

Generation Method of Equivalent Circuit for Electric Devices Considering Circuit Topology

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A novel circuit generation method considering circuit topology is proposed based on heuristic optimization algorithm. This method determines the type and value of elements by searching for a continuous space, and it automatically constructs the circuit topology. Given that this method handles real values, it can also be applied to circuits with non-existent elements, such as equivalent circuits, and it can be used as a design aid for electrical equipment. The proposed method is applied to an equivalent circuit that expresses the complex permeability of electromagnetic steel sheets.

Index Terms— *Circuit generation method, Equivalent circuit, Genetic algorithm.*

I. INTRODUCTION

THERE is a growing demand for enhanced efficiency and performance of a diverse range of electrical equipment. In the design process for such equipment, numerical analysis methods, such as the finite element method (FEM), are employed. In recent years, there has been a demand for a multiphysics analysis that integrates magnetic, stress, and thermal analyses to simultaneously consider various characteristics. Additionally, the drive frequency of the equipment is increasing. Furthermore, to analyze these physical phenomena accurately, it is necessary to make the time step exceedingly fine, which increases the cost of analysis.

To resolve these physical phenomena rapidly, equivalent-circuit methods have been proposed. The magnetic-circuit method is used to analyze motors, transformers, and other electrical components [1]. Additionally, Cauer circuit, which represents a diverse range of impedance characteristics as an equivalent circuit for magnetic components, has been proposed [2].

It is conventional to align the element values in these equivalent circuits with the values derived from FEM analysis or empirical data. However, the circuit topology, including the arrangement and element type, is often predetermined based on the designer's expertise and knowledge. Given the significant impact of this circuit configuration on the accuracy of the analysis, it is essential to design an optimal circuit. However, there is currently no established method for determining the elements that consider the topology of an equivalent circuit.

Therefore, in this study, we propose an equivalent circuit topology generation method. This generation method can simultaneously consider the circuit topology, element type, and element value using a heuristic algorithm termed as the real-code genetic algorithm (RCGA). The proposed method is innovative such that it determines not only the combination of elements[3] but also the element values as continuous values. The proposed method is applied to the complex permeability of

electromagnetic steel sheets, and the obtained solution is examined.

II. PROPOSED METHOD

An overview of the proposed method is presented in Figs. 1 and 2. In this method, the circuit is configured in a grid pattern, as illustrated in Fig. 1, with elements arranged on each circuit. The size of the circuit is determined based on the target problem. The type and value of the elements are determined using the gene vector $\mathbf{w}$. Considering N_{ele} elements, $\mathbf{w}$ is defined as follows:

$$\mathbf{w} = \{x_1, y_1, \dots, x_e, y_e, \dots, x_{N_{\text{ele}}}, y_{N_{\text{ele}}}\} \quad (1)$$

where x_e and y_e denote the information for the e -th element E_e . The information for the e -th element is determined using the two-dimensional Cartesian coordinates as shown in Fig. 2. Each region indicates the type of element, and the element value A is determined by radius r_e and the maximum and minimum element values A_{max} and A_{min} .

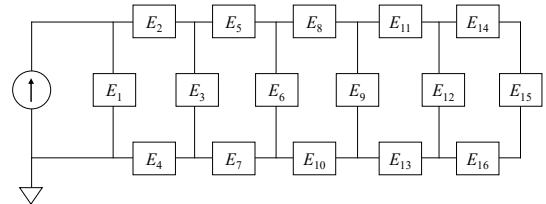


Fig.1 Target network

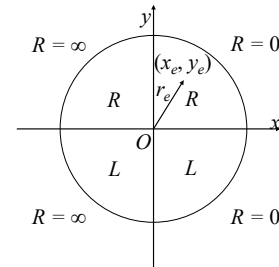


Fig.2 Element determination from Cartesian coordinates

$$r_e = \sqrt{x_e^2 + y_e^2} \quad (2)$$

$$A = A_{min} + (A_{max} - A_{min})r_e \quad (3)$$

w is updated using the RCGA. The circuits defined for each w are analyzed using LTSpice [4]. To fit the analyzed circuit output f_i to target $\hat{f}_i$, the mean-square error is minimized. Therefore, the objective function of the RCGA is as follows:

$$L = \frac{1}{M} \sum_{i=1}^M (f_i - \hat{f}_i)^2 \quad (4)$$

where M denotes the number of data point.

III. NUMERICAL EXPERIMENT

The proposed method is applied to the complex permeability of an infinitely sized electromagnetic steel sheet, as shown in Fig. 3 (a). The complex permeability of electromagnetic steel sheets $\hat{\mu}$ can be defined as follows:

$$k = \sqrt{-j\omega\sigma\mu}, \quad \hat{\mu} = \mu \frac{2}{kd} \tan(kd/2) \quad (5)$$

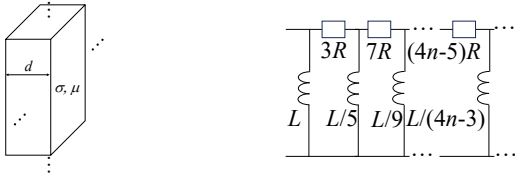
where ω denotes the angular frequency. Additionally, σ , μ , and d denote the conductivity, direct-current permeability, and thickness of the electromagnetic steel, respectively. Furthermore, $\hat{\mu}$ can be expressed using a Cauer circuit [2], as illustrated in Fig. 3 (b). The n shown in the Fig. 3(b) is the number of step. Furthermore, resistance R and inductance L can be obtained as follows:

$$R = \frac{4}{\sigma d^2}, L = \mu \quad (6)$$

In this study, we applied the proposed method to $\hat{\mu}$ and attempted to generate a similar equivalent circuit.

The optimization conditions are listed in Table I. The proposed method is applied to the circuit network shown in Fig.1. The number of elements N_{ele} is 16. Therefore, w length is 32. Additionally, M is 101. The maximum and minimum values of each element are listed in Table II. The amplitude and phase of $\hat{\mu}$ at each point were adjusted to match the target. The objective function is as follows:

$$L = \frac{1}{M} \sum_{i=1}^M \left\{ \left(\frac{\log_{10}|\hat{\mu}| - \log_{10}|\mu|}{\log_{10}|\hat{\mu}|} \right)^2 + \left(\frac{\arg \hat{\mu} - \arg \mu}{\arg \hat{\mu}} \right)^2 \right\} \quad (7)$$



(a) Electromagnetic steel (b) Cauer circuit
Fig.3 Complex permeability of electromagnetic steel sheet

Table I. Optimization setting

Number of dimensions	32
Number of individuals	600
Number of parents	60
Number of children	120
Method of crossing over	REXSTAR
Number of generations	4500
d [mm]	0.2
σ [S/m]	1.22×10^6
μ [H/m]	0.029
Frequency [Hz]	$1.0 \times 10^0 \sim 1.0 \times 10^6$

Table II. Minimum and maximum element value

Element	Minimum	Maximum
R	1.0×10^0	1.0×10^4
L	1.0×10^{-4}	1.0×10^0

IV. RESULTS AND CONCLUSION

The generated circuit using the proposed method is shown in Fig. 4 and is listed in Table III. The elements selected for short-circuiting using the proposed method are deleted from Fig.4. A structure in which L and R were arranged almost alternately was automatically derived. The frequency characteristics of complex permeability are shown in Fig.5. The black and red lines represent the frequency characteristics calculated using Equation (5), and the generated circuit is shown in Fig. 4. The solid and dotted lines indicate amplitude and phase, respectively. The amplitudes and phase matched well across the entire range of values.

In the future, we plan to improve the accuracy of these results. We will also consider applying the proposed method to complex problems.

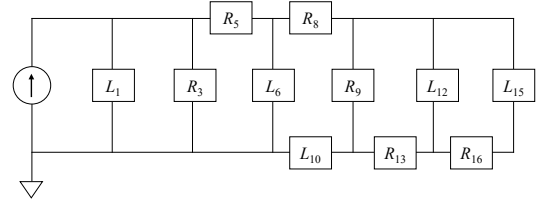


Fig.4 Generated circuit topology

Table III. Optimized circuit element type and value

e	Type	Value	e	Type	Value
1	L	2.8×10^{-2}	9	R	9.1×10^3
2	short	-	10	L	8.7×10^{-4}
3	R	9.1×10^3	11	short	-
4	short	-	12	L	3.8×10^{-3}
5	R	2.5×10^2	13	R	4.2×10^2
6	L	6.1×10^{-3}	14	short	-
7	short	-	15	L	3.7×10^{-3}
8	R	3.2×10^2	16	R	2.8×10^3

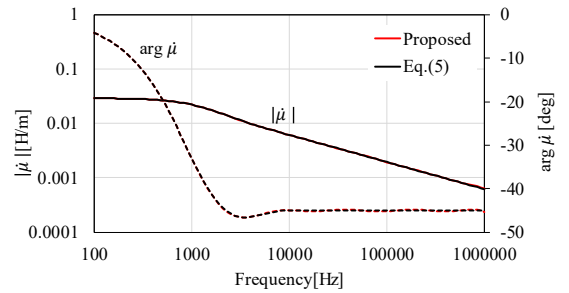


Fig.5 Frequency characteristics of complex permeability

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