Paper

A NEW APPROACH TO ANALYSIS AND MODELING OF EXTERNALLY EXCITED TRANSMISSION LINES USING FUZZY INFERENCE

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Fuzzy inference abilities were implemented to electromagnetic problems for the first time by the authors. After very successful results of applying the developed fuzzy modeling method to input impedance of a general monopole antenna and general transmission line, in this article we apply the proposed method to make a qualitative model for coupling of an external wave to a transmission line to show the abilities of the proposed method in EMC problems. It is shown that because of using a novel point of view and parameters, the system may be analyzed and modeled simply using a fuzzy inference system based on new parameters. It is notified that the proposed method basic structure remains unchanged as it was for monopole antenna and transmission line. It may be supposed because of the new qualitative view point which supports the proposed method.

Keywords: EMC, electromagnetic interference, fuzzy modeling, fuzzy applications

1. Introduction

Even now applying analytical approaches to EMC problems suffer from serious difficulties in identifying effective parameters and formalizing them efficiently [(1)~(3)]. Besides, human expertness plays indubitable and supporting role in facing this field [(4)(5)]. Toward investigating of new applications for qualitative analysis methods in the field of engineering electromagnetic problems, a novel analysis method and modeling algorithm were established utilizing fuzzy inference methods for the first time by the authors of the present article [(6)~(8)]. Following a certain methodology the established method were applied to two conceptually different categories of electromagnetic problems: antenna [(8)] and transmission line [(9)(10)]. Several advantages such as simple structure, high accuracy, very short executing time, ability of applying the expertness to the problem, similarity of the model structure to conceptual different problems and others, in addition to linguistic expertness extraction characteristic of the proposed method appear very promising in conquering the mentioned difficulties. All these encouraged us to generalize the idea to the field of EMC problems.

In this paper we are going to face one of the most common EMC problems, i.e., the coupling of an external wave to a transmission line. There were a lot of well worth investigations in this field, which we are going to use as very suitable substrates to apply our method. It is shown that quite good results may be regenerated using the proposed method very fast and efficient. In second section we try to introduce and discuss the basic idea of our qualitative method and in next sections this is applied to some examples to show its ability and advantages.

2. Modeling Algorithm

As the basic idea of the proposed qualitative modeling method, we start from some parameters as system input which are conceptually defined without noting their certain physical meaning in a specific problem. Then we derive an output, which may be supposed to cover the variations of a wide range of physical problems through a fuzzy inference method with some membership function sets as system dominant rules and some implications and inferences as calculating equations.

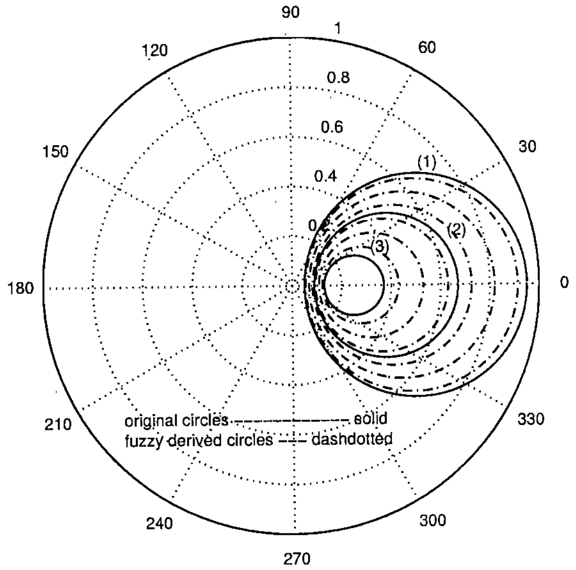

Fig. 1. The concept of periodicity

A circle in polar plane like the one specified by (1) in Fig.1, that we call it circle No.1, may be supposed as a locus for a general parameter that changes versus its variable periodically. This is simply the concept of *periodicity*. It is important to mention that we always assume the system as a SIMO (single-input multi-output) one. Deriving the output of a MIMO (multi-input multi-output) system using its individual SIMO knowledge is one of the capabilities of our proposed modeling method [8]. Circles No.2 and 3, specified by (2) and (3), respectively, in Fig.1 are also loci for a periodic parameter versus its variable. The only important difference between these three loci (circles) is their radius. For the time being the center of these three circles are not considerable here and we choose them as shown for simplicity in explanation of our idea. As it is shown in the following section, this choice results in impedance like curves in polar plane. Returning to the circles in Fig.1, the variation of the parameter with respect to a reference point, e.g., center of coordinates, in one period is getting smaller and smaller from circle No.1 to 3. If these three circles belong to a unique phenomena, experienced in different conditions or situations, decreasing in radius means that this system supports more *loss* from experience No.1 to 3, respectively. The above explanation reveals three independent experience of the same parameter variation with respect to the same variable, but in an actual case we face with varying loss when system variable changes in a unique experience. In this case, the circles in Fig.1 should be transformed smoothly from one to another. This can be modeled using a fuzzy inference system through following steps;

(1) Suppose each circle in Fig.1 belongs to one fuzzy set as

$$\begin{cases} \textit{Circle No.1} & \rightarrow \textit{Low loss} \\ \textit{Circle No.2} & \rightarrow \textit{Medium loss} \\ \textit{Circle No.3} & \rightarrow \textit{High loss.} \end{cases} \quad \cdots (1)$$

(2) Allocate a membership function to each of the above sets in a way that its belongingness value starts from the value 1 in the mid-band of the set and goes smoothly to zero in the mid-band of the adjacent set (sets). An example is shown in Fig.2.

(3) Use simple implications (*if − then rules*) such as

$$\begin{cases} (\textit{if Low loss})\ \textit{then}\ (\textit{circle No.1}) \\ (\textit{if Medium loss})\ \textit{then}\ (\textit{circle No.2}) \\ (\textit{if High loss})\ \textit{then}\ (\textit{circle No.3}). \end{cases} \quad (2)$$

(4) Utilize the above implications in inferences of Eq.3, generating new circles for each value of the system variable.

$$\begin{cases} x(\textit{variable}) & = \sum_{i=1}^{3} x_i \alpha_i(\textit{variable}) \\ y(\textit{variable}) & = \sum_{i=1}^{3} y_i \alpha_i(\textit{variable}) \\ r(\textit{variable}) & = \sum_{i=1}^{3} r_i \alpha_i(\textit{variable}) \end{cases} \quad (3)$$

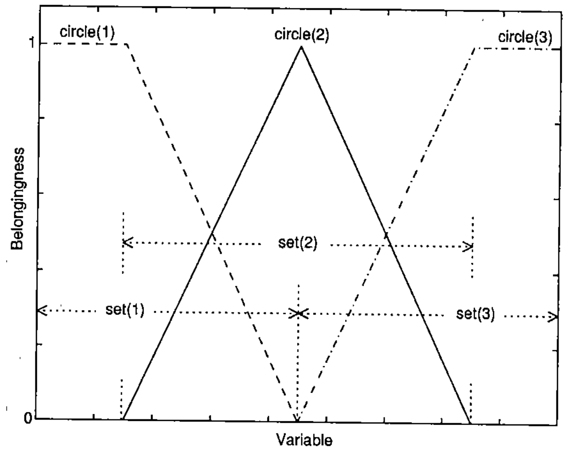

Fig. 2. Fuzzy set definition and membership function allocation

where x_i, y_i and r_i are center coordinates, and radius of the three basic circles, respectively. The α_i is the fire strength or belongingness for desired variable derived from Fig.2 and finally the newly inferred circles are specified by x, y and r as center coordinates and radius, respectively. Some samples are shown in Fig.1 (dash-dotted).

By doing this, we actually generate a partial locus for each value of variable. It means that the possible values of the output parameters are limited to those which are lying on the respected fuzzy derived locus for each value of the variable.

In the next step we clarify the output parameter as a unique point on its partial locus for each input variable. In this way, we have to specify a single phase on each fuzzy derived circle for each input variable value. The phase definition is definitely important. Defining the phase in a certain relation with the corresponding partial locus (the phase is defined with respect to the center of the corresponding fuzzy derived circle for each variable) facilitate to use the same modeling algorithm as explained in the last step but circles replaced by lines. Let us use the term *partial phase* for the phase defined

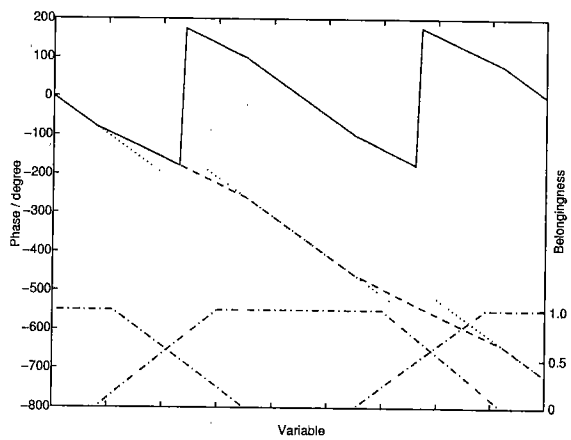

Fig. 3. An example of modeled phase curve

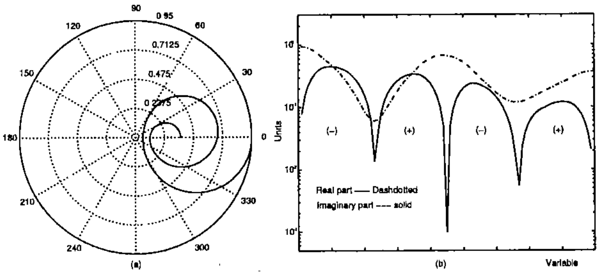

Fig. 4. System output parameter generated by proposed fuzzy algorithm (a) in polar plane (b)in Cartesian coordinates

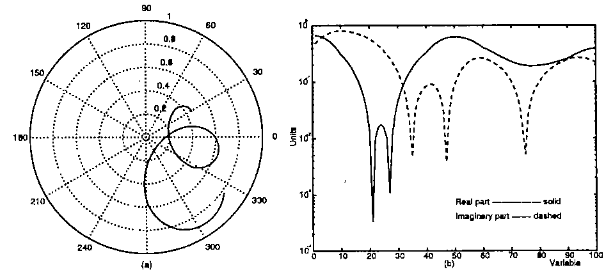

Fig. 5. System output parameter generated by proposed fuzzy algorithm including some parasitics(a) in polar plane (b)in Cartesian coordinates

as above to distinguish it from the conventional one. Assume three lines instead of circles in the full belongingness zone of sets like those shown in Fig.2 and let them be mixed up through a set of membership functions to result in a partial phase curve like what is shown in Fig.3 (solid line) as an example. Three membership functions (dash dotted) and three lines (dotted) on their full belongingness zone are defined as an example and are shown in Fig.3. Implications in this step are the same as those in Eq.2 but circles replaced by lines. The inference rules can be written as follows,

$$\begin{cases} a(variable) &= \dfrac{\sum_{i=1}^{3} a_i \alpha_i(variable)}{\sum_{i=1}^{3} \alpha_i(variable)} \\ b(variable) &= \dfrac{\sum_{i=1}^{3} b_i \alpha_i(variable)}{\sum_{i=1}^{3} \alpha_i(variable)} \end{cases} \quad \cdots\cdots (4)$$

where the α_i is the fire strength or belongingness for desired variable derived from Fig.3. The a_i and b_i are the slope and bias of the three basic lines, respectively and finally the newly inferred lines are specified by a and b as the same parameters. Defining the phase as mentioned above, i.e., making a tight relation between the original circles and basic lines here makes us needless of more data in this step of modeling process.

The modeled system output is shown in Fig.4 in both polar and Cartesian planes. These curves may be supposed as a general representation for a wide range of electromagnetic engineering problems. It is well worth noting that by changing the parameters of the generated model, i.e., basic circles of Fig.1 and phase lines of Fig.3 (dotted lines), as input parameters, and membership functions of Fig.2 and Fig.3 as system dominant rules, a wide range of curves in the category of those shown in Fig.4 can be covered. This means that the basic circles and lines are physically meaningful since they give us the ability of modeling the parameters of the same sort with the same degree of complexity even when the parameters belong to conceptually different phenomena.

2.1 Parasitics

Here we introduce another parameter that helps us model a very wider range of problems. Look at the curves of Fig.5. In first glance they seem more complicated than those were generated before, whereas they are the same curves as those of Fig.4 but the original circles were deviated in the plane as a result of another parameter. In other words we believe that a wide range of very complicated curves seen in various problems basically belong to the category of Fig.4. The only difference is that the original curves are affected by some external or internal phenomena, which we call them *parasitics* in general, result in a very complicated curve even in polar plane. In the example of Fig.5 deviation is made through multiplying the circle centers by the parasitic of Eq.5. Obviously using other parasitics other curves may be generated.

$$\begin{aligned} Parasitic &= \exp(-j(\cos(variable \cdot \pi/180) \\ &-0.4\sin(variable \cdot \pi/180))) \end{aligned} \quad \cdot (5)$$

Briefly, it was shown that starting from simple circles in polar plane and feeding them to the proposed fuzzy method, very wide range of complicated curves may be generated supposing three basic interpretation introduced as *periodicity*, *loss* and *parasitics*. Since the generated curves cover a wide range of electromagnetic problems, we may claim that the proposed method has the capability of modeling these problems simply.

3. Coupling of an External Wave to a Transmission Line

In previous works (8)~(10) it was shown that the proposed fuzzy modeling method can be applied to conceptually impedance problems successfully. In this paper it

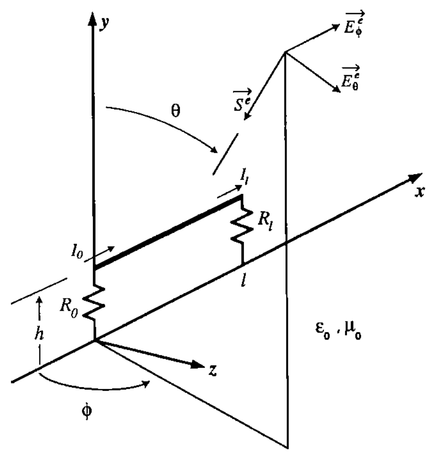

Fig. 6. Coupling Model

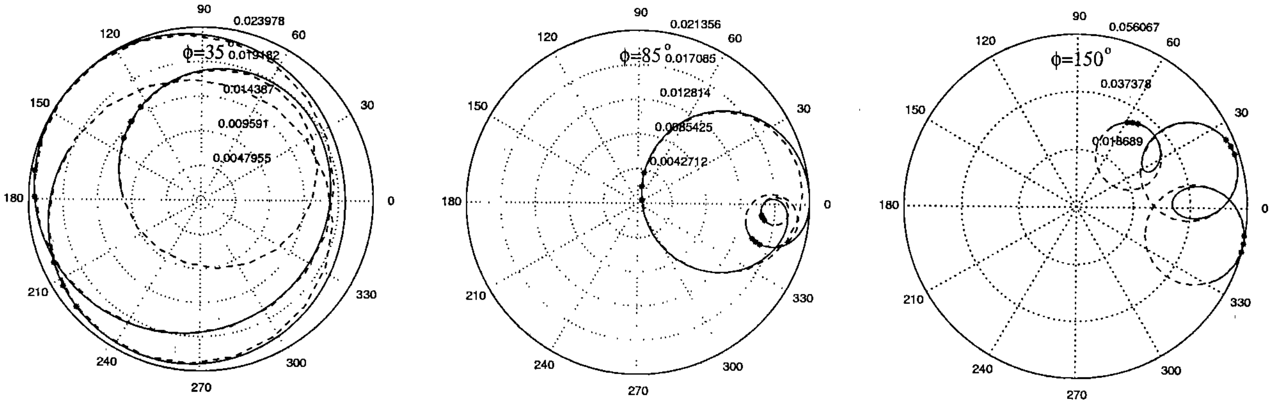

Fig. 7. Calculated induced current (in Amperes) and initial circles in polar plane

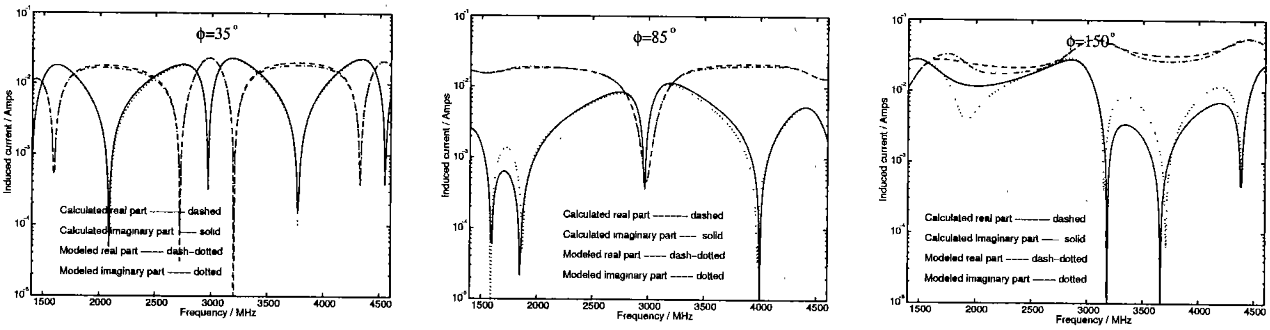

Fig. 8. Calculated and modeled induced current in Cartesian plane

is applied to a coupling problem as a starting point for EMI/EMC applications. The coupling model (12) used here is shown in Fig.6. The transmission line consists of a lossless wire of diameter d and length l suspended at height of h above a perfectly conducting ground plane in free space. The line is excited by an electromagnetic wave of angular frequency ω. It was shown (12) that under TEM assumption, the inducted current to terminal load R_0 may be calculated as

$$I_0 = -\frac{1}{\Delta}\Bigg\{ \left[\cos\beta_0(l-x') + j\frac{R_l}{Z_0}\sin\beta_0(l-x')\right] \cdot \int_0^h E_y^e(x',y,0)dy \Bigg|_{x'=0}^{x'=l} - \int_0^l \left[\cos\beta_0(l-x') + j\frac{R_l}{Z_0}\sin\beta_0(l-x')\right] \cdot E_x^e(x',y,0)dx' \Bigg\} \quad \cdots\cdots (6)$$

where $\beta_0 = \omega\sqrt{LC} = 2\pi/\lambda_0$ is the phase constant and Z_0 is the characteristic impedance of the line and

$$\Delta = (R_0+R_l)\cos\beta_0 l + j(Z_0+R_0R_l/Z_0)\sin\beta_0 l. \quad (7)$$

Considering a ϕ polarized or TE exciting plane wave results in following fields,

$$\begin{cases} E_x^e(x,y,0) = & 2jE_0\sin\phi\sin(\beta_0 y\cos\theta) \\ & \cdot\exp(-jkx) \\ E_y^e(x,y,0) = & 0 \end{cases} \quad (8)$$

where E_0 is the electric field intensity of the plane wave and $k = \beta_0\cos\phi\sin\theta$.

Inserting the above fields in Eq.6, the coupled or induced current in R_0 can be calculated. Some results are shown in Figs.7 and 8, considering $\theta = 45°$, versus frequency for several values of ϕ. As it is observed, at first glance they seem quite different and complicated specially in Cartesian coordinates. But looking at polar plane curves we realize they belong to the same category of the curve shown in Fig.5 and this means that they may be modeled using the method explained in the previous section. To make these samples, the transmission line is supposed to have a length of $l = 10$ cm of a $d = 0.2$ mm wire and suspended at height of $h = 3$ mm above the ground plane. Considering free space condition, the characteristic impedance of the line is determined about $Z_0 \approx 200\ \Omega$. The intensity of exciting electric field is also normalized to $E_0 = 1$ v/m and the terminating loads are $R_l = R_0 = 50\ \Omega$. Let us emphasize here that the above are just example values and there is no certain restriction on them.

3.1 Fuzzy model

Regarding to Sec.2 and background works (8)~(10), the modeling algorithm may be summarized in a flowchart as shown in Fig.9. Three

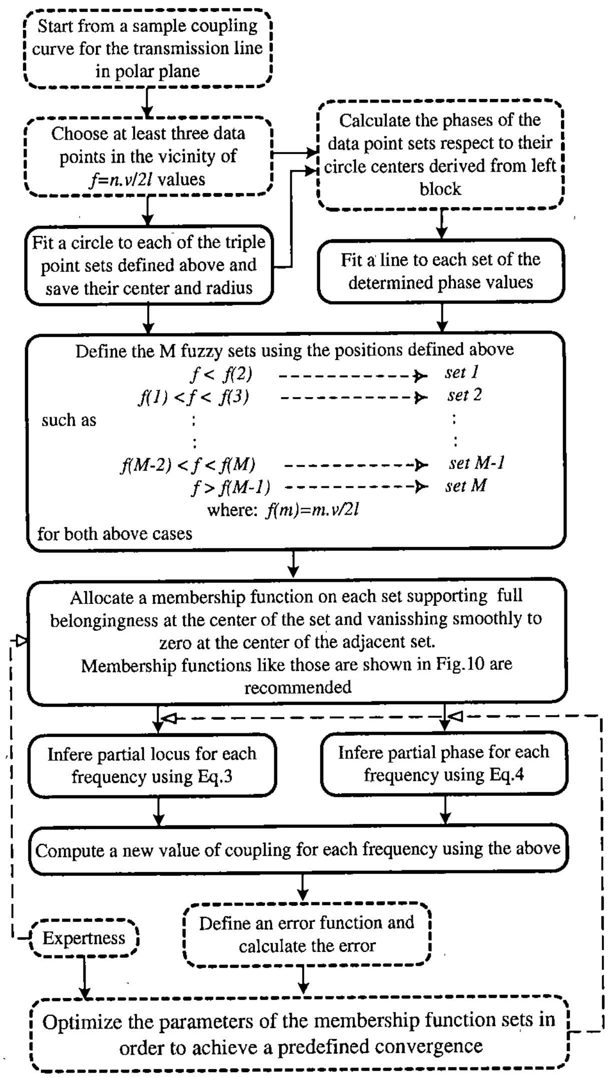

Fig. 9. Modeling algorithm

main parts are distinguishable in flowchart of Fig.9. The main part in the middle, i.e., the blocks drawn in solid line, is the calculating engine of the fuzzy system. The dashed blocks in the upper part of the flowchart contain the decision rule and define the starting values, i.e., circles and lines, and the third part including dashed blocks in the bottom is used for optimizing the model, i.e., the dominant rules in particular. Supposing the rules and inferences as Eqs.2 to 4, we have to decide the initial circles (lines) and define fuzzy sets and membership functions properly. We would like to emphasize that the modeling algorithm, implications and inference remain the same not only for both cases of circles and lines but also they are basically similar to those used in the cases of monopole antenna and transmission lines before [(8)(9)].

According to flowchart, the modeling starts from a sample data of the problem in polar plane because polar representation has been found more interpretable by human understandings [(6)(8)]. We define the initial circles to fit the data in the vicinity of multiples of half wave-length for the transmission line length, i.e., $l = n\lambda/2$, where n is a positive integer. In other words we need only three data points around the frequencies of $f = n \cdot v/2l$ to fit our initial circles, where v is the wave velocity in free space. In the next step, we have to decide the fuzzy sets and membership functions. The mth set is generally defined as:

$$\begin{cases} start\ freq. < f < (m+1)\dfrac{v}{2l} \\ for\ \ m = 1 \\ (m-1)\dfrac{v}{2l} < f < (m+1)\dfrac{v}{2l} \\ for\ \ m = 2, ..., M-1 \\ (m-1)\dfrac{v}{2l} < f < stop\ freq. \\ for\ \ m = M \end{cases} \qquad (9)$$

with the $f = m.v/2l$ in the center of the set. The above is the general rule for the primary set decision but in some cases we may add one set to them. For example when the stop frequency in close to $(M+1).v/2l$, it may be better to suppose the stop frequency as an edge and define one more set.

The membership functions are allocated to have a full belongingness of 1 in the center of the sets and are going smoothly to zero on the center of the adjacent set. Those we have used here are shown in Fig.10 (solid). These sinusoidal membership functions are defined by S.B. Shouraki [(11)] and used here because of their flexibility and smoothness. Now using these simply defined membership functions and the initial circles we may derive new circles through inference rules of Eq.3.

To define the initial lines for generating the partial phase curve, as discussed in Sec.2, there is no more data included and this is another important point of the proposed method. Since the membership functions have the value of 1 in the center of their individual set and the center of the sets are where the initial circles were defined, the fuzzy derived circles for these value of variables will be the original ones. Therefore without loss of generality by the partial phase concept [(9)], it is enough to calculate the phase of the triple initial data point sets respect to the center of their corresponding initial circles and fit a line to them in Cartesian plane as written in the upper right block of the flowchart of Fig.9.

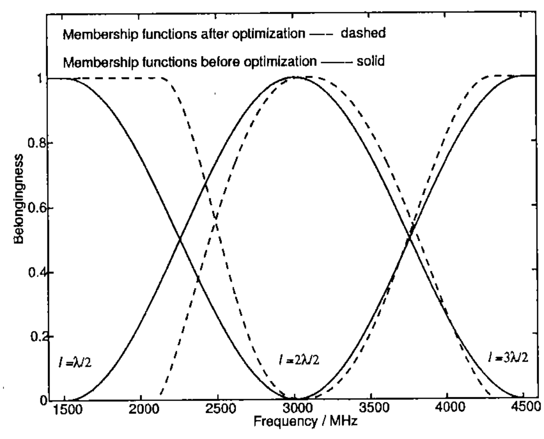

Fig. 10. Membership function allocation

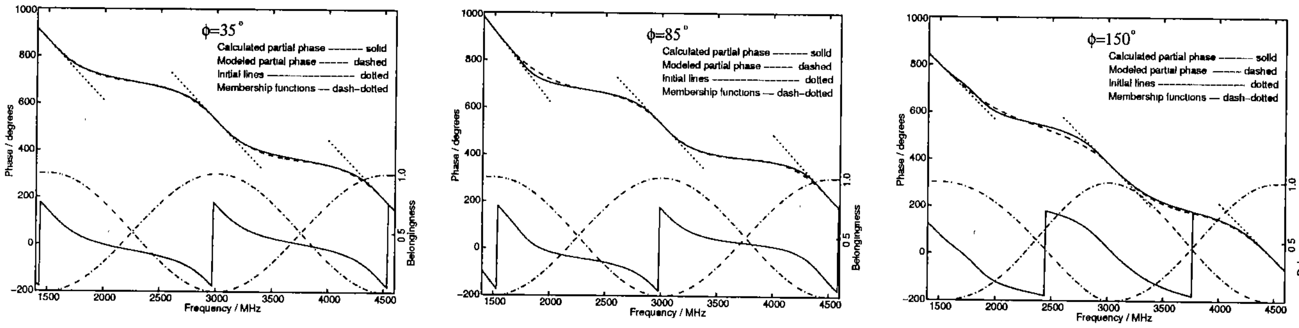

Fig. 11. Phase curve for induced current

Allocating some proper membership functions will enable us to generate a partial phase curve through the inference rules of Eq.4. The partial phase in addition to the fuzzy derived circles completes the regeneration of the induced current like those shown in Figs.7 and 8.

It is obvious that the membership functions may be optimized finally to achieve a desired error value as shown in lower part of Fig.9. It has been shown that using the proposed modeling algorithm the optimization can be done with even very simple techniques [(6)(8)]. Here we show that very simple but intelligent set decision and membership function allocation, even without optimization, reveal quite good results in our method. This may be supposed as the expertness applicability.

4. Outcomes

The samples of Figs.7 and 8 are modeled here as examples to show the ability of the proposed method. The results will be compared to original data and the executing time will be discussed.

The initial data points, which we need to define our initial circles and lines regarding to the decision rule explained above, are marked by asterisks and fitted circles to them drawn in dashed lines in Fig.7. Using the membership functions of Fig.10 (solid), implications of Eq.2 and inference of Eq.3, we may infer new fuzzy derived circles as discussed previously in detail. Calculating the phase respect to the center of the fuzzy derived circles, i.e., the partial phase, results in curves like those shown in Fig.11 in solid for the current examples. The initial lines, fitted to the partial phases of the initial point sets, are shown in dotted lines in the same figure. We emphasize here that to define these lines no new data is included. These lines in addition to a set of properly allocated membership functions, implications and inference such as Eqs.2 and 4 complete the data needed to generate the partial phase through the flowchart of Fig.9. The membership functions used in this case are shown in Fig.11 (dash-dotted). As it is clear these are the same as those used for generating the fuzzy derived circles of Fig.10 (solid). The generated partial phase is also shown in dashed lines and as it is seen the agreement is quite excellent.

Finally, we have generated a circle and a phase on it for each frequency value and it means that the modeled data is generated. The results are shown in Fig.8 in comparison with the original data in Cartesian coordinates to clarify them. As it is seen a very good agreement is achieved while no optimization on membership functions has been applied. In other words a set of membership functions is allocated by authors expertness as fuzzy system dominant rules and all the examples are modeled using them. Obviously these are not the optimum set but quite good as seen. We may optimize the model for a desired purpose. For example to have more uniform error, we may use the membership function set of Fig.10 (dashed). These membership functions have been optimized using Nelder-Mead type simplex search method. The results shown in Fig.12 reveal a good error uniformity comparing to the results of Fig.8. Note that the optimizing process is usually done with one set of sample data. The results may be verified or trimmed using a few others. The membership function set, obtained to satisfy a certain purpose, is saved as the fuzzy model dominant rules and the model is completed. It means, by only inserting the initial circles for any other sample, we can generate a full model very fast and satisfactorily good [(8)]. If good accuracy can not be achieved, the user may change the set definition or increase the number of them and make a new model.

Computing method	direct integration	proposed method
Executing time	$\approx$ 22sec.	$\approx$ 0.8sec.

Table 1. Comparing the executing time run on a Pentium*II* PC machine.

As a final point the executing time is compared between the direct integration method of Eq.6 and the proposed method here as shown in Table 1. The computation was run on the same machine with the same number of points and as it is seen the proposed method is quite faster.

It is well worth noting that, the same algorithm applied above to the examples of ϕ polarized excitation is also applicable to the θ polarized exciting cases and results in the same accuracy and same executing time.

5. Conclusion

The fuzzy modeling approach, developed by the authors based on a novel view point to the electromagnetic basic parameters and was greatly successful regarding

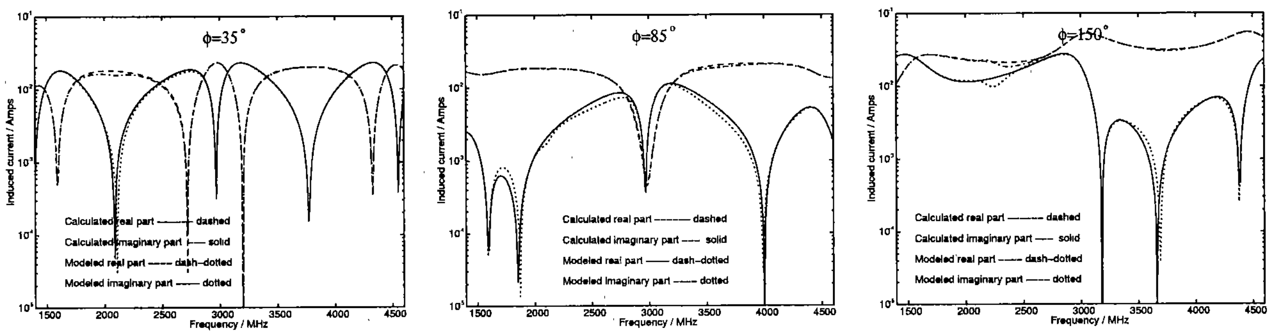

Fig. 12. Calculated and Modeled induced current using optimized membership functions

to monopole antenna and transmission lines, has been explained. It was shown that using the proposed algorithm and newly interpreted parameters, a category of curves in polar plane may be generated such that a lot of electromagnetic problems may belong to it. A modeling method was established and applied to a difficult and common EMC problem that is the coupling of an external wave to a transmission line. It was established that very good results can be achieved, in an absolutely short executing time, even without numerical optimization to emphasize the expertness applicability advantage of the proposed method. To show the accuracy of the method, simply optimized results were also presented. Regarding to successful application of the proposed method with the same structure in various cases of electromagnetic problems, applicability of the proposed modeling algorithm and analysis basic parameters to conceptually different problems with different analytical formulation was confirmed. The proposed method presents the same calculation complexity in all cases. This research may be a promising substrate for electromagnetic expert systems.

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References

(1) R.C. Booton, "Computational Methods for Electromagnetics and Microwaves," John Wiley & Sons, 1992.

(2) M. Hashimoto, M. Ideman and O.A. Tretyakov, "Analytical and Numerical Methods in Electromagnetic Wave Theory," Science House, 1993.

(3) C. Christopoulos, "Principles and Techniques of Electromagnetic Compatibility,"CRC press, 1995.

(4) A. Torralba, J. Chavez and G. Franquelo, "FASY: A Fuzzy-logic Based Tool for Analog Synthesis," IEEE Trans. Computer-Aided Design, vol. 15, No.11, pp. 705-715, July 1996.

(5) A. Torralba, J. Chavez and G. Franquelo, "Circuit Performance Modeling by Means of Fuzzy Logic," IEEE Trans. Computer-Aided Design, vol. 15, No. 11, pp. 1391-1398, July 1996.

(6) M.Tayarani and Y. Kami, "A New Modeling Approach in Engineering Electromagnetics Using Fuzzy Inference," International Symposium on Electromagnetic Compatibility, EMC'99 Tokyo, Japan, 1999, pp.106-109.

(7) M.Tayarani and Y. Kami, "A Fuzzy Model For Input Impedance of a General Monopole Antenna," 1999 IEEE International Conference on Systems, Man, and Cybernetics, SMC'99 Tokyo, Japan, 1999, pp.VI-173 - VI178.

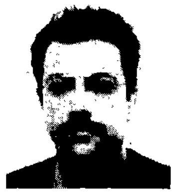
(8) M.Tayarani and Y. Kami, "Fuzzy Inference in Engineering Electromagnetics; An Application to Conventional and Angled Monopole-Antenna," IEICE Transactions on Electronics, Vol.E83-C, No.1 January 2000, pp. 85-97.

(9) M.Tayarani and Y. Kami, "Toward Qualitative Study of Transmission Lines Using Fuzzy Inference," 4th European Symposium on Electromagnetic Compatibility, EMC Europe 2000, Brugge, Belgium, September 2000.

(10) M.Tayarani and Y. Kami, "Fuzzy Modeling of Nonuniform Transmission Lines," 2000 International Symposium on Antennas and Propagation, ISAP 2000, Fukuoka, Japan, August 2000.

(11) S.B. Shouraki and N. Honda, "Fuzzy Prediction; A Method for Adaptation," 14th Fuzzy Symposium, Gifu, Japan, 1988, pp. 317-320.

(12) Y. Kami, "Mechanism of Electromagnetic Radiation from a Transmission Line," IEICE Transactions on Communications, Vol. E75-B, No.3 March 1992, pp. 115-123.



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