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FUZZY LOGIC TRANSFORMER DESIGN ALGORITHM (FLTDA)

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In the present communication we report a novel fuzzy based algorithm developed for transformer designing. The Fuzzy Logic Transformer Design Algorithm (FLTDA) incorporates the experience of human transformer designers and builders in terms of minimum of fuzzy rules. It easily accomodates the linguistic design concepts and linguistic values of transformer specifications. The FLTDA allows to use assumptions, approximations, estimations and guess-figures for specifications in the beginning of design-route and adjusts the parameters in iterations yielding optimum design results.

As a first attempt towards the development of FLTDA only preliminary results have been worked out in trial designs. Comparison between conventional design method and fuzzy based method is made by working out the typical design problems.

Keywords: Transformer; design algorithm; fuzzy logic

1. INTRODUCTION

1.1. Conventional Transformer Design

Transformer even today has remained indispensable component of electric and electronic circuits, inspite it has not received justifiable attention [2] in the proliferating world of technology. There are different trends [3] as regards to the transformer specifications and design approaches, however all aimed to secure the component in minimum possible time and at lowest possible cost. Although conventional

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methods employed in the transformer design are legion [1, 4, 5, 8], there is no agreed upon standard approach, as a result the methods suffer from one or the other drawback as highlighted below:

- The design process tends to be cut and try and pass through many iterations [4].
- The data base is not well organised [6].
- The lack of proper communication and language between the customer, casual experimenter and transformer designer end up with opposing views [2] on many design specifications and other aspects.
- The designing involves two entirely different aspects-the electrical data calculations and mechanical fitting followed by balanced compromise between them [2, 7, 8].

1.2. Fuzzy Logic Transformer Design Scheme

The fuzzy approach to design a transformer involves the flexibility to deal with heterogeneous data including those of linguistic and numerical character and allows to start with imprecise and little information with minimum rules, there by requiring less software [9, 10] to implement the design route. It dilutes the communication problem between the 'Field Expert' and 'Software Engineer' by offering languages at both the levels of expertise [11].

The linguistic concepts like 'Core is large', 'Window size is small', 'Turns per volt to be changed' normally difficult to implement, are incorporated in to the computer in fuzzy approach *via* membership functions [10, 12]. *E.g.*, the implementation of 'Current density' is shown in Figure 1.

Similar technique of assigning degree of membership can be extended to the variables involved in design course of a transformer.

The next step is decisions based on the linguistic variables which are made of 'IF-THEN' rules [13], where IF part contains a fuzzy condition and THEN part a fuzzy assignment. *E.g.*:

General Linguistic Rule

"IF calculated core cross-sectional is little larger than actual core area THEN number of turns per volt are to be increased slightly."

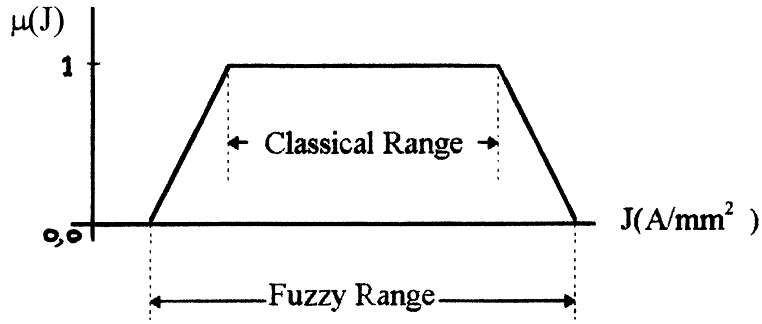

FIGURE 1 Membership function for Current Density (A/mm^2).

Fuzzy Logic Rule

"IF cal. core area is LL THEN turns per volt is SI."

[LL = Little Large, SI = Slightly Increase.]

These rules are then translated in to the computer code using Fuzzy Logic and Fuzzy Set Theory. Such rules are activated (fired) by input data and decisions/conclusions which are fuzzy sets are obtained through inference process [11, 14].

The defuzzification produces a single output value from decisions derived from fired rules *via* output membership functions. Several defuzzification methods exist [11].

2. DEVELOPMENT OF FLTDA [FUZZY LOGIC TRANSFORMER DESIGN ALGORITHM]

Conventional transformer designing requires exact numerical information of transformer specifications, in addition to the other relevant data. This makes design approach tedious. Here we propose FLTDA (Fuzzy Logic Transformer Design Algorithm) – a novel approach that overcomes above constraints and allows to use linguistic values for transformer specifications. The general schematics for FLTDA is shown in Figure 2.

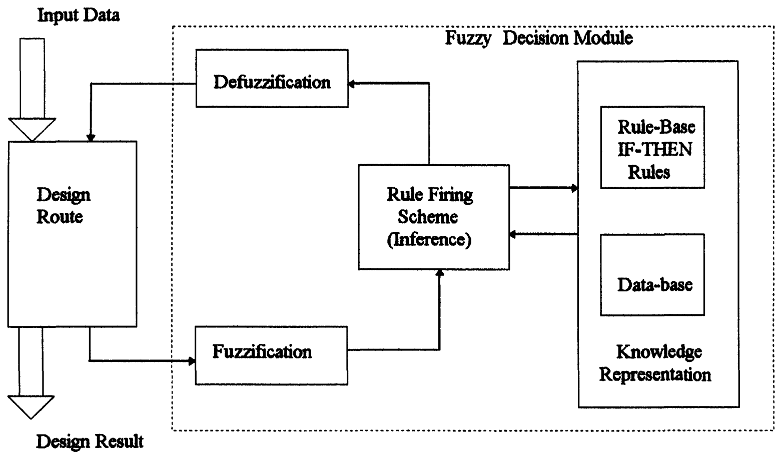

FIGURE 2 General schematics of FLTDA.

The phases involved in development of FLTDA are as follows:

1. Fuzzification
2. Knowledge Representation
3. Inference Scheme, and
4. Defuzzification

2.1. Fuzzification

First the input and output variables involved in every step of design algorithm have identified with their acceptable ranges. Out of which those variables conformable for fuzzification are selected and assigned meaningful linguistic values. Further fuzzification of linguistic specifications/parameters is carried out by expressing crisp (point-wise) values in to the fuzzy sets using appropriate membership functions on respective practical domains [14, 15]. These fuzzy sets have been labelled such as "LS", "JR", "SD" *etc.*

[LS = "Little Small", JR = "Just Right", SD = "Slightly Decrease"]

The fuzzification of Efficiency (η), Current Density (J), Core cross-sectional area (a) and Volts per Turn Figure (t') and Wire Size (WG) have been shown in Figure 3 below.

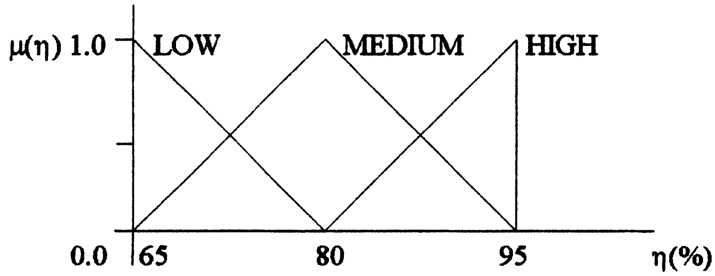

FIGURE 3a (Membership function of efficiency).

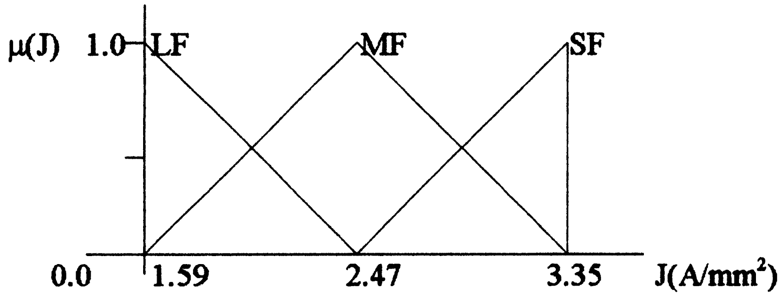

FIGURE 3b (Membership function of current density).

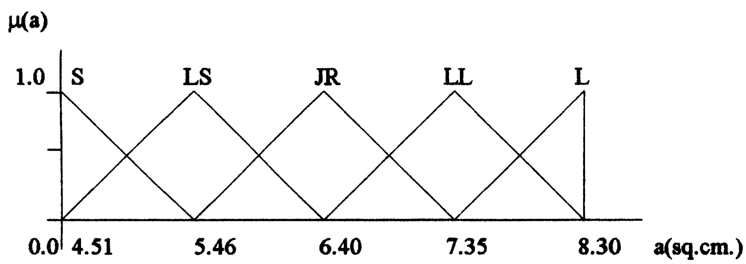

FIGURE 3c (Membership function of core area).

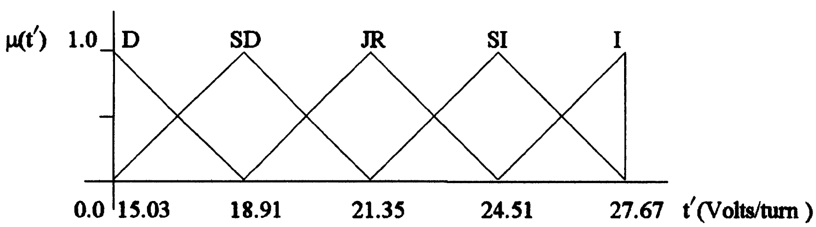

FIGURE 3d (Membership function of volts/turn).

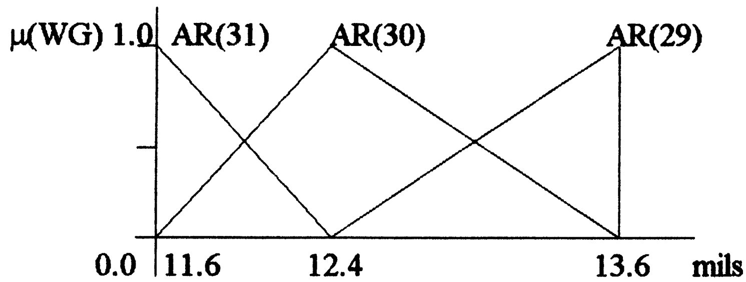

FIGURE 3e (Membership function of wire gauge for primary winding).

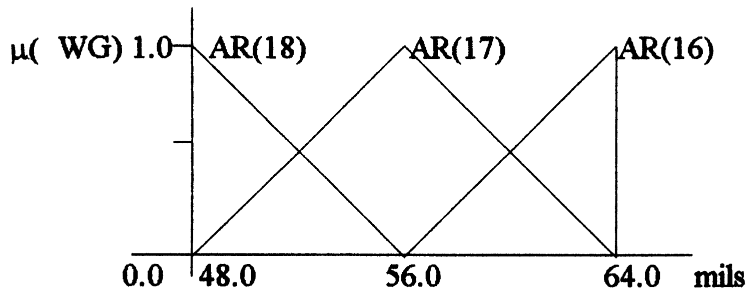

FIGURE 3f (Membership function of wire gauge for secondary winding).

2.2. Knowledge Representation (Knowledge-base) [11, 14]

The knowledge relevant to transformer designing is formulated in to fuzzy inference rules, which are supported by the data-base. The knowledge-base thus comprises a Data-base and a Rule-base.

Data-base

The data-base provides the required information to fuzzification, rule-base and defuzzification modules. The information includes: [11, 13, 16].

The membership functions representing meanings of linguistic values of input and output variables in addition to Labels, shapes, slopes and domain-ranges. *E.g.*, typical membership functions [11, 16] for input variables Efficiency (η), Core-area (a) can be defined as follows:

[Data shown is for Indian Standard C.R.G.O.-CORE of type No. 15 selected in the sample design problem.]

$$\begin{aligned} \mu_{\mathrm{L}}(\eta) &= \mathrm{L}(\eta, 65, 80) \\ \mu_{\mathrm{M}}(\eta) &= \Lambda(\eta, 65, 80, 95) \\ \mu_{\mathrm{H}}(\eta) &= \Gamma(\eta, 80, 95) \end{aligned} \tag{I}$$

[L = "Low", M = "Medium", H = "High"]

$$\begin{aligned} \mu_{\mathrm{S}}(a) &= \mathrm{L}(a, 4.51, 5.46) \\ \mu_{\mathrm{LS}}(a) &= \Lambda(a, 4.51, 5.46, 6.40) \\ \mu_{\mathrm{JR}}(a) &= \Lambda(a, 5.46, 6.40, 7.35) \\ \mu_{\mathrm{LL}}(a) &= \Lambda(a, 6.40, 7.35, 8.30) \\ \mu_{\mathrm{L}}(a) &= \Gamma(a, 7.35, 8.30) \end{aligned} \tag{II}$$

[S = "Small", LS = "Little Small", JR = "Just Right", LL = "Little Large", L = "Large"]

Typical membership functions for output variables Current density (J), Volts per turn (t') and Wire size (WG) can be defined as follows:

$$\begin{aligned} \mu_{\mathrm{LF}}(J) &= \mathrm{L}(J, 1.59, 2.47) \\ \mu_{\mathrm{MF}}(J) &= \Lambda(J, 1.59, 2.47, 3.35) \\ \mu_{\mathrm{SF}}(J) &= \Gamma(J, 2.47, 3.35) \end{aligned} \tag{III}$$

[SF = "Small Figure", MF = "Medium Figure", LF = "Large Figure"]

$$\begin{aligned} \mu_{\mathrm{D}}(t') &= \mathrm{L}(t', 15.03, 18.19) \\ \mu_{\mathrm{SD}}(t') &= \Lambda(t', 15.03, 18.19, 21.35) \\ \mu_{\mathrm{JR}}(t') &= \Lambda(t', 18.19, 21.35, 24.51) \\ \mu_{\mathrm{SI}}(t') &= \Lambda(t', 21.35, 24.51, 27.67) \\ \mu_{\mathrm{I}}(t') &= \Gamma(t', 24.51, 27.67) \end{aligned} \qquad [\mathrm{IV}]$$

[D = "Decrease", SD = "Slightly Decrease", JR = "Just Right", SI = "Slightly Increase", I = "Increase"]

A scaling factor of (10^{-2}) for t' is stored in the data-base. For linearity the 'Volts per turn' is defined using which 'Turns per volt' figure is computed as

$$t = N/V = 1/t'$$

The membership functions for Wire-Size can be defined as follows:
For primary winding:

$$\begin{aligned} \mu_{\mathrm{AR}}(31) &= \mathrm{L}(\mathrm{WG}, 11.6, 12.4) \\ \mu_{\mathrm{AR}}(30) &= \Lambda(\mathrm{WG}, 11.6, 12.4, 13.6) \\ \mu_{\mathrm{AR}}(29) &= \Gamma(\mathrm{WG}, 12.4, 13.6) \end{aligned} \qquad [\mathrm{V}]$$

For secondary winding:

$$\begin{aligned} \mu_{\mathrm{AR}}(18) &= \mathrm{L}(\mathrm{WG}, 48, 56) \\ \mu_{\mathrm{AR}}(17) &= \Lambda(\mathrm{WG}, 48, 56, 64) \\ \mu_{\mathrm{AR}}(16) &= \Gamma(\mathrm{WG}, 56, 64) \end{aligned} \qquad [\mathrm{VI}]$$

Where

WG = "WIRE-GAUGE"
AR = "AROUND".

The membership functions for Core-area are generated immediately after the selection of likely Core from standard Catalog having Wa-product closer to calculated figure, followed by membership functions for Volts per turn. The trial designs are based on the squarish core area, however it proposed to go for suitable shapes as to fit the core in standard available bobbins [2, 17]. The membership functions for wire-size are generated after the computation of mils (diameter) for each winding during the execution of design route.

The user can modulate these membership functions to tune to his data and obtain acceptable results.

Rule-base

The rule-base represents in a structural form the design policy of an experienced human transformer-designer using a set of fuzzy logic/ inference rules. Typical rules are given below:

TABLE I [3, 7, 8]: Inference Rules for Current-density

Rule 1 : IF	Efficiency is	L	THEN	Current-density is	LF
Rule 2 : IF	Efficiency is	M	THEN	Current-density is	MF
Rule 3 : IF	Efficiency is	H	THEN	Current-density is	SF

TABLE II [4, 7, 8]: Inference Rules for Volts/Turns

Rule 4 : IF	Cal. Core area is S	THEN	Volts/Turn is	I
Rule 5 : IF	Cal. Core area is LS	THEN	Volts/Turn is	SI
Rule 6 : IF	Cal. Core area is JR	THEN	Volts/Turn is	JR
Rule 7 : IF	Cal. Core area is LL	THEN	Volts/Turn is	SD
Rule 8 : IF	Cal. Core area is L	THEN	Volts/Turn is	D

TABLE III Inference Rules for Wire-size

Rule 9 : IF	DOM of SWG is HG	THEN	SWG is	AR(n)
Rule 10 : IF	DOM of SWG is EG	THEN	SWG is	AR($n-1$)

[AR = "Around", DOM = Degree of Membership, HG = Higher than 0.5, EG = Equal, n = Wire gauge number]

These rules are then incorporated using Fuzzy Set Theory and Fuzzy Logic. The user can also modulate this rule-base.

For every incoming numeric value of linguistic variable the FLTDA enters in to the fuzzy inference process.

2.3. Inference-scheme [11, 12, 14]

The FLTDA employs Mamadani type individual rule based fuzzy logic inference. This is a process where contribution of each fuzzy logic rule is evaluated. The purpose of inference is to compute the overall decision outcome based on the individual contributions of each rule in the rule base.

In the inference process each rule is individually fired by crisp-value of input variable (design specification/parameter) from fuzzification module and clipped fuzzy sets representing the overall fuzzy output variable of design step under execution are obtained. The process is exemplified for sample design problem in Figure 4.

2.4. Defuzzification

It is the last step in the development of FLTDA carried out to find a compromise from all clipped fuzzy sets that represent the overall fuzzy

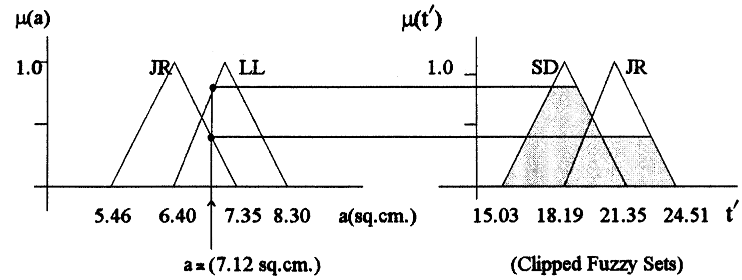

FIGURE 4 (Individual rule firing scheme).

output variable. It converts each fuzzy output variable resulted in inference process in to crisp (single point-wise) value.

Several defuzzification methods are available. However the FLTDA employs Height-Defuzzification (HD) [11] being simple and quick. The crisp output value u^* is given by:

$$u^* = \frac{\sum_{r=1}^{q} Pk^{(r)} \cdot h^{(r)}}{\sum_{r=1}^{q} h^{(r)}}$$

Where

q = number of rules fired
$Pk^{(r)}$ = peak value of rth clipped fuzzy set
$h^{(r)}$ = height of rth clipped fuzzy set.

The HD is illustrated for sample design problem in Figure 5 below.

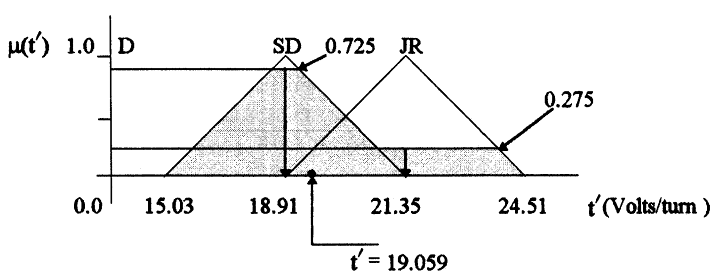

FIGURE 5 (Height defuzzification).

The resulting defuzzified output variable either triggers the next step of design route or represents the intermediate/final results of design.

3. EXPERIMENTAL RESULTS

Trial design problems have been worked out using FLTDA and quite satisfactory preliminary results have been obtained in comparision with conventional algorithm. It is also seen that the design goes through less number of iterations when checked for 'build' details [2, 5, 7] from conventional technique for good mechanical fit. The FLTDA computes the figures for various variables of transformer to the user's specifications and modify them accordingly to compromise for standard core-size, type and wire size available on manufacturer's catalog [17–19].

The comparative results of two techniques have been shown in Table -IV.

Sample Design Problem: Low Voltage Medium Current Power Transformer.

Specifications:

1. Primary (input) Voltage = 230 VAC, 50 Hz, Sine Waveform.
2. Secondary-Voltage = 6.0 V at 5.0 A.
3. Efficiency = 80%.
4. Insulation Class = Type B.

TABLE IV Comparative results of sample design

Parameter	*Coventional Technique*	*FLTDA Technique*
1. Current density (J)	User to enter	2.47 A/mm^2 FLTDA computes this value.
2. Core-cross sectional area (a)	For $J = 2.47 =$ A/mm^2 7.12 sq · cm.	7.12 sq · cm.
3. Turns per volt ratio	4.21	5.25
4. Mils of windings	Primary = 156.62 mils Secondary = 3200 mils	Primary = 145.44 mils Secondary = 3203.56 mils
5. Winding Turns (N)	Primary = 969 Secondary = 43	Primary = 1208 Secondary = 53
6. Wire-Size	SWG(P) = 30 SWG(S) = 17	SWG(P) = Around 30 with DOM = 0.575 SWG(S) = Around 17 with DOM = 0.925

From the computed figure for Wa-Product, the good choice as per Indian Standard [18] the EI-core selected is

Type No.: 15

Grade: C.R.G.O.

Maximum Flux Density, Bm = 15000 Gauss.

[Figure used in sample design is 12500 Gauss.]

Squarish core area, $a = 6.40\,\text{sq}\cdot\text{cm}$.

4. CONCLUSIONS

The aim of developing FLTDA is to accommodate the linguistic terms and human reasoning involved in the designing of a transformer. The testing of FLTDA has shown that the fuzzy logic based technique allows the transformer-designer to use guess-figures, approximations and imprecise values for specifications in the beginning and adjusts them in every iteration yielding desired optimal final results.

We found that the fuzzy-approach to transformer designing facilitates the incorporation of experience of design expert in the data-base in one hand and rule-base on the other hand. The potentiality of FLTDA however lies in defining the membership-functions and derive 'IF-THEN' rules that exactly reflects the designer's reasoning process.

At this stage of infancy of FLTDA only required minimum data is referred to and only preliminary results have been successfully implemented. The build-calculations followed by mechanical-fit, estimation of losses and computation of temperature-rise, and the other aspects such as effect of load, cooling type, extreme voltage and current conditions needed to be included. The later development of FLTDA takes care of these problems.

References

[1] Grossner, N. R. (1967). Transformer for Electronic circuits. (Mc Graw-Hill, New York), Chap. 10, pp. 5–10.

[2] Flanagan, W. H. (1988). Handbook of Transformer Applications, (Mc-Graw Hill, New York), pp. xii, 1–28, 44–46.

[3] Stigent, S. A. and Franklin, A. C. (1973). J. & P. Transformer Book. (Newnes-Butterworths, London), Chap. 4, pp. 74–111.
[4] Crompton, A. B. (1983). "Theory of Transformer Design Principles", Ed. Feinberg, R., Modern Power Transformer Practice, (Mc Millan Press Ltd.), Chap. 2, pp. 18–60.
[5] Rowe, K. (1983). "The use of Automatic Electronic Digital Computer as an Aid to the Power Transformer Designer". Ed. Feinberg, R., Modern Power Transformer Practice, (Mc Millan Press Ltd.), Chap. 3, pp. 61–83.
[6] Mudholkar, R. R. (1995). "Transformer Design-A Software Approach", *M.Phil. Dissertation*, (Shivaji University, Kolhapur, India), pp. 41–46.
[7] Lowden, E. (1985). Practical Transformer Design Handbook (B.P.B. Publications, Delhi), Chap. 4, p. 47, Chaps. 7, 8, pp. 100–156.
[8] Agrawal, R. C. (1987). "Design Procedure", Transformers, BHEL (Tata Mc Graw-Hill), Chap. 9, pp. 165–190.
[9] Kevin Self Correspondent, "Designing With Fuzzy Logic". (IEEE Spectrum, Nov. 1990), pp. 42–44, 105.
[10] Kosko, B. and Isaka, S. (1993) . "Fuzzy Logic". (Scientific American), p. 62.
[11] Driankov, D., Hellendoorn, H. and Reinfrank, M. (1996). An Introduction to Fuzzy Control, (Narosa publishing House, New Delhi), pp. 1–12, 37–144.
[12] Jonda, S., Fleischer, M. and Meixner, H. (1993). "Temperature Control of Semiconductor metal-oxide gas sensor by means of Fuzzy Logic", (Sensors and Actuators, S. A.), **B34**, 396–400.
[13] Fathi, M. and Llambrecht, M. (1995). "A fuzzy logic system to calculate and optimize parameters for an electron beam welding machine". (Fuzzy Sets and Systems), **69**, 3–13.
[14] Klir, G. J. and Bo, Yuan (1997). Fuzzy Sets and Fuzzy Logic. (Prentice-Hall of India, New Delhi), Chap. 12, pp. 327–338.
[15] Delgado, M. and Gonzales, A. (1993). "An inductive learning procedure to identify fuzzy systems", (Fuzzy Sets and Systems), **55**, 121–132.
[16] Cheok, Ka C., Kobayshi, K., Scaccia, S. and Scaccia, G. (1996). "A Fuzzy Logic based Smart Automatic Windshield Wiper". (IEEE Control Systems), pp. 28–34.
[17] CRGO Laminations, Copper wines, Bobbins, (GKW Ltd. Bangalore, India, 1995).
[18] Industrial-Laminations Catalog. (Central Steel Corporation, India, 1997).
[19] Enamelled Round Copper Winding Wires, (Indo-American Electric Ltd., India, 1996).