POLITECNICO DI TORINO
Repository ISTITUZIONALE

Analysis of Non-Linearly Loaded Antennas and Scatterers

Original
Analysis of Non-Linearly Loaded Antennas and Scatterers / Naldi, C., Filicori, F., Zich, R.. - STAMPA. - (1980), pp. 485-489. (10th European Microwave Conference Varsavia (Pl) 1980, 8-12 Sept.) [10.1109/EUMA.1980.332845].

Availability:
This version is available at: 11583/2666091 since: 2017-02-27T16:22:40Z

Publisher:
IEEE

Published
DOI:10.1109/EUMA.1980.332845

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright
IEEE postprint/Author's Accepted Manuscript

©1980 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collecting works, for resale or lists, or reuse of any copyrighted component of this work in other works.

(Article begins on next page)

26 November 2026

ANALYSIS OF NON-LINEARLY LOADED ANTENNAS AND SCATTERERS.

C.NALDI , R.ZICH (+) and F.FILICORI (++)

ABSTRACT. A very efficient numerical technique for the analysis of non-linearly loaded antennas and scatterers is proposed. It is based on a generalization of the piecewise harmonic balance method, which overcomes the need to examine the complete transient development in the time domain. The algorithm enables the analysis of multiport nonlinearities expressed even in implicit form and appears to be extremely useful even with strong nonlinearities. This approach is found to be highly recommended for applications which only require the steady-state responses such as co-operative targets and environmental measurement techniques. An example of application is given.

INTRODUCTION

At present there is considerable interest in developing efficient methods for the analysis of non-linearly loaded antennas. This problem is of importance since non-linear effects must be taken into account in systems of antennas which include semiconductor components, integrated circuits and voltage limiters with very strong incident fields such as those produced by lightning or by NEMP (Nuclear ElectroMagnetic Pulse) [1] . Moreover, some field measurement techniques such as the EDM (Energy Density Meter) now being developed at the National Bureau of Standards [2] make use of short dipoles loaded by a diode. It must also be noted that some radar applications with co-operative targets are based on the use of non-linearly loaded scatterers [3]. Examples are provided by the transponders with frequency duplication, used in anti-collision systems [4] in order to distinguish between the required signal and the clutter coming from the environment.

The behaviour of an antenna or a scatterer non-linearly loaded can be determined either in a strictly theoretical way (expansion in the Volterra series) or directly using suitable numerical techniques. The first method is particularly useful when special kinds of non-linearities must be handled, but the Volterra series, in its classic formulation, are of practical use only when dealing with nonlinearities that are not too strong. On the other hand the time domain direct integration of the differential equations of the system in the case of high frequency devices and with time constants much greater than the period of the signal can be found to be numerically impracticable owing to the excessive time necessary. In some applications, such as some kinds of co-operative scatterers, where steady-state responses are concerned, techniques that do not require the whole computation of the transient can be applied. These techniques have been recently developed in the field of power microwave devices.

Whichever method is used, it is necessary to accurately characterize the antenna on a very wide frequency range, in some cases up to sixteen times the excitation frequency. This can be done if: i) a high number of experimental data are available, ii) it is possible to define an accurate equivalent circuit and iii) efficient numerical techniques for analyzing the radiating structures exist.

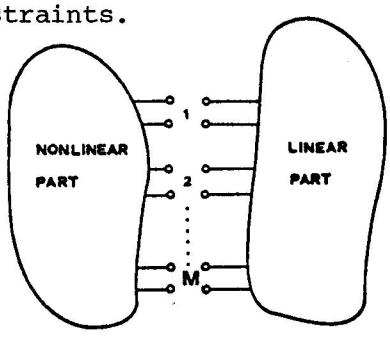
The study of the behaviour of non-linearly loaded antennas can be be described as an electric circuit analysis ptoblem with characteristics of non-linearity and reactivity, and in periodic steady-state conditions. The analysis techniques normally used are based on the numerical integration

(+) *Istituto di Elettronica e Telecomunicazioni, Politecnico-Torino, Italia.*
(++) *Istituto di Elettronica, Università di Bologna, Italia.*

in the time domain of the non-linear differential equations describing the network behaviour. In the case of strongly non-linear loads, such as a junction diode with exponential characteristics and breakdown phenomena, and in the case of microwave devices, where time constants may be present much longer than the period of the signal, direct integration could be too expensive in terms of computing time. In the applications where steady-state response is required, techniques can be adopted that do not need the complete knowledge of the transient phenomenon; namely shooting and extrapolation methods, methods based on the Volterra series analysis and harmonic balance methods.

GENERALIZED FORMULATION OF HARMONIC BALANCE

In the framework of harmonic balance methods a more general formulation can be defined which allows strongly non-linear multiports (which can also be described through implicit equations) to be taken into account and leads to numerical algorithms quite fast even with hard non-linear constraints.



The whole network is split so that a subnetwork composed only of linear elements is connected to other subnetworks which include all the non-linear elements (fig.1). It should be noted that a circuital model is not strictly indispensable, in fact the partitioning can be directly effected on the differential equations describing the system. Let $\underline{v}(t)$ and $\underline{i}(t)$ be the vectors of the electrical variables at the connection ports and T the period of the foundamental component of the forcing terms represented by the equivalent generators $\underline{x}(t)$. Let the non-linear subnetworks be described by a set of non-linear equations in the form :

$$\underline{f}\left[\underline{v}(t), \dot{\underline{v}}(t), \ldots \underline{v}^{(r)}(t), \underline{i}(t), \dot{\underline{i}}(t), \ldots \underline{i}^{(s)}(t)\right] = \underline{0} \qquad (1)$$

$$\forall t \ , \ 0 \leqslant t < T$$

Taking into account that the same variables could be used to represent the linear part of the antenna circuit in the frequency domain, it is :

$$\underline{H}(\omega)\ \underline{V}(\omega) + \underline{K}(\omega)\ \underline{I}(\omega) = \underline{X}(\omega) \qquad (2)$$

with : $\left[\underline{I}(\omega), \underline{V}(\omega), \underline{X}(\omega)\right] = \mathcal{F}\left[\underline{i}(t), \underline{v}(t), \underline{x}(t)\right]$

$\underline{H}(\omega)$ and $\underline{K}(\omega)$ being suitable network matrices. The analysis problem consists of solving simultaneously the system of equations (1) and (2).

When the electrical variables in the non-linear equations (1) are expressed as Fourier series, the linear equation can be used to eliminate one of the two types of variables (voltages or currents); the analysis problem may thus be reduced to the search for the solution of a set of non-linear time-varying equations in the form :

$$\underline{g}\left[\underline{I}(\omega), \underline{X}(\omega), t\right] = \underline{0} \ ; \ \forall t \ , \ 0 \leqslant t < T \qquad (3)$$

As an example of a possible procedure in equation (3) the unknown variables are the harmonic components $\underline{I}(\omega)$ of the currents at the interfaces with the non-linear subnetwork. Taking into account that, under the hypothesis of a steady state response, the time functions are periodic too and can be expressed as Fourier series, the system of eqns (3) takes the form :

$$\underline{G}\left[\underline{I}(\omega), \underline{X}(\omega)\right] = \underline{0} \qquad (4)$$

with $G = \mathcal{F}[g]$. If N is the maximum number of harmonics necessary to corre

ctly represent the electrical variables(according to Shannon's theorem) and ,if M is the number of connecting ports (fig.1), the system of equations (4) is made up of M(N+1) non-linear time-independent equations. The unknown variables may be represented,for example, by the (N+1) harmonic components of the currents at the M interfaces; the term $\underline{X}(\omega)$ can be considered as parameter of the system. The system can be solved efficiently by using, for instance, the Newton-Raphson iterative technique which has a second order convergence rate.

By using the algorithm :

$$\left(\frac{\partial \underline{G}}{\partial \underline{I}}\right)_{I^k} \cdot (\underline{I}^{k+1} - \underline{I}^{k}) = -\underline{G}(\underline{I}^{k}) \quad \text{with:} \quad \frac{\partial \underline{G}}{\partial \underline{I}} \rightarrow [g_{ij}] : g_{ij} = \frac{\partial G_i}{\partial I_j} \qquad (5)$$

and $i,j = 1 \div M(N+1)$, the problem is reduced to the search for the solution of a sequence of linear systems such that the matrix of the coefficients can be evaluated numerically or analytically, the unknowns being the differences between the variables at two successive iterations (k and k+1). When expressed in this form the method becomes essentially similar to the Volterra -series iterative application method recently proposed by Benedetto and Biglieri [5] . There is in fact a close relation between the iterative process which solves time varying linear systems and the successive linearizations operated in the system (4) by applying the Newton-Raphson algorithm (5). However, the method proposed here does have the advantage of greater generality and flexibility since it is possible to deal with non-linear elements described by equations in implicit form. It is also possible to reach a considerable degree of reliability of convergence by using a solution algorithm which operates by gradually increasing the signal amplitude.

CONVERGENCE AND LOCAL MINIMA PROBLEMS

The algorithm (5) has a second order convergence rate provided that an accurate starting-point for the iterative process is chosen. In the case of strong non-linearities a choice of $\underline{I}^0$ which is not close enough to the rue value may easily lead iterative process towards undefined domains of $\underline{G}$ (for instance, the "overflow" domain) or it may not converge. Moreover, if the number of variables M(N+1) is high it is likely that the process will stop at a local minimum which is not zero.

To overcome these difficulties the problem of solving system (5) with the parameter $\underline{X}(\omega)$ can be transformed into a sequence of problems with the same structure, but with different values of the signal amplitude, that is, with the parameter:

$$\underline{X}(\omega) = \underline{X}^{I}(\omega) + \alpha \left[\underline{X}^{F}(\omega) - \underline{X}^{I}(\omega) \right] \qquad 0 \leqslant \alpha \leqslant 1 \qquad (6)$$

where $\underline{X}^{I}(\omega)$ and $\underline{X}^{F}(\omega)$ are the initial and final values of the vector of the forcing terms and α is a number ranging from 0 to 1.Usually a solution of (5) is known for a particular value $\underline{X}(\omega) = \underline{X}^{I}(\omega)$, for example, for zero signal amplitude. By starting from this value and increasing step-by-step the value of α, the direct search for the solution of system (4) can be split into a sequence of solutions of well-conditioned systems. In fact, every solution obtained with a particular signal amplitude ($\alpha = \alpha_0$) is a good starting point for the system having a slightly higher signal ($\alpha = \alpha_0 + \Delta\alpha$) . In this way convergence problems are eliminated and the whole process is speeded up. The technique described can be refined by improving the prediction of the correct starting point for the iterative process, using an extrapolation procedure on the solutions obtained for weaker signals. It should be noted that this procedure provides, as a further result, the responses of the system for different values of the input signal amplitude.

ANALYSIS OVER A GIVEN FREQUENCY RANGE

It is often necessary to know the behaviour of the system within a frequency range. The hypothesis of a monochromatic signal, on which all the methods proposed are based, makes it necessary to repeat the non-linear analysis for the frequency values required. The step-by-step procedure proposed for the gradual modification of the signal amplitude can be generalized to allow for the analysis over an entire frequency range. In fact, each function $\underline{G}$ in system (4) besides being a function of the vector of the unknowns $\underline{I}(\omega)$ and the vector of the impressed terms $\underline{X}(\omega)$, is also a function of a vector $\underline{\xi}$ representing the state of the network, that is, the values of the parameters of the network, the bias condition and the value of the fundamental angular frequency ω_0 , that is:

$$\underline{G} = \underline{G}\left[\underline{I}(\omega) , \underline{X}(\omega) , \underline{\xi}\right]$$

If an analysis with variable frequency is required, let $\xi = \omega_0$ and perform the analysis of the network by means of the sequence (6), for a value of $\omega = \omega_0^I$ corresponding to one end of the frequency range. When $\alpha = 1$ the value of fundamental frequency is gradually modified:

$$\omega_0 = \omega_0^I + \beta \left(\omega_0^F - \omega_0^I \right) \qquad 0 \leqslant \beta \leqslant 1$$

where the parameter β may vary step-by-step until the other end of the range $\omega_0 = \omega_0^F$ is reached. This second step of the analysis corresponds to a sweeping of the signal frequency with the same amplitude. This procedure is very efficient in terms of computing time because the problem of the non-linear analysis need not be solved starting from scratch for each new frequency.

STRAIGHT-WIRE ANTENNA WITH A NON-LINEAR LOAD

As an example of application of the proposed method, a straight-wire antenna of length h and diameter 2a has been considered; the antenna is conncted at center to a non-linear load (fig.2).

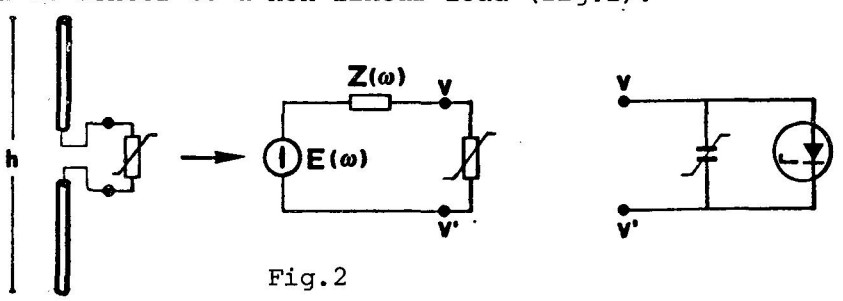


Fig.2

In this simple case, the linear subnetwork is given by the antenna itself and the connecting section reduces to a single port, so that the network unknowns are directly given by $V(\omega)$ and $I(\omega)$, that is the voltage and the current at the antenna and load terminals. Assuming a monochromatic incident field al frequency $f_0 = 100$ MHz, the antenna circuit can be represented by a Thévenin equivalent circuit as represented in fig.2 , where $E(\omega) = X(\omega) = \mathcal{F}[E_0 \sin \omega_0 t]$ is the open-circuit voltage produced by the incident field.

In order to obtain numerical results, the network analysis program has been interfaced with a program for the analysis of wire-antennas based on the solution of the integral equation for the wire current via the moment's method [7] with triangular test and expansion functions. Since the knowledge of the admittance is required over a large band, the number of the triangular functions is depending upon the wavelength and the required precision (segment basis $< \lambda/20$). For convenience in examining the circuit behaviour, the values of the network quantities, that is the real and imaginary part of the admittance $Y(\omega) = G(\omega) + j\, X(\omega)$ are shown in fig.3 for an antenna with $h = 1.5$ m and $a = 0.0025$ m .

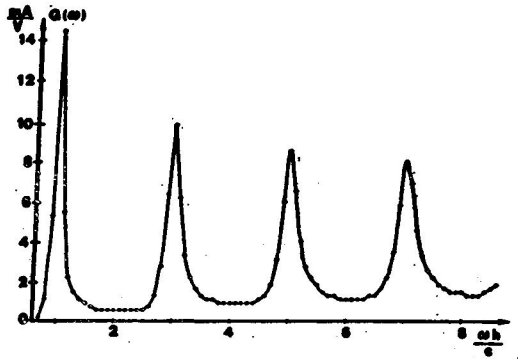
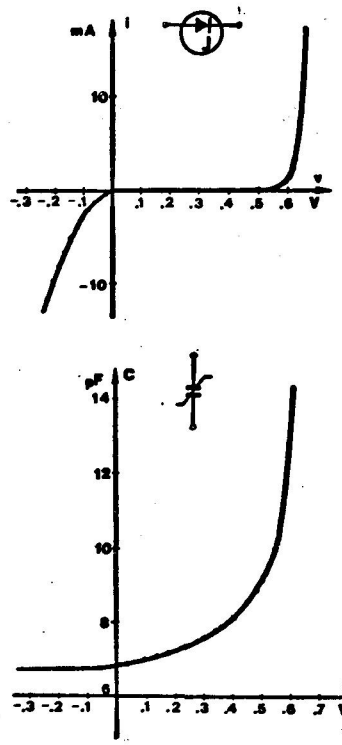


Fig.3



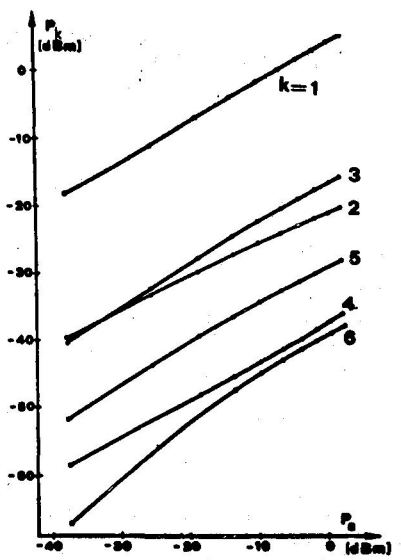


Fig.5

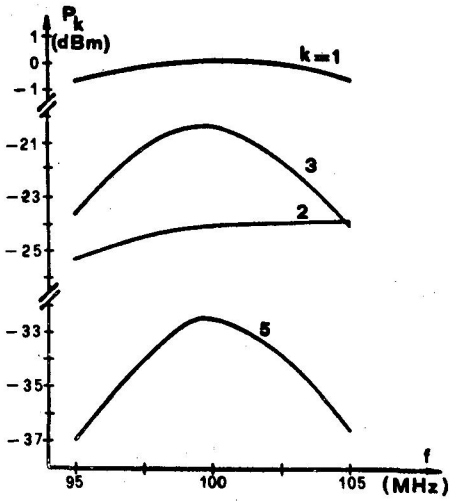


Fig.6

Fig.4

The load is a backward diode with $i = i(v)$ given in fig.4 and with the non-linear transition capacitance $C = C(v)$ of fig.4. A parallel inductance, included in the linear part of the circuit together with the parasitic diode elements has been introduced to assure the short circuit condition for the DC current. The results are given in fig.5, which present the harmonic containt in terms of back-radiated power versus the incident available power. The frequency analysis algorithm has been used to investigate the circuit behaviour in the range 95÷105 MHz for a given incident available power.

REFERENCES

[1] Liu & Tesche,"Analysis of antennas and scatterers with nonlinear loads", IEEE Trans. Anten.& Prop. ,vol.AP-24,pp.131-139,1976.

[2] Kanda,"Analytical and numerical techniques for analyzing electrically short dipole with nonlinear load", Trans.Anten.& Prop. vol.AP-28,p.71.

[3] King,"Microwave Homodyne Systems", IEEE Electrom.waves series 3 ,P.Peregrinus Ltd.,England 1978.

[4] Schefer & Klensh,"Harmonic radar helps autos avoid collisions", IEEE Spectrum,vol.10,n.5,pp.38-45,May 1973.

[5] Benedetto & Biglieri,"Analysis of strongly nonlinear circuits using Volterra series", ESA J.,vol.2,pp.303,311,1978.

[6] Filicori,Monaco & Naldi," Simulation & Design of microwave class-C amplifiers through harmonic analysis", Trans.MTT-27,n.12,pp.1043,1051,Dec.1979.

[7] Harrington," Field Computation by Moment Method", McMillan Comp.,NewYork 1968.