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Spatial harmonic current density basis for faults identification in fuel cell stack from external magnetic field measurements

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Abstract— An original approach used for the identification of faults in fuel cell stacks is presented. It is based on the 3D reconstruction of the current density from external magnetic field measurements which is an ill-posed magnetostatic linear inverse problem. Suitable current density and magnetic field basis are proposed in order to define both local and global faults on a fuel cell stack. In order to ensure the uniqueness of the solution, the inverse problem is regularized thanks to the truncated singular value decomposition (SVD).

Keywords— Fuel cell stack, magnetostatic, inverse linear problems, non-invasive diagnosis, truncated SVD

I. INTRODUCTION

Environmental issues present the fuel cell stacks as an alternative to the combustion engines in vehicles. Until now the improvement of their lifetime presents a major objective. Many works have been done dealing with the faults identification in fuel cells. Our work focuses on a non-invasive technique based on the external magnetic field measurements and the inversion of the Biot and Savart law. A key point for this approach is the choice of the current distribution basis in order to efficiently solve the inverse problem. In this paper, an original harmonic decomposition for the current density is presented.

II. 3D CURRENT DENSITY RECONSTRUCTION APPROACH

A. Principle

In a first step, we consider the forward approach which consists in solving an electro-kinetic problem. From the electrical conductivities of each part of the fuel cell and by coupling the model with an external electrical circuit representation, we get the current density distribution inside the fuel cell. The key point being the current solenoidality, a Finite Element (FE) approach based on face shape function interpolation for the current distribution has been selected. In a second step, thanks to the Biot and Savart law (1) numerically integrated, we calculate the magnetic field on magnetic sensors located around the stack. The magnetic field generated by a healthy fuel cell has previously been studied with the purpose of defining suitable magnetic sensors positions optimizing the measurement ranges [2].

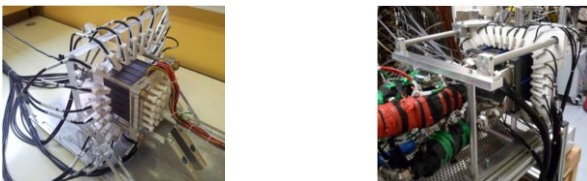


Fig. 1 Sensors around a stack simulator (left) and a real stack (right) [2]

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_{\Omega_s} \frac{(\mathbf{r}_s - \mathbf{r})}{|\mathbf{r}_s - \mathbf{r}|^3} \times \mathbf{j}(\mathbf{r}_s) d\Omega_s \quad (1)$$

Let us suppose that the fuel cell is meshed into elements carrying uniform current density \mathbf{J} . Equation (1) can be discretized and a linear relation between magnetic field on sensors and current density can be obtained.

$$\mathbf{B} = \mathbf{J}\mathbf{S} \quad (2)$$

with \mathbf{S} represents the discretized Biot and Savart operator, \mathbf{B} the measurements vector and \mathbf{J} the current density vector.

The forward model is used to simulate conductivity faults on fuel cell stacks and to obtain virtual measurements. In a second step, the measured radiated magnetic field \mathbf{B} is used to reconstruct the current density distribution \mathbf{J} by inverting the operator \mathbf{S} . The problem being ill-posed [2], we can get the pseudo inverse \mathbf{S}^+ from classical singular value decomposition (SVD) which can be truncated in order to limit the influence of measurement noise.

$$\mathbf{J} = \mathbf{S}^+ \mathbf{B} \quad (3)$$

B. Current density basis

A key point is the choice of a basis for \mathbf{J} which has to be sufficiently compact in order to limit the number of degrees of freedom but also sufficiently large to cover the space of all possible faults configurations.

Different strategies have been tested to define the current density basis on the previous works. Hauer et al.[1] construct a basis based on a lumped resistance equivalent circuit model. Each vector of the basis corresponds to the field generated by a current distribution flowing in the electric circuit with each resistant imposed to an infinite value successively. In [2], we have proposed a decomposition of the current distribution into a 2D spatial Fourier series completed by a 3D model in order to take into account the current flow in end plates. If this approach is suitable for 2D faults reconstruction (i.e homogenous current faults along the stack), it is not convenient for 3D local faults.

In this paper we propose to investigate another way to build the current density basis suitable for 3D current reconstruction. The vectors of the basis have to satisfy the free divergence of the current. Thus they are generated from an electrical vector potential \mathbf{T} interpolated by edge shape functions and obtained by applying the curl operator.

In our configuration, the main current flow is along the \mathbf{z} axis. In the case of faults, current loops on the \mathbf{x} - plane and \mathbf{y} - plane have to be added to a homogeneous current (Fig. 2).

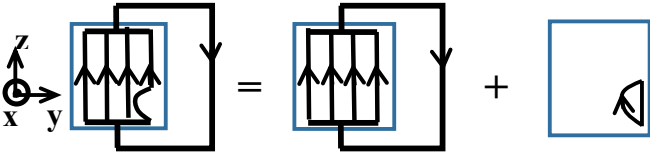


Fig. 2 Decomposition of a heterogeneous current into a sum of a homogeneous current and a faulty current loop

For a description of faults on the x -plane we have to decompose \mathbf{T} along the x axis.

$$\mathbf{T} = \sin(k_y \cdot y) \cdot \sin(k_z \cdot z) \cdot \mathbf{u}_x \quad (4)$$

with $k_y = n\pi$ and $k_z = m\pi$ where n and m are the decomposition orders.

The current vectors in the x -plane are obtained by applying the curl operator to the vector potential \mathbf{T} leading to different internal faulty loops configurations.

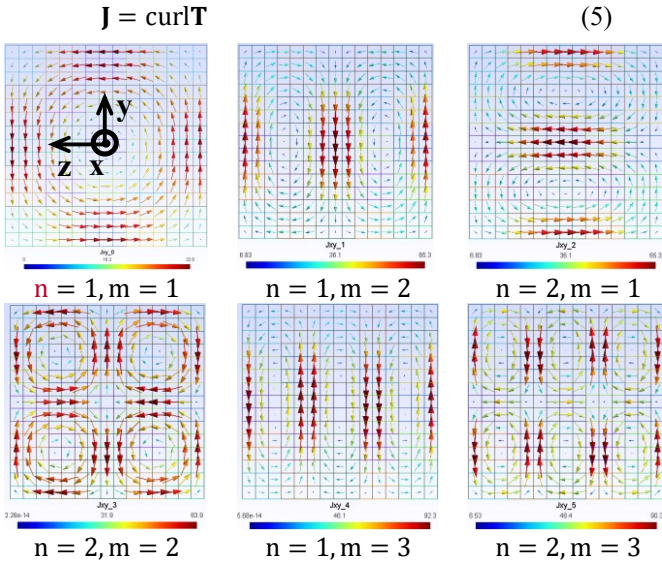


Fig. 3 The first vectors of the current density basis

The same process has to be applied in the y -plane in order to get the complete basis. The magnetic field basis is built by numerically integrating the Biot and Savart law (1) for each current distribution.

This spatial harmonic approach is very suitable for our problem. In theory the order of decomposition should tend to infinity but in practice it has to be truncated. Let us notice that a high expansion order corresponds to a large number of current loops (i.e a high order magnetic multipole) which creates a low field on sensors. In fact, order higher than 7 do not generate any significant signal on sensors enabling a proper truncation of the spatial decomposition.

C. Error criterion

The error of reconstruction is estimated by using the relative error defined as follows:

$$\text{err} = \frac{\int_{\Omega_s} (J_{\text{real}} - J_{\text{idn}})^T \cdot (J_{\text{real}} - J_{\text{idn}}) d\Omega_s}{\int_{\Omega_s} (J_{\text{real,max}}^T \cdot J_{\text{real,max}}) d\Omega_s} \quad (6)$$

with J_{real} is the real current, J_{idn} the identified current and $J_{\text{real,max}}$ the maximum value of the real current.

III. NUMERICAL RESULTS

A. Faulty fuel cell

A very low electrical conductivity is imposed on a part of the fuel cell (see Fig.4, left in blue). The electro-kinetic conduction problem is solved to get the total current distribution and the internal current loop caused by the fault. The faulty current is obtained by subtracting a homogeneous current (Healthy fuel cell) to the current distribution in the case of a fault.

The model to simulate the fault is presented in figure 4. 72 measurements points are placed around the fuel cell. The measurement vector contains the radial and the axial component of the magnetic field. The azimuthal component is not taken into account because it is mainly due to only the healthy current.

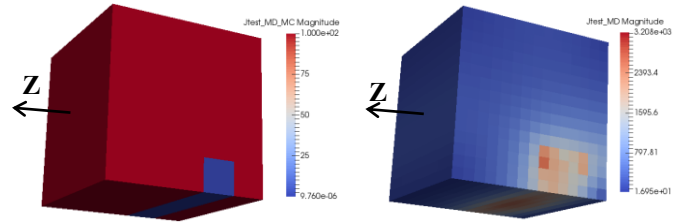


Fig. 4 Total current distribution (left) and faulty current (right)

B. Identification by external magnetic field

The radiated magnetic field created by the faulty current is inverted in order to identify the fault.

The equation system is composed of 98 unknowns and 144 equations which corresponds to the number of measurements.

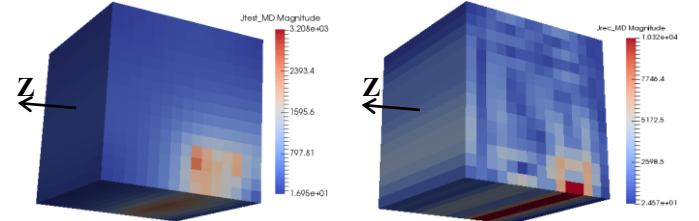


Fig. 5 Real current (left), Identified current (right)

After truncation of the matrix spectrum, the reconstruction error is calculated using (6) and an acceptable value of **11.35%** is obtained. The presented result shows a good match between the real current and the reconstructed one with a relatively small error.

IV. AKNOWLEDGMENT

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V. REFERENCES

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