FUZZY LOGIC IMPLEMENTATION OF AN ELECTROMAGNETIC INTERACTIONS MODELLING TOOL

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Abstract: An electromagnetic interactions modelling tool which is based on a fuzzy logic representation of the electromagnetic attributes in a topological decomposition of a system is described. The purpose of this tool is to help determine any electromagnetic compatibility problems in complex systems. This tool is an extension of the *HardSys/HardDraw* software [1, 2] enabling it to handle a fuzzy representation of the electromagnetic interaction data. HardSys, a prototype system implemented in Prolog, is used to propagate the electromagnetic information through the topology of the represented system. User interaction is through HardDraw, an electromagnetic topology drawing tool and an attribute interface.

Introduction

The adverse effects of electromagnetic interactions in electrical systems are of concern because of the increased pollution of the environment with electromagnetic emissions and because of the increasing susceptibility of system components. From a practical point of view, it is not a simple matter to ensure the electromagnetic integrity of systems even for relatively small interaction problems. *Non-algorithmic* or *heuristic* techniques are used daily by engineers to solve electromagnetic problems in electrical systems. An attempt to formalize these procedures in the form of a computer tool called HardSys/HardDraw was described in [1, 2]. The modification of the knowledge representation used in this prototype tool into a fuzzy form [3] is described. This allows the heuristics and uncertain information associated with an interaction problem to be modelled more realistically than was possible in the first version of the tool.

Electromagnetic Topology of Systems

The electromagnetically relevant attributes of an electrical system can be isolated by decomposing the system into its corresponding *electromagnetic shielding topology* and its dual graph or *interaction sequence diagram* [4, 5, 6]. The electromagnetic topology consists of a description of the electromagnetically distinct volumes and their associated surfaces. The volumes define the *electromagnetic components* involved in the interaction. The interaction sequence diagram keeps track of the *interaction paths* throughout the system. The interaction sequence diagram can be simply derived from a given electromagnetic topology. The graph representing a simplified topology of a computer is shown in Fig. 1. Note the different node representation for ***field nodes***, ***circuit nodes*** and ***interaction path nodes*** [1, 2].

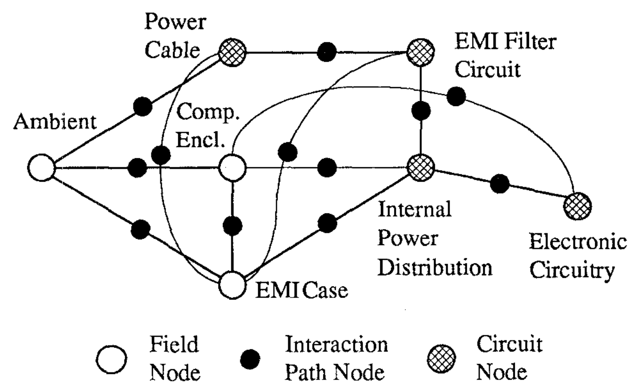

Fig. 1. Interaction Sequence Diagram for a Simple Topology

Interaction path nodes, or simply surfaces, are of four types: ***ff-nodes***, ***fc-nodes***, ***cf-nodes*** and ***cc-nodes***. These distinguish between paths connecting the different combinations of field nodes and circuit nodes. The specific type of surface node will determine the type of attribute required to approximate the propagation of energy across that surface.

Electromagnetic Attributes

The next step in modelling the electromagnetic system is to approximate the propagation of electromagnetic energy from one volume node to another. Fuzzy electromagnetic attributes are introduced for each electromagnetic component in the topology as well as for the interaction paths between the components. These attributes approximate the propagation of the electromagnetic disturbances throughout the topology and represent the electromagnetic knowledge which is known about a system.

Each volume node in an electromagnetic topology may have one or more electromagnetic disturbances (D) associated with it. These disturbances are represented as fuzzy variables with trapezoidal membership functions [3] as shown in Fig. 2 below. An important property of the trapezoidal functions is that they can be represented by the 4-tuple (a, b, c, d) with $a \le b \le c \le d$. The meaning of a designation such as [(10, 20) MHz, (10, 15, 20, 22) dBmV/m/Hz] could be translated as: " in the frequency range of (10, 20) MHz the electric field of this disturbance has a good possibility of lying between 15 and 20 dBmV/m/Hz but can be as low as 10 dBmV/m/Hz and as high as 22 dBmV/m/Hz ". An entry for a specific disturbance, such as circuit board radiation, is made up of a list of entries such as this which fully cover the required frequency range. For example, the emissions from a circuit board may be defined as (hypothetical):

(disturbance, circuit_board, cpu,
[[(10, 20), (10, 15, 20, 22)],
[(20, 25), (20, 25, 25, 30)],
[(25, 100), (5, 15, 15, 15)]]).

where the units for frequency and level are assumed to be MHz and dBmV/m/Hz respectively.

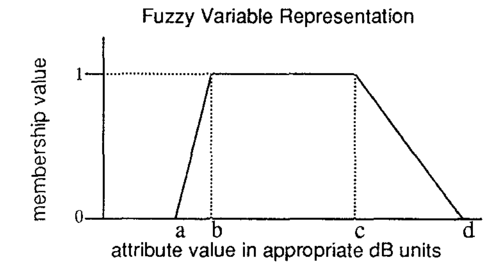

Fig. 2. Trapezoidal membership function for fuzzy attributes

Each volume node may have one or more susceptibility attributes (S) associated with it as well. For example the susceptibility attribute for a CMOS gate might be represented as:

(susceptibility, digital, cmos_gate,
[[(1, 2), (1, 2, 3, 4)],
[(2, 10), (2, 10, 10, 12)],
[(10, 50), (2, 3, 3, 4)]]).

Notice that both susceptibility and disturbance attributes are represented in the form:

(Attribute, Type, Sub_type, [list of fuzzy representation]).

These are stored in an electromagnetic properties database which can be loaded and edited by the user if necessary. If at a future time, more precise models are derived for an attribute only the database needs to be changed since the attributes are loaded into the topology via their *Type* and *Sub_type* labels.

In a similar way each surface node will have shielding effectiveness (SE) attributes associated with it. These attributes have the same form as the susceptibility and disturbance attributes, but represent the amount of attenuation a disturbance encounters while crossing from one volume to another via that surface path. The units for this quantity depend on the two nodes which the path connects (i.e. ff-path, fc-path, cf-path or cc-path). Again, more than one attribute may be associated with a surface node. This would indicate parallel paths of entry from one volume to another.

The total disturbance, susceptibility and shielding effectiveness representations for a node are derived from the fuzzy representations of all the disturbances and susceptibilities present in that volume. The individual attributes are *frequency range normalized* to a user specified global frequency range list and *added in parallel* to determine the *total disturbance*, *total susceptibility* and *total shielding effectiveness* for the node as shown in Fig. 3. This procedure is analogous to that described in [1, 2] with fuzzy variables replacing fixed discrete intervals.

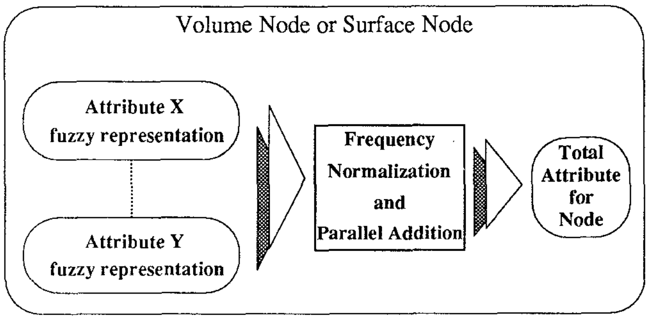

Fig. 3. Total attribute (D, S, or SE) for a node.

Frequency Normalization

All attributes entered at a node (volume or surface) are first frequency normalized over a *global* frequency range set F_g specified by the list of N frequency ranges:

$$F_g = ((f_{g0}, f_{g1}), (f_{g1}, f_{g2}), \dots (f_{gj-1}, f_{gj}), \dots (f_{gN-1}, f_{gN})).$$

If a specific attribute A_x is stored over a specific frequency range set F_x given by the set of M frequency ranges:

$$F_x = ((f_{x0}, f_{x1}), (f_{x1}, f_{x2}), \dots (f_{xj-1}, f_{xj}), \dots (f_{xM-1}, f_{xM})),$$

then A_x can be represented by the set of M fuzzy variables:

$$A_x = ((a_{x1}), (a_{x2}), \dots (a_{xj}), \dots (a_{xM-1}), (a_{xM})).$$

That is, each of the a_{xj}'s is a four-tuple representing a trapezoidal membership function described previously. The frequency normalization of A_x over the global frequency range F_g produces A_{xn} where:

$$A_{xn} = ((a_{xn1}), (a_{xn2}), \dots (a_{xnj}), \dots (a_{xnN-1}), (a_{xnN})).$$

Functionally, this process can be described as that performed by the algorithm shown in figure 4. The actual implementation uses a more efficient, but more complicated procedure.

Frequency Normalization Algorithm

Loop 1: over the F_g ranges (f_{gj-1}, f_{gj}), j =1, ... N;
    set a_{xnj} to *unknown*;
    Loop 2: over the F_x ranges (f_{xi-1}, f_{xi}), i = 1, ... M;
        If $f_{xi} \le f_{gj-1}$ then continue loop 2;
        If $f_{xi-1} \ge f_{gj}$ then continue loop 2;
        otherwize: set a_{xnj} to ***fuzzy_norm***(a_{xnj}, a_{xi});
    end *Loop 2*;
end *Loop 1*;

Fig. 4. Frequency normalization algorithm

The function ***fuzzy_norm***(a_1, a_2) is a fuzzy operator defined differently depending on which attribute is being added (D, S or SE), but returns ***unknown*** if and only if both a_1 and a_2 are ***unknown***. For example:

- *fuzzy_norm(**unknown**, a_x)* returns a_x;
- *fuzzy_norm(**unknown, unknown**)* returns ***unknown***;

Disturbance Normalization: if the attributes to be normalized are disturbances then the ***fuzzy_norm***(D_1, D_2) uses the maximum fuzzy operator, ***max***(a, b), as follows:

$$\begin{cases} S_1 = (a_1, b_1, c_1, d_1)\ ,\ S_2 = (a_2, b_2, c_2, d_2) \\ \boldsymbol{max}\,(D_1, D_2) = \\ (\boldsymbol{max}\,(a_1, a_2), \boldsymbol{max}\,(a_1, a_2), \boldsymbol{max}\,(a_1, a_2), \boldsymbol{max}\,(a_1, a_2)) \\ \mathit{fuzzy\_norm}\,(D_1, D_2) = \boldsymbol{max}\,(D_1, D_2) \end{cases}$$

Susceptibility and Shielding Normalization: if the attributes to be normalized are susceptibilities or shielding effectiveness attributes then the ***fuzzy_norm***(S_1, S_2) uses the fuzzy operator, ***min***(a, b), as follows:

$$\begin{cases} S_1 = (a_1, b_1, c_1, d_1)\ ,\ S_2 = (a_2, b_2, c_2, d_2) \\ \boldsymbol{min}\,(S_1, S_2) = \\ (\boldsymbol{min}\,(a_1, a_2), \boldsymbol{min}\,(a_1, a_2), \boldsymbol{min}\,(a_1, a_2), \boldsymbol{min}\,(a_1, a_2)) \\ \mathit{fuzzy\_norm}\,(S_1, S_2) = \boldsymbol{min}\,(S_1, S_2) \end{cases}$$

Parallel Addition

When more than one specific attribute is specified for a volume or surface node a procedure called ***Parallel Addition*** is performed. Each attribute is first frequency normalized according to the methods described above. The total attribute A_T is determined performing a fuzzy operation between all attributes for each global frequency range. Specifically, the algorithm shown in figure 5.

Parallel Addition Algorithm

Loop 1: over the A_j attribute sets, j = 1, ... k;
    frequency normalize A_j;
end *Loop 1*;
Loop 2: over the F_g ranges (f_{gi-1}, f_{gi}), i = 1, ... N;
    set a_{Ti} to ***unknown***;
    Loop 3: over the A_j attribute sets, j = 1, ... k;
        if a_{ji} = ***unknown*** then set ***unknown flag***;
        set a_{Ti} to ***fuzzy_add***(a_{Ti}, a_{ji});
    end *Loop 3*;
end *Loop 2*.

Fig. 5. Parallel addition algorithm

The ***fuzzy_add*** procedure handles ***unknown*** attributes in the same way as the ***fuzzy_norm*** procedure. It is also defined differently according to the specific attributes it is operating on.

Disturbance and Shielding Addition: if the attributes to be added are disturbances or shielding effectiveness attributes then the ***fuzzy_add***(X_1, X_2) procedure adds the two disturbance fuzzy variables as follows:

$$\begin{cases} X_1 = (a_1, b_1, c_1, d_1)\ ,\ X_2 = (a_2, b_2, c_2, d_2) \\ a_3 = 10\log\,(10^{((\pm 0.1)\,a_1)} + 10^{((\pm 0.1)\,a_2)}) \\ b_3 = 10\log\,(10^{((\pm 0.1)\,b_1)} + 10^{((\pm 0.1)\,b_2)}) \\ c_3 = 10\log\,(10^{((\pm 0.1)\,c_1)} + 10^{((\pm 0.1)\,c_2)}) \\ d_3 = 10\log\,(10^{((\pm 0.1)\,d_1)} + 10^{((\pm 0.1)\,d_2)}) \\ \mathit{fuzzy\_norm}\,(X_1, X_2) = X_3 = (a_3, b_3, c_3, d_3) \end{cases}$$

The negative exponent is used for shielding effectiveness attributes and the positive for disturbance attributes.

Susceptibility Addition: if the attributes to be added are susceptibility attributes then the ***fuzzy_add***(S_1, S_2) adds the two susceptibility fuzzy variables using the minimum operator, ***min***(a, b) as in the *fuzzy_norm* operator for susceptibilities.

Propagation of Disturbances Through Topology

Information regarding the interaction between any two nodes in the topology is explicitly derived by determining the worst case shielding path between them. A search for the worst case shielding path from each susceptible node to all other emitting nodes is performed using a modified *Dijkstra's algorithm* [1, 2] which now uses the *fuzzy distances* corresponding to the fuzzy shielding level.

A new multiple equivalent paths algorithm has been developed to determine if more than one path having the same effective shielding exists. This procedure determines equivalency within a delta which can be varied.

The *likelihood of failure* is determined at the susceptible nodes, by a comparison of the *propagated* electromagnetic disturbance through the worst case shielding path from an emitting node to the susceptibility of the node. The *propagated disturbance* (PD) is determined by using a fuzzy subtraction operator. The total shielding effectiveness of the path traversed (i.e. the TSE value) is subtracted from the total disturbance associated with the emitting node (TD):

PD = ***fuzzy_subtract*** (TD, TSE).

$$\boldsymbol{\mathit{fuzzy\_subtract}}\,((a_1, b_1, c_1, d_1), (a_2, b_2, c_2, d_2)) = (a_1\text{-}d_2, b_1\text{-}c_2, c_1\text{-}b_2, d_1\text{-}a_2)$$

The total propagated disturbance (TPD) impinging at a node is equal to the fuzzy sum of all propagated disturbances from all emitting nodes. The likelihood of failure for a node is based on the determination of a failure index, denoted FI, and calculated by

FI = ***fuzzy_subtract*** (TPD, TSS).

The FI variable is also a trapezoidal membership function. The area under this curve which lies to the right of zero indicates the possibility of the susceptible node failing. For example, if TPD in a specific frequency range is (20, 25, 30, 40) dBmV and TSS is (25, 30, 35, 40) then FI is (-40, -10, 0, 15). This is depicted in figure 6.

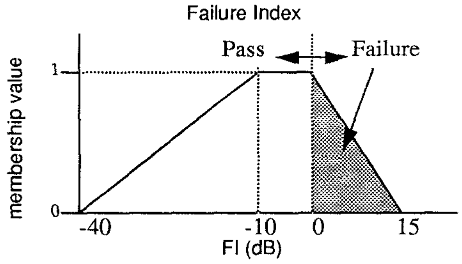

Fig. 6. Failure Index Calculation Example

If the likelihood of failure of any susceptor is too great, then parameters in one or all of the three constraining factors must be modified at one or more locations in the topology.

Implementation

The implementation of the fuzzy logic techniques and procedures described herein as modifications of the HardSys/HardDraw prototype have been completed. Testing of this prototype on the analysis of real systems has commenced at various laboratories which have received licenses for the use of this software.

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