

ANALYSIS OF THE SIGNAL NETWORK NON-LINEARITY IN A METROLOGICAL LABORATORY

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Abstract – Test signals that are used by high precise measuring have to contain minimum harmonic components of basic frequency. All non-linearity in electronic circuits may be sources of harmonic components in testing signals. Traditional methods and new method for the small non-linearity measuring of electronic components and circuits are described in this paper. There are presented examples of measured intermodulation product levels on transmission lines components.

Keywords: passive intermodulation, non-linearity

1. INTRODUCTION

Line wires, transmission lines and wiring are usually considered to be passive and linear electric circuits. Their non-linearity is minimum and it is practically unidentifiable according to a deviation of a VA characteristics from the linear curve. Linearity errors are overlapped by other phenomena during monitoring of VA characteristics - by temperature dependence, noise, measurement inaccuracy and it is almost impossible to determine them in this way. At the same time, this kind of the non-linearity does not cause disturbance even upon measurements with a high accuracy, if voltage levels, direct or alternate currents are measured. Measurement will not be effected even by a non-linearity, if it is drawn in order not to be affected by disturbing phenomena, which have a higher level than a non-linearity.

But other situations occur, if the voltage time response will be measured. Let us say, if this course will be used as a primary standard. The problem of this kind has been detected, if high pure sine – wave signal should be used for ADC testing. Requirements imposed on test signals are very high for converters with approximately 20-bit resolution. This test signal has to contain minimum harmonic components of basic frequency and minimum noise level. Quality of the test signal is characterized e.g. by the ratio of the signal (carrier) to all disturbance signals, which is given by a value SINAD (Signal to Noise and Distortion Ratio), (1), [1]. (P_{All} is power of all signal components, P_0 power direct component, and P_1 power of the carrier).

SINAD, needed for testing of the 20 bit ADC, is then c. 125 dB, for 24 bit ADC nearly 160 dB [2].

$$SINAD = 10 \log \frac{P_1}{P_{All} - P_0 - P_1} \quad (1)$$

This further means from the standpoint of the non-linearity, that if we neglect the influence of the noise, the sum of powers of all harmonic components of the test signal has to be more than the value of SINAD, lower than power of the carrier.

Although hardly, but it is nevertheless possible to implement generators (Fig. 1), which produce that high-quality test signal. The implementation is difficult. Further problems, at the first sight unexpected, can however emerge, if we lead a signal thru one metre long jumper cable in the midst of devices on the table in a laboratory. An unsuitable cable, which shows some non-linearity, can quite degrade the test signal and the level of 3rd harmonic increase about 80 dB and quite prevent the measurement, on which the high sine signal spectral purity has been needed.

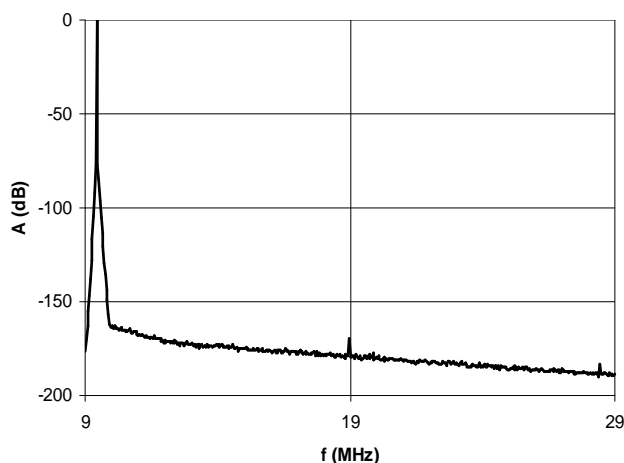


Fig.1 Frequency spectrum of high pure sine – wave signal generator 9,484 MHz

A non-linearity evaluation of also almost quite linear electric circuit is therefore an important problem. Sometimes it is impossible to measure without the solving of this problem.

2. PASSIVE INTERMODULATION (PIM)

Very seldom the systems are used for direct evaluation of a higher harmonic frequency, which is generated by a passive circuit at the exciting of a sine signal. CLT1 apparatus manufactured by RADIOMETER Company, which was produced in the late 1960s, was an example of that arrangement [3]. The principle of operation is indicated in the block diagram shown in Fig. 2.

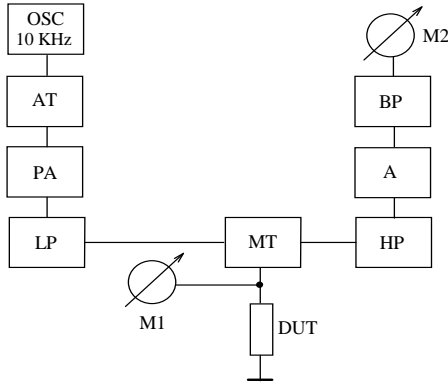


Fig.2. The component linearity test equipment CLT-1

The output from the 10 kHz oscillator is feed via Attenuator AT to the special low distortion Power Amplifier PA. The output voltage of the latter is feed to the Low-Pass-Filter, LP, suppressing more the 3rd harmonic, in order to obtain a very pure sinusoidal signal, which is applied to the, DUT, via the Matching Transformer. The exciting voltage, which is applied to the component, is measured by means of the Voltmeter M1. The 3rd harmonic voltage generated in the component under test, is passed via the Matching Transformer to the High Pass Filter, HP, which suppresses the exciting signal in order to avoid overloading of the Preamplifier A. The 30 kHz output signal of the Preamplifier is fed via the Band Pass Filter, BP, which keeps the noise bandwidth sufficiently low, to the 30 kHz Voltmeter M2, which indicate the 3rd harmonic level.

This measurement procedure is however very difficult, because the used excitation generator and selective micro-voltmeter have to show such harmonic distortion, which is insignificant against measured values, the apparatus has the sensitivity about -160 dBc in optimal case and it is possible to use it for two-terminal networks with the impedance from several Ω to hundreds of k Ω .

At the present time the non-linearity of low-nonlinear circuits is especially monitored by an evaluation of intermodulation signals [4]

Intermodulation signals are disturbing signals in general, which is based on two signals of different frequencies in the non-linearity. The frequency of the intermodulation signal f_n is different from the frequency of the exciting signal f_1 and f_2 . The value $n=n_1+n_2$ is described as an order of the intermodulation product- See (2), fig.3.

$$f_n = n_1 f_1 + n_2 f_2 \quad (2)$$

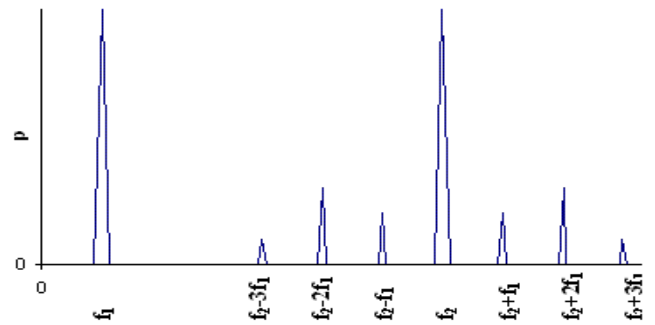


Fig.3: Spectrum of intermodulation signals

The power level of the intermodulation product increases with the raising power of the exciting signal and with increase of the non-linearity.

In case of equal levels of exciting signals $P_1=P_2=P$, a power dependence of the level of intermodulation product P_n and order of product n (3) is usually supposed.

$$P_n = cP^n \quad (3)$$

where c is a constant that is given by the deviation of the nonlinear dependence of non-linearity from the linear course.

This measurement of the third harmonic correspond to these measurement for a special case $n=n_1+n_2 = 3$ and $f_1 = f_2$ too.

Radio communications systems, especially mobile radio systems at present, are the most important field, where the inter-modulation distortion is monitored. Measuring equipment to this goal usually evaluates intermodulations of the third order using frequencies of the order of hundreds of MHz to order of GHz and they are designed for measurements in circuits with the characteristic impedance of 50 Ω with a use of directional coupling elements [5]. The sensitivity of the arrangement is -160 dBc at the excitation power 43 dBm with regard to noise floor and IN noise floor of the equipment.

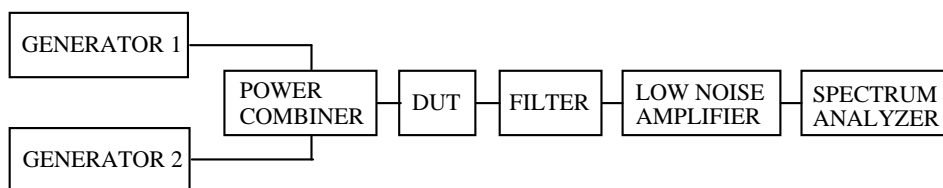


Fig. 4 Schematic diagram of measuring system

For our purposes, these measurements cannot be considered too representative. Our systems work with frequencies about 2-3 orders lower. Characteristics of circuits with distributed parameters are far less significant at measured part. A skin effect displays otherwise too. The block diagram arrangement, which has been realized and further used for measurement PIM, is shown in Fig. 4.

The system works on lower frequencies, c. 100 kHz until 4,5 MHz. Its construction is based on available equipment and should achieve the maximum intermodulation immunity. Only this way it is possible to achieve a maximum sensitivity of measuring intermodulation; signals generated by the measuring object do not overlap the signals, which are generated by the system.

The most demanding parts of the system from the construction point of view are the power combiner and filter. In these the exciting signals f_1 and f_2 with the high power act at the same time and undesirable IM products are likely to emerge.

The frequency plan according to the narrow band crystal filter with a central frequency 4,4 MHz and with the bandwidth 8 kHz, which was available, has been chosen for realized measuring system.

The first generator works in frequency bandwidth from 3 to 4,5 MHz, second generator works in frequency bandwidth from 0,1 to 0,5 MHz and the measurement is realized at the frequency $f_1 + 2f_2$.

High requirements are set also on excitation generators, which must embody a high spectral purity, in order for its signal noise in the frequency band of the evaluated signal not to reduce the sensitivity of the measuring.

Higher requirements are imposed from this point of view on the first generator, because the measuring frequency is always near to its operating frequency, where inconsiderable noise level is produced by common generators too. The typical frequency dependence of the signal to noise ratio of the phase noise in surroundings of carrier for generator SMY 01 and frequency 4,1 MHz is displayed in Fig.5.

The noise level of this generator is too high to be used in measuring system, as well as by other tested generators. With its usage, it would be possible to measure only intermodulatory products with the signal to noise ratio that is higher than approximately -140dB.

A resulting filtering out of disturbing signals, which are produced by frequency filter of generator on its output, is very difficult too. A complicated generator (synthesizer) with a complicated signal processing on a low level always generates phase and broadband noise with a high level.

A simple generator with direct way of the signal is preferable to be used from aspect of achievement of the highest spectral purity of the test signal. The signal is generated directly on required frequency and on a high level and it does not have to be amplified anywhere to achieve the required output power with a high gain in this signal generator. The used generator has been specially designed for described measuring system as an electron-coupled oscillator using electron tube. This solution, resembling a small electronic CW transmitter from half of the last century, has been chosen, since it allows achievement of the highest spectral purity of the test signal.

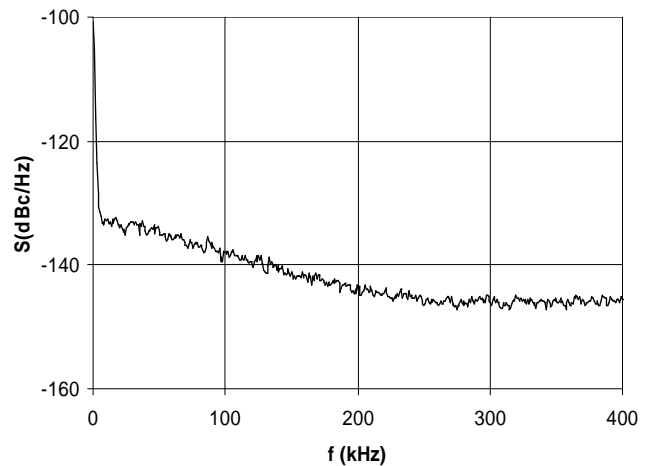


Fig.5 Frequency spectrum of sine-wave signal generator SMY 01 at frequency 4,1 MHz with frequency spacing of carrier 0 to 400 kHz

The generator is planted by 12 W wideband pentode with anode mutual conductance 15 mmhos and mutual conductance for g_2 3 mmhos. It supplies maximum output power 10 W. Spectrum of the output signal for working frequency 4,1 MHz is displayed in Fig. 6.

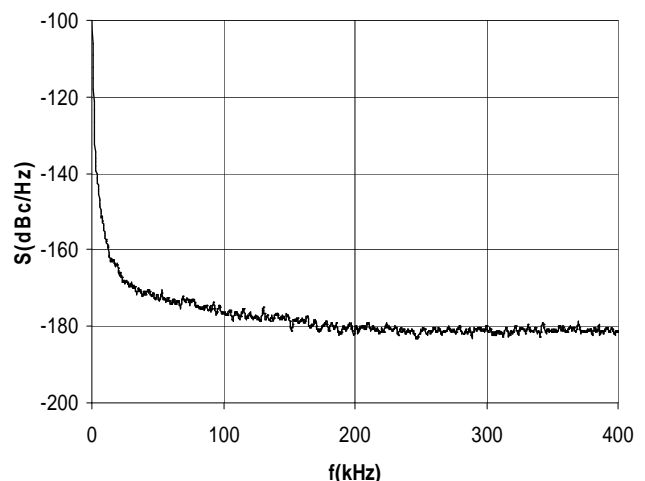


Fig.6 Frequency spectrum realised electron coupled oscillator at frequency 4,1 MHz with frequency spacing of carrier 0 to 400 kHz

The realized generator gives far better spectral purity of the signal than a commercial signal generator. Its disadvantage is only lower stability of the frequency, so that the frequency of the generator has to be continuously checked by a counter during the measuring, in order to enable adjustment of the generator in case of need.

The second generator can be implemented with better use of commercial equipment and parts, with regard to higher frequency spacing towards the measuring frequency,

The undesirable disturbing signals, that are produced by the generator in the area of measuring frequencies, can be cleared out by use of filter, e.g. by low-pass filter, because measuring frequency is almost about one order higher, than operating frequency of the generator.

The second generator is composed together from commercial signal generator, linear power amplifier and filter. The signal generator supplies a test signal with a low level, approximately 10 dBm with possibility to control amplitude and frequency. Signal to noise ratio in the range of measuring frequencies for carrier at intervals 0,1 to 0,5 MHz, corresponds to the signal to broadband noise ratio and it ranges from -120 to -140 dBc/Hz. The used amplifier supplies maximum output power 20 W, it has the gain practically 40 dB and a noise from 10 to 16 dB. The signal to broadband noise ratio at the output of amplifier is slightly worse than at an exciting generator, but however always better than -100 dB. At the output of amplifier, the connected filter makes it possible to achieve further marked improvement of the signal to noise ratio. The frequency response, displayed in Fig.7, is reached with a simple low-pass filter LRC with ladder structure of the 11th order. The total suppression of disturbing products of the second generator in the area measuring frequencies reaches approximately 200 dB.

The power combiner is implemented as a diplexer with high-pass and low-pass filter, which always transmits the signal of the connected generator and suppresses the signal of the second generator, see Fig.8.

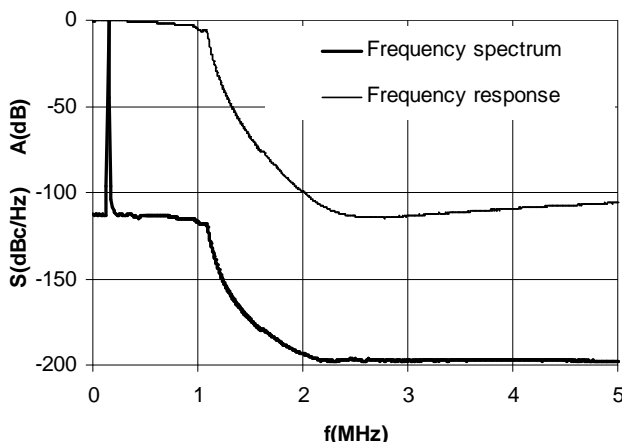


Fig.7 Frequency response of low-pass filter; resulting spectrum of the 2nd generator.

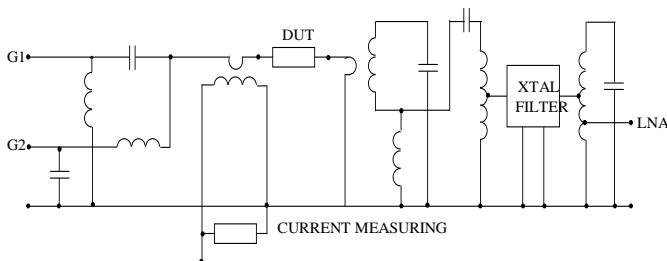


Fig.8: Principal circuit diagram of power combiner and filter

Only this way it is possible to provide the minimal influence of one generator on the second even if the load of the power combiner would be very mismatched. High intermodulation immunity implicates the using of special components. Coils must not have ferro-magnetic core. No ferro-magnetic materials can be used by the construction,

not even as screws. Capacitors are micaceous, consisted of the unplated mica, with electrodes made of metal foil, because even the contact terminal with plating causes non-linearity.

A current sensor, which serves as indication of service current during measurement too, is inserted at the output of a power combiner. Common current transformer or current probe cannot be used, with regard to requirement of maximal linearity, here also valid. The special current transformer used here is implemented without ferro-magnetic core, rather by method corresponding to Rogowsky potentiometer. The voltage at the resistor, whose value is at the loading small, when compared to the absolute value of reactance of potentiometer coil, is approximately proportional to the current carried through conductor, which is enlaced by potentiometer.

Attenuation of the signal transmission is 0,5 dB maximum, from generator to DUT past a channel of low-pass filter and also a channel of high-pass filter in the area of used frequencies. Attenuation of signal transmission between outputs of generators is approximately 40 dB and it is sufficient to suppress the creation of measurable level of intermodulation products in circuits of generators.

The filter ensures separation of a measured intermodulation signal with very small level and power exciting signals. Then it must have a minimal input impedance for an exciting signals, in order to reflect these signals and instead of being loaded with their power and higher impedance (real) for the evaluated signal, which goes through with the low attenuation.

Filter has to be considerably selective, in order to prevent creation of the intermodulation products in the following low noise amplifier or directly in spectral analyzer were not generated owing to penetrating exciting signals. The design of the filter comes out of a piezoelectric crystal filter, which has suitable narrow band-pass characteristic and a great attenuation in the stop band. However, the crystal filter does not bear up against power of the exciting signal and its intermodulation immunity is low for our function. Therefore the filter was buffered by special tuned circuit with a high Q factor and intermodulating immunity on a feeding side. The circuit has to be again designed by a special way, it has an air coil and a vacuum capacitor placed in a dimensional shield, see Fig.9. The tuned circuit works like a high linear band pass filter and on the whole it remarkably improves characteristics of the filter. The total suppression of both exciting signal by the filter is better than 100 dB, the attenuation of the measured signal is at the limit of 6 dB.

The low noise amplifier significantly increases total sensitivity of measuring system. It decreases its noise figure, which can reach also value about 32 dB when a common spectral analyzer is used as a selective detector of level. The low noise amplifier with noise 3 dB and gain 40 dB decreases the noise to value from 3 to 4 dB and so it increases the system sensibility by approximately 28 dB.

The spectral analyzer HP 8560 is used for evaluating the intermodulating signal level.



Fig. 9. Input resonant circuit of the filter

This arrangement allows to work with currents up to 0,6 A and power to 40 dBm in measured circuit. The arrangement sensitivity is approximately - 180 dBc with regard to a noise floor and IM noise floor of the equipment at the maximal level of the excitation signal.

3. NON-LINEARITY EVALUATION

Measurement has been made by described above arrangement on connectors of N type and jumper cables with connectors of N type that are used in our laboratory.

Tested connectors were interconnected with measuring equipment by segments of coaxial cable, which has been soldered on equipment terminals.

An AIRCOM PLUS type cable, out of cables, which were available, has been chosen. This cable, with length section approximately 1 m, did not generate intermodulation products at measurable level.

Further cable section was broken. Furthermore, this cable section was broken and fixed by male connectors N, which were connected each other by female-female adapter and measuring has been repeated. The dependence of intermodulation products of 3rd order level on a level of a driving signal is stated in Fig. 10 at the connection by various adaptors.

If a mechanical defect is not on contacts or these are not polluted, the materials, out of them contacts and connector are produced, have the biggest influence from the point of view of the level of generated intermodulation products. The lowest level of PIM was shown by connectors with a pure silver-coated surface, in which ferro-magnetic metals are not used, e.g. types BN 922484, adapter BN 293750, manufactured by Spinner company, 1AA4549, manufactured by Tesla company. On the contrary, the used, e.g. types BN 922484, adapter BN 293750, manufactured by Spinner company, 1AA4549, manufactured by Tesla company. On the contrary, the connectors with nickel-coated surface or steel parts, e.g. NC1459, supplied GES company types, shown high-level of PIM. Connectors with gold-coated contacts or their parts show ambiguous results. The technological production process of gold plating is an evident reason for this; Gold plating is prepared with Ni interlayer between background material and gold in order to

improve the adhesion. Ni layer, if it is not prepared with a special process, is ferromagnetic and causes non-linearity of the conductor, in which it is integrated.

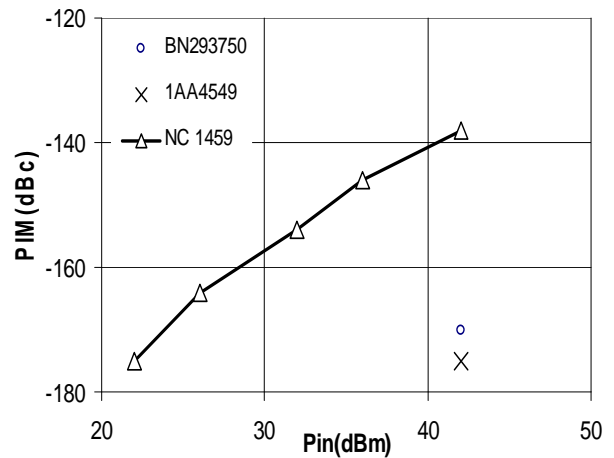


Fig. 10 The dependence of N adaptors generated IM products level on a level of driving signal

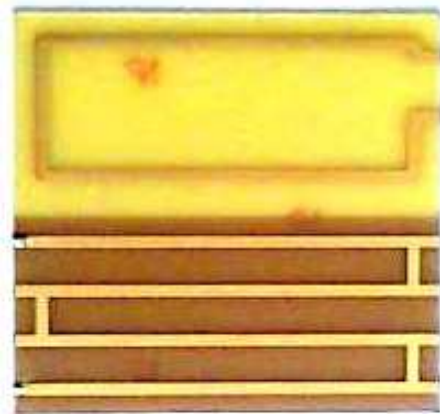


Fig. 11. Tested PCB line-meander line

This effect was experimentally tested on PCB with various surfaces of lines connection, see fig 11. A strip line of a length 360 mm with characteristic impedance 50 Ω on glass epoxy resin material FR4 has been compared, see fig.12. The PIM level generated by line with pure Cu surface, with tin-plated surface or chemical gold plating was practically the same and very low, on the resolution limit of the measuring system. Markedly higher was the PIM level at the power line with a galvanic gold plated surface with Ni interlayer (3μm Ni, 1 μm Au).

Roughly 1 m long sections of cables with male N connectors at their ends were tested for measuring on jumper cables. The gates of the measuring arrangement were settled by female connectors N of the type BN 290500 and hoods BN 005670 by means of short sections of AIRCOM PLUS cable, on which it was possible to connect tested cables. Measuring results on the cable with higher level of PIM are summarized in Fig. 13.

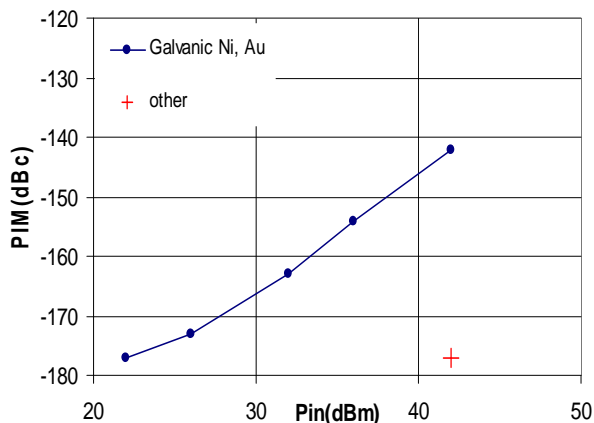


Fig.12: The dependence of PCB lines generated IM products level on a level of driving signal

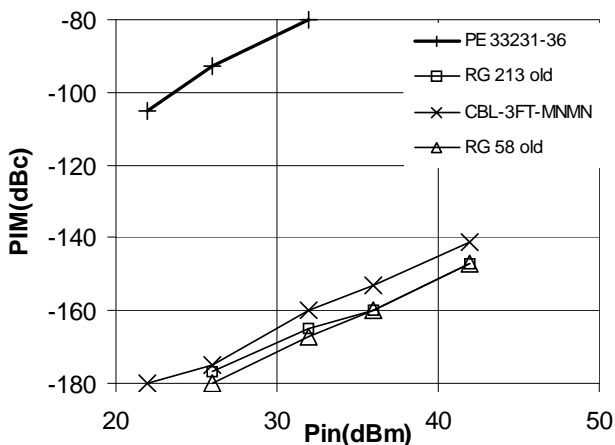


Fig. 13: The dependence of N jumper cables generated IM products level on a level of driving signal

Maximum IM level was found at cable PE 33231-36 manufactured by Pasternack company. This result is evidently caused ferro-magnetic materials, which were used in the construction of cable and connectors – the coaxial cable has a steel core of inner conductor, whereas the steel outer conductor is in connectors. Cable CBL-3FT-NMNM by manufactured by MINI-CIRCUITS company generates approximately by 80 dB smaller level of IM product. Here, the coaxial cable is also used with the steel core of inner conductor [6]. Older classic cable of common construction RG213 and RG58 have also had approximately the same properties. The non-linearity is probably caused by a slight corrosion of the outer conductor of cables. This corrosion was even observable on these samples. The same, but new cables embodied a hardly notable level of IM products at intervals from -177 to -175 dBc only for maximum level of an actuating signal.

The AIRCOM PLUS cable with the connector BN 922484, cable RG400 with connectors 53S107-108N3 manufactured by Rosenberger company and unexpectedly

also old cable QYB 500 02 by Tesla company embodied the level of IM products about -177 dBc, which is measurable only for a peak level of an excitation signal.



Fig.14: Coaxial cable with foil outer sheath

CONCLUSION

PIM of cables and connectors has been evaluated that are used in calibration system with high pure sine-wave signal generator in our laboratory. Products with ferro-magnetic parts made of steel, stainless steel or nickel usually generate a high-level of IM products. A contact non-linearity between metal conductors of all kinds is also further source of IM products, especially if metal surfaces are not perfectly clean. Conductor in the form of braided rope can embody non-linearity. Line wire in the form of wire braid can also embody the non-linearity. This line wire is used as an outer conductor of a coaxial cable, where the HF current is led alternatively by several segments of line wire and has to pass among them.

The cable with a smooth cylindrical inner Cu conductor and outer sheath made of Cu foil (see Fig. 14-AIRCOM PLUS) had the best properties, out of tested cables.

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