An Artificial Intelligence System for a Complex Electromagnetic Field Problem: Part II—Method Implementation and Performance Analysis

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***Abstract*—An artificial intelligence system has been developed to determine the electromagnetic field in the complex problem of a faulted overhead transmission line above earth and a buried pipeline. The amplitude and phase of the magnetic vector potential (MVP) in the earth around the pipeline neighborhood, including pipeline itself, are calculated. The performance of the trained fuzzy logic system (FLS) described in Part I was tested extensively for various configurations of the above electromagnetic field problem, differing significantly from the cases used for training. The trained FLS parameters required to calculate the electromagnetic field by simple formulas are also presented.**

***Index Terms*—Finite element method, fuzzy logic, power transmission electromagnetic interference.**

I. Introduction

THE use of finite element method (FEM) for the solution of Maxwell's differential equations describing an electromagnetic field problem always leads to useful conclusions [1]–[5]. However, the complicated geometries of complex electromagnetic field problems leads to a large number of discretization nodes and consequently to a huge computational effort. Therefore, the method proposed in [6] has been extended in Part I of this paper in order to solve complex electromagnetic field problems such as the problem of a power overhead transmission line above earth and a buried pipeline. A suitable developed fuzzy logic system (FLS) has been trained using FEM results, in order to calculate the MVP distribution in the earth around the pipeline neighborhood, including pipeline itself, without the necessity of an additional FEM calculation.

In this present paper, the membership functions $\mu_d^j, \mu_x^j, \mu_y^j, \mu_\rho^j$ and the consequence factors $\lambda_0^j, \lambda_d^j, \lambda_x^j, \lambda_y^j, \lambda_\rho^j$ obtained from the training of the FLS developed in Part I are reported. Using the above trained parameters and simple formulas, it is easy to compute the electromagnetic field for every configuration case of the above problem. This paper also summarizes the test results of an extensive performance analysis of the trained FLS in various configuration cases, differing significantly from the cases used for training. These cases have different separation distances d between the overhead transmission line and the buried pipeline and different earth resistivities ρ.

II. Method Implementation

A. Fuzzy Logic System Trained Parameters

The magnetic vector potential (MVP) of the steady state electromagnetic field problem of an overhead transmission line above earth and a buried pipeline is expressed using complex phasors, and therefore, it consists of two parts, the amplitude and the phase. Since the proposed FLS method has a single output, two different FLS's are required to calculate MVP distribution. Therefore, in Part I of this paper, two different FLS's have been developed and trained, the first one in order to match MVP amplitude and the second one in order to match MVP phase. The FLS's training has been executed using the training scheme and the training data base (TDB) of Part I. Training has been made with a mean absolute error of 1%. At the end of the training procedure the rule base of each FLS contained 11 rules.

The mean values $\overline{a}_d^j, \overline{a}_x^j, \overline{a}_y^j, \overline{a}_\rho^j$ and the standard deviations $\sigma_d^j, \sigma_x^j, \sigma_y^j, \sigma_\rho^j$ of the membership functions $\mu_d^j, \mu_x^j, \mu_y^j, \mu_\rho^j$, obtained from the FLS's training in Part I are given in Tables I and II, respectively. In Fig. 1 the membership functions which characterize the jth rule fuzzy sets defined in the space of one of the input variables, the separation distance d, are shown. From this figure it is evident that membership functions cover suitably the practical premise space of input variable d. This also holds for all other three input variables x, y, ρ. The factors $\lambda_0^j, \lambda_d^j, \lambda_x^j, \lambda_y^j, \lambda_\rho^j$ of the consequent part of the jth rule, obtained from the FLS's training in Part I, are given in Table III.

In Part I the developed FLS's have been trained using FEM MVP results for different configuration cases of the problem of an overhead transmission line above earth and a buried pipeline, having a phase to ground fault current equal to 1000 A. It should be mentioned that the MVP distribution is proportional to the fault current. Therefore, the trained FLS's may be easily used to estimate the MVP distribution for any value of the phase to ground fault current.

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TABLE I
MEMBERSHIP FUNCTION MEAN VALUES OF THE RULES OF THE TWO FLS'S WHICH HAVE BEEN TRAINED IN ORDER TO MATCH (a) THE MVP AMPLITUDE AND (b) THE MVP PHASE

	α_d	α_x	α_y	α_ρ
Rule 1	632.44	-186.56	-11.54	336.07
Rule 2	2019.47	1981.04	-20.09	-6.86
Rule 3	816.03	363.25	-10.67	495.54
Rule 4	289.50	311.13	-10.96	357.60
Rule 5	328.85	396.86	-11.02	-158.82
Rule 6	-9.53	-149.20	-30.03	145.76
Rule 7	854.71	1088.51	-21.92	877.93
Rule 8	417.16	447.21	-20.17	852.86
Rule 9	1999.99	2029.88	-14.95	999.99
Rule 10	552.47	126.86	-24.67	595.45
Rule 11	1550.07	1547.51	-16.88	907.86

(a)

	α_d	α_x	α_y	α_ρ
Rule 1	456.60	41.78	-13.96	212.83
Rule 2	2018.79	1988.87	-22.28	-18.76
Rule 3	967.85	999.49	-1.92	912.10
Rule 4	486.63	474.08	-13.91	223.16
Rule 5	340.15	693.82	-14.11	-173.34
Rule 6	-22.66	-92.72	-27.93	113.72
Rule 7	800.04	800.49	-17.51	900.02
Rule 8	554.79	579.37	-21.55	994.68
Rule 9	2000.00	2029.44	-14.93	1000.00
Rule 10	1485.36	1484.47	-17.32	900.04
Rule 11	-18.21	-12.30	-8.84	987.00

(b)

TABLE II
MEMBERSHIP FUNCTION STANDARD DEVIATIONS OF THE RULES OF THE TWO FLS'S WHICH HAVE BEEN TRAINED IN ORDER TO MATCH (a) THE MVP AMPLITUDE AND (b) THE MVP PHASE

	σ_d	σ_x	σ_y	σ_ρ
Rule 1	386.00	194.33	6.00	190.65
Rule 2	254.78	297.78	4.58	61.36
Rule 3	356.11	137.86	5.93	181.35
Rule 4	385.97	143.61	5.90	193.99
Rule 5	272.56	167.92	5.97	139.88
Rule 6	64.33	66.36	5.77	32.33
Rule 7	385.23	242.94	5.06	55.96
Rule 8	385.99	394.55	1.90	46.88
Rule 9	64.33	122.17	1.29	32.33
Rule 10	107.36	66.33	5.99	97.07
Rule 11	266.83	288.25	1.00	36.29

(a)

	σ_d	σ_x	σ_y	σ_ρ
Rule 1	341.41	397.36	5.96	98.94
Rule 2	311.28	326.44	5.91	32.33
Rule 3	299.11	212.62	5.97	91.09
Rule 4	385.76	294.87	5.97	108.50
Rule 5	365.27	255.90	6.00	145.94
Rule 6	64.33	66.33	6.00	40.99
Rule 7	64.52	67.09	4.06	32.42
Rule 8	206.06	119.45	4.36	144.76
Rule 9	64.33	66.71	1.37	32.33
Rule 10	386.00	398.00	1.07	32.55
Rule 11	79.17	66.33	5.66	55.91

(b)

The calculated MVP distribution is accurate for a faulted phase conductor height of 11 m. However, it has been found using FEM formulation of Part I, that for separation distances $d > 50$ m, the MVP distribution differs less than 3.5%, for phase conductor heights between 8–30 m. Therefore, the trained FLS is also capable of calculating the MVP distribution for all the phase conductor heights encountered in practice.

Using the membership function mean values and standard deviations of Tables I and II, the consequence factors of Table III, and the FLS architecture described in Part I, it is easy to calculate the MVP values at any point of the earth around the pipeline neighborhood, including pipeline surface, for every different configuration case. Using the pipeline's surface MVP values, pipeline induced voltages may also be calculated as explained in Part I.

B. Calculation Example

The procedure to compute the MVP values may be explained using the following example. Suppose that the MVP amplitude in a point with coordinates $x = 249$ m and $y = -17.48$ m, for a separation distance $d = 250$ m between the overhead transmission line and the buried pipeline and for earth resistivity $\rho = 600$ Om, is required.

The MVP output of the FLS for an input vector (d, x, y, ρ) is given by

$$A)d, x, y, \rho) = \frac{\sum_{j=1}^{m=11} A^j \mu^j}{\sum_{j=1}^{m=11} \mu^j} \tag{1}$$

where

$$\mu^j = \mu_d^j(d)\mu_x^j(x)\mu_y^j(y)\mu_\rho^j(\rho) \qquad (j = 1, \cdots, m = 11) \tag{2}$$

gives the degree of fulfillment of the jth rule by the input vector (d, x, y, ρ), and

$$A^j = \lambda_0^j + \lambda_d^j d + \lambda_x^j x + \lambda_y^j y + \lambda_\rho^j \rho \qquad (j = 1, \cdots, m = 11) \tag{3}$$

is the MVP proposed by the jth rule for the input vector (d, x, y, ρ).

Using the membership function mean values and standard deviations of Tables I(a), II(a), and (9a)–(9d) of Part I, it is possible to calculate the membership values $\mu_d^j, \mu_x^j, \mu_y^j, \mu_\rho^j$ for the input vector $d = 250$ m, $x = 249$ m, $y = -17.48$ m, and $\rho = 600$ Ωm. The calculated membership values are given in Table IV. Using Table IV and (2) the degrees of fulfillment of each rule $\mu^j (j = 1, \cdots, m = 11$ rules) can be found. These degrees of fulfillment are given in Table V. The firing strength of the fuzzy rule base may now be obtained from Table V as

$$\sum_{j=1}^{m=11} \mu^j = 0.3275. \tag{4}$$

As explained in Part I of this paper, the consequence factors $\lambda_0^j, \lambda_d^j, \lambda_x^j, \lambda_y^j, \lambda_\rho^j$ have been normalized in the interval [0.0, 3.0] and therefore (3) holds in this interval. Consequently, input variables d, x, y, and ρ must be normalized in the same interval. The range of these input variables may be easily found from Part I of this paper. For example, input $d = 250$ m is being normalized from interval [70, 2000] to interval [0.0, 3.0] using the following:

$$\frac{2000 - 250}{250 - 70} = \frac{3 - d_{\text{norm}}}{d_{\text{norm}} - 0}. \tag{5}$$

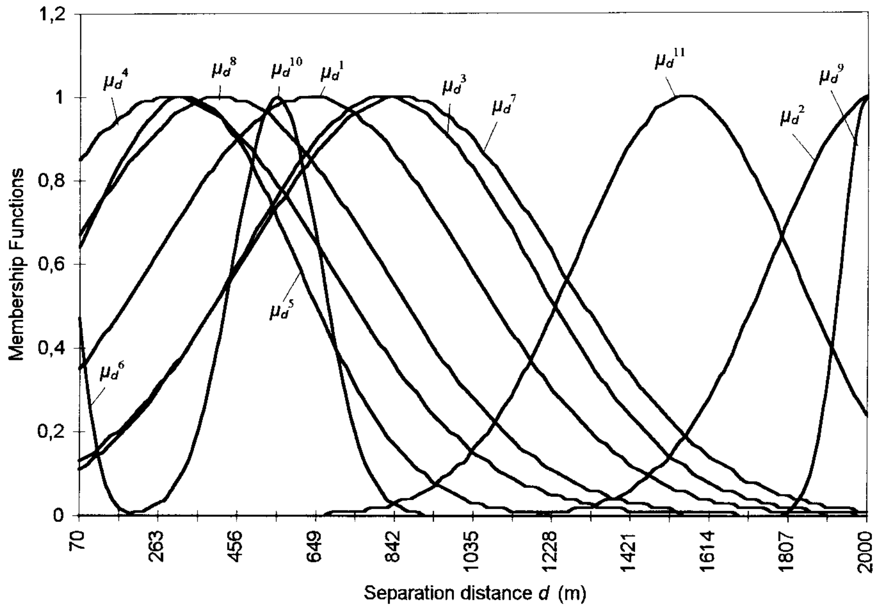


Fig. 1. Membership functions of the first FLS, which has been trained in order to match the MVP amplitude for input variable d.

TABLE III
CONSEQUENCE FACTORS OF THE RULES OF THE TWO FLS'S WHICH HAVE BEEN TRAINED IN ORDER TO MATCH (a) THE MVP AMPLITUDE AND (b) THE MVP PHASE

	λ_0	λ_d	λ_x	λ_y	λ_ρ
Rule 1	2.4361	-1.2468	-2.3158	0.2716	0.4442
Rule 2	0.3184	-0.0497	-0.0553	-0.00008	0.2739
Rule 3	1.3255	-0.1387	-0.4030	-0.0011	0.1447
Rule 4	1.6166	-0.0754	-1.3009	-0.0043	0.3854
Rule 5	0.3745	0.0569	-0.2625	-0.0023	1.1337
Rule 6	2.1714	-0.0091	-0.0211	-0.0178	0.0365
Rule 7	1.0376	-0.1710	-0.1332	-0.0161	0.1247
Rule 8	1.4613	-0.5169	-0.5053	-0.1449	0.4195
Rule 9	0.5026	-0.0029	-0.0052	0.0226	-0.0030
Rule 10	1.6509	-0.1982	-0.2034	-0.2500	0.0895
Rule 11	0.6571	-0.0131	-0.0124	0.0070	0.0151

(a)

	λ_0	λ_d	λ_x	λ_y	λ_ρ
Rule 1	3.0000	-0.2513	-0.5511	0.0291	0.0987
Rule 2	0.4573	-0.0003	-0.1324	0.0618	1.5110
Rule 3	2.5706	-0.1394	-0.2105	-0.0101	0.1132
Rule 4	2.2969	0.0035	-0.3964	-0.0014	0.3053
Rule 5	1.0927	-0.2816	-0.3719	0.0387	0.3213
Rule 6	2.8680	-0.0071	-0.0109	0.1159	0.0096
Rule 7	2.4398	-0.0009	-0.0018	0.0232	-0.0022
Rule 8	2.7860	-0.2223	-0.2372	0.0017	0.0549
Rule 9	1.8750	-0.0038	-0.0069	0.0301	-0.0038
Rule 10	2.0705	0.0018	0.0017	-0.0010	-0.0020
Rule 11	2.9660	-0.2123	-0.2532	0.0038	0.0012

(b)

TABLE IV
MEMBERSHIP VALUES FOR INPUT VARIABLES $d = 250$ m, $x = 249$ m, $y = -17.48$ m, AND $\rho = 600\ \Omega$m, AS CALCULATED USING TABLES I(a), II(a), and (9a)–(9d) OF PART I.

	Inputs ε			
	$\varepsilon = d$	$\varepsilon = x$	$\varepsilon = y$	$\varepsilon = \rho$
$\mu_\varepsilon 1$	0.6121	0.0810	0.6129	0.3835
$\mu_\varepsilon 2$	0.0000	0.0000	0.8503	0.0000
$\mu_\varepsilon 3$	0.2827	0.7097	0.5184	0.8471
$\mu_\varepsilon 4$	0.9947	0.9109	0.5445	0.4581
$\mu_\varepsilon 5$	0.9590	0.6789	0.5581	0.0000
$\mu_\varepsilon 6$	0.0002	0.0000	0.0940	0.0000
$\mu_\varepsilon 7$	0.2916	0.0025	0.6798	0.0000
$\mu_\varepsilon 8$	0.9104	0.8815	0.3704	0.0000
$\mu_\varepsilon 9$	0.0000	0.0000	0.1489	0.0000
$\mu_\varepsilon 10$	0.0189	0.1831	0.4877	0.9989
$\mu_\varepsilon 11$	0.0000	0.0000	0.8381	0.0000

TABLE V
DEGREES OF FULFILLMENT OF EACH RULE $\mu^j (j = 1, \cdots, m = 11$ RULES) FOR INPUT VARIABLES $d = 250$ m, $x = 249$m, $y = -17.48$ m, AND $\rho = 600\ \Omega$m

$\mu 1$	$\mu 2$	$\mu 3$	$\mu 4$	$\mu 5$	$\mu 6$
0.0117	0.0000	0.0881	0.2260	0.0000	0.0000

$\mu 7$	$\mu 8$	$\mu 9$	$\mu 10$	$\mu 11$
0.0000	0.0000	0.0000	0.0017	0.0000

The normalized values of input variables $d = 250$ m, $x = 249$ m, $y = -17.48$ m, and $\rho = 600\ \Omega$m are $d_{\text{norm}} = 0.279$, $x_{\text{norm}} = 0.315$, $y_{\text{norm}} = 1,251$, and $\rho_{\text{norm}} = 1.762$, respectively. Using the consequence factors $\lambda_0^j, \lambda_d^j, \lambda_x^j, \lambda_y^j, \lambda_\rho^j$ of Table III(a), the normalized input variables in the interval [0.0, 3.0], and (3), the MVP A^j proposed by each rule are obtained. These values of $A^j (j = 1, \cdots, m = 11$ rules) are given in Table VI. Using Tables V and VI it is possible to compute the FLS MVP output given by (1) as

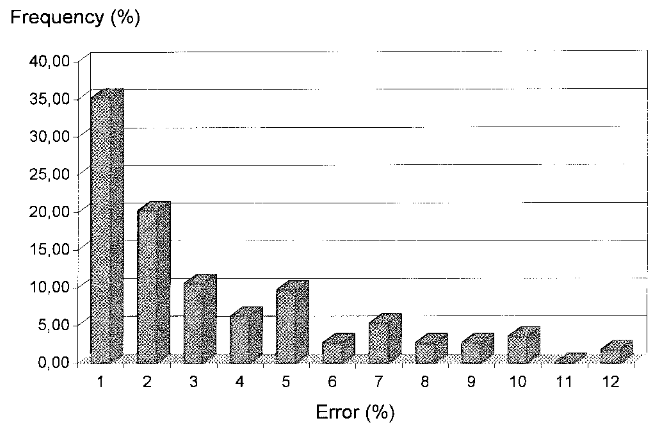
$$A(d, x, y, \rho) = \frac{\sum_{j=1}^{m=11} A^j \mu^j}{\sum_{j=1}^{m=1} \mu^j} = \frac{0.5761}{0.3275} = 1.759. \tag{6}$$

The computed MVP amplitude value is normalized in the interval [0.0, 3.0]. The MVP amplitude values used in FLS training vary between 4.36E-06 and 7.03E-04 Wb/m. There-

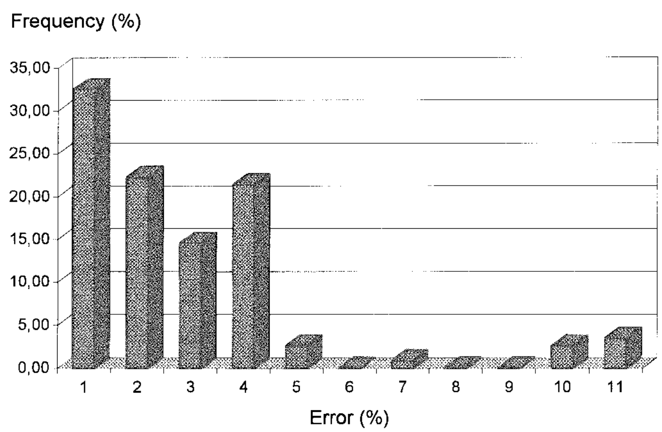
TABLE VI
MVP A^j PROPOSED BY THE jth RULE FOR INPUT VECTOR
($d = 250$m, $x = 249$ m, $y = -17.48$ m, AND $\rho = 600$ Ωm

A^1	A^2	A^3	A^4	A^5	A^6
2.4805	0.7699	1.4133	1.8595	2.3035	2.2044

A^7	A^8	A^9	A^{10}	A^{11}
1.1473	1.7156	0.5234	1.3762	0.6850



(a)



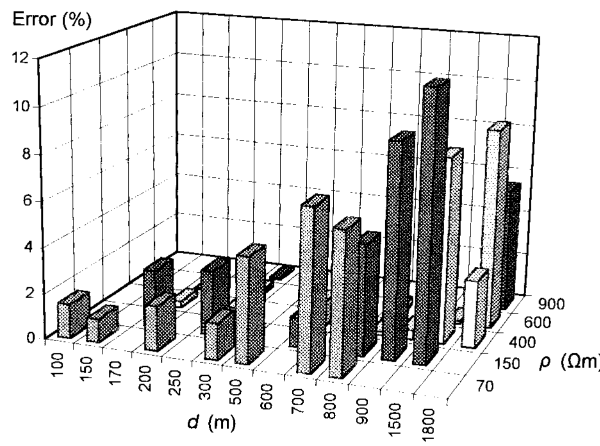
(b)

Fig. 2. Frequency distribution of the FLS errors concerning (a) the amplitude and (b) the phase of the MVP values in the earth around the pipeline neighborhood.

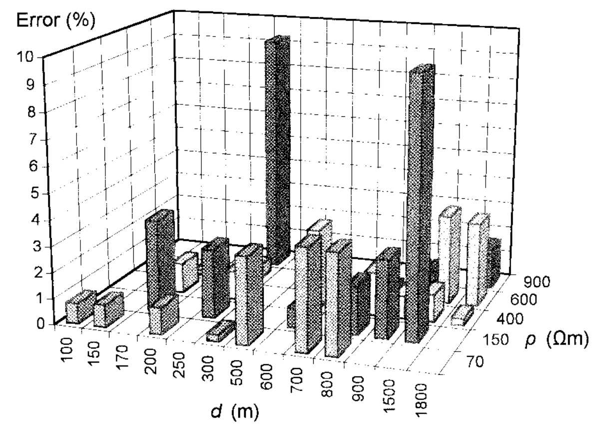
fore, the MVP amplitude value 1.759 must be denormalized from the interval [0.0, 3.0] to the interval [4.36E-06, 7.03E-04]. Finally, the MVP amplitude value for input variables $d = 250$ m, $x = 249$ m, $y = -17.48$ m, and $\rho = 600$ Ωm is calculated equal to 4.14E-04 Wb/m. A FEM computation for the same separation distance d and the same earth resistivity ρ leads to a MVP amplitude in the node with coordinates $x = 249$ m and $y = -17.48$ m equal to 4.11E-04 Wb/m. The difference between FEM and FLS calculation is negligible, however FEM requires a huge computational effort, while the proposed FLS needs only simple calculations.

III. PERFORMANCE ANALYSIS

The performance of the trained FLS in the computation of MVP distribution in the earth around the pipeline neighborhood, including pipeline itself, has been tested in several configuration cases of the complex electromagnetic field problem of an overhead transmission line above earth and a buried pipeline. These cases have various separation distances d between power line and pipeline as well as various earth resistivities ρ. In order to make these tests, the finite element procedure described in Part I of this paper has been applied and a suitable database has been constructed.



(a)



(b)

Fig. 3. FLS errors for different separation distances d and earth resistivities ρ concerning (a) the amplitude and (b) the phase of pipeline surface MVP.

The results of the FLS have been compared with results obtained using the FEM described in Part I. The FLS errors concerning the MVP have been computed relative to the corresponding MVP FEM results and in absolute values, i.e. $\text{Error} = |(A_{\text{FEM}} - A_{\text{FLS}}/A_{\text{FEM}}) \cdot 100|$. The FLS average error concerning the MVP amplitude is equal to 2.77%, while the FLS average error concerning the MVP phase is equal to 2.12%. However, once FLS is trained, the electromagnetic field in new cases with different configuration may be easily calculated. The computing time is negligibly small, compared to the time needed for FEM calculations of the new configuration case. In all reported cases, one FLS calculation requires a computing time approximately equal to 0.000 055% of the corresponding FEM calculation.

The frequency distribution of the FLS errors concerning the computation of the MVP amplitude values in the earth around the pipeline neighborhood is shown in Fig. 2(a). From this figure it can be seen that 66% of the errors is less than 3.0%. Fig. 2(b) shows the corresponding frequency distribution of the FLS errors in MVP phase calculations. Fig. 2(b) shows that 69% of the errors is less than 3%.

Fig. 3 shows the FLS errors for different separation distances d and earth resistivities ρ concerning pipeline surface amplitude and phase MVP values. From Figs. 2 and 3 it is evident that FLS results are in a good agreement with those obtained by FEM.

Finally, using pipeline's surface MVP values derived from FLS and (6) of Part I, the voltage V_{PN} induced by the electromagnetic field on the buried pipeline may also be calculated. This voltage is defined as the inductive voltage across point P at a distance $l_z = 1000$ m from J and remote earth N, as shown in Fig. 2 of Part I of this paper.

IV. Conclusions

Artificial intelligence has been used to determine the electromagnetic field in a complex electromagnetic field problem of a faulted overhead transmission line above earth and a buried pipeline. In Part I of this paper, a suitable FLS has been developed and trained in some configuration cases of the above problem. In this part, FLS performance has been tested for many configuration cases, differing significantly from the cases used for training. From the test results it could be concluded that, after suitable training, FLS has a comparable accuracy with FEM, while it needs negligibly small computing time. Using the mean values and the standard deviations of membership functions as well as the consequence factors of the trained FLS presented in this paper, the electromagnetic field as well as the pipeline induced voltages may be quickly and easily computed for every practical configuration case of the above problem.

References

[1] P. Silvester and R. Ferrari, *Finite Elements for Electrical Engineers*. Cambridge, U.K.: Cambridge Univ. Press, 1983.

[2] Konrad, "The numerical solution of steady-state skin effect problems—An integrodifferential approach," *IEEE Trans. Magn.*, vol. MAG-17, pp. 1148–1152, Jan. 1981.

[3] J. Weiss, V. K. Garg, and E. Sternheim, "Eddy current loss calculation in multiconductor systems," *IEEE Trans. Magn.*, vol. MAG-19, pp. 2207–2209, Sept. 1983.

[4] J. Weiss and Z. Csendes, "A one-step finite element method for multiconductor skin effect problems," *IEEE Trans. Power Appart. Syst.*, vol. PAS-101, pp. 3796–3803, Oct. 1982.

[5] D. Labridis and P. Dokopoulos, "Finite element computation of field, losses and forces in a three-phase gas cable with nonsymmetrical conductor arrangement," *IEEE Trans. Power Delivery*, vol. PWDR-3, pp. 1326–1333, Oct. 1988.

[6] K. J. Satsios, D. P. Labridis, and P. S. Dokopoulos, "Fuzzy logic for scaling finite element's solutions of electromagnetic field," *IEEE Trans. Magn.*, vol. 33, pp. 2299–2308, May 1997.

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