Examination of Evaluation Method of Power Generation Current Using Static Magnetic Field Around Polymer Electrolyte Fuel Cell

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Abstract. A polymer electrolyte fuel cell (PEFC) is the clean energy converters, it is developed as a power supply for electric vehicle. In order to raise the power generation efficiency of PEFC, it is important to know the power generation state inside MEA (membrane electrode assembly). In this paper, an measurement method for monitoring the distribution of the power generation current in the MEA of PEFC from static magnetic field around the fuel cell is investigated. The inverse problem analysis of the power generation current distribution in the MEA using 3D finite element method is examined, and the effectiveness of this method is investigated.

Keywords: Polymer Electrolyte Fuel Cell (PEFC) · MEA (membrane electrode assembly) · Power generation current · Heuristic search · Inverse problem analysis · 3-D finite element method

1 Introduction

The fuel cell is the clean energy converters by electrochemical reaction between hydrogen and oxygen. In the fuel cell, there is no emission of air pollutants such as carbon dioxide. Therefore, contributing to energy problems and environmental problems are expected by the development of the improvement in the power generation efficiency of the fuel cell. Since the polymer Electrolyte Fuel Cell (PEFC) is one of the fuel cell with a quick power generation, it is used for the power supply of an electric vehicle or home, etc. The power generation efficiency of the fuel cell is influenced by movement and distribution of hydrogen, oxygen and steam in it. Therefore, it is important to clarify the distribution of the power generation current that has close relation to there mass transfers. Especially, the measurement of the power generation current inside MEA (membrane electrode assembly) is necessary [1]. The generation current distribution was measured by taking out currents externally through divided elements of MEA or a separator [2].

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The static magnetic field around the fuel cell is generated by the power generation current in the fuel cell. Therefore, the distribution of power generation current inside MEA may be measured using the static magnetic field around the fuel cell.

In this paper, the measurement method of the distribution of power generation current inside MEA using of the magnetic field around the PEFC is proposed. In this research, the static magnetic field calculated [3–6] by the forward electromagnetic finite element method is used as the measured value in the proposed inverse problem analysis using 3D heuristic search method. Then the power generation current distribution inside MEA is determined. In addition, the equivalent experimental verification is also carried out.

2 Model and Method of Analysis

Model of PEFC and Measurement Domain of Flux Density

Figure 1 shows the structure of a single cell type fuel cell of the PEFC. This is composed of a pair of copper end plates, a pair of separators made from carbon, which is the passage of hydrogen and oxygen, and a sheet of MEA (membrane electrode assembly).

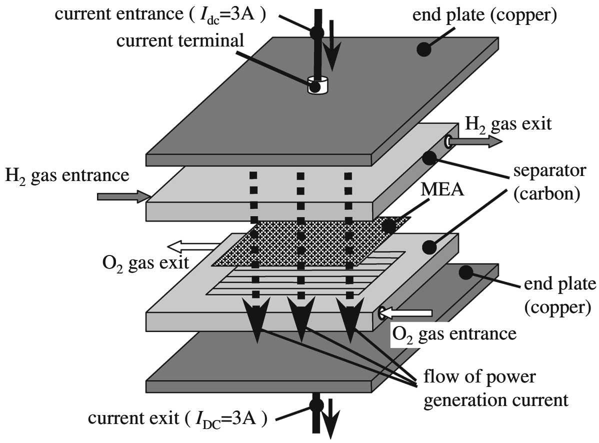


Fig. 1. Single type of polymer electrolyte fuel cell

Figure 2 shows the analyzed model of the fuel cell using the 3D electro magnetic FEM. The MEA is a sheet and its dimension is 50 mm × 50 mm × 1 mm.

The total amount of power generation in the PEFC is 3A. The static flux density around the fuel cell is generated by power generation current in the fuel cell. Therefore, the distribution of power generation current inside the MEA may be determined using the static magnetic field around the fuel cell. The *x*-, *y*-, and *z*-components of the magnetic field, B_x, B_y and B_z along the line a-b-c-d-a shown in Fig. 3, obtained by the forward analysis, are used in 3D inverse problem analysis method. MEA is divided into one-hundred elements and its currents are treated as unknown variables by the inverse problem analysis. Table 1 shows the conditions of the 3D FEM analysis.

Inverse Problem Analysis Using Heuristic Search Method

The measurement of the distribution of power generation current inside MEA in PEFC is an inverse problem analysis using 3D FEM. There are various techniques in the inverse problem method. When the Evolution Strategy [7, 8] using Tikhonov's method is used, the optimal solution was not obtained if the number of design variables is large.

Table 1. Conditions of 3D FEM Analysis

Total power generation current	I_{dc} = 3A
End plate (copper)	Width in the x-direction = 100 mm,
	Length in the y-direction = 100 mm,
	Thickness in the z-direction = 3 mm
	$\sigma = 5.9 \times 10^7$ S/m
Separator (carbon)	Width in the x-direction = 100 mm,
	Length in the y-direction = 100 mm,
	Thickness in the z-direction = 15 mm
	$\sigma = 8.1 \times 10^4$ S/m
MEA	50 × 50 × 1 mm (100 elements)
Nodes and elements	95220, 101614
Convergence criterion	N-R method: 1.0×10^{-6} T
	ICCG method: 1.0×10^{-9}

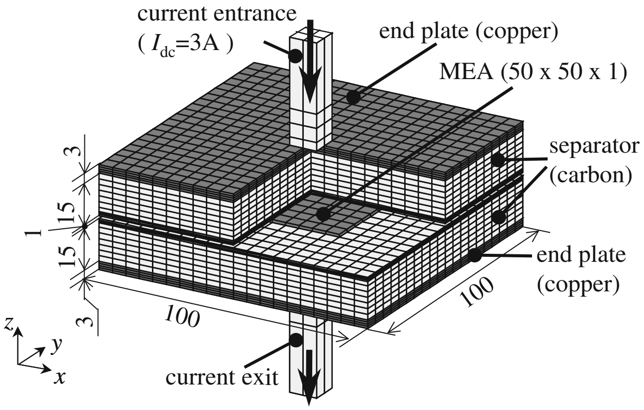


Fig. 2. Model of the PEFC using 3D FEM.

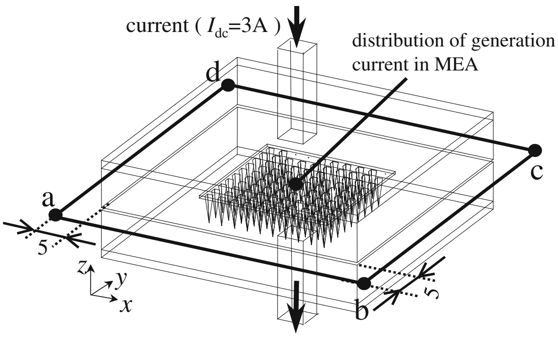


Fig. 3. Position where static magnetic field is measured.

In this research, the inverse problem analysis using the heuristic search method which determines an "ON" or "OFF" domain of the power generation current in MEA which satisfies the specified flux distribution is introduced. The iteration calculation process of the inverse problem analysis is shown in Fig. 4 and the algorithm is as follows:

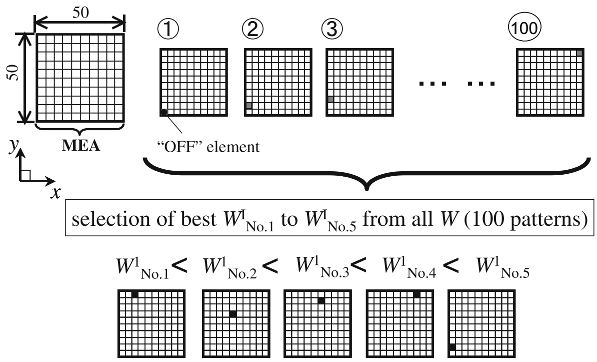
(I) Process 1
One "OFF" element of no power generation current is generated as shown in Fig. 4. Then put it in one hundred kinds of MEA from the left bottom to the right top as shown in Fig. 4(a). The following objective function W at the kth iteration is calculated:

$$W^k = \sum_{i=1}^{n} \left\{ (B_{ix} - B_{0x})^2 + \left(B_{iy} - B_{0y}\right)^2 + (B_{iz} - B_{0z})^2 \right\} (\text{k} = 1, 2, 3\ldots\ldots) \tag{1}$$

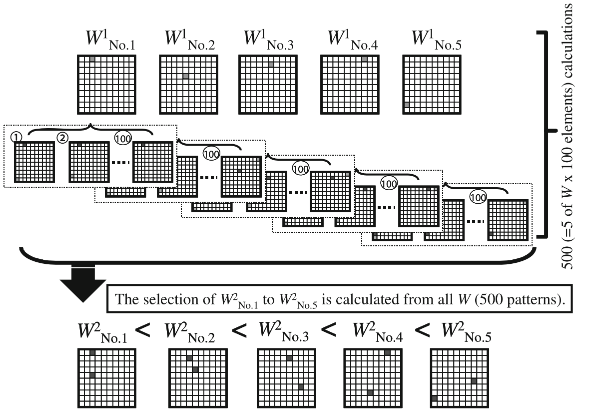
where n is the number of elements along the line a-b-c-d-a around the fuel cell shown in Fig. 3. B_{ix}, B_{iy} and B_{iz} are the x-, y-, and z-components of the flux density at a point i calculated along the line a-b-c-d-a around the fuel cell using 3D electromagnetic FEM. "k" of the superscript of W shows the calculation process k. B_{0x}, B_{0y} and B_{0z} are the x-, y-, and z-components of flux density calculated along the line a-b-c-d-a around the fuel cell by the forward analysis. The power generation current distribution that minimizes the objective function W in (1) is the desired value.

(I) Calculation process 1
The W in the position of the power generation current "OFF" domain by one hundred places inside MEA is calculated. Then, the smallest five which are defined as $W^1_{\text{No.1}}$ to $W^1_{\text{No.5}}$, are chosen from all W^1. The element of black shows an "OFF" element of the power generation current in MEA as shown in Fig. 4.

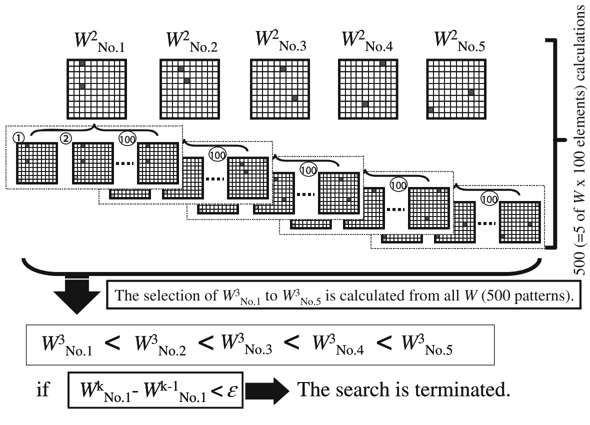
(II) Calculation Process 2
The W in the position of the power generation current of the additional one "OFF" domain by one hundred places inside MEA is calculated as shown in



(a) process 1



(b) process 2



(c) process 3

Fig. 4. Iteration process using proposed heuristic search.

Fig. 4(b). Then, new power generation current distributions of $W^2_{No.1}$ to $W^2_{No.5}$ are selected to five hundred patterns.

(III) Calculation Process 3
The calculation of Calculation process 2 is iterated as shown in Fig. 4(c). "K" in Fig. 4(c) shows the number of the iteration times. If $W^k_{No.1} - W^{k-1}_{No.1}$ is less than ε ($= 1.0 \times 10^{-20}$), the search is terminated.

3 Forward and Inverse Problem Analysis

In order to confirm the usefulness of the proposed inverse problem analysis of heuristic search method, the distribution of power generation current inside MEA using forward problem analysis is estimated by the inverse problem analysis. The distribution of the "OFF" power generation currents of five domain in MEA as shown in Fig. 5 is examined by the proposed inverse problem analysis. In forward problem analysis, the power generation current of five domain inside MEA is calculated as "OFF". Figure 6 shows the whole distribution of power generation current in MEA when the total value of the power generation current is 3A.

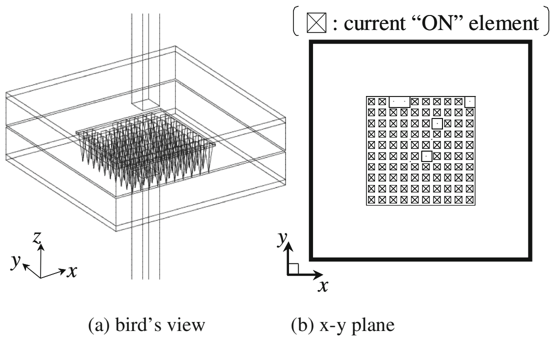


Fig. 5. Distribution of current density set up in forward analysis (total I_{dc} = 3A).

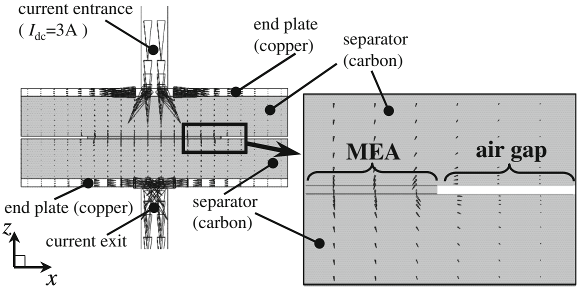


Fig. 6. Whole distribution of power generation current in the fuel cell.

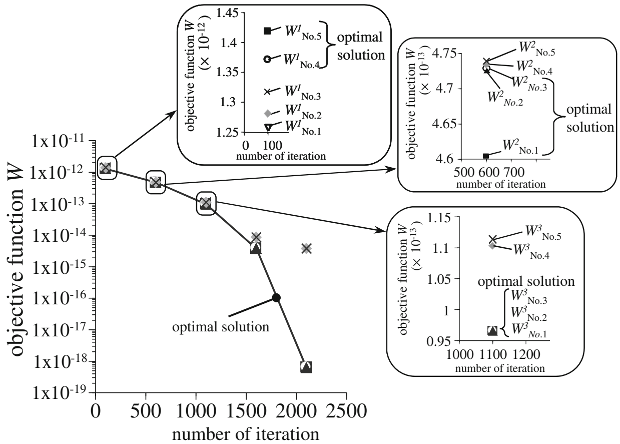


Fig. 7. Calculation process of an objective function *W*.

The figure illustrate that the current generated within MEA flows through a separator, an end plate, and a current terminal wire. As the conductivity of the end plate of copper is larger than that of the separator, the current density in the end plate is the largest within the fuel cell. The values of $|B|_{max}$ and $|B|_{min}$ of magnetic field around the fuel cell are 0.1151×10^{-4} T and 0.1023×10^{-4} T, respectively.

Figure 7 shows the calculation process of objective function W at each iteration by the proposed inverse problem analysis of the heuristic search method. The figure illustrates that $W^1_{\mathrm{No.\,4}}$ and $W^1_{\mathrm{No.\,5}}$ at the calculation process 1 are reached to the final optimal solution. The inverse problem analysis is converged by about 2100 iterations.

Figure 8 shows the comparison between the power generation current distribution inside MEA by the forward analysis and that by the inverse problem analysis. The figure denotes that the "OFF" domain inside MEA is presumed by the proposed inverse problem analysis using the magnetic field around the fuel cell.

4 Equivalent Experimental Verification

Equivalent Experimental Model

An equivalent experimental model of a single cell type fuel cell as shown in Fig. 9 was made and the current distribution in the MEA composed of a conductive rubber board was estimated. This is composed of a pair of copper end plates, a pair of separators made from carbon, a sheet of conductive rubber board that imitates MEA and sixty magnetic sensors. In this model, direct current of 8A is compulsorily impressed from the current entrance by a direct-current power supply. The dimension and conductivity of imitated MEA model are 50 mm × 50 mm × 1 mm and 4 S/m, respectively. The x-, y-, and z-components of static magnetic field, B_x, B_y and B_z obtained by the MI (Magneto-impedance) sensors of sixty positions around the fuel cell are used in 3D heuristic search. The giant magneto-impedance effect of magnetic amorphous metal wire is used in the MI sensor and can detect up to 1×10^{-10} T of the minute-magnetic fields. The case when the currents of two elements in MEA are "OFF" domain as shown in Fig. 9(a) is examined. The total current in MEA is 8A (dc). $|B|_{max}$ and $|B|_{min}$ at the measured points of flux density of sixty MI sensors are 0.3222×10^{-4} T and 0.2783×10^{-4} T, respectively.

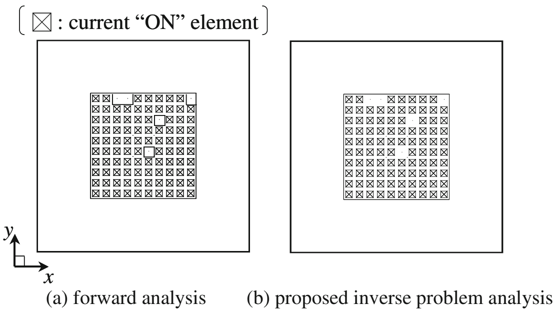


Fig. 8. Distribution of current density in MEA.

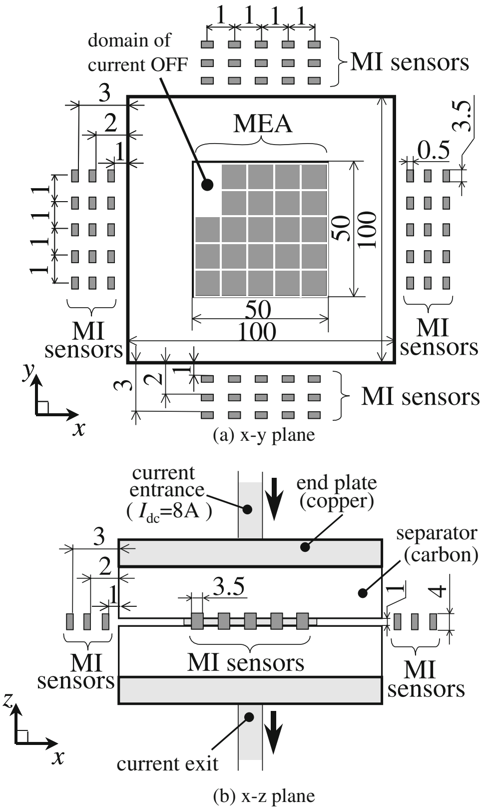


Fig. 9. Equivalent experimental model of the fuel cell (total I_{dc} = 8A).

Results and Discussion

Figure 10 shows the change of objective function W at each iteration. The history of reduction of five kinds of objective functions $W^1_{\mathrm{No.}\,1}$ to $W^1_{\mathrm{No.}\,5}$, which were selected at the process 1, are monitored. The figure illustrates that $W^1_{\mathrm{No.}\,1}$ and $W^1_{\mathrm{No.}\,2}$ at the process 1 are reached to the final optimal solution. The heuristic search is converged by 275 iterations. Figure 11 shows the current distributions in MEA obtained by the heuristic search. Two "OFF" elements in MEA in Fig. 10 obtained by the heuristic search are the same with Fig. 9(a). The figure shows that the current distribution in MEA of the fuel cell can be obtained by the proposed heuristic search using the flux distribution around the fuel cell.

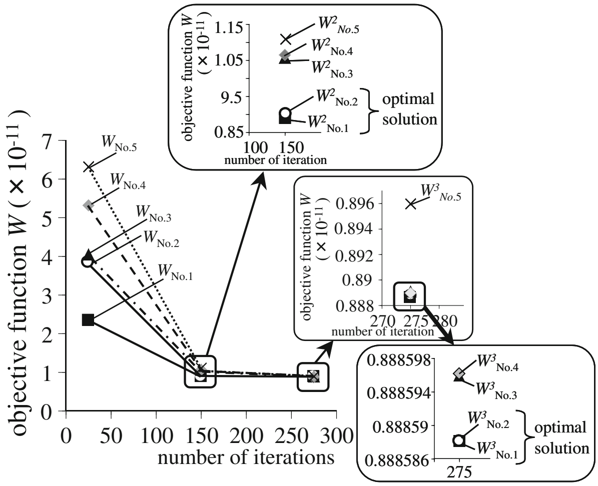


Fig. 10. Calculation process of an objective function W by equivalent experimental model.

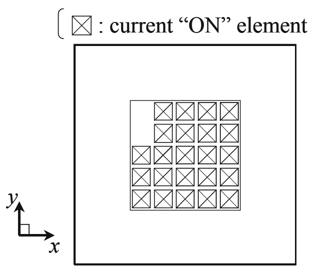


Fig. 11. Distribution of current density in MEA obtained by the proposed inverse problem analysis.

5 Conclusions

The inverse problem analysis of the heuristic search method for measurement of the distribution of the power generation current inside MEA using the static magnetic field around the fuel cell is proposed. The power generation situation inside MEA may be able to presume by this proposed technique, without stopping power generation of the PEFC. The increase in the division of the current distribution in MEA and the evaluation by the fuel cell in a stack state are a future research subject.

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