



HAL
open science

Fuel Cell Stack Magnetic Tomography with Adjoint Method

Leonard Freisem, Olivier Chadebec, Gilles Cauffet, Yann Bultel, Sébastien Rosini

► **To cite this version:**

Leonard Freisem, Olivier Chadebec, Gilles Cauffet, Yann Bultel, Sébastien Rosini. Fuel Cell Stack Magnetic Tomography with Adjoint Method. 21st Biennial Conference on Electromagnetic Field Computation (CEFC 2024), Jun 2024, Jeju, South Korea. 10.1109/CEFC61729.2024.10585971 . hal-04677313

HAL Id: hal-04677313

<https://hal.science/hal-04677313v1>

Submitted on 26 Aug 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Fuel Cell Stack Magnetic Tomography with Adjoint Method

Leonard Freisem
Univ. Grenoble Alpes, CNRS
Grenoble INP, G2Elab
Grenoble, France

leonard.freisem@g2elab.grenoble-inp.fr

Olivier Chadebec
Univ. Grenoble Alpes, CNRS
Grenoble INP, G2Elab
Grenoble, France

olivier.chadebec@g2elab.grenoble-inp.fr

Gilles Cauffet
Univ. Grenoble Alpes, CNRS
Grenoble INP, G2Elab
Grenoble, France

gilles.cauffet@g2elab.grenoble-inp.fr

Yann Bultel
Univ. Grenoble Alpes, Univ. Savoie-Mont Blanc, CNRS
Grenoble INP, LEPMI
Grenoble, France
yann.bultel@grenoble-inp.fr

Sebastien Rosini
Univ. Grenoble Alpes
CEA LITEN
Grenoble, France
sebastien.rosini@cea.fr

Abstract—To diagnose Fuel Cell stacks (FC-stacks) and augment their durability, this paper presents a novel approach with an inverse algorithm based on magnetic tomography. The goal is to determine internal local resistivities of the stack from external magnetic measurements in order to provide a diagnosis. The inverse problem is solved by minimizing the difference between simulated and measured magnetic field. Sensitivities are computed with the adjoint state method and first numerical results are presented.

Index Terms—Fuel Cell, magnetic tomography, inverse problem-solving, adjoint state method, non-linear optimization

I. INTRODUCTION

A Proton Exchange Membrane (PEM) Fuel Cell (FC) stack is an environmentally friendly power generator as a possible alternative to fossil fuel-based systems. A FC-stack consists of several FCs connected in series. Beside others, aging is a major problem of FC-stacks and must be diagnosed to adapt controls or exchange single cells to ensure the continuous power supply same as durability and lifetime [1], [2]. The magnetic tomography (MT) can be found in literature as non-invasive FC-stack diagnostic method to obtain the local current densities (J). For the MT, the external magnetic field (B_{mes}) is measured with sensors placed around the stack, while the FC-stack is generating an electrical current and thus a magnetic field. Subsequently, numerical inverse methods are applied to calculate the local current densities in the stack [1]–[3].

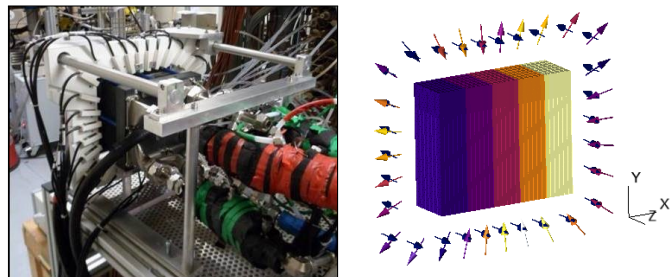
In this paper, we introduce an innovative non-invasive method for assessing the physical properties within a FC-stack. While most works propose methods for determining current densities, the originality of our approach lies in the direct identification of local resistivities using a non-linear optimization algorithm.

The Authors would like to thank the Institute Carnot - Energies du futur for funding this project.

II. METHODOLOGY

A. Data acquisition and inverse problem parametrization

To measure the magnetic field B_{mes} , we use the experiment environment firstly presented by Ifrek et al. (see Fig. 1a) [2]. 60 magnetic field sensors are placed around the FC-stack (see arrows in Fig. 1b). The active region of the FC-stack is mapped into 25 volume regions along the current flow (z-axis) (see Finite Element Method (FEM)-model in Fig. 1b) with different resistivities. Let us notice that this inverse problem parametrization only allows determining 2D faults, such as flooding, which affect the whole length of the stack. For 3D faults, like catalyst poisoning, additional layers of volume regions must be complemented. Solving the inverse problem involves the determination of the local resistivities ρ_{local} .



(a) Test bench with FC-stack and sensor array (b) FEM-Model of FC-stack and sensors

Fig. 1: FC-stack on test bench (a) FEM-Model with magnetic field sensors (arrows) around (b)

B. FEM Forward Problem-Solving

In this section, the numerical method used to compute the external magnetic field from the resistivity map is briefly described. A FEM model (Fig. 1b) is used for the resolution of an electrokinetic problem to calculate the current distribution

in the FC-stack. The used FEM-Model is divided in 27 volume regions thereof, two for the end plates and 25 for each local resistivity of the FC-stack itself, which is discretized to 9960 finite elements in total. Fig. 1b shows the 25 volume regions and the 60 sensors around the stack. In the context of optimization, it is very important to operate at a constant current supply, even if the resistivity changes. A J-conform finite element method with an imposed value of the total current flowing through the stack is then chosen. Face shape functions are used for the current density interpolation. It ensures strongly the free divergence of the current, leading to an accurate evaluation of the external magnetic field [4].

After calculating the local current densities, the magnetic field \mathbf{B}_{sim} on each sensor is computed with a numerical integration of the Biot-Savart law.

C. Inverse Problem-Solving

The original part of this paper is the novel inverse method to determine the local resistivities in the FC-stack by using the gradient descent method [5] to fit \mathbf{B}_{mes} . Therefore, we define the objective function as followed:

$$r(\boldsymbol{\rho}) = \|\mathbf{B}_{mes} - \mathbf{A}\mathbf{J}(\boldsymbol{\rho})\|^2 + \alpha\|\mathbf{L}\boldsymbol{\rho}\|^2, \quad (1)$$

where $r(\boldsymbol{\rho})$ represents the residual which must be minimized by varying the resistivity vector $\boldsymbol{\rho}$ containing the ρ_{local} , \mathbf{A} the discretized Biot-Savart matrix and $\mathbf{J}(\boldsymbol{\rho})$ the current densities depending on the local resistivities in the stack. This problem is ill-posed, so it needs to be regularized. We assume a quite regular resistivity among the surface of the FC-stack, so a regular gradient between adjacent volume regions. Consequently, we add the regularization term $\alpha\|\mathbf{L}\boldsymbol{\rho}\|^2$, with α as regularization factor and \mathbf{L} as normalized neighbor regularization matrix. Beside the objective function, we provide its gradients with the following equation:

$$\frac{dr(\boldsymbol{\rho}, \mathbf{J}(\boldsymbol{\rho}))}{d\boldsymbol{\rho}} = 2(\mathbf{A}^T \mathbf{A}\mathbf{J}(\boldsymbol{\rho}) - (\mathbf{B}_{mes} \mathbf{A}^T)) \frac{\partial \mathbf{J}(\boldsymbol{\rho})}{\partial \boldsymbol{\rho}} + 2\alpha \mathbf{L}^T \mathbf{L}\boldsymbol{\rho}, \quad (2)$$

where $\frac{\partial \mathbf{J}(\boldsymbol{\rho})}{\partial \boldsymbol{\rho}}$ is the key term to compute. To avoid its computation for each volume region, which would lead to the solving of many FEM-Models at each iteration, we apply the adjoint state method to obtain the gradients solving only one FEM-like matrix system [7]. The comprehensive calculations will be given in the full paper. The gradient descent optimization algorithm varies $\boldsymbol{\rho}$ to minimize the residual by using an interior-point optimization algorithm coupled with a Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm for the hessian approximation [6]. To obtain a unique solution, we use prior knowledge from the current and voltage measurements to constraint the admittance of the stack.

III. APPLICATION ON A NUMERICAL EXAMPLE

For the validation, we defined a numerical resistivity map (see Fig. 2a) with a constant gradient from the left to the right-hand site. The result, obtained with our novel method, an $\alpha = 4^{-12}$ and $I = 100$ A, can be observed in Fig. 2b. We

can see a smoother resistivity map, compared to the searched one. The relative error of each volume region can be observed

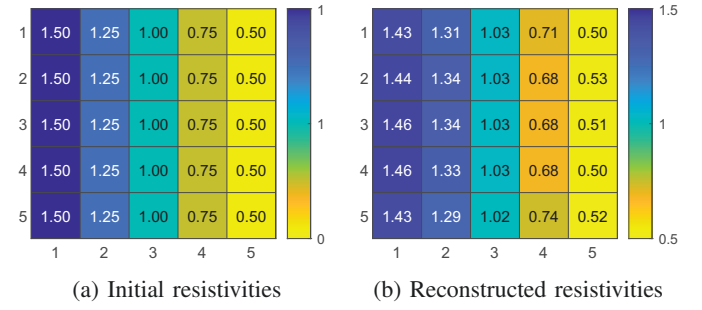


Fig. 2: Numerical test map (a) and result of reconstructed resistivities (b)

in Fig. 3a. In our example, the error is below 10% and shows a symmetry along the x-axis. The smoother map in 1b and the latter mentioned error can be explained by the regularization term. The Fig. 3b shows the convergence of the residual. This

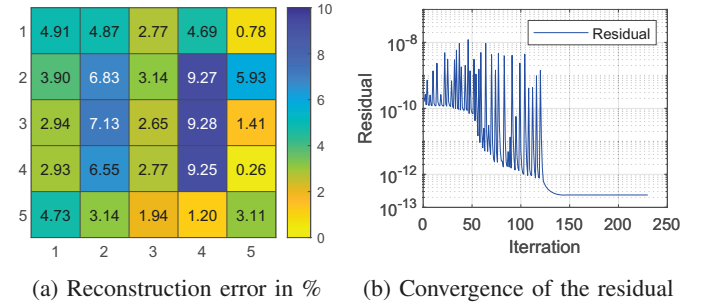


Fig. 3: Relative error (a) and convergence of the residual (b)

first numerical test demonstrates quite good convergence and accuracy for our novel MT approach for the diagnostics of FC-stacks. For the conference, we will present results obtained with measurements from a real FC-stack and compare our reconstructions with the results from past works [2].

REFERENCES

- [1] M. Le Ny et al., “Current Distribution Identification in Fuel Cell Stacks From External Magnetic Field Measurements,” IEEE Transactions on Magnetics, vol. 49, no. 5, pp. 1925–1928, 2013.
- [2] L. Ifrek, S. Rosini, G. Cauffet, O. Chadebec, L. Rouveyre, and Y. Bultel, “Fault detection for polymer electrolyte membrane fuel cell stack by external magnetic field,” Electrochimica Acta, vol. 313, pp. 141–150, 2019.
- [3] K.-H. Hauer, R. Potthast, and M. Wannert, “Algorithms for magnetic tomography—on the role of a priori knowledge and constraints,” Inverse Problems, vol. 24, no. 4, p. 045008, Aug. 2008.
- [4] T.-T. Nguyen, G. Meunier, J.-M. Guichon, O. Chadebec, and T.-S. Nguyen, “An Integral Formulation for the Computation of 3-D Eddy Current Using Facet Elements,” IEEE Trans. Magn., vol. 50, no. 2, pp. 549–552, Feb. 2014, doi: 10.1109/TMAG.2013.2282957.
- [5] H. B. Curry, “The method of steepest descent for non-linear minimization problems,” Quart. Appl. Math., vol. 2, no. 3, pp. 258–261, 1944, doi: 10.1090/qam/10667.
- [6] R. Fletcher, Practical methods of optimization, 2nd ed. Chichester; New York: Wiley, 2008.
- [7] J. Cea, “Conception optimale ou identification de formes, calcul rapide de la dérivée directionnelle de la fonction coût,” M2AN - Modélisation mathématique et analyse numérique, vol. 20, no. 3, pp. 371–402, 1986.