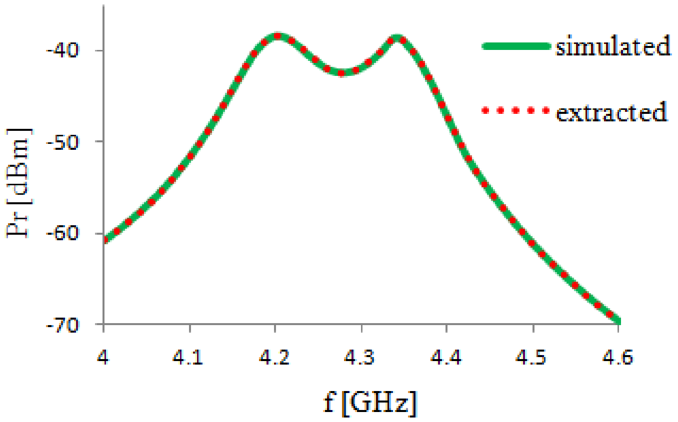

Fig.2.1 Comparison between simulated model and values obtained from extracting the influence of connections

The result of the simulation according to the second method is presented in Fig. 2.1.

As can be seen, the values extracted by the proposed method 1 are virtually the same as simulated values that are thus validated. Thus the proposed method is validated. [31]

Using a procedure similar to that described above, the input power to PORT 1 is "calibrated" to obtain an incident power of 28 dBm and 30 dBm at the entry of the T filter connections.

Transfer Feature | S21 (f) | shown in Fig. 2.22.

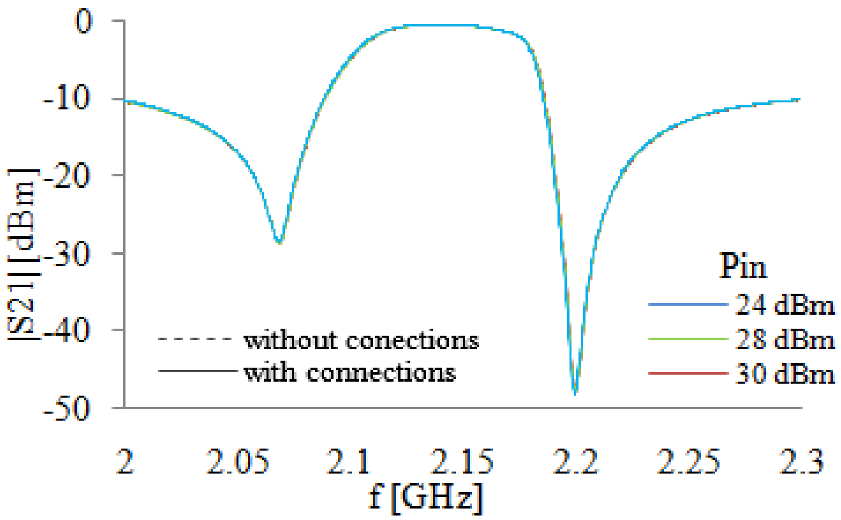

Fig. 2.22. Filter transfer function T

It is noted that the amplitude-frequency effect can be neglected in the case of this filter. The power frequency feature on the 2f frequency reflected at output is given in Fig. 2.23.

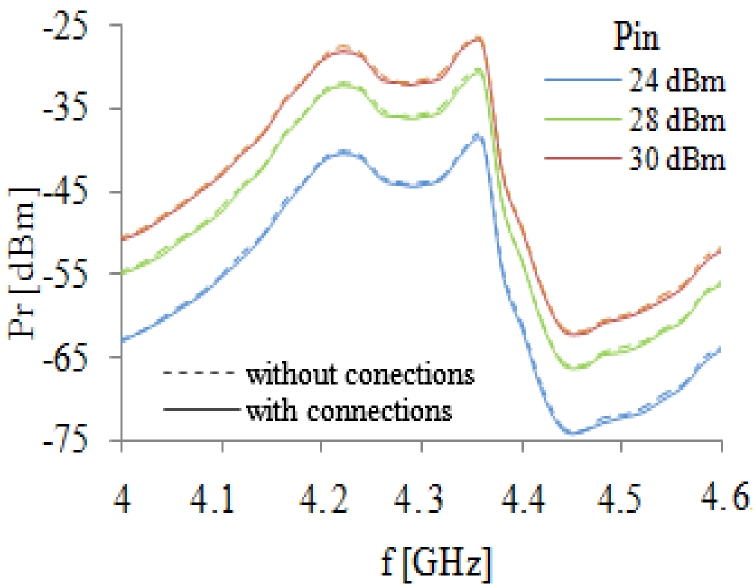

Fig. 2.23. Power frequency feature reflected on output on frequency 2f

2.3. CONCLUSIONS

Circuit behavioural models [23], [27], [28] for the power BAW resonators and filters having as AlN piezoelectric material reproduce the two important non-linear effects – the amplitude-frequency effect and the occurrence of the upper harmonics of excitation, if these passive devices are with uni-tone sinusoidal signals. The parameters of these models can be determined in such a way that simulated responses are very close to those measured, at least in a certain range of frequencies and powers of excitation.

Measurements are made using connections between the resonator (filter) and the sources of arousal and measuring devices. In general, these connections influence the measured results and, in order to build a correct model, this influence must be properly eliminated or minimized with acceptable errors. This chapter proposes solutions for two such situations.

The model correctly reproduces the amplitude-frequency effect, but does not reproduce the frequency characteristic of the reflected output power on the 2f frequency correctly. To correct this error, a model is proposed to interpolate from a set of measured frequency characteristics of the second harmonic output power. The interpolation method was implemented using the instructions available in the programming language in the ADS software.

The following is to be aimed at extracting the features of a filter (without the network of connections) from the values measured with this network. It is assumed that the model correctly reproduces the amplitude-frequency effect, but does not reproduce correctly the power frequency characteristic reflected on output on frequency 2f. Knowing the equivalent diagram of the connection between the signal source and the filter input, the source power shall be calculated for each frequency of interest so that the incident power at the filter input has the constant value required in the reflected output frequency on frequency 2f. Using the nonlinear model of the filter, the result obtained is the correct one. In fact, this is a model that uses high signal S parameters, used for the first time in solving the problem of compensating for the influence of connections of a POWER BAW filter. This way you can correctly determine the characteristics of a filter without calculating results affected by this.

CHAPTER 3 HIGH SIGNAL BEHAVIORAL MODELS FOR FREQUENCY ANALYSIS OF NON-LINEAR CIRCUITS WITH MULTI-TON EXCITATION

3.1. MĂSURAREA PRODUSULUI DE INTERMODULAȚIE PENTRU FILTRUL EPCOS B39202B8004P810

3.1.1. Measurement method

The diagram and installation of work used to measure intermodulation products are shown in the figures 3.1 and 3.2.

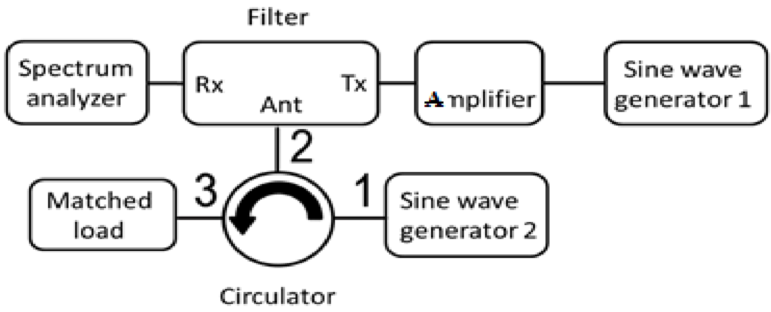

Fig. 3. 1 Scheme for measuring intermodulation products

The first measured filter is the EPCOS B39202B8004P810 duplexer designed to work for frequency bands: 1852.4 MHz – 1907.6 MHz for Tx signals and 1932.4 MHz -1987.6 MHz for antenna signals. These specifications correspond to the W-CDMA bands. [45]

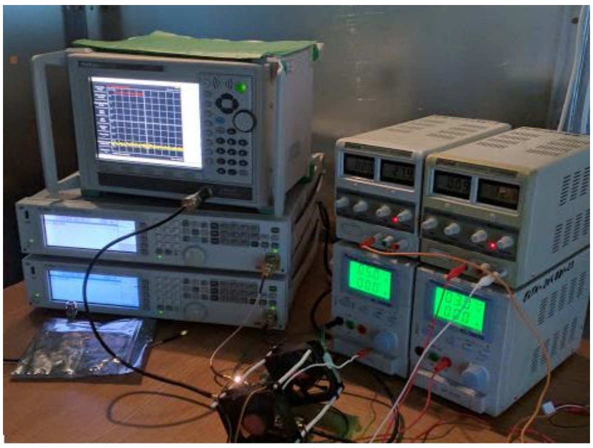

Fig. 3. 2 Laboratory installation for measuring intermodulation products

I. Connects to the TX terminal of the duplexer filter in the study, the sinusoidal signal with f = 1880 MHz generated together with its second harmonic 3760 MHz. , while its second harmonic, is attenuated by 47 dB on the same path. In addition, on the Tx-Ant path the frequency signal f is attenuated only by 1dB, while its second harmonic is attenuated by 19 dB.

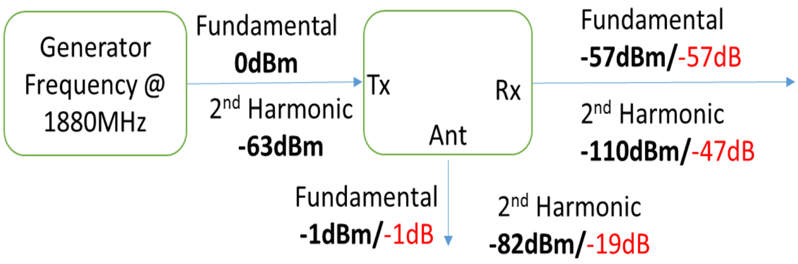

Fig. 3.3. Attenuation of the fundamental 1.88 GHz signal containing and the second harmonic on the Tx-Rx path

II. Connect to the TX terminal of the duplexer filter in the study, with the sinusoidal signal of 0dBm having the second harmonic frequency f=3760 MHz (Fig. 3.4). It is attenuated with 26 dB on the Tx-Ant path and 52dB on the Tx-Rx path.

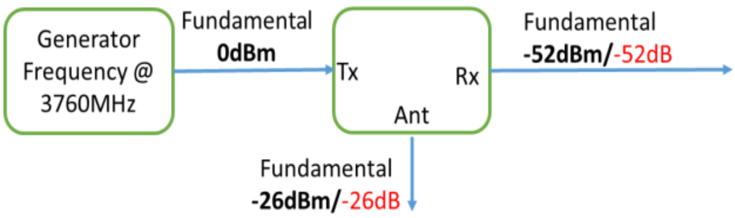

Fig. 3.4. Attenuation of the second harmonic of the 1.88 GHz signal without the fundamental component on the Tx-Rx path

It follows from these measurements that a generator in the emission band (with or without any second harmonic), mounted at the Tx terminal of the duplexer filter, and does not generate a significant 2fTx frequency component at the Rx terminal.

The following experiments refer to the possibility that the second harmonic of the Tx signal generated by the power amplifier (Fig. 3.2) contributes to the development of the measured, frequency 2* fTx - fAnt intermodulation product.

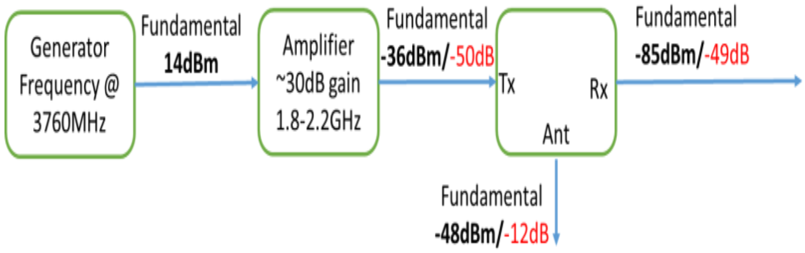

Fig. 3. 5 Frequency signal propagation scheme 2 f through duplex filter

III. Fig. 3.5 data the measured values illustrating the propagation of the 2fTx frequency signal through the power amplifier chain – duplexer filter. It follows that this second harmonic of the Tx signal generator cannot produce the 2fTx -fAnt frequency intermodulation product.

IV. Finally, a fundamental component of high signal (0 dBm), associated with a second harmonic of - 63 dBm is applied to the power amplifier circuit - duplexer filter (Fig. 3.6).

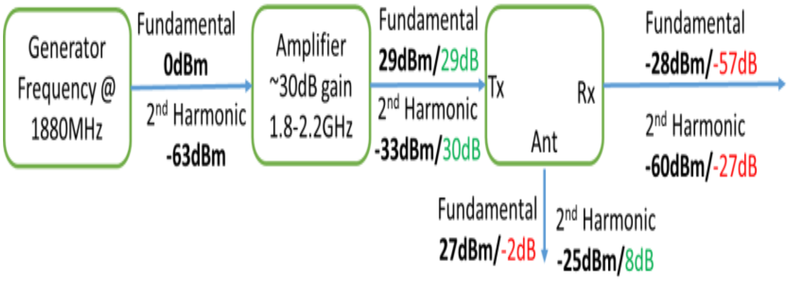

Fig. 3.6. Block scheme for determining the intermodulation product

In this case the fundamental component is amplified by 29 dB and applied to the Tx terminal of the duplexer filter. This signal is attenuated to the Rx terminal with 57 dB and at the 2 dB Ant terminal. Moreover, the second 3760 MHz harmonic is amplified by 30 dB in the amplifier, being attenuated by 27 dB on the Tx-Rx path and amplified by 8 dB on the Tx-Ant path. 2fTx-fAnt frequency measured at Rx terminal.

In conclusion, also taking into account the known phenomenon of the production of the second harmonic of arousal in any BAW power filter [19], [28], [33] it is clear that the frequency intermodulation product $2f_{Tx}$-f_{Ant} is generated in the duplexer filter.

3.2. 2. Measurement results

The values of the intermodulation product 2f1-f2, measured at the Rx terminal, when the signal with the frequency f1 is applied to the terminal Tx and the signal with the frequency f2 is applied to the terminal Ant are shown in the following three figures..

The measured values, used to make the graph in Fig. 3.7 can be found in the annex, in table3-1 of the thesis.

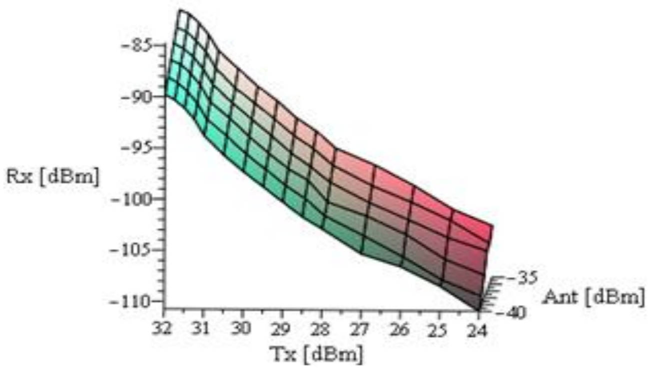

Fig. 3.7 Intermodulation product 2f1-f2=1990 MHz, f1=1882 MHz, f2=1774MHz

The reference sensitivity for operating band II, which is the frequency band for which this filter was manufactured, is -120 dBm [11]. Any intermodulation product that has been measured to be greater than this value is applied to the input of the low noise amplifier of the receiver and can be considered as a noise that prevents a good quality demodulation of the received signal.

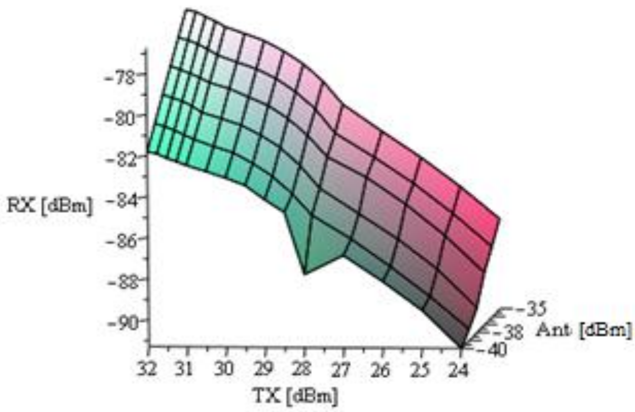

Fig. 3.8 Intermodulation product 2f1-f2=1934 MHz, f1=1854 MHz, f2=1744 MHz

The measured values used to make the graph in Fig. 3.8 are found in the thesis annex in Table 3-2

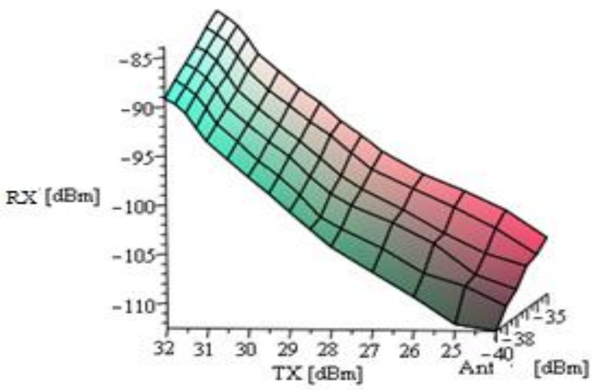

Fig. 3.9 Intermodulation product 2f1-f2=1960 MHz, f1=1881 MHz, f2=1802 MHz

The measured values used to make the graph in Fig. 3.9 are found in the thesis annex in Table 3-3.

3.3. MEASUREMENT OF THE INTERMODULATION PRODUCT FOR QORVO QPQ1282 FILTER

3.3.1. Transfer function characteristic of TX- ANT and ANT-RX for duplexer filters

QPQ1282 type duplexer filter manufactured by Qorvo, filter characterized by: TX band: 1920 - 1980 MHz, RX band 2110 - 2170 MHz, corresponding to band 1 for signals from the LTE standard, with a bandwidth of 60MHz. Given a certain uncertainty regarding the characteristics of the filter tested, we measured the transfer characteristics TX-ANT and ANT-RX of this filter.

The assembly used to determine the TX-ANT transfer characteristic is composed of two Keysight sinusoidal signal generators, a spectrum analyzer, an RF amplifier, an attenuator for the high signal protection of the spectrum analyzer, the QPQ1282 filter, and elements shown in Fig. 3.11.

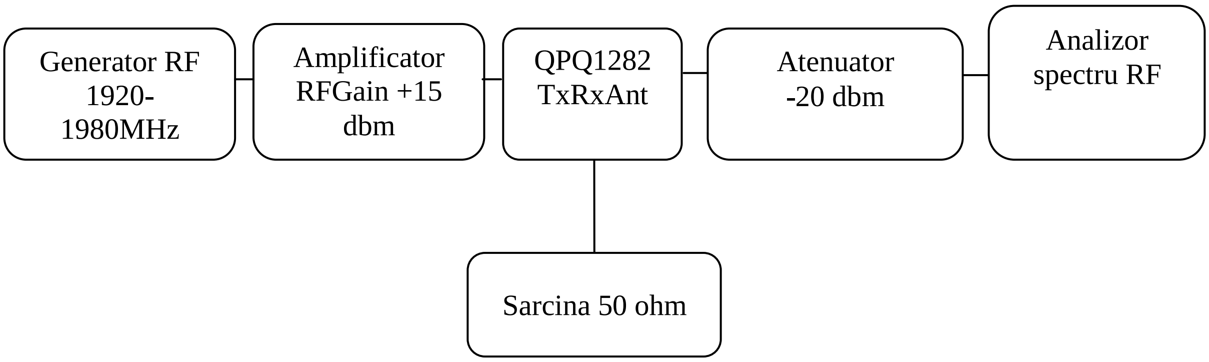

Fig. 3.11 Diagram block for lifting the TX-ANT feature for the QPQ1282 filter

The amplifier used in the montages in Fig. 3.11 and 3.13 is TQP9111 (see Appendix in thesis).

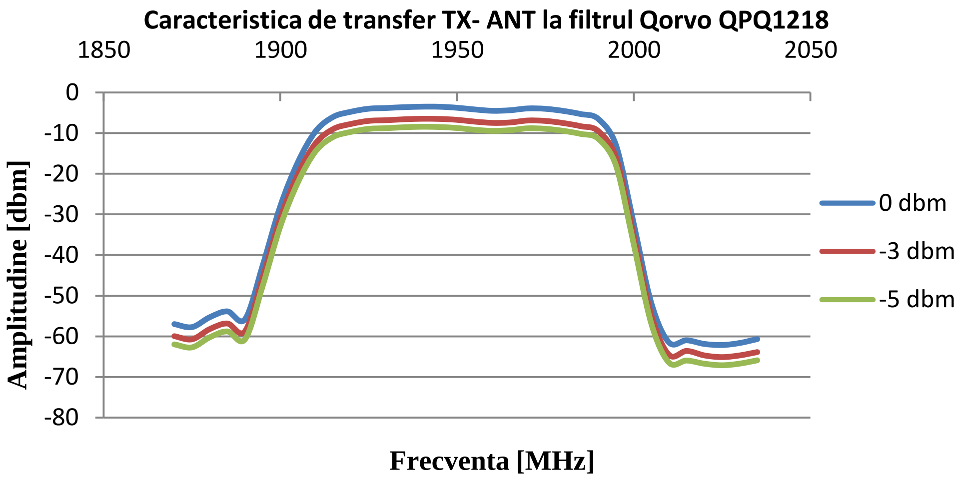

Fig. 3. 12. TX-ANT transfer feature for Qorvo QPQ1218 filter at constant power to TX port

The values on the basis of which the above graph was made are contained in Table No 3-4 of the annex of this thesis.

Similar installation is used to measure the ANT-RX transfer feature

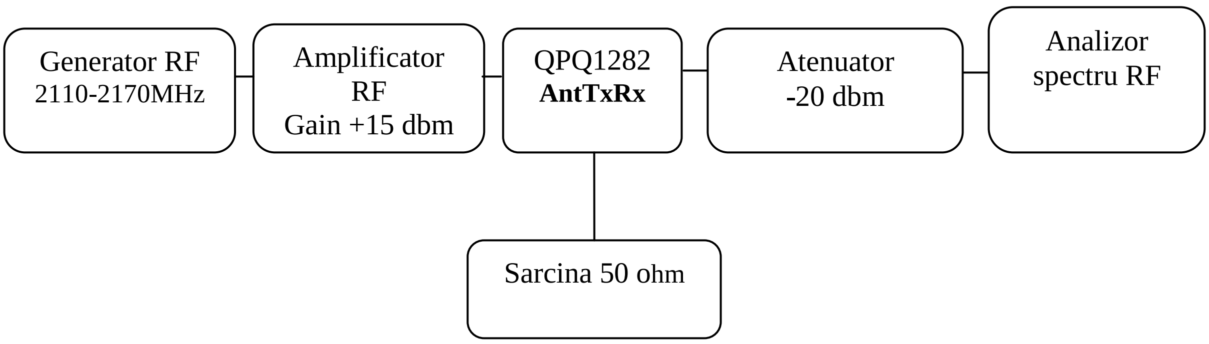

Fig. 3.13. Installation block diagram used to lift ant-rx transfer feature

The values on the basis of which the graph below was made are contained in Table No 3-5 of the annex to the sentence.

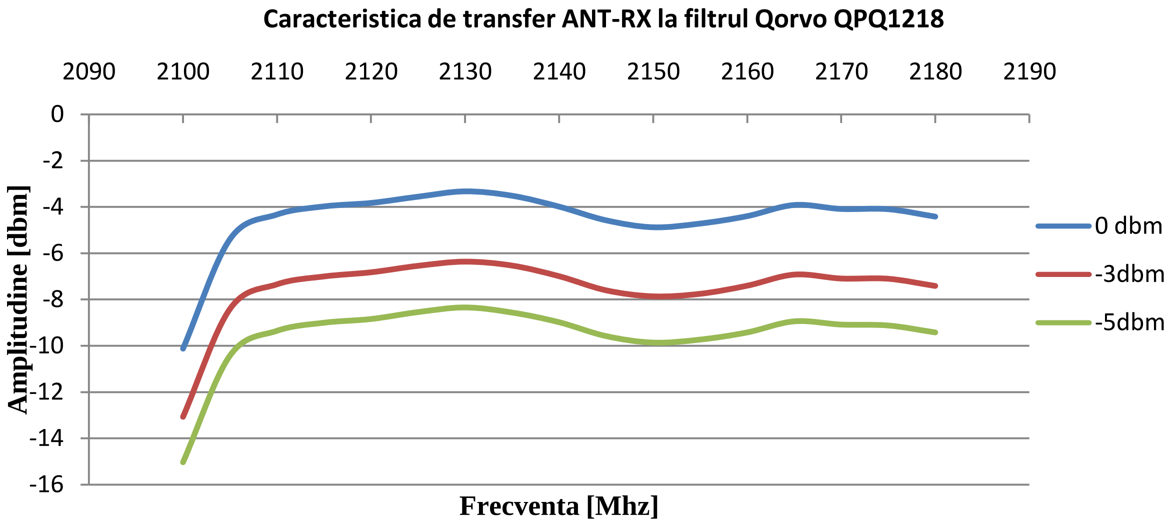

Fig. 3. 14. Transfer characteristic of ANT-RX, at constant power on gate ANT for Qorvo QPQ1218 filter

3.3.2. Frequency characteristics of intermodulation products at constant emission power

The values of the intermodulation frequencies were determined by assuming that a frequency signal f2 of some origin is applied to the ANT, so that together with the frequency signal f1 applied to TX, it produces a frequency intermodulation signal 2f1-f2, the signal of high frequency to be within the bandwidth of the ANT - RX feature.

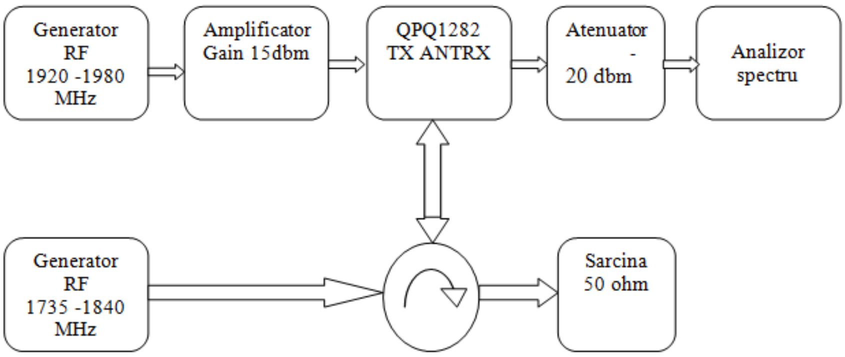

Fig. 3. 15 Diagram block for mounting used to determine the intermodulation product at Quorvo filter QPQ1282

For the determination of the intermodulation product at constant power, fTx = 1948 MHz was chosen, resulting in the frequency values of the blue intermodulation products in Table 3.6. TX, from the thesis.

Following the measurements made using the assembly of Fig. 3.15 the frequency characteristic of the intermodulation product, shown in Fig. 3.16, for more powers applied to the filter in the test. Measurements were performed for the frequency bands 1920-1980 MHz (TX-ANT) and 2110-2170 MHz (ANT-RX).

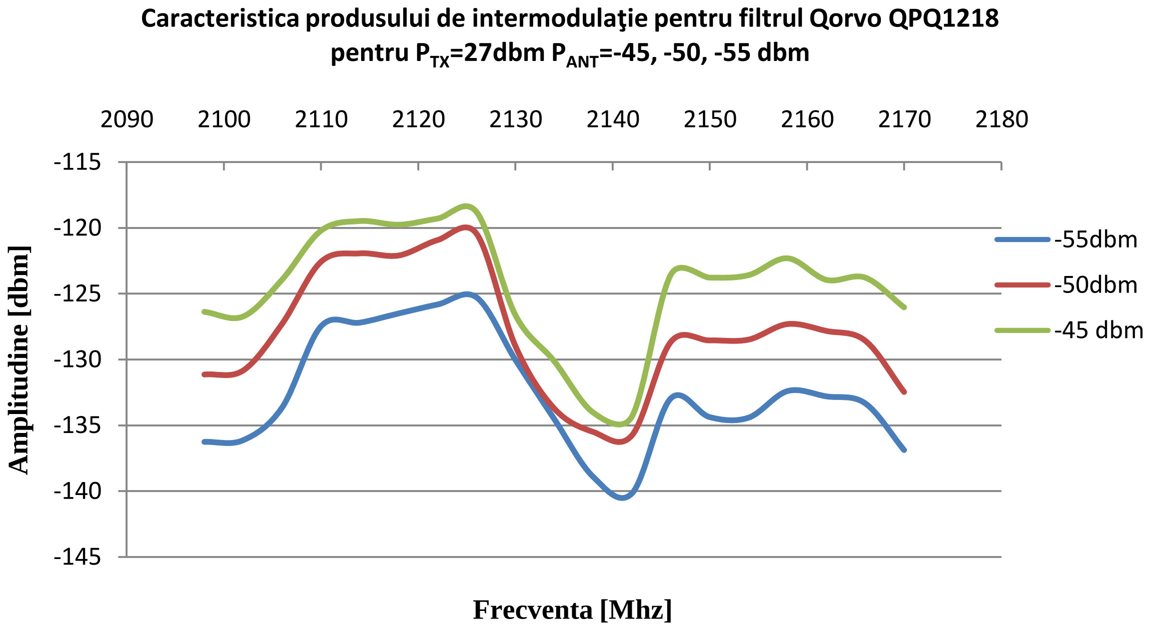

Fig. 3.16 Qorvo QPQ1218 Qorvo filter feature for PTX=27dbm and PANT= -55dbm, -50 dbm, -45 dbm

The values on the basis of which the above graph was made can be found in table no.3-7 of the sentence.

The reference sensitivity for the operating band for which this filter was manufactured is -140 dBm [11], so signals of the size of those measured can disrupt receiver operation.

Also, isolation of frequencies in the affected area is not possible due to the fact that GSM networks use the TDMA (time domain multiple access) or FDMA (frequency domain multiple access) [45] algorithm for efficient use of the radio spectrum.

3.3. CONCLUZII

For the Epcos B39202B8004P810 filter as well as for the Quorvo QPQ1282 filter, an intermodulation product of significant value between the Tx and Ant signals of a power BAW duplex filter manufactured with AlN was measured. This signal has the frequency 2fTx -fAnt, where fAnt comes from an arbitrary source.

It has been shown that the presence of this intermodulation product could prevent a good quality reception of the antenna signal from the filter bandwidth.

This signal has been shown to occur due to nonlinear behaviour of the BAW AlN filter. This behaviour has two consequences: the second harmonic generation of the Tx signal 2f1 and the generation of intermodulation 2 f1-f2. These consequences cannot be eliminated by using the anti-serial connection of resonators. [36]

CHAPTER 4 FREQUENCY ANALYSIS OF ENERGY SYSTEMS WITH HOUSEHOLD CONSUMERS

4.1. MODELE DE TIP SURSE DE CURENT

4.1.1 Rectifier with a diode

The circuit in Fig. 4.1 is powered by a sine source of voltage with:

V = 220 V and f = 50 Hz, with C1 = 2 mF and R1 = 37 Ω.

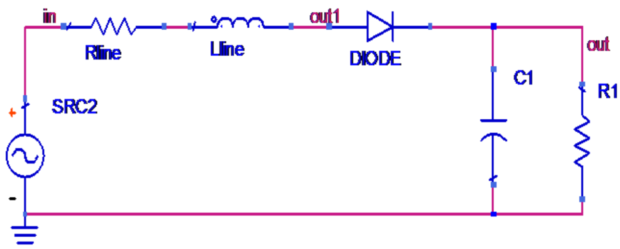

Fig. 4.1 Rectifier with diode and C filter

The rectifier is connected to the source via a cable with section of 10 mm^2 and a length of 30 m (R_{line} = 0.1104 Ω, L_{line} = 72 μH). The circuit model, is described by the power supplied, ordered by the fundamental component of the rectifier input voltage (defined by the V_1 and faze phase(V_1)), shown in Fig. 4.2. The FDD1 (frequency defined device) circuit element is defined by the parameters of the current sources corresponding to the harmonics of significant amplitudes (in this case the continuous, fundamental component of 50 Hz and the other until the 20th harmonic is included).

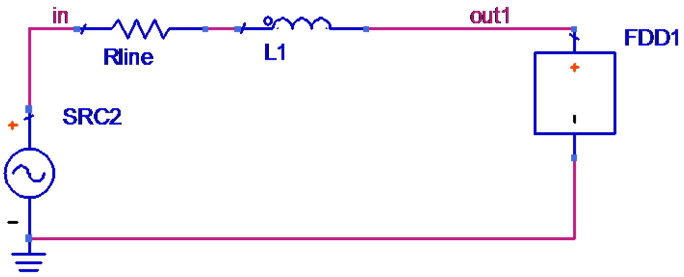

Fig. 4. 2 Linearly controlled current source model for the circuit in Fig. 4.1

The description of these ordered sources, in the case of a rectifier with a diode, is detailed in the thesis.

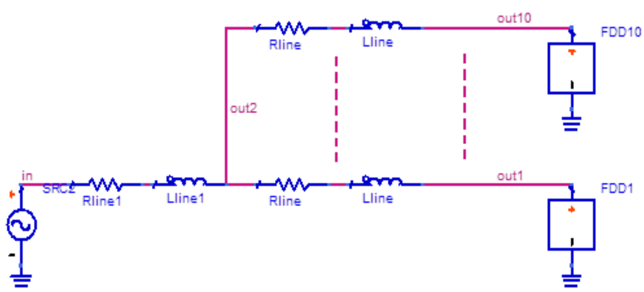

Fig. 4. 3 Test circuit for highlighting harmonics produced by nonlinear circuit elements.

In order to simulate by the harmonic balance method, a test circuit (Fig. 4.3) was considered consisting of ten rectifiers with one diode, identical, connected to a sinusoidal source having the following circuit parameters:

f = 50 Hz and V = 220 V, cable cross-section de 50 mm^2 and cable length de 30 m with R_{line1} = 0,0348 Ω, L_{line1} = 57,6 μH

4.1.2. Two diode rectifier

Starting from the rectifier module with one diode, the analysis for the two diode rectifiers can be extended (Fig. 4.4).

The circuit in Fig. 4.4 represents the simplified model of a fluorescent lamp.

The simulation model of a two-diode rectifier for the ADS program is as described in the thesis (Equations 4.2).

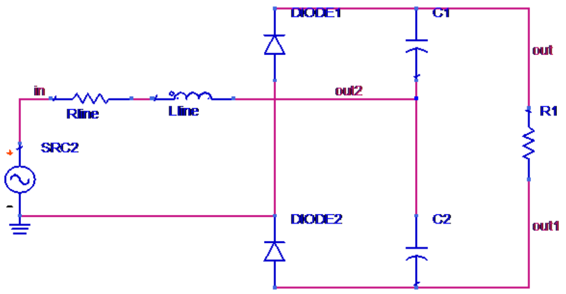

Fig. 4. 4 Two-diode rectifier model [46], [47]

It was simulated a test circuit, with ten rectifiers, with two diodes, and sinusoidal signal is presented in Fig. 4.3.

4.1.3. Simulation results

The simulation results using the models mentioned above and using the ADS (Advanced Design System) simulation environment were compared with the results obtained by simulating the same energy networks using the transient analysis method.

The graphs below present the results - the waveforms and the red spectral lines were obtained using classical nonlinear models and the blue results are obtained using the frequency domain models.

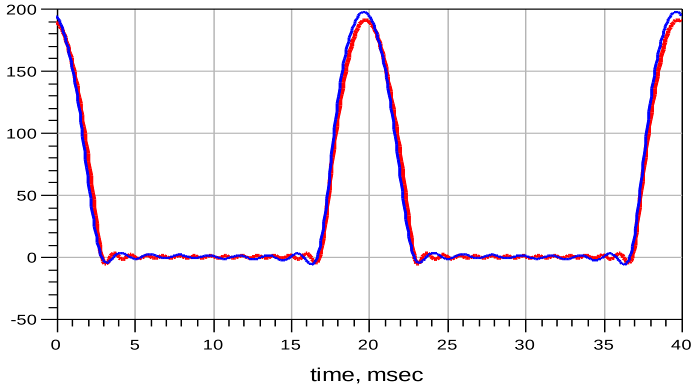

Fig. 4. 5 The waveform of the current through the voltage source for the model in Fig. 4.2. with rectifiers with a diode

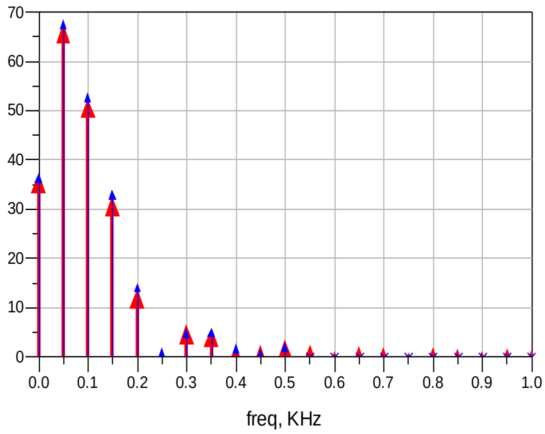

Fig. 4. 6 The spectrum of the harmonics of the current through the voltage source for the circuit in fig. 4.2 with rectifiers with a diode in Fig. 4.3

The results obtained using the classical models described in the time domain (Equations 4.1) are almost identical to those calculated using the proposed model (see Fig. 4.5 and Fig. 4.6, and the processing time is shorter in the case of the proposed model. Similar results were also obtained for the harmonic balance simulation of the test circuit.

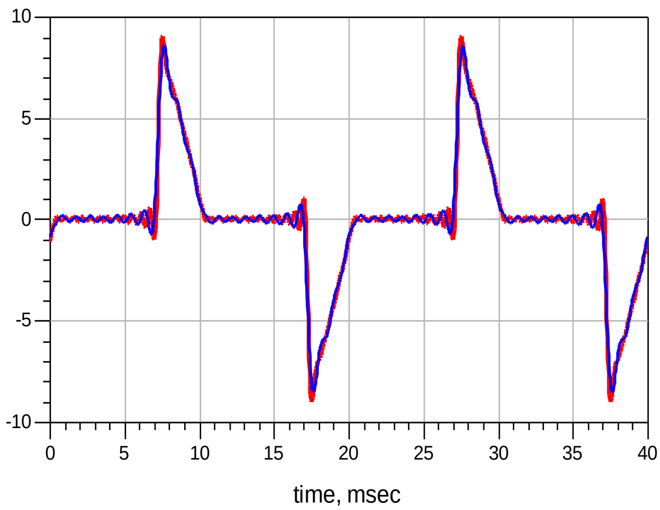

Fig. 4. 7 The waveform of the current through the voltage source for the circuit in Fig. 4.3 with two diode rectifiers

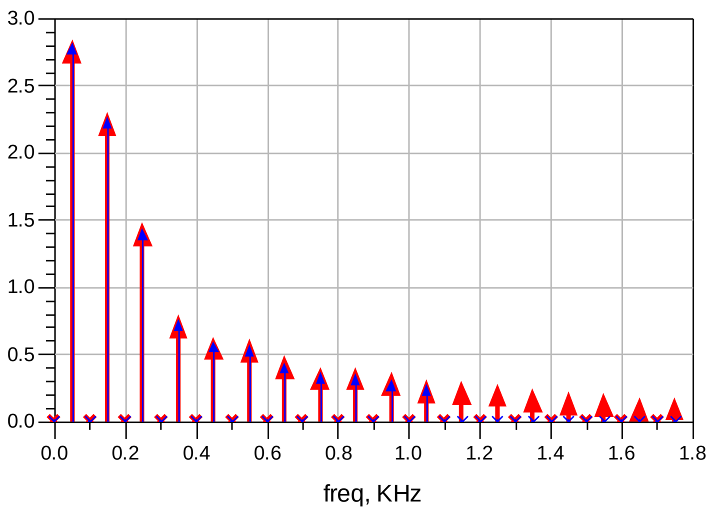

Fig. 4. 8 The spectrum of the current through the voltage source for the circuit in Fig. 4.3 with two diode rectifiers

4.2. ATTENUATION OF THE THIRD HARMONIC CURRENT

The attenuation effect of the current harmonics is found in the circuits with fluorescent lamps and consists in attenuating the third harmonic of the load current with the increase of the third harmonic voltage of the voltage source supplying the fluorescent lamp.

This effect can be observed in the test circuit in which the two-diode rectifier model, fed from a sinusoidal voltage source, was introduced for relatively large lengths of the power cord. The variation of the input voltage of the rectifier with two diodes, relative to the line length is shown in Fig. 4.9. and illustrated in FIG. 4.10 and Fig. 4.11.

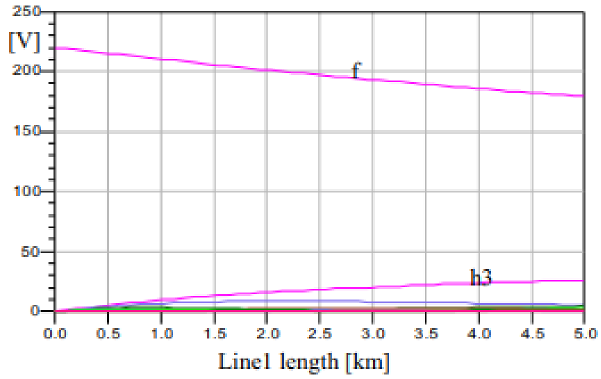

Fig. 4. 9 Harmonics of fluorescent lamp voltage (two-diode rectifier) depending on the length of the line

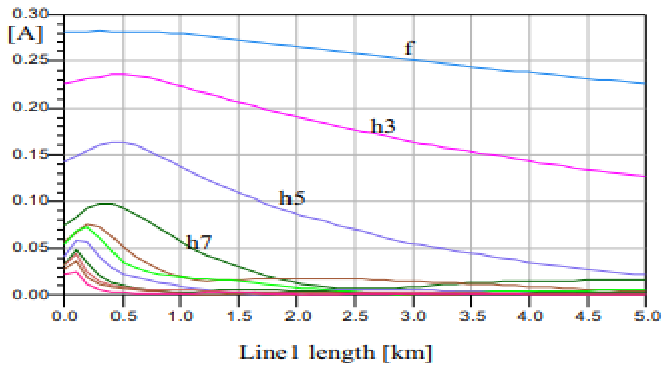

Fig. 4. 10 Harmonics of fluorescent lamp voltage (two-diode rectifier) depending on line length – detail

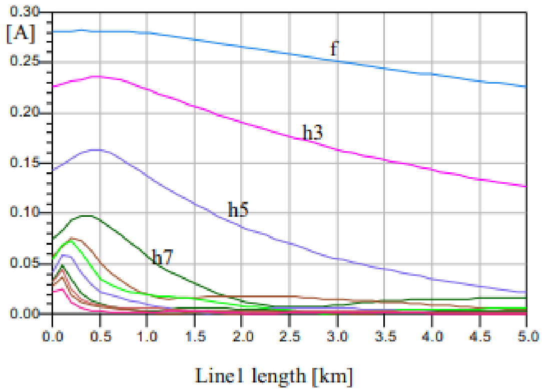

Fig. 4. 11 Input current harmonics (fundamental and harmonics 3, 5, 7) for the fluorescent lamp, depending on the line length

These results are obtained using time-domain analysis and classical models for nonlinear consumers. The proposed model in the frequency domain only partially reproduces the effect of the attenuation of the third harmonic current under the conditions mentioned above.

In the case of household appliances, the sinusoidal source could in principle be placed at a distance greater than 60 m of load, so we added a third harmonic component to the sinusoidal voltage of the source in the test circuit in Fig. 4.3.

Considering the above, for the circuit with 10 two-diode rectifiers, a frequency component 150 Hz and voltage V3 that can have values of 5 V or 10 V and an initial phase of -96.69 degrees have been added to the voltage source. The waveform of the current through the voltage source, calculated for the values V3 = 0 V, V3 = 5 V and V3 = 10 V, using the classical nonlinear models described in the time domain, is shown in Figures 4.12 and 4.13 together with the obtained waveform. using the proposed model (model)

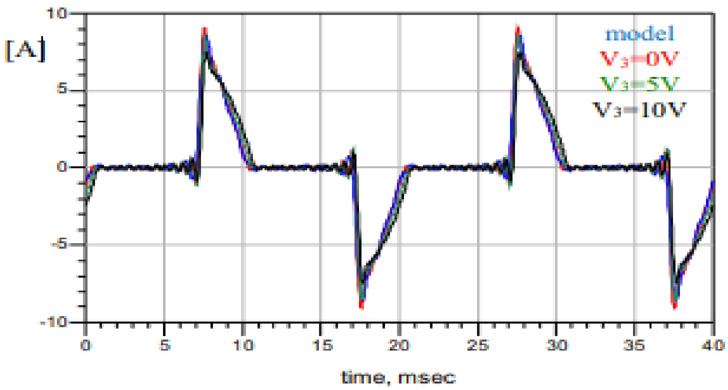

Fig. 4. 12 Waveform of the current through the voltage source in the test circuit

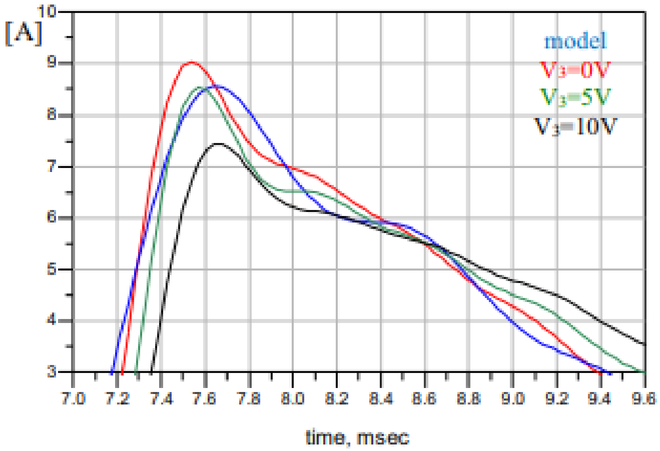

Fig. 4. 13 Waveform of the current through the voltage source in the test circuit - detail

4.3. CONCLUSION

New models have been proposed to analyze non-linear receivers in a single-phase energy network. The models, described in the frequency field, are used in the harmonic balance analysis and have been implemented in the ADS program. There were simulations of circuits containing rectifiers with a diode and two diodes.

The results of these simulations show that these methods analyze a circuit using a computation time with an order of magnitude smaller than that required for the transient analysis using models described by time formulated equations. This result is explained by the fact that, using the models described in the field of time, the ADS program must use the "source stepping" procedure. This process significantly extends the field of applications for which the harmonic balance method implemented in the ADS is convergent, as opposed to the harmonic balance method implemented in the APLAC program, which in such cases does not provide the correct solution. This result is obtained by the initial reduction (by one or two orders of magnitude) of the amplitudes of the independent sources in the circuit so that the harmonic balance method is convergent (the overall error for the whole circuit is below a certain limit). Further these amplitudes are gradually increased to the nominal values, considering as an initial approximation the result of the previous analysis in which these amplitudes are smaller. Using the models proposed by us this process is not necessary.

It was found that the analysis with the proposed models gives acceptable results and if the third harmonic amplitude of the voltage at the consumer terminals does not exceed 2.2% of the amplitude of the fundamental component of this voltage.

CHAPTER 5. CONCLUSIONS AND ORIGINAL CONTRIBUTIONS

5.1. GENERAL CONCLUSIONS

The work begins with Chapter 1, an introduction that has three parts in which it is presented:

• Non-linearity in the analogue radio frequency interface of mobile communications devices, a chapter to which many of the contributions of this thesis could be added.

• Bulk Acoustic Wave (BAW) resonators with piezoelectric material AlN, their construction and properties, insisting on radio frequency applications.

• Small and high signal models of power BAW resonators. Their operation is affected by nonlinear effects such as amplitude-frequency effect and intermodulation effect. Described are the small and high signal circuit models of these resonators, which simulate the nonlinear effects mentioned. The behavioural models of the BAW power filters constructed with such resonators are presented.

• Methods of calculating the permanent response of energy systems with nonlinear consumers with emphasis on the analysis of networks with non-linear household consumers. There are highlighted the classical methods of analysis in the field of time, as well as methods of analysis in the field of frequency with limited applicability to simple examples.

Chapter 2 deals with behavioural models for BAW power filters that operate with one-tone excitation. In subchapter 2.1. an original way of simulating the operation of power BAW filters based on the use of high signal S parameters is presented. These parameters, which depend on the frequency and power incident at the input, are described in the form of tables. The analysis, implemented in the ADS program, is reduced to interpolation starting from the data in these tables. This method allows the simulation times to be reduced compared to the case of using the circuit models that have to be analyzed with relatively complicated numerical algorithms. In subchapter 2.2 is presented a method of compensating the influence of the connection wires, which allows the selection of the filter parameters without connections, starting from the measured parameters of the filter with connection wires. This method is used to determine the frequency characteristic of the second harmonic of the power reflected at the output port.

Chapter 3 presents some high-signal behavioural models for frequency analysis of duplex filters. By the measurements made it was identified that, under certain conditions, the received useful signal can be disturbed by a parasitic signal outside the radio spectrum of the filter. Basically, inside the filter a mixing occurs between the frequency signal f1 emitted by the transmitter (Tx) and a frequency signal f2 received at the antenna (Ant), signal outside the Ant-Rx filter band of the duplexer filter. The signal resulting as a frequency intermodulation product 2 f1 -f2 is found at the receiving port (Rx), which is in the filter's pass band, and having a power large enough to cover the useful signal to be received correctly. Epcos B39202B8004P810 and Qorvo QPQ1282 filters were analyzed. Through a series of measurements it has been shown that the frequency component 2f1 is generated in the duplexer filter, as well as the frequency component 2f1-f2. The amplitude characteristics of the intermodulation product were measured according to the amplitude of the signals applied to the Tx and Ant terminals. These characteristics were high for pairs (f1 = 1882 MHz, f2 = 1774MHz), (f1 = 1854 MHz, f2 = 1744 MHz), and (f1 = 1881 MHz, f2 = 1802 MHz) for the Epcos B39202B8004P810 filter. It has been shown that under these conditions amplitudes of the intermodulation product can be obtained greater than the reference sensitivity of -120dBm, corresponding to this frequency band. For the Qorvo QPQ1282 filter, the frequency characteristics of the intermodulation product for the receiving band (2110 MHz - 2170 MHz) were measured considering the applied power at Tx of 27 dBm and the signal strengths at Ant of -55dBm, -50dBm, -45dBm. The reference sensitivity in the receiver band being -140dBm, the measured signal may disrupt the receiver's operation.

Chapter 4 presents a new method for analyzing the frequency of energy systems with non-linear household consumers. This method is based on the fact that in a low frequency network all consumers are supplied with approximately the same voltage, and the value of the fundamental component of this voltage does not vary by more than 10% around the nominal value. As a result, the current harmonics of any non-linear consumer depend linearly only on the parameters of the fundamental component of the voltage at the terminals of this consumer. This model can be easily implemented in the ADS program and leads to a reduction in order of magnitude of the computation time, compared to the commonly used time domain analysis. This advantage is important when optimizing the placement of devices that reduce the complementary power consumed by the network (passive and active filters).

5.2. ORIGINAL CONTRIBUTION

Chapter 2 proposes a new model for the frequency characteristic of the Pout2f power reflected on the frequency 2f at the output of a BAW filter excited on the frequency f. This model is based on the table of Pout2f (f) characteristics measured for a set of input powers. The desired characteristic is quickly determined by interpolation starting from the data in the mentioned table, the algorithm being implemented in the ADS program. Due to the short computation time, this model can be used to optimize the design of a power BAW filter.

In the same chapter we propose a new algorithm to eliminate the influence of the connection wires on the frequency characteristic of the Pout2f power for a frequency-excited BAW filter f. This algorithm is based on a simulation of the circuit with the input and output connections excited by a source whose power is calculated so that at the actual input of the filter (after the input connection) we have an incident power constant of the desired value. The simulation is done with the ADS program using nonlinear circuit models of power BAW resonators. This algorithm can be useful in designing BAW power filters.

In Chapter 3 the intermodulation product with frequency 2f1-f2 (f1-frequency Tx, f2-frequency of an antenna picked up signal) is identified by measurements and it is shown that this signal measured at the Rx terminal may disturb the functioning of the mobile phone. The measurements were made for the Epcos B39202B8004P810 and Qorvo QPQ1282 duplexers. For this purpose, duplexer filters were assembled (involving the design of wiring and assembly of the BAW EPCOS filters) and an RF amplifier for the 1800-2100 MHz band.

Chapter 4 presents new models in the field of frequency for non-linear household consumers in single-phase networks. The implementation of this method in the ADS program leads to a reduction of the computing time by about an order of magnitude, which makes them very suitable for solving problems of optimizing the losses in the energy networks.

5.3. FURTHER DEVELOPMENT PERSPECTIVES

The models and rapid calculation methods discussed in Chapter 2 can be improved and used in designing power BAW filters with AlN.

A more detailed study of the intermodulation products that are generated in the duplex filters built into the BAW AlN power technology may be the subject of future research. Measuring the effects of these intermodulation products on a mobile phone would be a very interesting objective.

Frequency models elaborated in this thesis can be extended to consumers with controlled opening angle such as thyristors or IGBT mounts.

LIST OF ARTICLES ELABORATED BY THE AUTHOR OF THE THESIS

1. Report No. 1 within the doctoral internship: „Modele comportamentale pentru analiza filtrelor BAW (bulk acoustic wave) în domeniul frecvență”.
2. Report No. 1 within the doctoral internship: „Compensarea influentelor datorate conexiunilor, în cazul modelelor comportamentale ale filtrelor de putere”.
3. Report No. 1 within the doctoral internship: „Indentificarea produselor de intermodulație în cazul filtrelor BAW duplexoare”.
4. Ovidiu Silviu Taus, Florin Constantinescu, Alexandru Gabriel Gheorghe, Compensation of the connection wires influence for a behavioral model of a power BAW filter, 2015 IEEE 21st

International Symposium for Design and Technology în Electronic Packaging (SIITME), October 22nd–25th, 2015, Brasov, Romania, WOS:000377765500037.

5. Florin Constantinescu, Ovidiu Taus, Alexandru Gheorghe, A new behavioral model for frequency domain analysis of power baw filters, 13TH INTERNATIONAL CONFERENCE ON ENGINEERING OF MODERN ELECTRIC SYSTEMS (EMES 2015), June 11-12, 2015, Oradea, Romania, WOS:000363815100005, ISBN:978-1-4799-7650-8.
6. Mihai Eugen Marin, Florin Constantinescu, Ovidiu Silviu Taus, Alexandru Gheorghe, Intermodulationproducts in AlN power BAW duplexer filters, ISSCS 2017, Technical University Iasi, Romania, July 13-14 2017.WOS:000425211500087.
7. *Florin Constantinescu, Mihai Eugen Marin, Alexandru Gheorghe, Ovidiu Silviu Taus*, Harmonic balance analysis of home appliances power networks, 2017 14th International Conference on Engineering of Modern Electric Systems (EMES), June 1-2, 2017, WOS:000427085200061.
8. F. Constantinescu, A.G. Gheorghe, M. Nitescu, M. E. Marin, O. Taus, Behavioral Models of AlN Power BAW Resonators and Filters, International Symposyum on Electrical and Electronics Engineering, Galati, Romania, Invited paper, October 20-22, 2017.

BIBLIOGRAPHY

[1] *Ken-ya Hashimoto, Tatsuya Omori,Kazuki Maruta,Chang-Jun Ahn***.** Nonlinearity in RF Front-End as a Bottleneck.s.l. : 2017 International Symposium on Nonlinear Theory and Its Applications, 2017

[2] *Ali M. Niknejad*, University of California, Berkeley**.**Lecture 9: Intercept Point, Gain Compression and Blocking. [http://rfic.eecs.berkeley.edu/~niknejad/ee142_fa05lects/pdf/ lect9.pdf] University of California, Berkeley : s.n.

[3] Cascaded 2-Tone, 3rd-Order Intercept Point (IP3), *http://www.rfcafe.com/ references/electrical/ip3.htm.*

[4] *Fl. Constantinescu, M. Nitescu*,. Bazele Electrotehnicii :ParteaI - Teoria Circuitelor Electrice, Curs pentru Facultatea de Automatica și Calculatoare. *http://ferrari.lce.pub.ro/studenti* . [Interactiv] 2001-2015.

[5] IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Standard 519-1992.

[6] *V. R. Pandi, H. H. Zeineldin, W. Xiao.* Determining Optimal Location and Size of Distributed Generation Resources Considering Harmonic and Protection Coordination Limits. s.l. : IEEE Transactions on Power Systems, vol. 28, No. 2, May 2013, pp. 1245-1254.

[7] *Task Force on Harmonics Modelling and Simulation, "Modelling and Simulation of the Propagation of Harmonics in Electric Power Networks, Part I: Concepts, Models, and Simulation Techniques",.* s.l. : IEEE Transactions on Power Delivery, vol. 11, no. 1, January 1996.

[8] *A. Medina, J. Segundo-Ramirez, P. Ribeiro, W. Xu, K. L. Lian, G. W. Chang, V. Dinavahi, and N. R. Watson*, Harmonic Analysis in Frequency and Time Domain. s.l. : IEEE Transactions on Power Delivery, vol. 28, no. 3, July 2013, pp. 1813-1821.

[9] *P. Heikkila, M. Valtonen, T. Veijola* Harmonic balance of nonlinear circuits with multitone excitation. s.l. : Proceedings of the European Conference on Circuit Theory and Design, 1991.

[10]*K. L. Lian, P. W. Lehn*, Harmonic Analysis of Single-Phase Full BridgeRectifiers Based on Fast Time Domain Method. s.l. : IEEE International Symposium on Industrial Electronics (ISIE 2006), July 9-12, 2006, Montreal, Quebec, Canada.

[11] *F. Constantinescu, A.-G. Gheorghe, M. Nitescu*,. Large signal analysis of RF circuits – an overview, Proceedings of ATEE (Advanced Topics in Electrical Engineering). s.l. : Politehnica University, Bucharest, Romania, November 24-25, 2006.

[12] *A. G. Gheorghe, F. Constantinescu*, New Topics in Simulation and Modeling of RF Circuits. s.l. : River Publishers, 2016.

[13] *K. S. Kundert, A. Sangiovanni_Vincentelli*,. Simulation of Nonlinear Circuits in the Frequency Domain.s.l. : IEEE Transactions on Computer-Aided Design, Vol. CAD-5, NO. 4, October 1986, pp. 521-535.

[14] *R. Uhl, M. Mirz, T. Vandeplas, L. Barford, A. Monti*,. Measurement-based parameter identification of non-linear polynomial frequency domain model of single-phase four diode bridge rectifier. s.l. : IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, pp. 6292 – 6297.

[15] *M. Mirz, R. Uhl, T. Vandeplas, L. Barford, A. Monti*,. Measurement-based parameter identification of non-linear polynomial frequency domain model of single-phase four diode bridge rectifier. s.l. : Instrumentation and Measurement Technology Conference (I2MTC) 2017 IEEE International, pp. 1-6, 2017**.**

[16] *Maas, S. A*,. Nonlinear microwave and RF circuits. s.l. : Artech House, 2003.

[17] *S. Rosenbaum, J. F.*,Bulk Acoustic Waves Theory and Devices. Boston : Artech House, 1988.

[18] *Morris, S. A.*,Equivalent circuit modeling for thin disk and bar type piezoelectric transducers. s.l. : Master Thesis, The University of Tulsa, USA,, 1986.

[19] *Stroe, G.*, Modelarea dispozitivelor pasive de radiofrecvenţă. Teza Doctorat, Universitatea Politehnica Bucuresti, 2013, conducător ştiinţific prof.dr. ing. Florin Constantinescu

[20] *R. S. Ketcham, G. R. Kline, K. M. Lakin*, „Performance of TFR filters under elevated power conditions", 42-nd Annual Frequency Control, Symposium, 1988.

[21] *J.Nosek*, „A Precise Measurement of Some Nonlinear Effects and Its Application to the Evaluation of Nonlinear Elastic Constants of Quartz and GaP04", IEEE Trans. on Ultrasonics, Ferroel. and Freq. Control, 46, pp. 823- 829.

[22] R. Aigner, N.-H.Huynh, M. Handtmannn, S. Markensteiner, Behavior of BAW devices at high power level, Proceedings of 2004 IEEE MTT-S International Microwave Symposium.

[23] *F. Constantinescu, A. G. Gheorghe, M. Nitescu*,. „New circuit models of power BAW resonators", Rev. Roum. Sci. Techn., Ser. Electrotechnique et Energ. No. 1, 2008, pp. 59-66.

[24] *F. Constantinescu, A. G. Gheorghe, A. Florea, M. Nitescu, O. Llopis*,Artificial transmission line model for power BAW resonators with mechanical nonlinearity. s.l. : Rev. Roum. Sci. Tech., Ser. Electrotechn. et Energ., vol. 56 (2011), No. 2, http://revue.elth.pub.ro/.

[25] *G. Stroe, A. Florea, O. Llopis, F. Constantinescu, M. Nitescu*,Measurement of nonlinear effects in filters based on BAW resonators with AlN. Targoviste, Romania : International Symposium on Electrical Engineering (ISEE'11), November 22-23 ,2011.

[26] *K. M. Lakin*, "Thin film resonator technologies", IEEE Trans. UFFC,vol.52, No. 5 (May 2005), pp. 707-716.

[27] *F. Constantinescu. A. G. Gheorghe, M. Nitescu, A. Florea, O. Llopis, P. Taras*, „Parameter identification for new nonlinear circuit models of power BAW resonators", Advances in Electrical and Computer Engineering, vol. 11 (2011), No. 1, pp. 55-62.

[28] *G. Stroe, F. Constantinescu, A. G. Gheorghe, M. Nitescu, O. Llopis,*. Measurement and Modeling of Nonlinear Effects for Power BAW Filters with AlN, Proceedings of Advanced Topics in Electrical Engineering, Politehnica University Bucharest, Faculty of Electrical Engineering, May 23-25 2013.

[29] *Ovidiu-SilviuTaus, Florin Constantinescu, Alexandru Gabriel Gheorghe,*. A New Behavioral Model forFrequency Domain, 2015 13th International Conference on Engineering of Modern Electric Systems (EMES). s.l. : IEE Explore, pp 1-4, 2015.

[30] *Ovidiu - Silviu, Taus,* Modele comportamentale pentru analiza filtrelor BAW (bulk acoustic wave) în domeniul frecvențăReferat de doctorat numarul 1.

[31] *Taus Ovidiu-Silviu, Constantinescu Florin, Gheorghe Alexandru Gabriel,* Compensation of the connection wires influence for a behavioral model of a power BAW filter,2015 IEEE 21st International Symposium for Design and Technology in Electronic Packaging, pp. 209-212.

[32] *F. Constantinescu. M. Nitescu, A. G. Gheorghe, A. Florea, O. Llopis, P.Taras*, „Behavioral circuit models of power BAW resonators and filters”, Analog Intergated Circuits and Signal Processing, Vol. 73, Nr 1, 2012, pp.57-64.

[33] *D. Popovici, F Constantinescu, M Maricaru, FI. I. Hantila, M. Nitescu, A Gheorghe,*Modeling and simulation of piezoelectric devices”, in Recent advances in modeling and simulation. INTECH Open Access Publisher, Vienna, 2008.

[34] *V. Lee, S. Lee, S. A. Sys, A. Mortazawi,*. Large signal performance of ferroelectric FBARs. s.l. : Microwave Symposium Digest, Montreal, QC, Canada, 17-22 June 2012.

[35] *S. Lee, V. Lee, S. A. Sys, A. Mortazawi,*. Linearity analysis of intrinsically switchable ferroelectric FBAR filters,. s.l. : Microwave Symposium Digest, Seattle, WA, 2-7 June 2013.

[36] US Patent No. US 2006/0290446 A1, December 28, 2006.

[37] *P.L. Lui*, “Passive intermodulation interference in communication systems”. Electronics & Communication Engineering Journal (1990), pp. 109–115.

[38] *M. Vladimirescu, R. Kwiatkowski, and K. Engel*, Passive Intermodulation Distortion in RF Coaxial Electro-Mechanical Switches For Space Applications, 1999.

[39] *G. CEhrlich,. and A. C.Bailey*, “A study of rf nonlinearities in nickel”.Journal of Applied Physics 50 (1 1979), pp. 453–461.

[40] *Banna, B. El*, “Passive Intermodulation from Printed Circuit Boards”, MA thesis. Royal Institute of Technology (KTH), 2006.

[41] *G. Macchiarella, G. B. Stracca, and L. Miglioli,*. Experimental Study of Passive Intermodulation in Coaxial Cavities for Cellular Base Stations Duplexers,34th European Microwave Conference. 2004, pp. 981–984.

[42] *E. Rocas, C. Collado, N. D. Orloff, J. Mateu, A. Padilla, J. M.O’Callaghan, and J. C. Booth,*. “Passive intermodulation due to self-heating in printed transmission lines”,IEEE Trans. Microw. Theory Tech., vol. 59, no. 2, pp. 311–322, Feb. 2011.

[43] *C. Vicente et al*,“An Experimental Investigation on Passive Intermodulation at Rectangular Waveguide Interfaces, ”. Microwave Symposium Digest, 2006. IEEE MTT-S International. (San Francisco, CA, USA, June 11,.

[44] *Hartnagel, C. Vicente and H. L*, Passive-Intermodulation Analysis Between Rough Rectangular Waveguide Flanges”. IEEE Trans Microwave THEORY AND TECHNIQUES, VOL. 53, NO. 8, AUGUST 2005.

[45] http://www.qtc.jp/3GPP/Specs/25101-6c0.pdf

[46] *A. Nassif*, Modeling, Measurement and Mitigation of Power System Harmonics, PhD thesis in Electrical and Computer Engineering, University of Alberta, Edmonton, Canada, 2009.

[47] *J. Yong, L. Chen, A. Nassif, W. Xu*, A Frequency-Domain Harmonic Model for Compact Fluorescent Lamps, IEEE Transactions on Power Delivery, vol. 25, No. 2, April 2010, pp 1182-1189.

[48]. O. S. Taus, Compensarea influentelor datorate conexiunilor, în cazul modelelor comportamentale ale filtrelor de putere, Referat numarul 2.

[49] O. S. Taus, Indentificarea produselor de intermodulație în cazul filtrelor BAW duplexoare, Referat numarul 3.

[50]. F. Constantinescu, A.G. Gheorghe, M. Nitescu, M. E. Marin, O. Taus, Behavioral Models of AlN Power BAW Resonators and Filters, International Symposyum on Electrical and Electronics Engineering, Galati, Romania, Invited paper, October 20-22, 2017.

[51] G. Stroe, A. Florea, O. Llopis, F. Constantinescu, A. G. Gheorghe, M. Nitescu, Measurement of Nonlinear Effects for Anti-series and Anti-parallel Connections of Power Bulk Acoustic Wave Resonators, IEEE COMCAS 2011, Tel Aviv; Israel, November 7-9, 2011.