A Hybrid Model in Analyzing Nonlinearly Loaded Dipole Antenna and Finite Antenna Array in the Frequency Domain

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ABSTRACT: In this article, a hybrid model is introduced in which our previous fuzzy inference approach is used for extracting the behavior of receiving antenna and predicting the induced current and mutual coupling effects with an excellent accuracy and then it is combined with Volterra series model to analyze nonlinearly loaded finite antenna array. As it is expected, the computation time of the resulted hybrid model is much faster than the accurate ones, without loss of accuracy. © 2009 Wiley Periodicals, Inc. Int J RF and Microwave CAE 00: 000–000, 2009.

Keywords: fuzzy inference; nonlinear loading; antenna arrays

I. INTRODUCTION

A technique used to control the scattered fields, is impedance loading. Using this technique, the surface of scatterer is loaded with distributed or lumped impedances. The position and value of loaded impedance is chosen to produce the desired scattering response [1–5]. One of the conventional scatterers with impedance loading is nonlinearly loaded dipole antenna array [6–13]. A schematic diagram of nonlinearly loaded dipole antenna in single and array structure are shown in Figures 1a and 2a, respectively. As shown in Figures 1a and 2a, an incident plane wave illuminates each antenna and a nonlinear load is connected to each antenna terminal. The equivalent microwave circuits related to Figures 1a and 2a are shown in Figures 1b and 2b, respectively in which the excited antenna due to the incident plane wave is modelled by an induced current and the input admittance of antenna in transmitting mode for single antenna. The nonlinear load is connected to antenna terminal to control scattering response. Also, a linear network is considered in Figure 2b to include mutual coupling effects.

The central problem in such applications is to compute the induced voltage at different harmonic frequencies by one of nonlinear techniques [14].

There are a number of hybrid approaches for analysis of such problems based on method of moments [15], MoM, together with one of nonlinear techniques [14]. In these hybrid approaches, MoM is used for computing the induced current in different incidence directions, input admittance of transmitting antenna and mutual coupling effects among antennas, and accordingly, nonlinear techniques for instance, Volterra series [6], harmonic balance [7], reflection algorithm (RA) and Newton inexact approach (INA) [8, 9], genetic algorithm [10], nonlinear currents [11] and neural networks [12, 13] are used to compute the induced voltage across nonlinear load at different harmonic frequencies.

All mentioned hybrid methods above suffer from repetitive, complex and time consuming computa-

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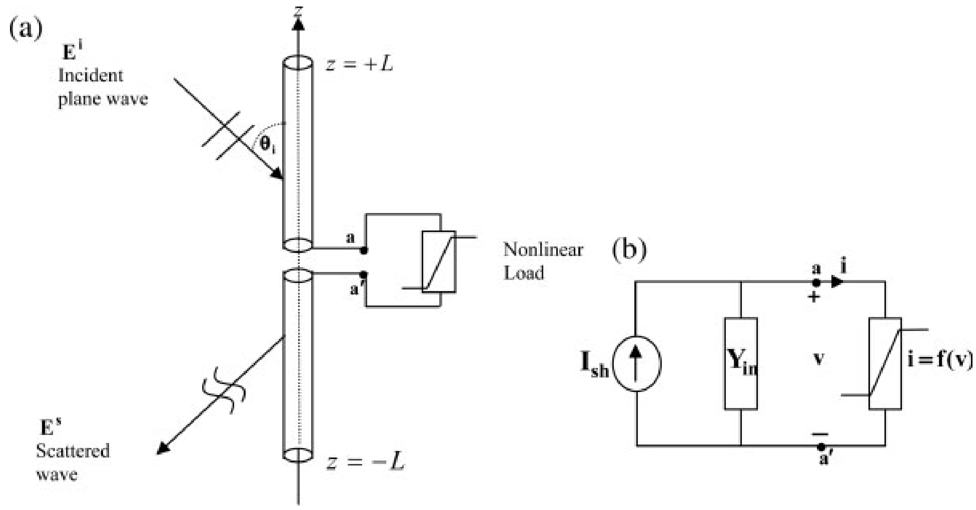

Figure 1. (a) Schematic diagram of nonlinearly loaded dipole antenna. (b) equivalent microwave circuit.

tions of induced current and mutual coupling effects by MoM in any incident direction and for any spacing among antennas respectively.

To remove the mentioned drawbacks, qualitative methods based on fuzzy inference can be taken into consideration [16–18].

A fuzzy-based approach was introduced by one of authors [19] to model input impedance of straight monopole antenna in general form, and it was then used by authors to model input impedance of two coupled dipole antennas in three different arrangements [20], and scattered field from linearly loaded dipole antenna [21].

In this article, at first, the introduced method in [20] is used to model the induced current in receiving dipole antenna. During the modeling process, behavior of receiving dipole antenna is extracted as unchanged membership functions and well approximated to behavior of transmitting dipole antenna obtained in our past study [20]. After then, the knowledge base of the incident angle is saved as very simple curves. The predicted results of the induced current by our proposed method show an excellent agreement with accurate results (MoM), while computation time is vanishingly short. Finally, combining this fuzzy model with Volterra series technique

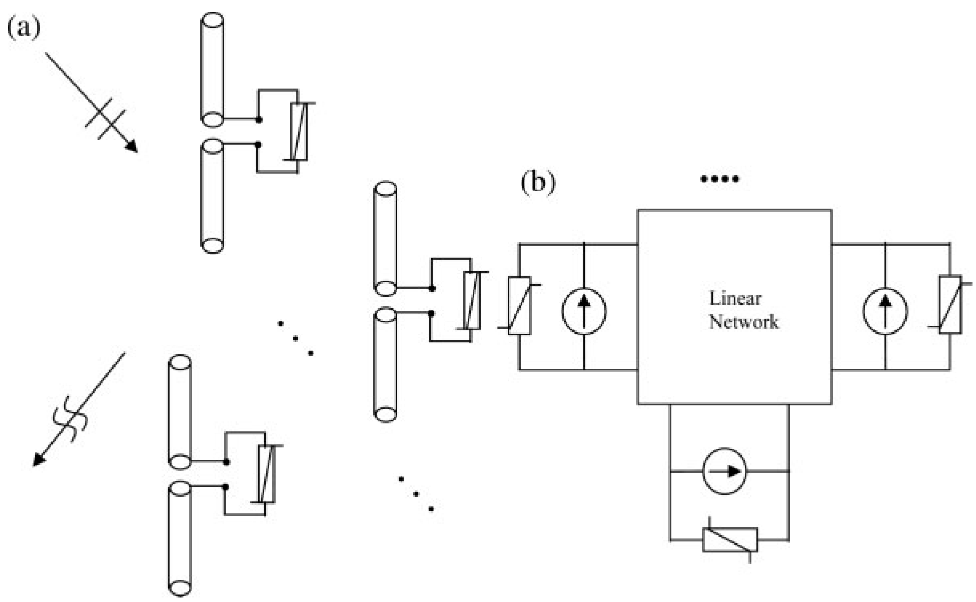

Figure 2. (a) Schematic diagram of nonlinearly loaded dipole antenna array. (b) Equivalent microwave circuit.

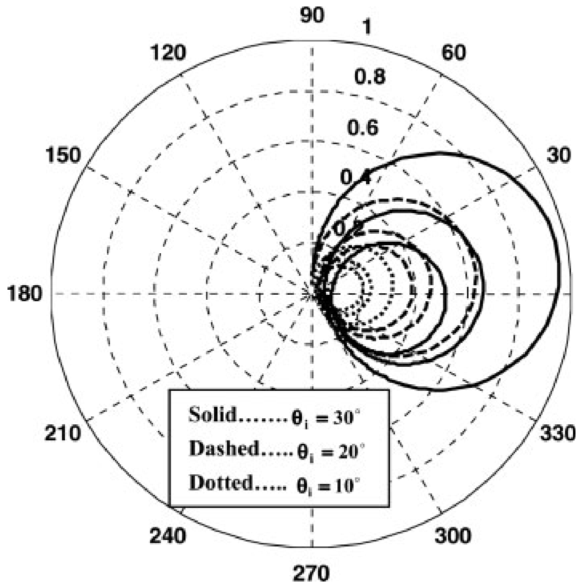

Figure 3. The induced current (in mA) of receiving dipole antenna for a few incident angles in polar plane.

makes a hybrid model that is much faster than previous studies [6–13] without loss of accuracy. The case of nonlinearly loaded antenna array is the same as single one, except that the input admittance of single antenna is replaced with the fuzzy model of input admittance of each antenna of array including mutual coupling effects.

II. FUZZY MODELING OF INDUCED CURRENT IN EXTERNALLY EXCITED DIPOLE ANTENNA

In this section, a receiving dipole antenna having total length-to-diameter ratio 74.2 and illuminated by an incident plane wave in an arbitrary direction is considered. At first, the induced currents versus L/λ for a few incident angles are computed by MoM and shown in polar plane in Figure 3. The curves in Figure 3 for each incident angle denote the magnitude of the induced current versus phase of induced current.

As it is seen in Figure 3, the curves in this figure have the same circular movement as the curves in [19]. Therefore, one can model this curves simply through the introduced method in [19] or [20] including three following steps:

1. Choosing three three-point sets around even resonances (L/λ = 0.25, 0.75, 1.25) in order to fit a circle and line on each three-point set.
2. Modeling the moving circles: this step includes assigning a membership function for each fitted circle having belongingness value 1 on it and smoothly decreasing to zero on the neighbor fitted circles, and then inferring new fuzzy circle for each L/λ by equations (3) in [20].
3. Modelling the Partial Phase, new kind of phase defined in [19] as the phase respect to the centre of the above fuzzy derived circles for each L/λ: modelling this step is the same as previous one, except that the circles are replaced with the lines.
4. Computing new induced current for each L/λ through the above steps.
5. Optimize the parameters of the above membership functions to minimize error.

Further detailed information about membership functions, moving circles and Partial Phase can be found in [19, 20].

The resulted membership functions through modelling the moving circles and Partial Phase for a few incident angles are shown in Figures 4a and 4b, respectively. In addition, membership functions through modelling input admittance of dipole antenna in transmitting mode, obtained in our past study [20], are shown in the same figure.

As shown in Figures 4a and 4b, membership functions of receiving dipole antenna at different incident angles are slightly changed around membership functions of single transmitting dipole antenna. Therefore,

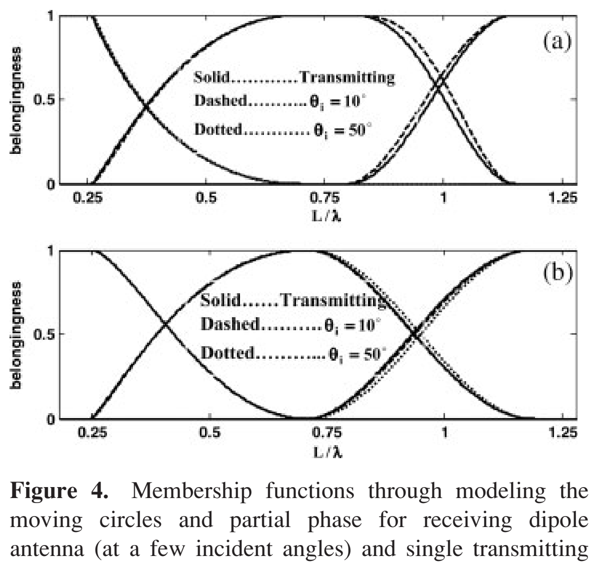

Figure 4. Membership functions through modeling the moving circles and partial phase for receiving dipole antenna (at a few incident angles) and single transmitting dipole antenna (a) for moving circles, (b) for Partial Phase.

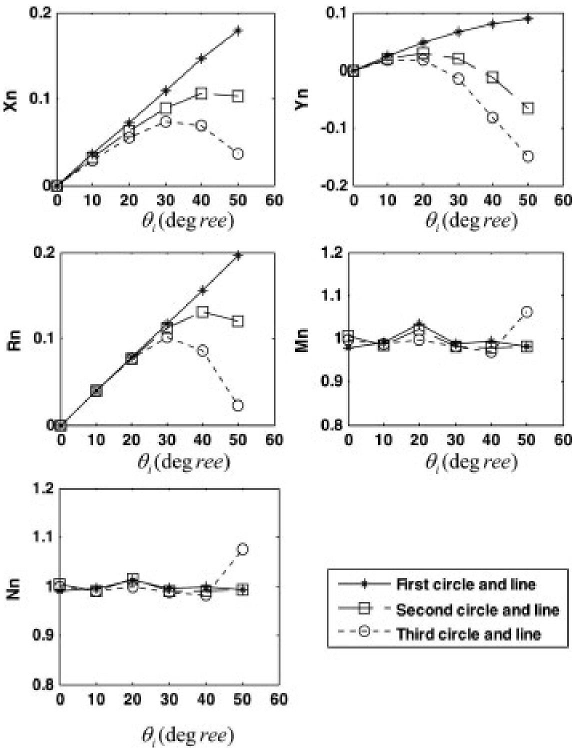

Figure 5. The knowledge base of incident angle (degree) in receiving dipole antenna.

we approximate behavior of receiving dipole antenna to the behavior of single transmitting dipole antenna as a first order approximation.

Hence, the only parameters changing at different incident angles through our proposed algorithm are fitted circles and lines as fuzzy inputs computed by MoM for each incident angle. These are computed just for a few incident angles so that coordinates and radii of the fitted circles and accordingly slopes and biases of the fitted lines are computed and shown as star/square/circle in Figure 5. As coordinates and radii of the fitted circles and also slopes and biases of the fitted lines are not in the same scale, they are normalized to individual ones in the single transmitting dipole antennas obtained in [20]. In other words, (X_n, Y_n, R_n) in Figure 5 are the normalized coordinates and radii of fitted circles and (M_n, N_n) are the normalized slopes and biases of fitted lines.

As shown in Figure 5, the stars, circles, and squares can be fitted by very simple curves (solid, dashed and dotted curves). It means that for computing coordinates and radii of the fitted circles and accordingly slopes and biases of the fitted lines of other incident angles, it is not needed to use MoM any more.

Meanwhile normalized slopes and biases, M_n, N_n, in Figure 5 are slightly changed around one. Therefore we approximate them to one as the second approximation. From now on, the very simple curves in Figure 5 as fuzzy inputs and membership functions of single transmitting dipole antenna as behavior of the receiving dipole antenna complete our fuzzy system, and it can be used to predict the induced current at any incident angle. It is obvious that through this proposed method, the run-time is considerably reduced. The general flowchart of used fuzzy algorithm is shown in Figure 6.

Now by reading coordinates and radii of the fitted circles and accordingly slopes and biases of the fitted lines for an arbitrary incident angle, then with the use of membership functions of single transmitting dipole antenna, the induced current is easily predicted.

For instance, a sample with $E^i = 1V/m$, $\theta_i = 45°$ is chosen. The predicted induced current as well as accurate ones (MoM) are shown in Figure 7. As it is seen in Figure 7, an excellent agreement with vanishingly short computation time is achieved.

III. ANALYSIS OF NONLINEARLY LOADED DIPOLE ANTENNA

In this section, without loss of generality, a nonlinear load the same as [6–13] is chosen, and connected to terminal of dipole antenna. This nonlinear load has the following $(i - v)$ characteristics:

$$i = \frac{1}{75} v + 4v^3 \qquad (1)$$

Now, using the predicted induced current by our fuzzy approach in the previous section, and one of nonlinear techniques [6–13] (here the Volterra series model [8]), the equivalent microwave circuit in Figure 1a is analyzed and finally the induced voltage at different harmonic frequencies is computed. Hence, the nonlinearly loaded dipole antenna in Figure 1a is illuminated by an incident plane wave of $E^i = 0.5V/m$, $\theta_i = 45°$, and the induced voltage across the nonlinear load at three different harmonics by our proposed approach is computed and shown in Figure 7a. Finally the normalized scattering responses by the two hybrid approaches (Present work and [8]) are computed and shown in Figure 7b.

In Figure 8b, MoM+Volterra means a hybrid model in which MoM computes the induced current for any incident angle and Volterra series model computes the induced voltage across the nonlinear load using the modelled current by MoM. Similarly, Fuzzy+Volterra is the same as MoM+Volterra except that our fuzzy proposed method is used instead of MoM.

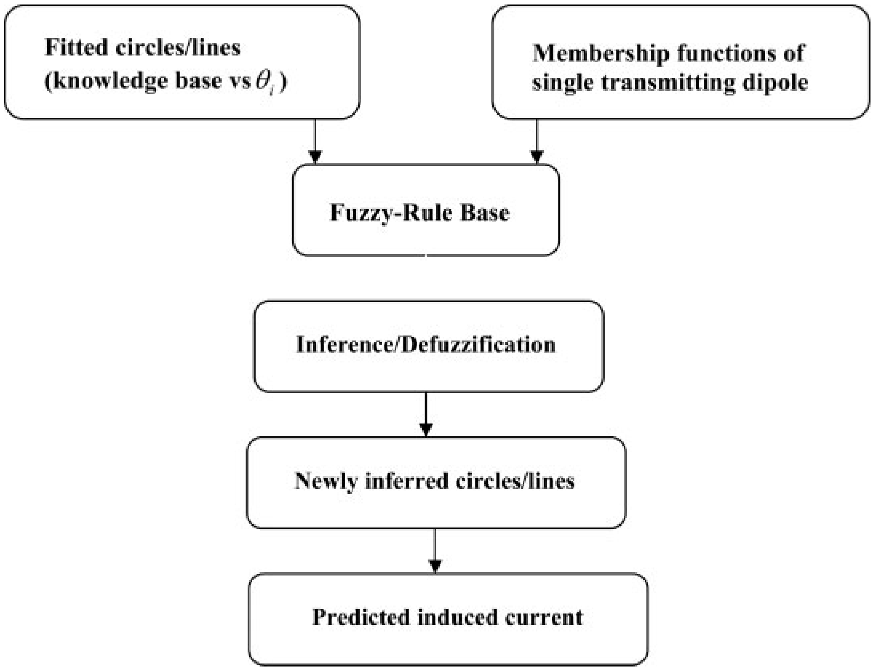

Figure 6. The general flowchart of used algorithm for predicting the induced current.

As shown in Figure 8b, our proposed hybrid approach (Fuzzy+Volterra) is in an excellent agreement with accurate method (MoM+Volterra); moreover the run-time is considerably reduced.

IV. ANALYSIS OF NONLINEARLY LOADED FINITE ANTENNA ARRAY

Our analysis for nonlinearly loaded finite antenna array is the same as single one, except that the fuzzy model of input admittance of each antenna of the array including mutual coupling effects [20] is used instead of input admittance of single dipole antenna in Figure 1b.

Therefore, with the use of the knowledge base of incident angle (Figure 5 in this study), the knowledge base spacing between antennas obtained in [20], and membership functions of single transmitting dipole antenna, induced current and input admittance of

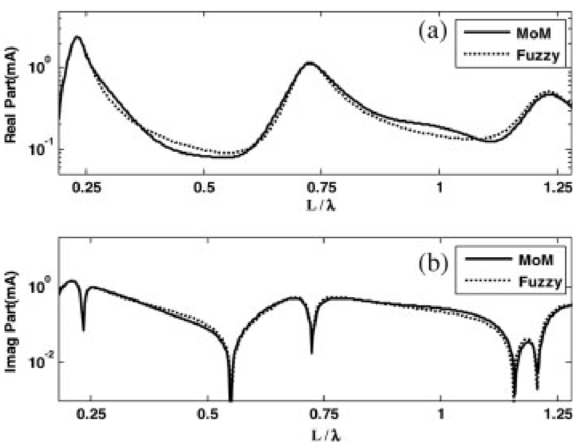

Figure 7. Comparing the modeled results of induced current by MoM and Fuzzy. (a) Real part, (b) imaginary part.

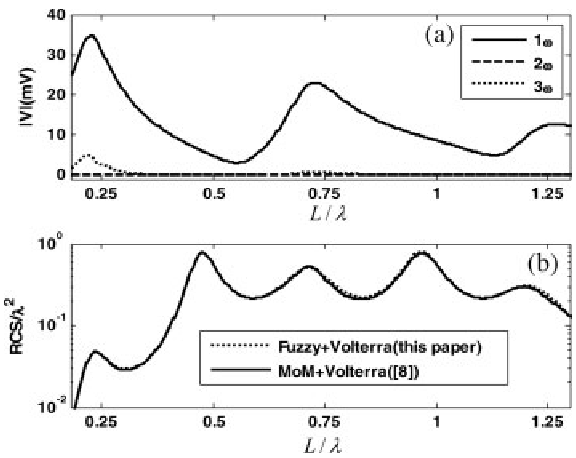

Figure 8. (a) Computing the induced voltage across nonlinear load at different harmonic frequencies by our proposed hybrid approach (Fuzzy + Volterra), (b) normalized scattering response at fundamental frequency by two hybrid methods.

each antenna including mutual coupling are separately computed. Finally, using these two parameters and Volterra series model, the microwave equivalent circuit in Figure 2b is analyzed and the induced voltage for different harmonics is computed.

To see, how accurate our proposed hybrid approach is, array of two collinear-coupled dipole antennas loaded nonlinearly with $D_v = 42$ cm is considered, and illuminated the same as previous section. The induced voltage across nonlinear load for different harmonics by the two different hybrid approaches (Present work and [8]) is shown in Figure 9.

Note that owing to nonlinearity of load, the harmonic 2ω is zero and not shown in Figure 9.

Comparing the two hybrid approaches in Figure 9 shows an excellent agreement, in addition the computation time in our proposed hybrid approach (Fuzzy+ Volterra) is much faster than accurate one (MoM+ Volterra).

It should be noted that due to linear term in eq. (1), the voltage component at the fundamental frequency ω in Figures 8a and 9 is much greater than those of higher order mixing frequencies. In addition, the voltage component at mixing frequency 3ω is slightly greater than that at mixing frequencies 2ω. This is due to the effect of cubic term in eq. (1).

Table I shows comparing the computation time of the induced voltage by the two hybrid methods from analyzing single antenna and finite antenna array loaded nonlinearly. Meanwhile, the run-times by (Fuzzy + Volterra) in Table I is valid when completed fuzzy model is used, and the computations of two methods were carried out by Matlab 7.1 software on a 2.41-GHZ Pentium 4 with 2GB of Ram.

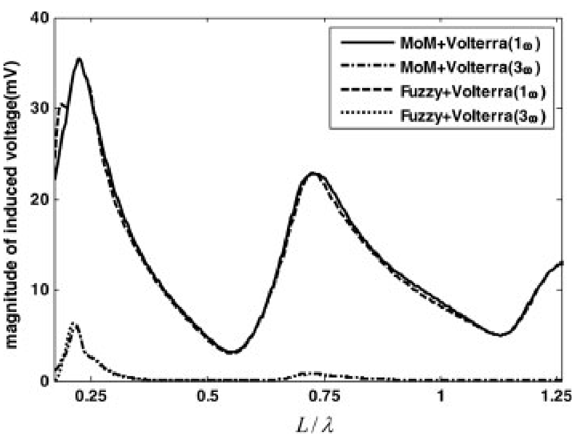

Figure 9. Magnitude of induced voltage at different harmonies by two different hybrid approaches for array of two collinear-coupled dipole antennas loaded nonlinearly.

TABLE I. Comparing the Computation Time of the Induced Voltage by the Two Hybrid Approaches

	Hybrid Model	
Problem	Fuzzy + Volterra (Present work) (sec)	MoM + Volterra ([8]) (min)
A dipole antenna loaded nonlinearly	≈0.2	≈1.3
Array of two collinear-coupled dipole antennas loaded nonlinearly	≈0.5	≈4.9

V. CONCLUSION

In this article, a hybrid model consisting of fuzzy model and Volterra series technique was introduced. Using the fuzzy model, the induced current in receiving dipole antenna was well predicted. Throughout fuzzy modeling process, behavior of receiving dipole antenna was well approximated to behavior of transmitting dipole antenna, and the knowledge base of incident angle was extracted as very simple curves. As a result, the execution time was considerably reduced. Moreover, an excellent agreement between fuzzy method and accurate result was achieved.

It is confirmed again that the membership functions have the behavior of problem and this is a reason for similar membership functions in transmitting and receiving cases. Combining the fuzzy models of induced current and input admittance including mutual coupling effects with Volterra series model made a new hybrid model so as to compute the induced voltage. The proposed hybrid approach was much faster than past studies [6–13] with an excellent agreement with accurate ones.

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BIOGRAPHIES

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