3-D optimization of design variables in x-, y- and z-directions of transformer tank shield model

Makoto Horii* Norio Takahashi†

Jun Takehara‡

*Okayama University

†Okayama University

‡The Chugoku Electric Power Corporation, Incorporated

3-D Optimization of Design Variables in x-, y- and z-Directions of Transformer Tank Shield Model

Makoto Horii, Norio Takahashi, *Fellow, IEEE*, and Jun Takehara

***Abstract*—By using the automatic 3-D mesh generation technique using hexahedral elements, which is applicable when design variables are changed in x-, y- and z-directions, a transformer tank shield model is optimized. The volume of tank shield can be considerably reduced by using the Rosenbrock's method (RBM) compared with the previous result having design variables in one direction. It is shown that the determination of initial values for RBM using the experimental design method (EDM) is indispensable for the practical application of the optimization method to get a desired result within an acceptable CPU time.**

***Index Terms*—Optimization, Rosenbrock's method, transformer tank shield model.**

I. Introduction

THE "transformer tank shield model [1]" which was proposed by the Investigation Committee of the IEE of Japan is a benchmark model for reducing the volume V of shielding plate and for constraining the maximum eddy current density J_{em} in the tank within a specified value J_{emo}. This model can be expanded to the full 3-D benchmark model having design variables in x-, y- and z-directions to examine the possibility of applying the optimal design method using 3-D FEM to the practical design of magnetic devices.

In this paper, in order to establish the full 3-D optimization technique using the finite element method, 3-D mesh generation software using hexahedral element [2] is developed, and applied to the optimization of design variables in the x-, y- and z-directions of the tank shield model. The effect of the number of design variables on the optimal shape of the tank shield model is shown. The result obtained using only the Rosenbrock's method (RBM) [3] and that obtained using the combined method [4] of the experimental design method (EDM) [5] and RBM are also compared.

II. Analyzed Model and Analysis Condition

Fig. 1 shows the transformer tank shield model. The iron plate is made of steel and eddy currents are taken into account (conductivity: 0.75×10^7 S/m). The shielding plate is made of grain-oriented silicon steel [grade (JIS): 30G140] in which it is assumed that no eddy current flows. The rolling direction of steel is the y-direction. The ampere-turns of the coil are 5484 AT(max) [12 A(max), 457 turns, 60 Hz]. As the steel is not saturated, the phasor method (so-called $j\omega$ method) is applied in 3-D eddy current analysis by assuming that the magnetic characteristic of magnetic material is linear. The relative permeability of iron plate is assumed as 1000, and those in the rolling and transverse directions of silicon steel are assumed as 3000 and 30, respectively. The dimension of analyzed region is 1000 mm $\times$ 1000 mm $\times$ 1000 mm.

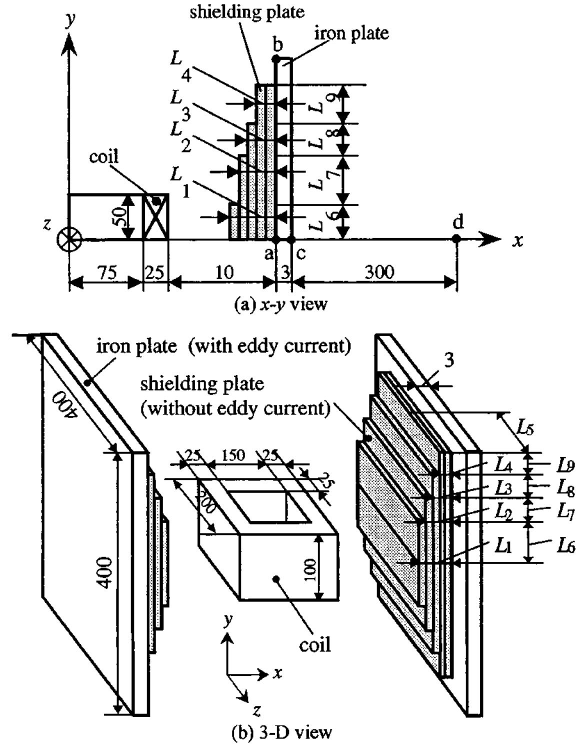

Fig. 1. Transformer tank shield model.

The following three kinds of models having design variables in x-, y- and z-directions are optimized by using the Rosenbrock's method:

[4 Design Variables]

$L_1 \sim L_4$: unknown

$L_5 = 0.2$ m

$L_6 = L_7 = L_8 = L_9 = 0.05$ m

$$V = (L_1 + L_2 + L_3 + L_4) \times 0.05 \times 0.2 \text{ [m}^3\text{]} \tag{1}$$

[6 Design Variables]

$L_1 \sim L_5$: unknown

$L_6 = L_7 = L_8 = L_9$: unknown

$$V = (L_1 + L_2 + L_3 + L_4) L_5 L_6 \text{ [m}^3\text{]} \tag{2}$$

Manuscript received June 5, 2000.

M. Horii and N. Takahashi are with the Department of Electrical and Electronic Engineering, Okayama University 3-1-1, Tsushima, Okayama 700-8530, Japan (e-mail: {horii; norio}@eplab.elec.okayama-u.ac.jp).

J. Takehara is with Technical Research Center, the Chugoku Electric Power Co., Inc., Higashi-Hiroshima 739-0046, Japan (e-mail: 477241@pnet.energia.co.jp).

Publisher Item Identifier S 0018-9464(01)07900-6.

TABLE I
LEVELS

design variables [10^{-3}m]	levels		
	1	2	3
L_1, L_2, L_3, L_4	2.5	5.0	7.5
L_5	125	150	175
L_6, L_7, L_8, L_9	12.5	25	37.5

TABLE II
ORTHOGONAL ARRAY (9 VARIABLES)

model No.	design variables									V [10^{-4} m^3]	J_{em} [10^6 A/m^2]
	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9		
1	1	1	1	1	1	1	1	1	1	0.156	2.333
2	1	1	1	1	2	2	2	2	2	0.375	0.814
3	1	1	1	1	3	3	3	3	3	0.656	0.365
4	1	2	2	2	1	1	1	2	2	0.430	1.337
5	1	2	3	1	2	2	2	3	3	0.844	0.455
6	1	3	1	2	3	3	3	1	1	0.820	0.730
7	1	1	3	2	1	1	1	3	3	0.664	0.728
8	1	2	1	3	2	2	2	1	1	0.469	1.204
9	1	3	2	1	3	3	3	2	2	0.984	0.394
10	2	1	2	3	1	2	3	1	2	0.586	0.732
11	2	1	2	3	2	3	1	2	3	0.938	0.536
12	2	1	2	3	3	1	2	3	1	0.711	0.910
13	2	2	3	1	1	2	3	2	3	0.742	0.540
14	2	2	3	1	2	3	1	3	1	0.844	0.815
15	2	2	3	1	3	1	2	1	2	0.602	1.396
16	2	3	1	2	1	2	3	3	1	0.703	0.637
17	2	3	1	2	2	3	1	1	2	0.656	1.024
18	2	3	1	2	3	1	2	2	3	0.875	0.758
19	3	1	3	2	1	3	2	1	3	0.781	0.611
20	3	1	3	2	2	1	3	2	1	0.656	0.949
21	3	1	3	2	3	2	1	3	2	1.094	0.731
22	3	2	1	3	1	3	2	2	1	0.703	0.784
23	3	2	1	3	2	1	3	3	2	0.844	0.555
24	3	2	1	3	3	2	1	1	3	0.984	0.924
25	3	3	2	1	1	3	2	3	2	0.898	0.546
26	3	3	2	1	2	1	3	1	3	0.797	0.859
27	3	3	2	1	3	2	1	2	1	0.766	1.399

[9 Design Variables]

$L_1 \sim L_9$: unknown

$$V = (L_1L_6 + L_2L_7 + L_3L_8 + L_4L_9)L_5 \text{ [m}^3\text{]}. \tag{3}$$

These models are optimized so that the objective function W shown in (4) becomes minimum, and the maximum value of the eddy current density J_{em} in the iron plate should be less than the specified value J_{emo} (=0.25 × 10^6 A/m^2) in order to avoid the local heating:

$$W = V + P \tag{4}$$

where P is the penalty function which is defined by

$$P = \begin{cases} 0 & (J_{em} < J_{emo}) \\ J_{em} & (J_{em} \geq J_{emo}) \end{cases} \tag{5}$$

J_{em} is given by

$$J_{em} = \sqrt{\left|\dot{J}_{ex}\right|^2 + \left|\dot{J}_{ey}\right|^2 + \left|\dot{J}_{ez}\right|^2} \tag{6}$$

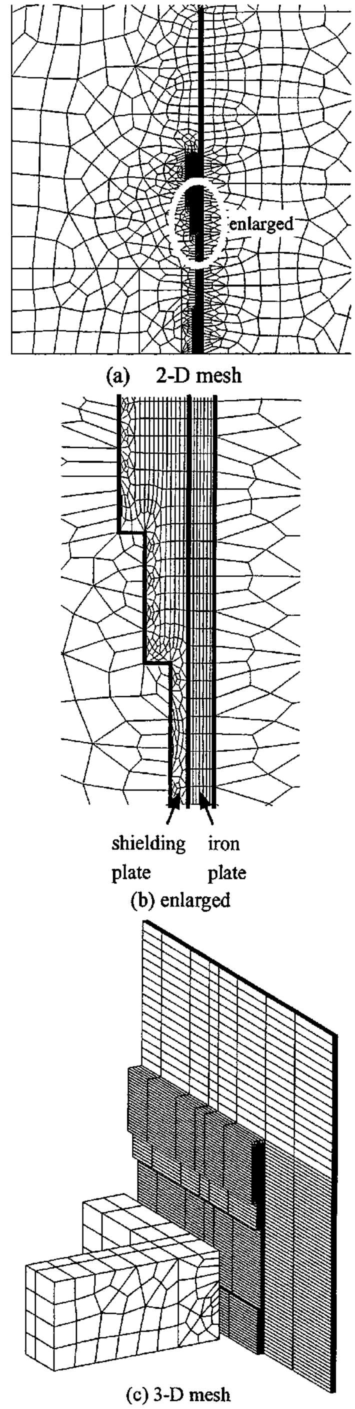

Fig. 2. Meshes.

where dot($\cdot$) means the complex number. As J_{em} [A/m^2] is of the order of 10^5 and V [m^3] is of the order of 10^{-4}, (1) and (3) can be approximated as follows:

$$W = \begin{cases} V & [\text{m}^3] & (J_{em} < J_{emo}) \\ J_{em} & [\text{A/m}^2] & (J_{em} \geq J_{emo}) \end{cases} \tag{7}$$

The constraint of $L_1 \sim L_9$ is given by

$$\begin{aligned} &0 < L_1,\, L_2,\, L_3,\, L_4 < 0.01 \text{ [m]} \\ &0.1 < L_5 < 0.2 \text{ [m]} \\ &0 < L_6,\, L_7,\, L_8,\, L_9 < 0.05 \text{ [m]}. \end{aligned} \tag{8}$$

TABLE III
RESULTS OF OPTIMIZATION (WITH EDM)

		initial		optimal		
number of variables		6	9	4	6	9
design variables $[10^{-3}$ m]	L_1	2.5		4.25	4.01	4.38
	L_2	2.5		2.00	2.38	2.13
	L_3	2.5		1.00	2.38	1.00
	L_4	2.5		0.50	2.50	1.50
	L_5	175		—	124.4	130.0
	L_6	37.5		—	44.7	46.9
	L_7	37.5		—	44.7	47.5
	L_8	37.5		—	44.7	31.9
	L_9	37.5		—	44.7	37.4
$V\,[10^{-4}$ m^3]		0.66		0.78	0.63	0.51
$J_{em}\,[10^6$ A/m^2]		0.365		0.238	0.249	0.247
number of iterations		—		26	75	90
CPU time [h]		—		8.6	25.4	27.8

computer used : VT-Alpha533 (SPECfp95:22.5)
convergence criterion of RBM : 0.3 mm
convergence criterion of ICCG method : 5×10^{-4}

III. METHOD OF OPTIMIZATION

Although, for example, the evolution strategy is suitable to obtain the global minimum of the objective function, the number of iterations becomes huge and it is not applicable to 3-D optimization. Then, the Rosenbrock's method (RBM) [3], which is the direct search method, is used for the optimization from the standpoints of small number of iterations. By the way, the experimental design method (EDM, Taguchi's method) [5] is useful for the determination of initial values of design variables [4]. Therefore, first, the EDM is used for the determination of initial values, then the Rosenbrock's method (RBM) is applied to the search for the optimal value.

As an example, the procedure for applying EDM in determining initial values for the case of 9 design variables is explained. The constraints are divided into three levels as shown in Table I. The objective function W, which have 27 patterns are calculated from the orthogonal array (Nos. 1–27) shown in Table II. As J_{em} in all cases is larger than J_{emo} ($= 0.25 \times 10^6$ A/m^2), the objective function W is equal to J_{em}. J_{em} of model no. 3 is the smallest in Table II. Then, the design variables of model No. 3 are chosen as initial values.

IV. 3-D MESH GENERATION TECHNIQUE

As there is no universal automatic mesh generator for hexahedral elements, a technique for making the pile in the z-direction of 2-D mesh shown in Fig. 2(a) is introduced. The outline of the shielding plate in the x–y plane is treated as a polygon. The shape of the polygon is changed according to the amplitudes of design variables $L_1 \sim L_4$, $L_6 \sim L_9$. Then, the polygon is subdivided into quadrilateral elements as shown in Fig. 2(b). There is no limitation of the resolution of the changes in the design variables, because the shape of the polygon can be precisely denoted using the design variables and any shape of polygon can be subdivided using quadrilateral elements. The modification of mesh in the z-direction is carried out by changing the material constant in each pile according to the value of design variable L_5 as shown in Fig. 2(c).

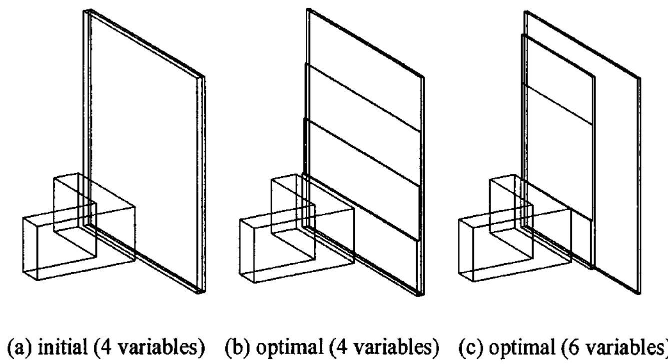

Fig. 3. Initial and optimal shapes.

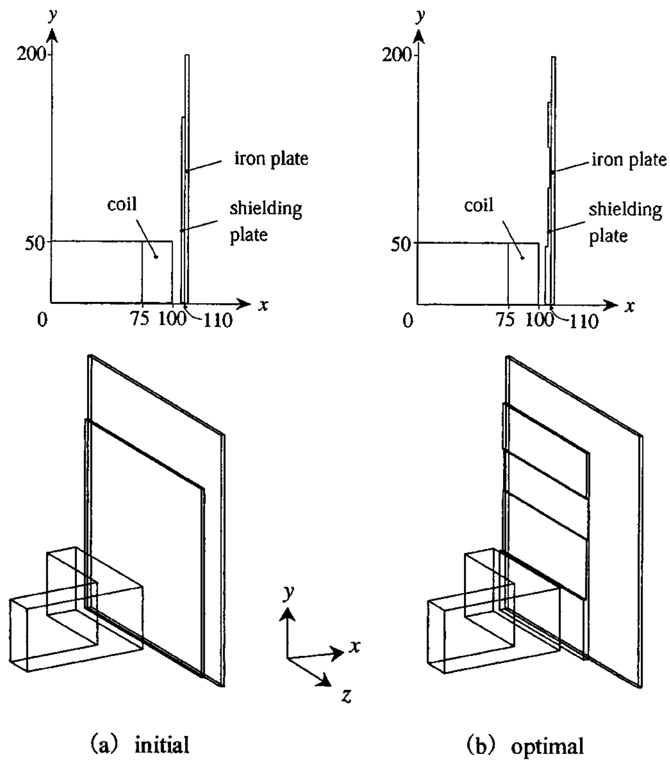

Fig. 4. Initial and optimal shapes ($\omega t = 0°$, 9 design variables).

V. COMPARISON OF OBTAINED RESULTS

A. Results Using EDM and RBM

Table III shows the obtained results of three kinds of models using the combined method of EDM and RBM. The initial values in Table III are obtained using EDM. If the change of design variables $L_1 \sim L_9$ becomes less than 0.1 mm in the process of direct search of RBM, it is judged that the final (optimal) result is obtained. The convergence criterion of ICCG method is 5×10^{-4}.

The volume V in the case of 9 design variables is smaller than those in the cases of 4 and 6 design variables. However, the CPU time in the case of 9 design variables is longer than that in the cases of 4 and 6 design variables.

Fig. 3 shows the initial and optimal shapes in the cases of 4 and 6 design variables. Figs. 4–7 show the shapes, flux and eddy current distributions and contour lines of eddy current density

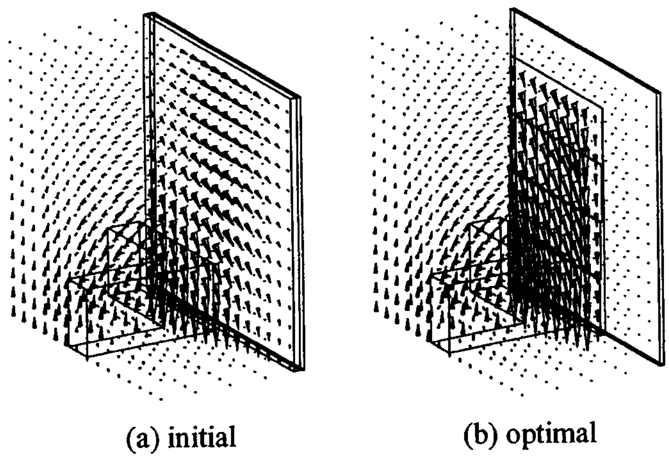

Fig. 5. Flux distributions ($\omega t = 0°$, 9 design variables).

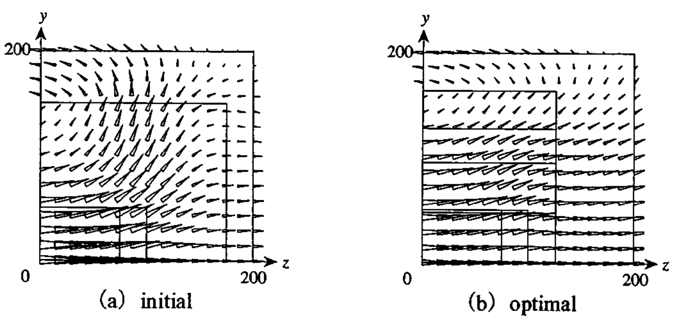

Fig. 6. Eddy current density on surface of iron plate ($\omega t = 0°$, 9 design variables).

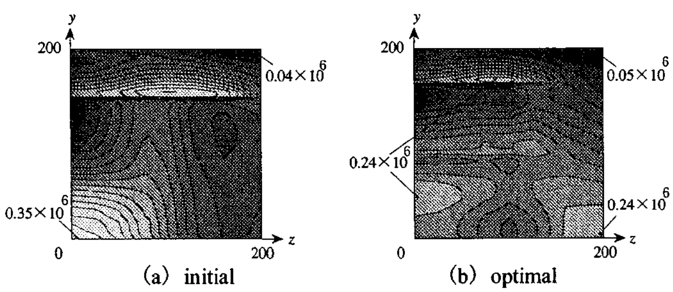

Fig. 7. Contour lines of eddy current density on surface of iron plate ($\omega t = 0°$, 9 design variables).

at the initial and final shapes in the case of 9 design variables. Fig. 6 is the distribution on the surface of the iron plate which is observed from the coil side. Figs. 3, 4, 7 and Table III show that the volume V of shielding plate is reduced by using the optimization method, and the eddy current density can be limited within the specified value by the shielding plate. The volume V in the case of 9 design variables can be reduced by approximately 35% compared with that in the case of 4 design variables (only x-directed variable).

B. Results Using Only RBM

Table IV shows the obtained results using only RBM. The initial values are chosen as the middle value of each constraint of

TABLE IV
RESULTS OF OPTIMIZATION (WITHOUT EDM)

		initial		optimal		
number of variables		6	9	4	6	9
design variables [10^{-3} m]	L_1	5		4.23	4.81	6.03
	L_2	5		2.00	7.84	5.09
	L_3	5		0.83	6.22	7.88
	L_4	5		1.18	7.18	6.34
	L_5	150		—	142.7	176.8
	L_6	25		—	40.5	36.5
	L_7	25		—	40.5	35.7
	L_8	25		—	40.5	40.4
	L_9	25		—	40.5	38.1
V [10^{-4} m^3]		0.75		0.83	1.50	1.70
J_{em} [10^6 A/m^2]		0.805		0.241	0.247	0.249
number of iterations		—		29	130	129
CPU time [h]		—		8.8	51.7	49.2

computer used : VT-Alpha533 (SPECfp95:22.5)
convergence criterion of RBM : 0.3 mm
convergence criterion of ICCG method : 5×10^{-4}

design variable. The volumes V of obtained (optimal) results are increased compared with those at initial values. This suggests that the obtained result without EDM has reached to a local minimum. But J_{em} can be within the specified value J_{emo} ($= 0.25 \times 10^6$ A/m^2). The number of iterations of optimization was also increased considerably in the cases of 6 and 9 design variables. This suggests that the combination of EDM and RBM is especially effective for such a 3-D optimization.

VI. CONCLUSIONS

The obtained results can be summarized as follows:

a) It is shown that the technique for making the pile in the z-direction of 2-D mesh of quadrilateral element in the x–y plane is effective in the optimization in x-, y- and z-directions.
b) It is shown that better result can be obtained if more dimensions of the model are chosen as design variables in the case of tank shield model.
c) The determination of initial values for direct search method using the experimental design method is especially effective for 3-D optimization from the view points of CPU time and getting a better result.

REFERENCES

[1] N. Takahashi, T. Kitamura, M. Horii, and J. Takehara, "Optimal design of tank shield model of transformer," *IEEE Trans. Magn.*, vol. 36, no. 4, pp. 1089–1093, 2000.
[2] A. Kameari, "Calculation of transient 3-D eddy current using edge-elements," *IEEE Trans. Magn.*, vol. 26, no. 2, pp. 466–469, 1990.
[3] D. M. Himmelblau, *Applied Nonlinear Programming*: McGraw-Hill, 1972.
[4] N. Takahashi and M. Natsumeda *et al.*, "Optimization of permanent magnet type of retarder using 3-D finite element method and direct search method," *IEEE Trans. Magn.*, vol. 34, no. 5, pp. 2996–2999, 1998.
[5] D. C. Montgomery, *Design and Analysis of Experiments*: John Wiley & Sons, 1976.