REPORT 1049-1*

CONTROL OF PASSIVE INTERMODULATION PRODUCTS

(Question 86/8)

(1986-1990)

1. Introduction

This Report deals with the subject of passive intermodulation and emphasizes the importance of careful consideration of the relevant mechanisms applying to satellite design and system operations that cause such intermodulation effects.

2. History

Passive intermodulation products (PIMs) were initially observed at HF radio stations where high level transmitted signals produced intermodulation which caused interference to communications receivers. The intermodulation was found to be due to oxidation of the iron bolts used to fix the transmitting antennas together (rusty bolt effect). Latterly, the phenomenon has been identified as occurring in maritime satellites at 1.5 GHz where similar electrical conditions to those at the HF radio stations occur, i.e. high level transmitted signals and very low level received signals.

It seems that a necessary condition for production of passive intermodulation products, is that a difference of signal level of around 130 dB should exist between transmitted and received signals. Such conditions occur in maritime satellite antenna feeds both in the satellites and at the shore stations. However, passive intermodulation has only been noted as occurring in satellites and attention to the differences of construction between these two areas may yield conclusions as to its fundamental cause.

3. General

Intermodulation is a phenomenon that occurs in non-linear devices. If two or more signals are transmitted through such devices, further signals are generated whose frequencies and levels are a function of the frequencies and levels of the wanted signals at the input to the device.

Intermodulation products commonly cause adjacent-channel interference and, in the case of multiple carrier systems, interference throughout the radio channel bandwidth.

The level of intermodulation products is determined not only by the voltage transfer characteristic of the device but also by the bandwidth of its response. Thus in the case of active devices, where the bandwidth is limited, the level of intermodulation products having frequencies outside the bandwidth of the device is commonly negligible. In the case of passive devices (e.g. waveguide) the bandwidth constraint is much less and products may also be generated after transmission of the wanted signals through filters intended to suppress intermodulation products and/or reduce spurious or noise power at receive frequencies. Where systems have more than about 150 dB gain, it is possible for passive intermodulation products to be generated at the output, which are of sufficient level to make the system unusable because of interference to the system input signal.

* This Report should be brought to the attention of Study Groups 1 and 4.

4. Generation of passive intermodulation products (PIM)

It is believed that the most dominant mechanisms in the generation of PIMs are:

- semi-conductor effects of surface oxide layers;
- micro-discharges due to metal defects;
- non-linearities associated with carbonization and oxidisation at metal surfaces, the deposition of other contaminants, and loose or dirty connections;
- the non-linearity of all ferro-magnetic materials, including stainless steel, nickel-plating and all ferrite components.

It also appears that PIM is far more likely to occur in a vacuum than under ambient pressure conditions.

In practice the non-linearities in passive devices, responsible for the generation of PIM, are a result of the summation of many different micro-currents. Microscopically, all surfaces are highly irregular and moreover they have an oxide layer several angstroms thick on their surfaces. Where contact occurs between surfaces, the oxide layer affects the impedance at the contact point. The oxide and voice regions generate a displacement current and the relative magnitude of this current to the conduction current determines the non-linearity of the junction.

A comprehensive review of PIM generation in high power communication satellites is contained in a paper by Hoebar, Pollard and Nicholas [1986]. In the context of maritime mobile-satellites this covers the background to the problem design considerations, causes of PIM's, and guidelines for their mitigation.

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5. Experimental investigations by:

5.1 *Nuding*

Nuding [1974] of AEG-Telefunken carried out an experimental investigation of PIM produced in a waveguide using RF powers up to 1000 W in the 2 GHz band. With powers in the range 0-500 W the amplitudes of the third-order intermodulation products were found to vary as the third power of the applied RF power, i.e.:

$$Nk = \alpha N^3 \tag{1}$$

where:

Nk: amplitude of an intermodulation product of the third order;

N: RF signal power (same level for both test signals);

α: constant which depends on the degree of non-linearity of the device.

The experimental results of Nuding indicate that for two RF carriers, N_1 and N_2, of equal power up to 500 W, the PIM signal power levels obey the law of equation (1), i.e. αN^3. Third, fifth and seventh order PIMs ($k3$, $k5$, $k7$) vary in amplitude with respect to the carrier power in the same manner. Also, for a fixed RF carrier level the difference in amplitude between 3rd and 5th orders is approximately equal to the difference between 5th and 7th orders, i.e. $\alpha = \beta$ (see Fig. 1).

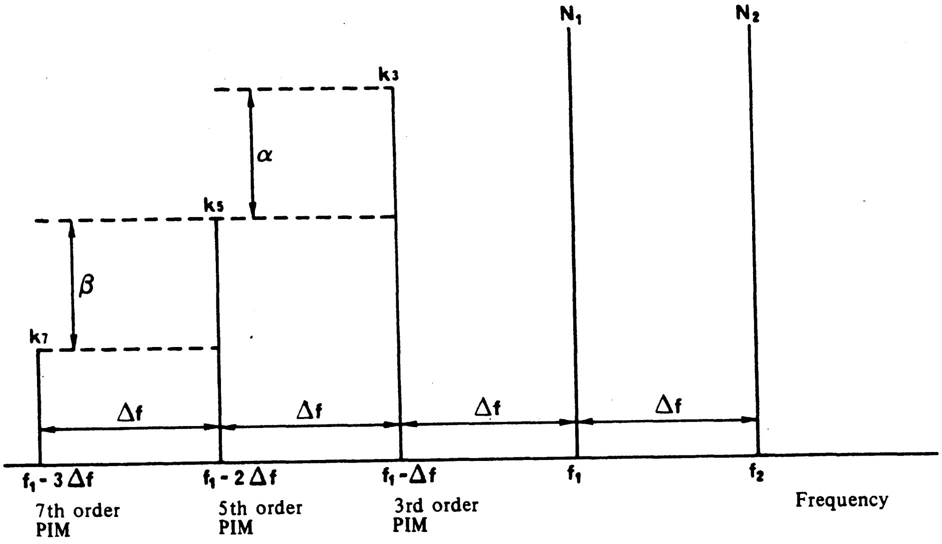

FIGURE 1 – *Passive intermodulation product levels*

Table I below gives some values quoted in Nuding's paper, or extrapolated from his results.

TABLE I

Carrier power, N (W)	Average change in power per order (dB)	PIM power level (dBm)		
		3rd order	5th order	7th order
200	34 (1)	−60	−94	−128 (1)
250	33 (1)	−56	−90	−122 (1)
1000	20	−45	−66	−86

(1) Extrapolated.

5.2 *Cox*

Earlier experimental work by Cox [1970] used a 1 W power source and frequencies around 6.0 GHz. However, because of the low power used the results may not be directly transferable to that which would happen at higher powers. As an example he found that a loose waveguide flange could give rise to third-order PIMs as high as −25 dBm for 1 W carrier power, and −50 dBm for fifth-order PIMs. Flexible waveguide gave third-order products in the range −55 dBm to −110 dBm.

One of the conclusions in Cox's paper is that PIM generation is essentially independent of changes in transmitter frequency separation. On this basis it is likely that results can be extrapolated to other frequency bands.

Another observation of Cox was that loose metal-to-metal surfaces exposed to RF fields such as waveguide joints or tuning screws, generated strong but erratically changing PIM levels. For one circulator for example, a third-order PIM product was measured at −65 dBm with up to 20 dB variations. Tightening of screws which held the circulator together reduced the same PIM level to −90 dBm steady, a reduction of 25 dB.

5.3 *Chapman et al.*

Chapman and colleagues [Chapman *et al.*, 1976] measured a third-order PIM at −80 dBm with two equal power test signals of frequencies 7.9 and 8.05 GHz and a total power of 5 kW. They concluded that third-order PIM varies by about 3 dB for each dB variation of total power. Regarding the higher order PIMs they found that the level reduced by between 10-20 dB per order for a typical feed assembly with 1000 W total applied power. They recommended that tuning screws be eliminated to remove the most significant cause of PIM products.

6. Variation of PIM with increasing order

Nuding's conclusion on the variation of PIM levels with increasing order gives extremely low results for the thirteenth order and higher orders. Nuding's conclusion was that the decrease in PIM power per odd order was −34 dB, however other authors have quoted lower figures; for example [Roorsey *et al.*, 1973] gives a figure of −8 dB per odd order and others about −10 dB per odd order. In addition the third-order power level obtained by others is significantly lower than those obtained by Nuding. The following table gives a comparison between various figures for the third-order PIM level and the rate of decrease per odd order.

It is probable that in going from third to fifth order and from fifth to seventh order the PIM power level does drop by around 34 dB but for higher orders the change is less as different mechanisms come into effect. Nuding's results do indicate that the variation is less with increased carrier power.

TABLE II

	Authors		
	Nuding [1974]	Roorsey *et al.* [1973]	Chapman *et al.* [1976]
3rd order PIM power level (dBm)	−60	−85	−82
Variation per increased odd order (dB)	−34	−8	−10

The minimization of PIM's should be part of overall satellite design philosophy, and thus at the outset the materials used for waveguides, filters connectors, cables, etc., should be carefully selected to reduce them to an acceptable level. A concerted effort to overcome these problems should also be made by component and system designers as well as assembly and testing personnel.

A number of general design guidelines exist which, if properly employed, can help to minimize the problem. These are as follows:

- if possible, frequencies chosen for the up-link should be such as to ensure that PIM products from the satellite transmitter are outside the satellite receiver carrier bands;
- the satellite design should be optimized to limit the sources of passive intermodulation (non-linear passive devices) to a minimum . For example transmit and receive signals should, as far as possible, be carried over completely separate paths, use separate electronic components and separate transmit and receive antennas;
- the use of high-Q resonant circuits should be kept to a minimum in appropriate areas. For example, hybrid filter designs for band-stop filters could be used instead of band-pass filters;
- the use of mechanical contacts in appropriate areas should be minimized. In particular, connections should not be made by use of metallic contacts, and sliding contacts should be avoided;
- ferromagnetic materials in or adjacent to the system should be avoided if possible. If used they should be plated with high conductivity materials (i.e gold, copper);
- the RF current density in transmission lines and resonators should be kept to a minimum e.g. by increasing the dimensions of transmission lines and resonators. For coaxial cables, solid sheaths are to to be preferred. If braided cables are used the braiding should be dense;
- care should be taken in the design of mechanical components in appropriate areas; sharp edges should be avoided;
- care should be taken in fabrication and cleaning procedures to avoid contamination at critical interfaces;
- the use of metals which readily oxidize should be avoided, e.g. aluminium;
- good electrical conductivity should be ensured by using high contact pressures and smooth surfaces at flanges;
- operating temperature ranges should be as small as practicable to limit consequent physical changes.

Experience has shown that metallic interfaces are the most likely sources of system non-linearity. This does not mean that an acceptable low level PIM system cannot exist without junctions but a junction can be linear only if it is tight, smooth, flat and clean. These are of course relative terms and are somewhat inter-related in that non-smooth surfaces can be made smooth by sufficient pressure. In general, it is good practice either to make contact surfaces smooth and tighten them until satisfactory contact is achieved or to braze joints using high quality methods and materials.

8. Conclusions

Passive intermodulation products (PIM's) only cause problems where a common signal path exists for transmitted and received signals having a level difference of about 130 dB. A necessary condition for their production is that elements in the transmission path exhibit non-linear properties.

The limitation of PIM's to an acceptable level in satellites is an extremely difficult task, but experience has shown that with extreme care and by paying careful attention to the guide-lines set out in Section 7 systems can be designed and built where PIM's are controlled to an adequately low level.

PIM's are much more of a problem in satellites than in ground terminals, and this is accounted for by the fact that ground terminals do not have mass constraints so that the use of light-weight materials such as aluminium, which is subject to the formation of oxides with their inherent non-linear properties, is unnecessary. In addition, at ground terminals better waveguide flange joints are generally achievable using higher flange pressures etc.

Because of the importance of this subject and the fact that problems due to this cause exist in maritime satellites currently in service, administrations and other participants are encouraged to contribute more information on this subject particularly with regard to the design of maritime satellites and operation of maritime satellite systems. Relevant information with regard to satellites currently in service is requested.

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