Design of Microwave Antennas: Neural Network Approach to Time Domain Modeling of V-Dipole

Z. Lukes   *Z. Raida*

Dept. of Radio Electronics, Brno University of Technology, Purkynova 118, 612 00 Brno, Czech Republic

ABSTRACT − The paper deals with the analysis of a wire V-dipole by Time-Domain Method of Moments (TD-MoM) and with approximating full-wave results by an artificial neural network.

In the first part, the numerical analysis of a wire V-dipole is described and implemented in MATLAB. The numerical solution is compared with published results.

In the second part, the numerical model of a wire V-dipole is used as a teacher of an artificial neural network (ANN) from the Neural Network Toolbox of Matlab. The input patterns of ANN consist of doublets [the length of the antenna arm; the angle between the arms]. The output targets of ANN are corresponding current responses in the source cell. For modeling, three different types of ANN are used and their properties are compared.

1 INTRODUCTION

In today's communication systems, broadband equipment plays more and more significant role. Therefore, efficient and broadband modeling techniques are intensively developed. In case of communication antennas, attention is turned to the time-domain method of moments (TD-MoM), which enables us to compute parameters of the antenna system for wide band of frequencies in a single run of the analysis.

In the paper, TD-MoM is applied to the analysis of wire antennas in order to enable a simple verification of results. The analysis consists of three basic steps:

- We analyze a symmetric wire dipole in order to verify the basics of the TD-MoM analysis.
- We modify the algorithm in order to analyze a wire V-dipole.
- We train a feed-forward ANN (FF-ANN) in order to simply approximate results of the CPU-time consuming TD-MoM analysis of the wire V-dipole preserving the reached accuracy.

2 TD-MoM ANALYSIS OF SYMMETRIC WIRE DIPOLE

2.1 TD-MoM principle

The basic principle of the TD-MoM is depicted in Figure 1. We excite an unknown system $H(Z)$ by a known input quantity $X(Z)$; Gaussian pulse of electrical intensity or voltage in our case. Then, we compute the response quantity of the system $Y(Z)$; current transient in our case. Next, we can compute parameters of the system

$$H(Z) = \frac{Y(Z)}{X(Z)}. \tag{1}$$

In case of our wire antenna, output quantity Y is understood as induced current, input quantity X means the excitation electric intensity and H is the antenna admittance (when multiplied by the length of the excitation gap).
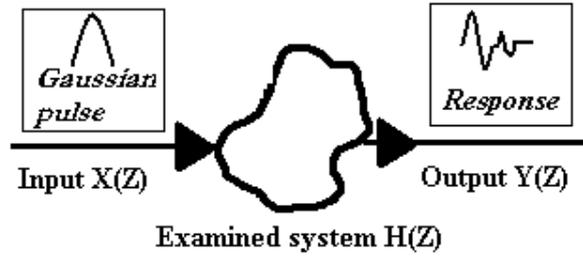
Figure 1: Principe of method

2.2 Gaussian pulse

The antenna is excited by a perpendicularly-incident plane wave, which is of the form of Gaussian pulse in time [1] as shown in Figure 2. Vector of the electric field intensity is in parallel to the antenna axis.

  Changing the width of the Gaussian pulse, the width of the frequency band of the analysis is influenced. Using Gaussian pulse, well-defined frequency-limited excitation is applied.
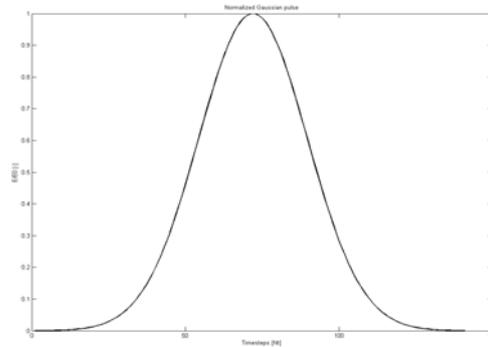

Figure 2: Normalized Gaussian pulse

2.3 TD-MoM algorithm

Interactions between the incident wave and the antenna, which consists of perfect electrical conductor (PEC) in the vacuum, are described using retarded potentials [2]. Scalar potential describes contributions of charges, and vector potential models contributions of currents. Both currents and charges are assumed to be concentrated on the antenna axis (*thin-wire approximation*, [3]). Using known potentials, current distribution on the antenna can be computed. Knowing current distribution, all the antenna parameters can be determined [2].

  Exploiting TD-MoM, the antenna wire is divided into segments, and also the time space is properly discretized. In the ideal case, the time step equals to the time, which is consumed by a wave when traveling from an antenna segment to the neighboring one.

  In our computations, piecewise-constant approximations are used, and derivatives are replaced by central differences.

  Exploiting continuity theorem and boundary conditions, an iterative loop for computing current distribution over antenna segments in prescribed time steps can be composed. Current distribution in t_n is computed exploiting all the known current history in foregoing time samples. This makes the algorithm very efficient on one hand and causes an error cumulation on the other hand [1], [4].
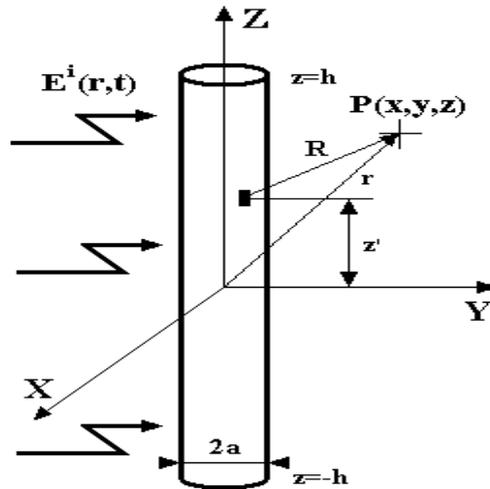
Figure 3: Finite length wire excited by an incident electromagnetic plane wave

3 TD-MoM ANALYSIS OF WIRE V-DIPOLE

The basic geometrical structure of the wire V-dipole is shown on Figure 4. Here, we can see three basic differences, which appear when analyzing the V-dipole compared to the symmetric dipole analysis:

- Magnitude of the component of the incident intensity E, which is tangential to the antenna surface, depends on the angle between the arms of the V-dipole.
- Waveform of the incident wave reaches different antenna segments in the different time moments. Time delays depend on the angle between the antenna arms too.
- Let us define a time interval Δt_1, which is consumed by the incident free-space plane wave traveling between central points of two neighboring antenna segments. Let us define Δt_2, which is consumed by the secondary along-arm spherical wave traveling between central points of two neighboring antenna segments. As depicted in Figure 4, the intervals are different ($\Delta t_1 \neq \Delta t_2$).
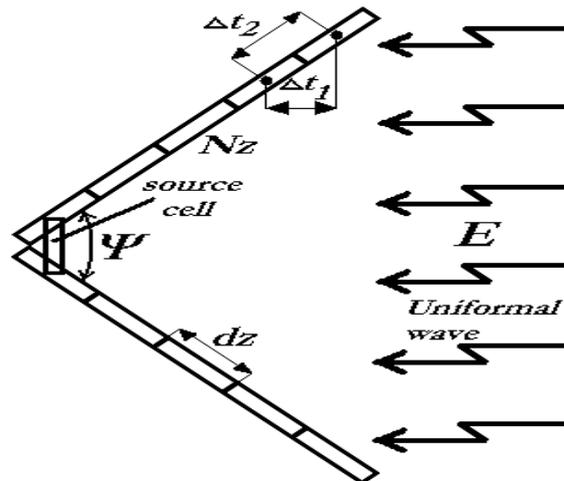

Figure 4: Geometrical structure of V-dipole

3.1 Exciting V-dipole

As show in Figure 4, the component of electric intensity, which is tangential to the antenna surface, depends on the angle between the antenna arms; thus

$$E = E_0 \sin(\Psi/2), \tag{2}$$

where E_0 is magnitude of electrical intensity of the incident wave and Ψ is the angle between arms. Now, we can compute the time delay $\Delta t_2 = dz/c$, where dz is the length of the antenna segment and c is velocity of light in vacuum. Next, we define the entire time interval, during which the light travels from the end of antenna arms to the source segment, which is in the middle of the dipole

$$T = N_z \Delta t_1 = N_z \frac{dz}{c} \cos(\Psi/2), \tag{3}$$

where N_z is the number of segments to which one arm of the dipole is divided.

The time interval T has to be properly discretized for the purpose of the numerical analysis. As the basic time step, the time interval consumed by the secondary wave for the travel between the centers of the neighboring antenna segments Δt_2 is elected. Considering the excitation plane wave, the time interval T is divided into $N_{TD} = T/\Delta t_2$ steps. Obviously, the number of samples of the excitation wave N_{TD} does not equal to the number of samples of the secondary spherical wave N_z (to the number of one-arm antenna segments).

In order to solve the described problem, index of the spherical wave sample m is "projected" to the direction of the plane wave propagation

$$n_r = m \cos\left(\frac{\Psi}{2}\right), \qquad m = 1, 2, ..., N_z. \tag{4}$$

Naturally, the index projection n_r is a real number. Since the number of the time sample of the incited wave has to be integral, n_r has to be rounded. The numerical error caused by the described rounding can be minimized using large enough number of the antenna segments N_z (antenna discretization has to be fine). In the Figure 5, we can see the time-space distribution of the time derivative of Gaussian pulse for exciting V-dipole with angle 90° between arms. For end-points of the arms, time delay is minimal, and for the central segment, the time delay is maximal.
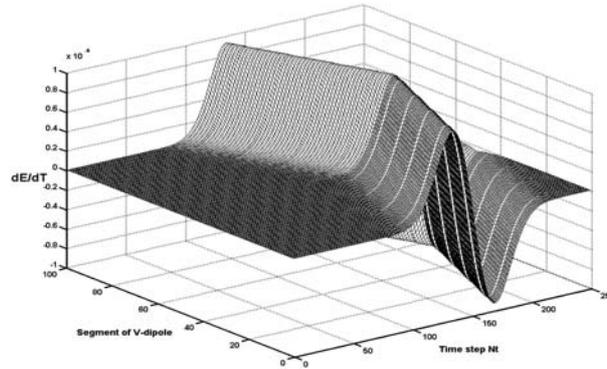

Figure 5: Time-space distribution of the time derivative of Gaussian pulse

3.2 TD-MoM Algorithm

Principe of the TD-MoM analysis of the V-dipole is very similar to the analysis method of the symmetrical wire dipole described in the section 2.3. Both the arms of the V-dipole are divided into $2N_z$ segments, where N_z is the number of segments on one arm of the V-dipole only. Using the excitation wave shown in Figure 5, we can perform all the computations the same way as in the case of the symmetrical wire dipole.

3.3 Results of TD-MoM analysis of V-dipole

Next we can start the analysis. Analyzing the V-dipole for various angles between arms when the length of the arm is constant ($l = 1$ m), we obtain the currents transients over the excitation segment as depicted in Figure 6. In this figure, the angle (in degrees) between the arms of the V-dipole plays the role of the parameter.
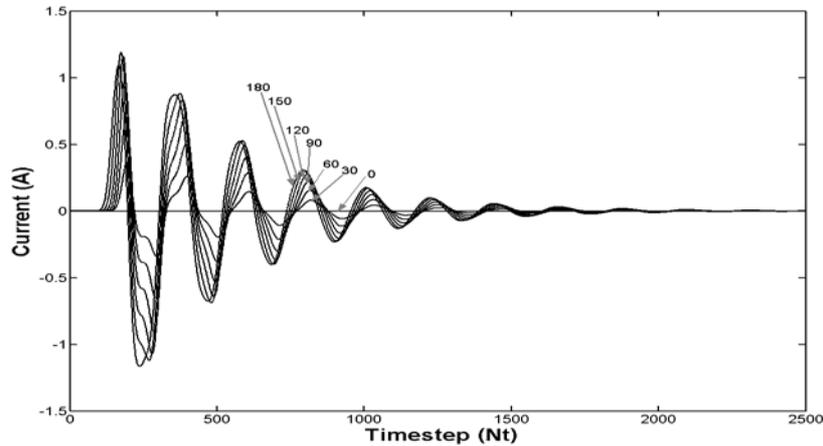

Figure 6: Time response of current in source slot

Exploiting computed transients of current distribution of the V-dipole, parameters of the modeled antenna can be determined. In our case, input impedance is the computed parameter.
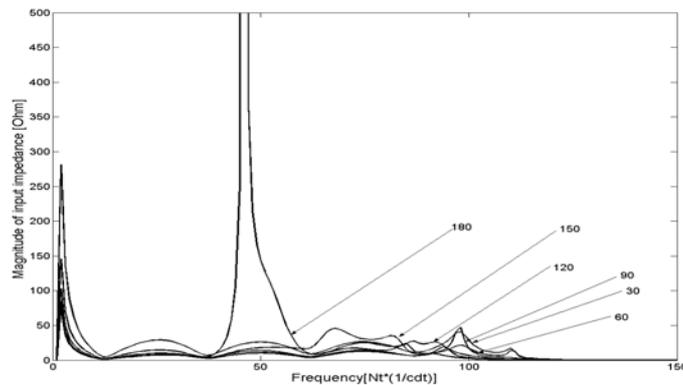

Figure 7: Magnitude of input impedance

In the first step, time course of the input quantity (electric intensity of incident wave transformed to voltage over antenna segment) and the output quantity (currents over antenna segments) is transformed by FFT (Fast Fourier Transformation) to the spectral domain. In the spectral domain, we can compute the input impedance on every frequency by $Z_{VST}(f) == U(f) / I(f)$. In Figure 7, the magnitude of input impedance for various angles between arms of the V-dipole (for arm l=1m) is depicted.

4 NEURAL NETWORK ANALYSIS

TD-MoM is relatively CPU-time consuming. Incorporating the analysis code into the complex design systems is therefore rather problematic. Nevertheless, the described problem can be solved by the approximation of full-wave results exploiting artificial neural networks.

In this section, we use feed-forward neural networks from *Neural Network Toolbox* of MATLAB to quick modeling of V-dipole. In our case, input patterns consist of doublets [l, Ψ] where $l \in$ <0.5 m, 2.0 m> is the length of the antenna arm and $\Psi \in$ <0°, 180°> is the angle between antenna arms. Output patterns consist of time samples of the current transient over the excitation segment.

For training, following algorithms were used:

- Gradient descent back propagation (GD)
- Levenberg-Marquardt back propagation (LM)
- Bayesian Regulation back propagation (BR)

In total, three neural models were developed (models #1, #2, #3a had two inputs and a model #3b had an angle as a single input quantity):

net	output	hidden	train
#1	2500	250-150-350	GD
#2	250	100-50-150	GD
#3a	50	30-20-35	GD, LM, BR
#3b	50	30-20-35	GD, LM, BR

Table 1: Parameters of the developed time-domain neural models of V-dipole.

In Figure 8, we compare approximation abilities of the #3b model with TD-MoM output. In this case, the models trained by GD, LM and BR give practically the same results, and the error between the neural model and the numerical one vary between $2.954 \cdot 10^{-4}$ and $2.992 \cdot 10^{-4}$.
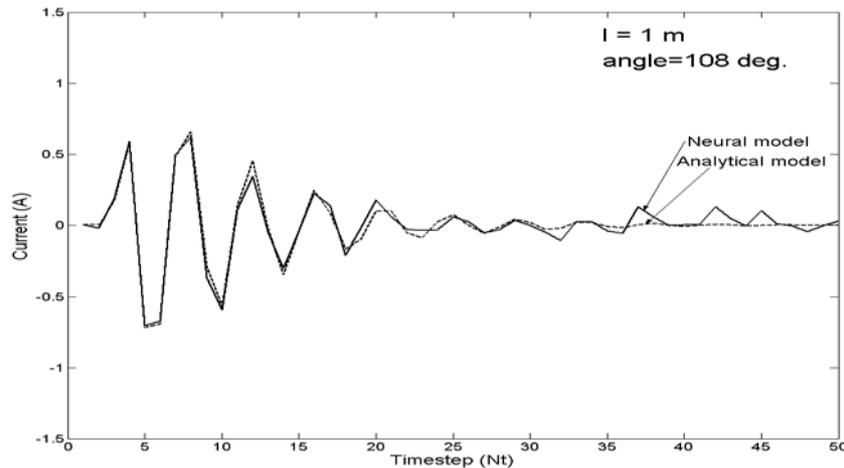

Figure 8: Analytical vs. GD Neural model

Properties of the #3a model are very close to the properties of the #3b model. Increasing the number of outputs, training and memory problems appear. Therefore, a solution of this situation is intensively searched these days.

In Figure 9, absolute error of current response of V-dipole model #3b is depicted.
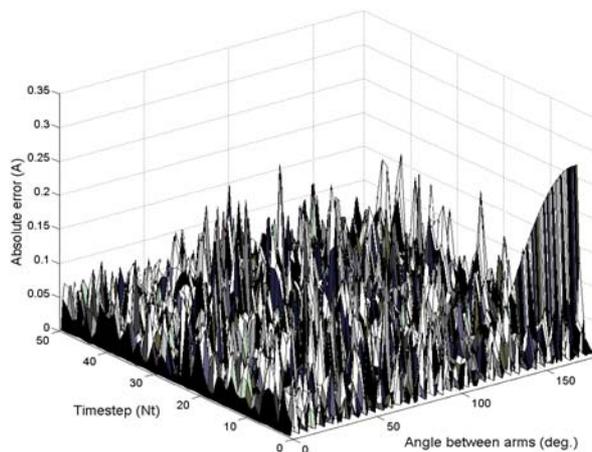
Figure 9: Absolute error between the neural model #3b and the numerical model (current responses are compared).

CONCLUSION

In the paper, an original simplified way of TD-MoM analysis of a wire V-dipole is presented. The method exhibits good accuracy and good efficiency.

Even if the efficiency is quite good, CPU-time demands of the method does not enable a direct incorporation of the model to the complex design tools. For the design properties, results of the time-domain analysis are approximated exploiting feed-forward neural networks.

We describe three neural models of the V-dipole. Practical results are obtained for a network of 50 outputs (50 samples of the current transient). Increasing the number of outputs, training problems appear.

These days, the described difficulties are solved by rearranging the architecture of the feed-forward network and by exploiting recurrent networks.

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Contact Address:

E-mail: lukes@feec.vutbr.cz
Phone: +420 541 149 117