Evaluation of different models dedicated to fuel cell diagnosis through magneto-tomography method

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***Abstract* — This paper presents a comparison of different models developed to assess the health status of a fuel cell. To evaluate their capabilities, these models are tested under various conditions. Experimental results are presented as a reference, and the inverse model can be used to reconstruct the current density distribution. The multi-layer model emerges as the most effective, showcasing minimized resolution time and relative error.**

I. INTRODUCTION

Magneto-tomography stands out as one of the most efficient non-invasive methods specifically designed for fuel cell (FC) diagnosis. It involves measuring the magnetic field generated by the device, and by solving the inverse problem, it becomes possible to estimate the current density distribution inside the FC [1].

In the initial phase, several methods are available to estimate the magnetic field based on the known current density distribution. Noteworthy among these methods are the finite-element method [2], Biot & Savart model [3], and the multi-layer model [4].

This paper summarizes and compares the various developed models. An experimental setup is established to facilitate result comparisons, and the discussion will focus on current density reconstruction and relative error analysis.

II. MODELS PRESENTATION

In this investigation, the examined FC is sourced from the ZSW company. The FC consists of multiple cells, each having an active surface area of 100 cm^2, surrounded by an inactive part essential for assembly and support. To assess the viability of different models, the authors have uniformly applied each model with the same discretization. The operational principles and fundamental equations of each model are detailed to clarify the various electromagnetic models developed using Matlab®.

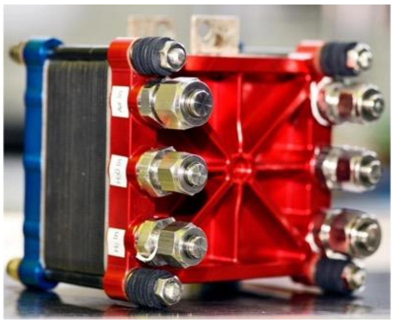

Fig. 1. ZSW fuel cell with a surface active of 100 cm^2.

A. Finite-Element Method

This model is implemented using the FEMM software. The key components of the FC are modeled, and the magnetic behavior of the FC is comprehensively analyzed. The specific elements are illustrated in Fig. 2. The figure also depicts the mesh after resolving this model, with the active part of the FC discretized into 10 x 10 elements.

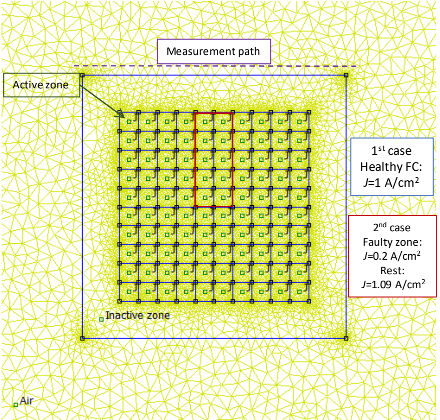

Fig. 2. FC modeling on FEMM software.

B. Biot & Savart Model

The distribution of the two-dimensional (2-D) magnetic field in the FC bipolar plate was investigated using a model that solves Biot & Savart's law in Cartesian coordinates, viz.,

$$H = \frac{I}{2\pi\cdot r} = \frac{I}{2\pi\cdot\sqrt{x^2+y^2}} = \frac{J\cdot S_e}{2\pi\cdot\sqrt{x^2+y^2}} \qquad (1)$$

where I is the electrical current [A], J the density current [A/m^2], S_e the element surface [m^2], H the magnetic field [A/m], r the distance between the central point of the electrical current and the location of the magnetic field measurement [m], and (x, y) the points in Cartesian system [m].

With knowledge of the current density distribution within the FC, it becomes feasible to accurately estimate the magnetic field distribution generated around the FC, and vice versa, by solving the inverse problem.

C. Multi-Layer Model

The magnetostatic partial differential equations, expressed in the magnetic vector potential $\boldsymbol{A}$, are defined by Laplace's equation in inactive regions and Poisson's equation in the active zone. The electromagnetic source in these

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equations is the (non-)homogeneous distribution of current density within the FC stack. By employing the separation of variables method, the general 2-D solution for $\boldsymbol{A}$ in each region is formulated using Fourier's series [4]. The analytical determination of the integration constants of series requires solving a linear matrix system that adheres to classical boundary conditions.

III. RESULTS COMPARISON

To evaluate the capabilities of different models, an experimental FC emulator has been developed and is considered as the reference in presenting the results. Two scenarios are elaborated upon: one assumes a uniform current density distribution inside the FC, and the other depicts a fault in the top center of the FC, as indicated in Fig. 2 (in red).

A. *Magnetic Field Generated Around the Fuel Cell*

The magnetic field results are compared along the same measurement path, as illustrated in Fig. 2. Fig. 3 presents the comparisons of the magnetic field obtained using different models under a uniform current density distribution (1 A/cm^2). Both components of the magnetic field are plotted on the same figure.

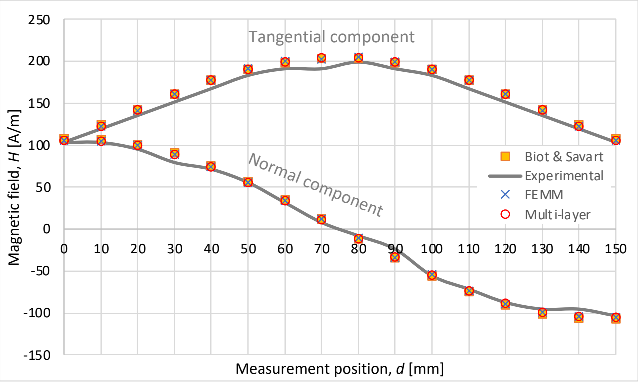

Fig. 3. Magnetic field for healthy state.

Considering a fault, as depicted in Fig. 2, where the current density is set to 0.2 A/cm^2 in the specified region while the remainder of the FC maintains 1.09 A/cm^2, a reduction in the magnetic field along the measurement path is observed, as illustrated in Fig. 4. The different models demonstrate consistency, with notable effectiveness, as the differences do not exceed 8 A/m.

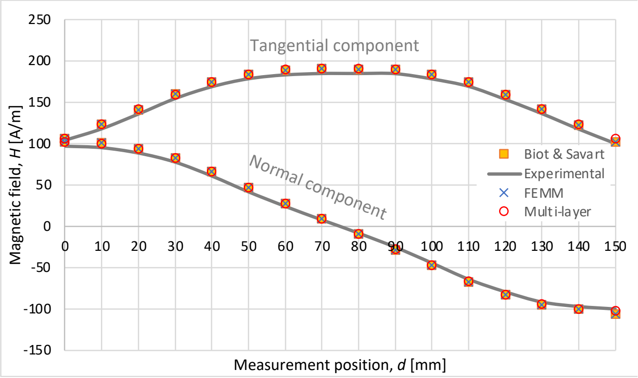

Fig. 4. Magnetic field for faulty FC.

Finally, the computation time and relative error of each model are presented in Table 1.

TABLE I. MODELS COMPARISON

Models	**Computation time (s)**	**Relative error (%)**
FEMM	30	3.93
Biot & Savart	0.02	4.17
Multi-layer	0.05	3.85

B. *Discussions and Analysis*

The FEMM resolution provides accurate results, but direct inversion is not feasible. This is in contrast to other models that allow for the generation of a matrix representing the relationship between electrical current (I) and magnetic field (H). Additionally, the computation time for FEMM is approximately 30 seconds. In contrast, for the two other models, the computation time is similar and under 1 second, indicating significantly higher efficient.

Concerning the estimation of the magnetic field, it is noteworthy that the relative error, when compared to theoretical predictions, consistently remains below 5 %. This regularity is primarily attributed to inherent uncertainties in the measurement process. It is crucial to emphasize that measurement data inherently carries imprecision, reflecting a fundamental characteristic of experimental measurements.

The decrease in the magnetic field between the two cases is more pronounced around the fault. However, each fault, depending on its discretization, implies a distinctive magnetic signature.

IV. CONCLUSION

This paper presents an assessment of various methods for translating the current density distribution based on the magnetic field generated by a rectangular electromagnetic device, such as a FC. The current density is directly correlated with the magnetic field.

Overall, the optimal choice of model, striking a balance between accurate results and reduced computation time, is the multi-layer model. This model allows for the most accurate determination of the magnetic field with a computation time reduction compared to FEMM and a computation time similar to the Biot & Savart model.

The next phase involves introducing the inverse model and determining the current density distribution by utilizing the magnetic field generated by a FC and measured around it.

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